Exponential Profile Formation in Simple Models of Scattering Processes

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Exponential profiles are ubiquitous in galaxy disks

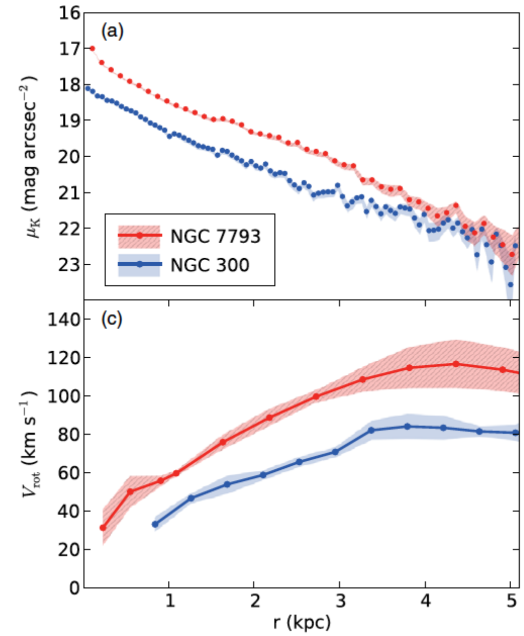
• In recent years the profiles have been tracked out as far as 10 scale lengths (*a factor of 22,000 in surface brightness*).

• They are observed across spiral types, including bars, though there are often breaks in barred exponentials.

• They are found in dwarf galaxies (e.g., Hunter, et al. 2011, ApJ 142, 121).

• They are found in LSB galaxies, though not as cleanly (see J. M. Schombert, S. McGaugh, 2014, PASA, 31, 11)

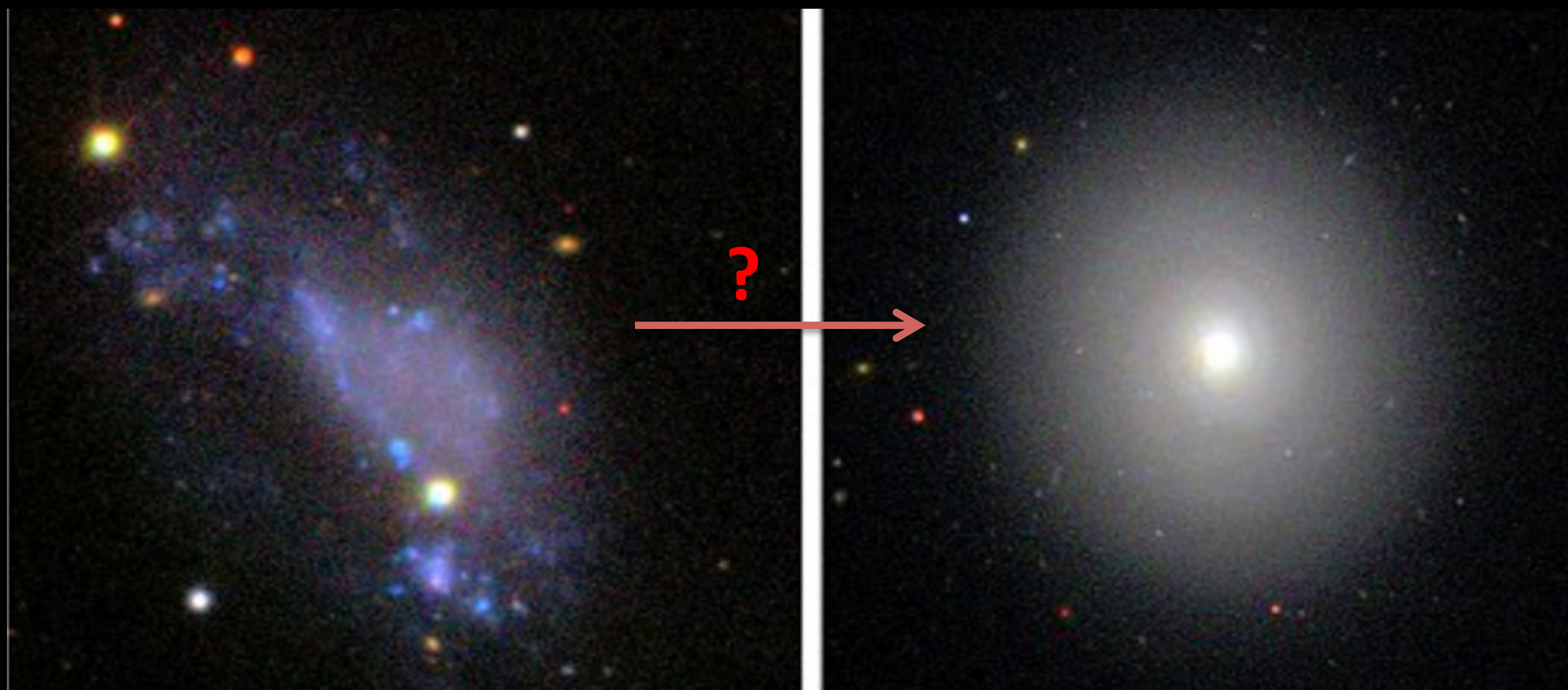
• And they go out to quite high redshifts (see Fathi, et al. 2012, MNRAS, 423, L112)



Radburn-Smith, et al. (2012, ApJ, 753, 138)

There have been a number of proposals to account for the exponential profiles, incl.: minor mergers, scattering off a bar potential, or off transient spirals. We wondered about another possibility…

Does scattering of stars by clumps in young disks (and other inhomogeneities) produce exponential profiles?



Some Simple Numerical Experiments

See 2013ApJ, 775, L35, also, ApJ submitted, and work in progress.

1. Fixed, rigid halo potentials of various forms (especially the flat rotation curve, logarithmic potential and the solid-body potential).

2. 2-dimensional disk consisting of test particle stars.

3. From a few to a hundred massive "perturbers," on fixed circular orbits. The stars feel the (softened point-mass) gravity of the perturbers, and are scattered to various degrees.

4. Constant density initial disk.

Goals: to see whether particle distributions relax to a steady form, and if it is exponential. Can clump (and spiral, bar and satellite) scattering generate the exponential from very different starting conditions?

Results:

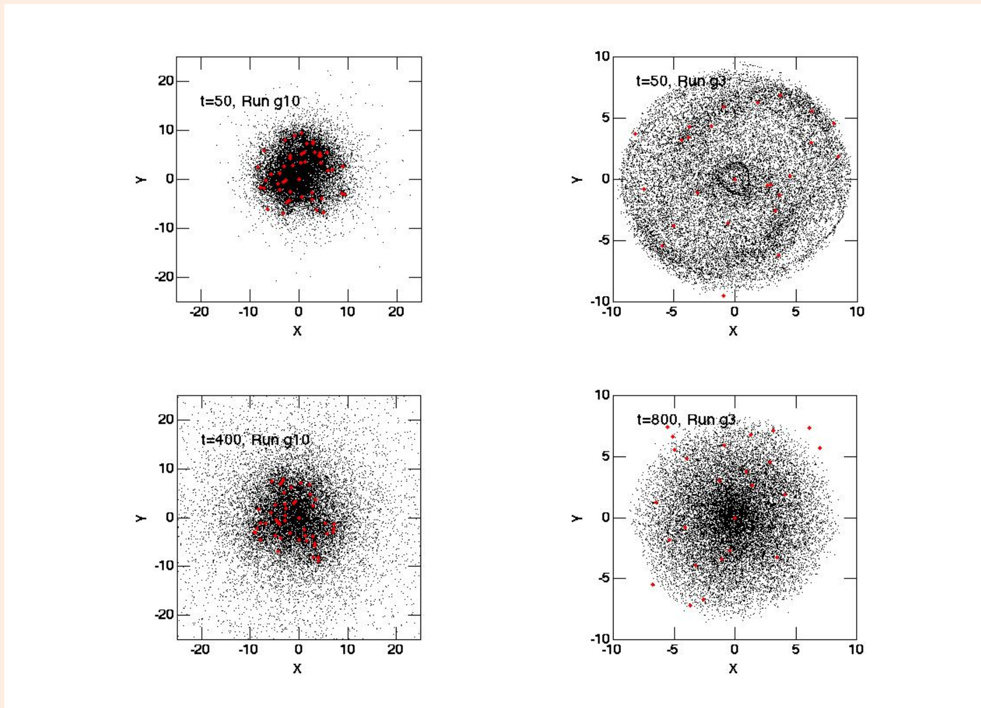
1. Exponential profiles are generically formed.

FRC

Solid-body

Early stages

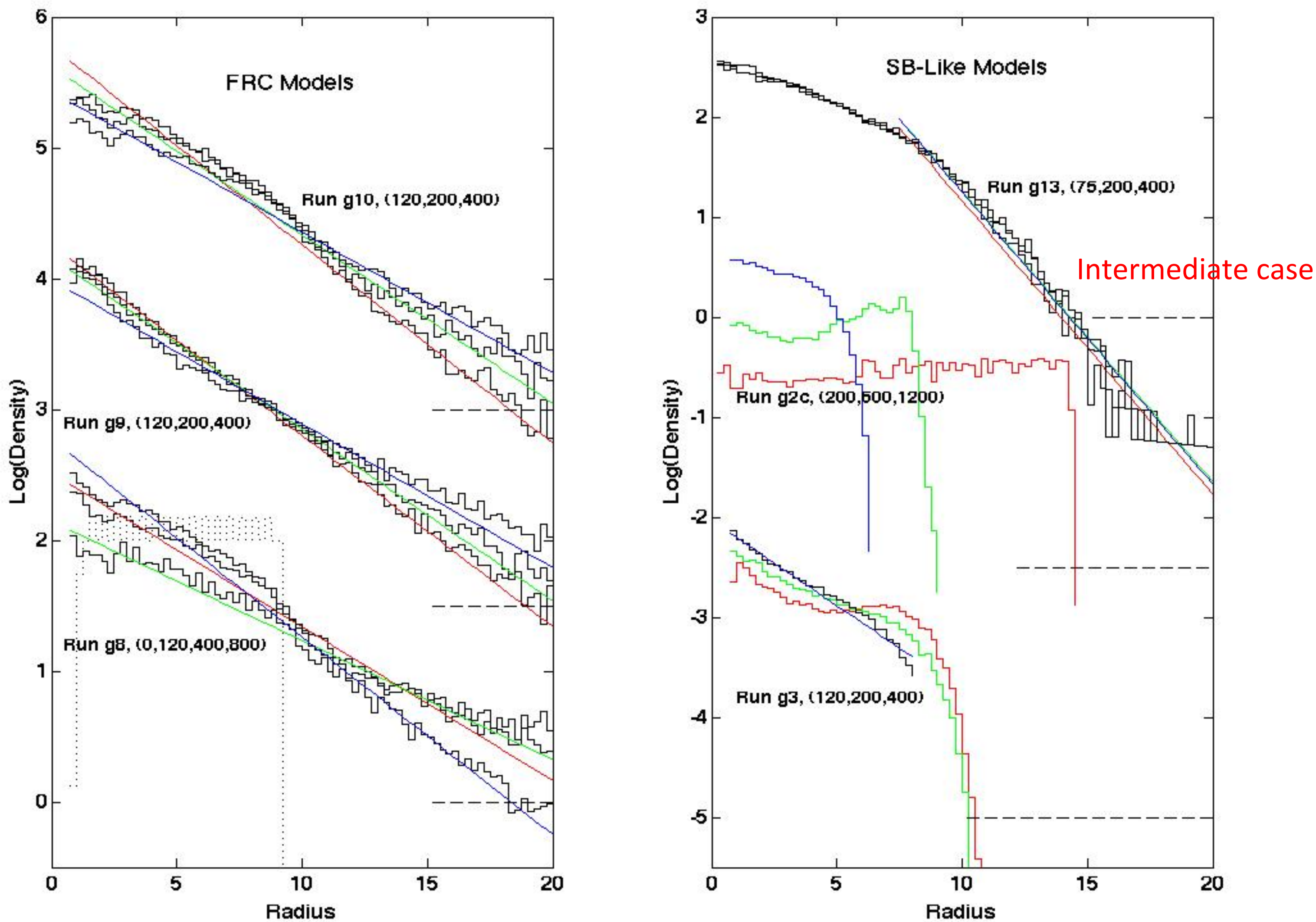
Late stages,
Fuzzy, exp. form



2. The form of the gravitational potential doesn't affect the profile outcome, but

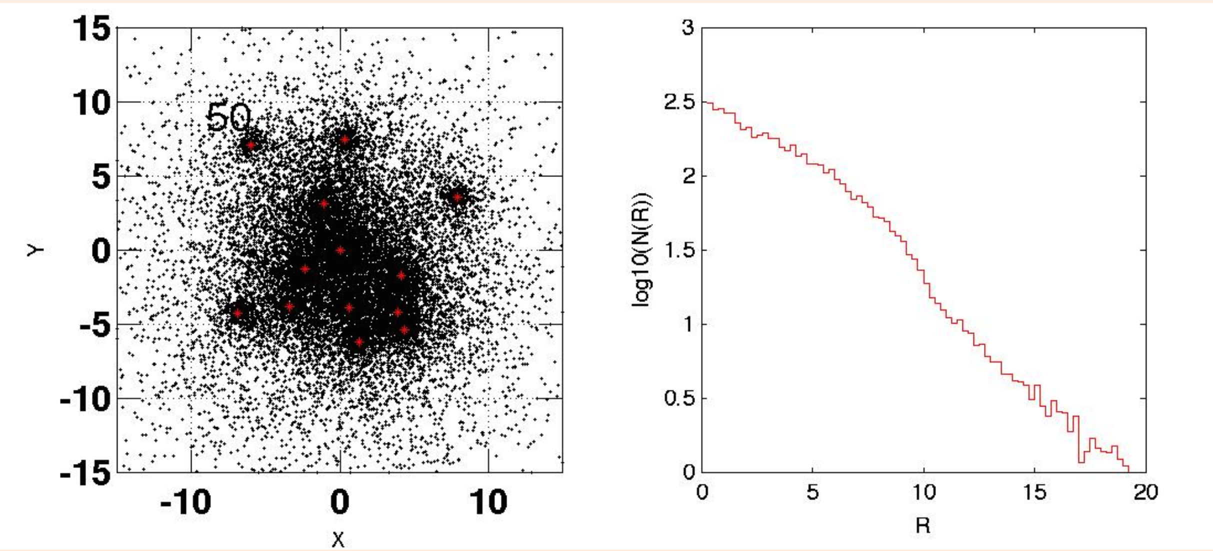
FRC disks expand, while SB disks contract in forming the exponential.
Intermediate potentials don't change much.

An overview of profile evolution in models with different numbers and masses of clumps.



3. The nature of the scatterers affects the timescale for profile evolution.

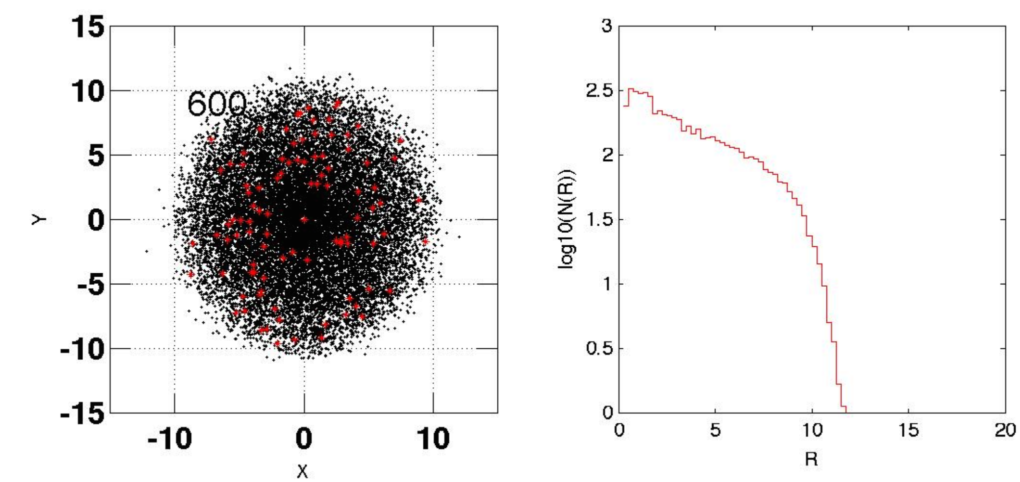
- A few large ones scatter fast, and far in the FRC case.



Model g10 with 12 clumps of mass 1.6 x10^9 M_{sun} in a galaxy of mass 2.2 x 10^{11} M_{sun} within 20 kpc, and over a time period of 450 Myr.

- Many small ones of equal total mass take longer, don't go out as far.

Model g12 with 96 clumps of mass 2.2 x10^7 M_{sun} in a galaxy of mass 2.2 x 10^{11} M_{sun} within 20 kpc, and over a time period of 2.7 Gyr.

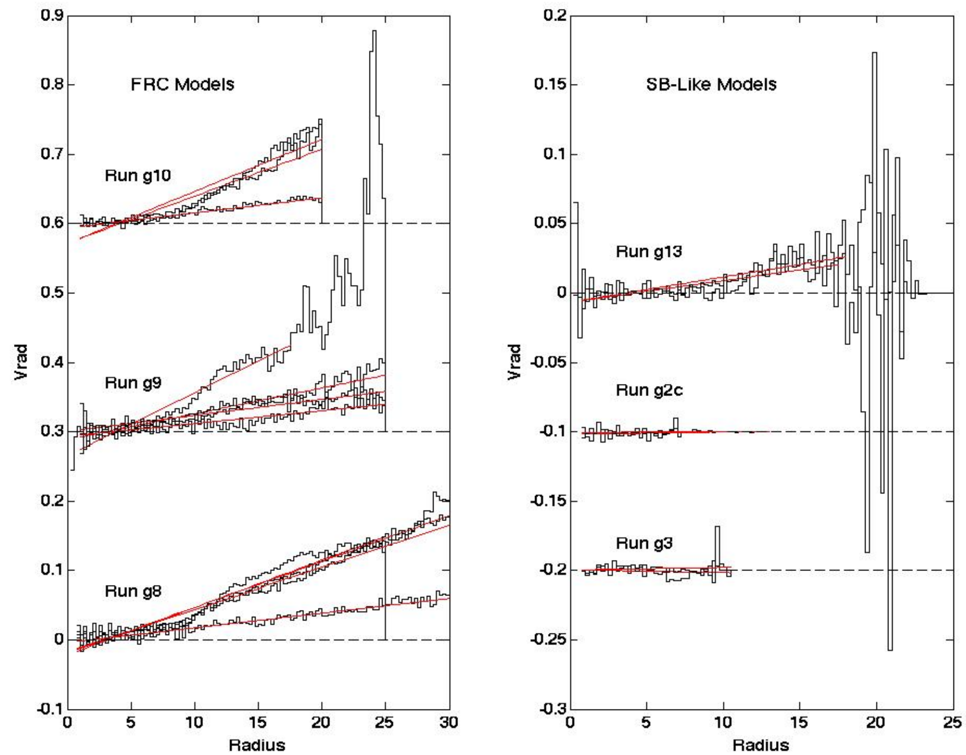


4. The effects on radial drift velocities, velocity dispersion, and orbital eccentricity are significant.

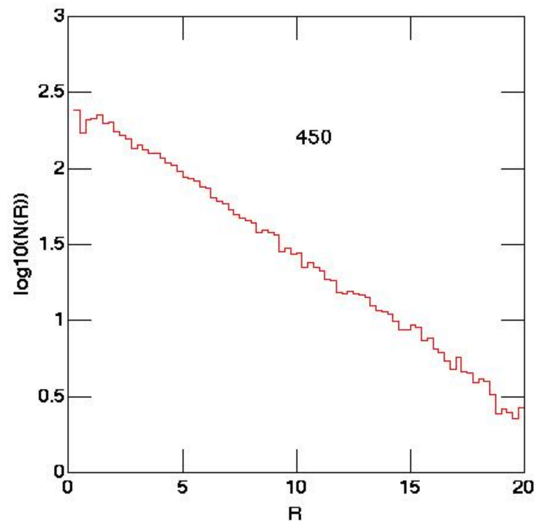
• Most of our exploratory models have used strong scatterers to generate easily visible profile effects. They produce high eccentricities and large radial drift velocities.

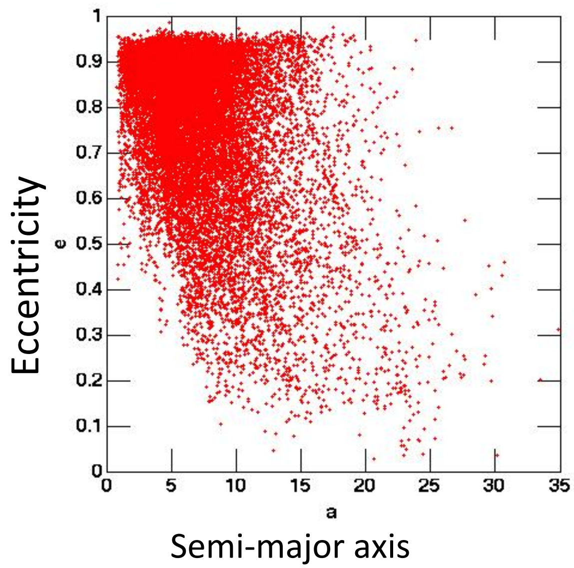
• Lower (individual) mass and softer clumps produce gentler effects. Ultimately need N-body models.

Binned radial velocity examples



Eccentricity Examples (FRC cases)

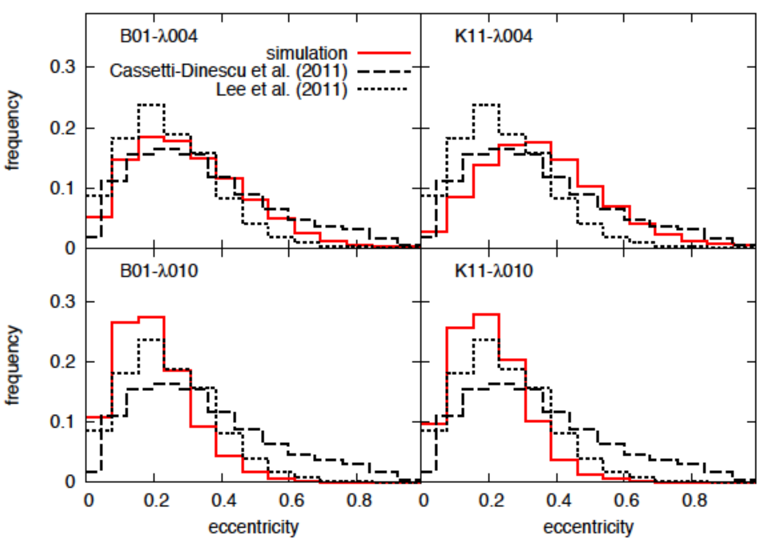


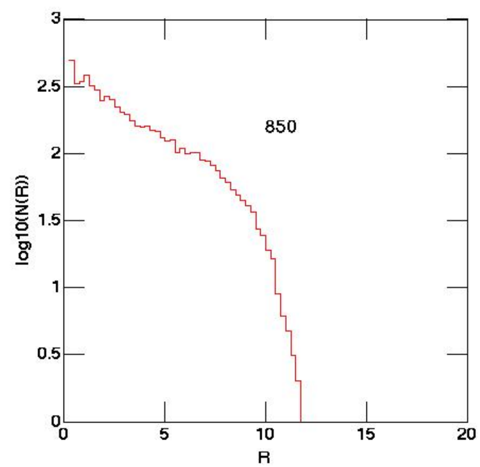


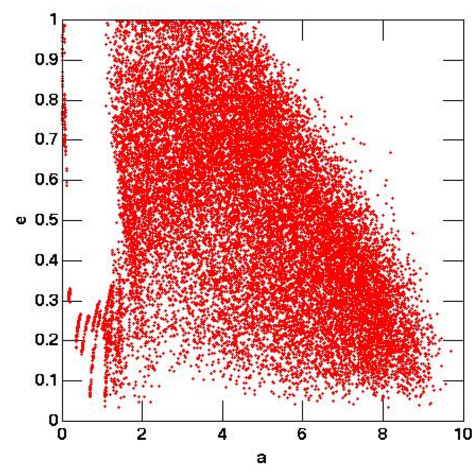
Strong scattering (Model g10)

Note eccentricities estimated from a few radial maxima, so underestimated at large radii, slightly overestimated at low radii.

Moderate scattering (Mod g12)







Clumpy disk evolution models of Inoue & Saitoh 2014MNRAS.441..243I

Conjectures on the mechanism

• Plots of individual star trajectories show that they generally go around their orbits several times or more between significant scatterings. The scattering rate does not seem to depend greatly on the radius. The scattering process may be essentially blind to azimuth, and essentially 1-dimensional in radius.

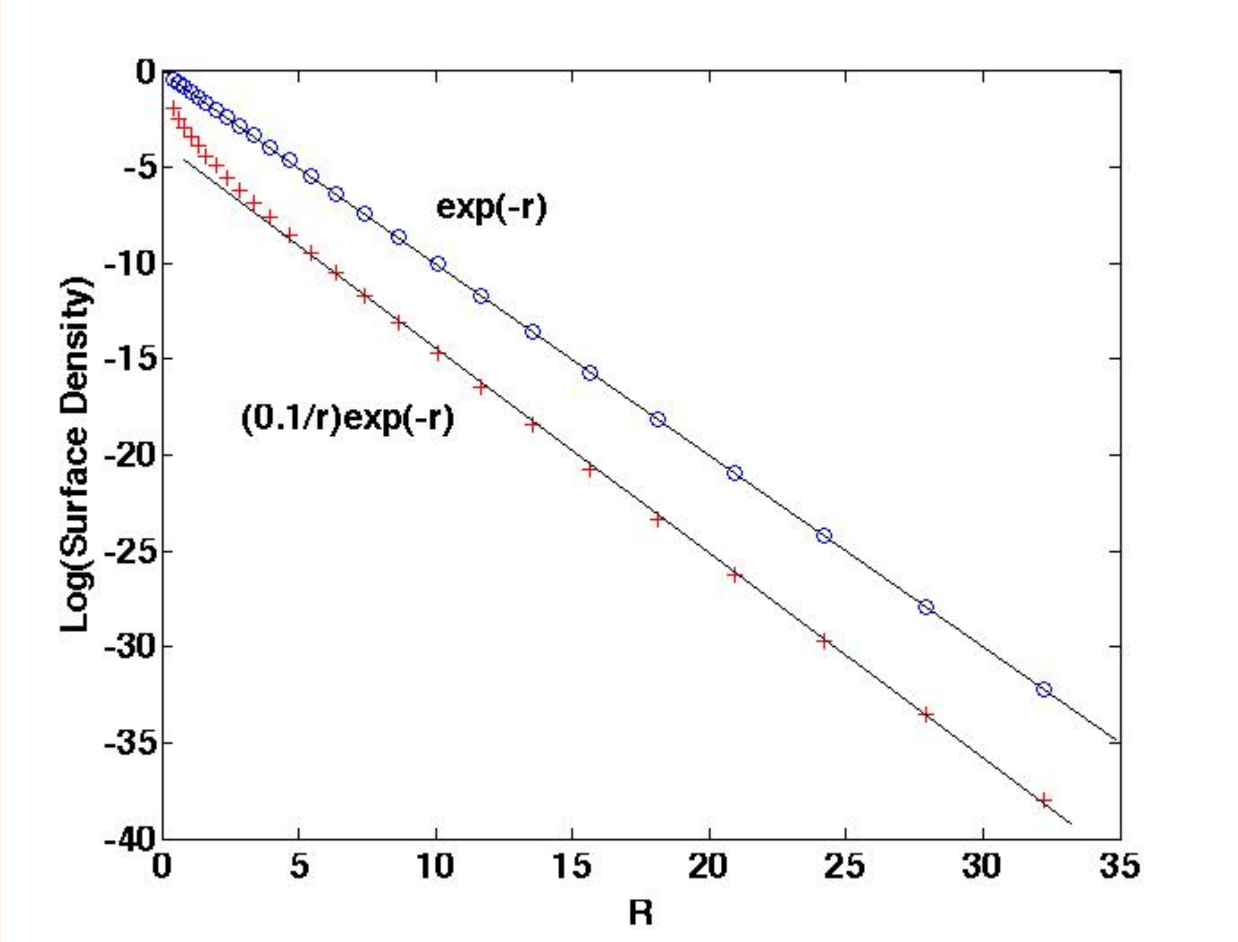
• As long as external influences and the 'temperature gradients' aren't too strong, the exponential profile in radius may be a maximum entropy profile (Boltzmann thm.), analogous to the isothermal atmosphere.

• Yet, the surface areas of consecutive annuli containing those exponentially distributed stars do increase with radius (and circumference).

Thus, the surface density decreases with radius as the product of the exponential falloff due to scattering and the 1/r geometric factor.

$$\Sigma \sim \frac{b}{r} e^{-r/a}$$

This function is not exactly an exponential, but its very close,



So possibly the ‘exponential’ profile isn’t exactly that.

This density profile above has another advantage…

The condition of (Jeans eq.) hydrostatic equilibrium, with incomplete centrifugal balance, can be satisfied with simple velocity dispersion profiles.

$$\frac{GM(r)}{r^2} - \frac{v_\theta^2}{r} = \frac{GM_{eff}(r)}{r^2} = -\frac{1}{\Sigma}\frac{\partial(\Sigma\sigma^2)}{\partial r}.$$

2 limits:

Flat rotation curve disk: $M(r) \sim r$

Substitute and solve for the dispersion to get, $\sigma^2 = \sigma_o^2\left[\frac{a}{r} - 2\left(\frac{a}{r}\right)^2 + ...\right]$

or $\sigma^2 \sim 1/r$, when $r >> a$.

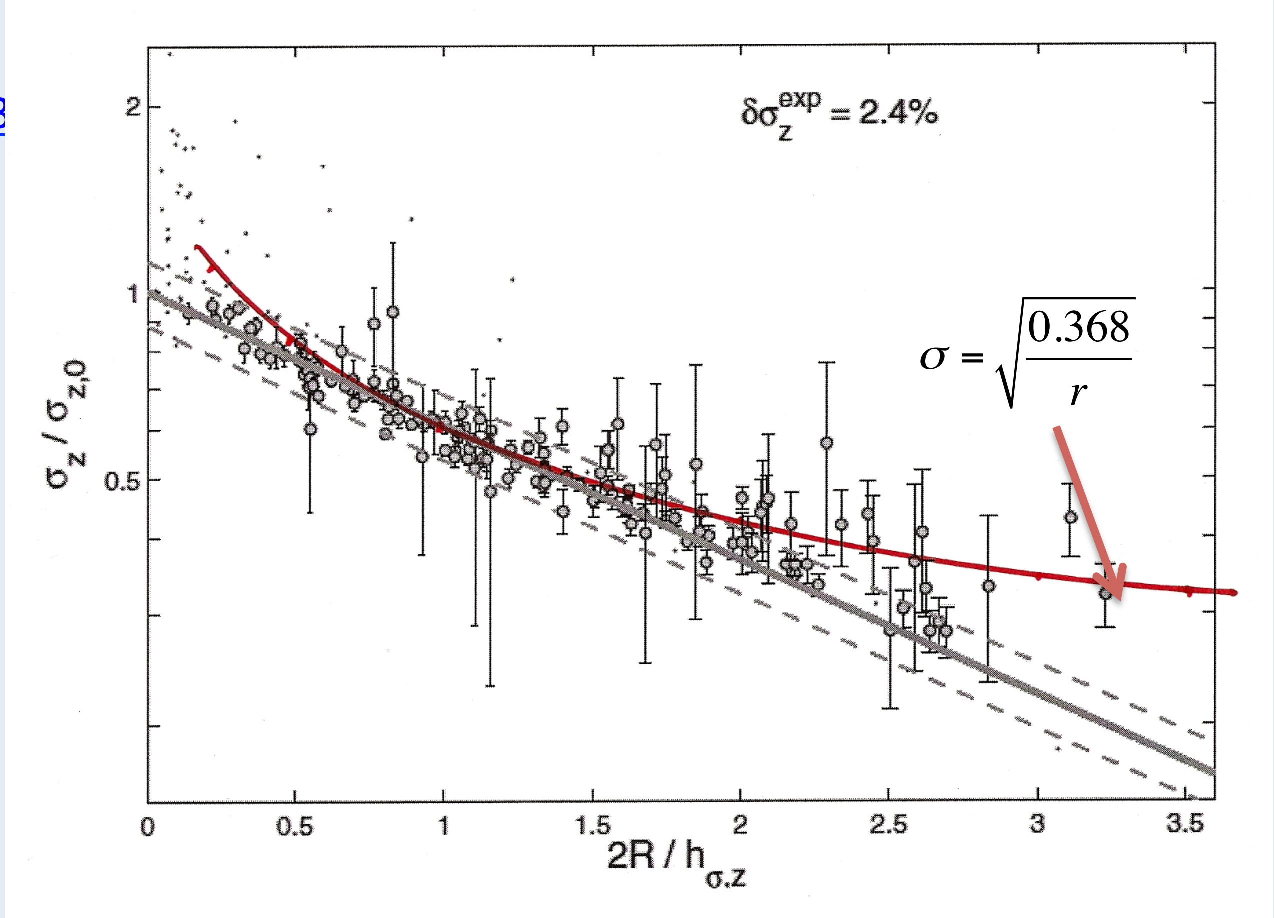
Solid-body rotation curve case: $M(r) \sim r^3$

We get, $\sigma^2 \sim r.$

Some dispersion data…

Though for the z, not the r component. (From face-on galaxies.)

From Martinsson, et al. 2013



Summary

• Clump scattering can produce exponential stellar profiles over the full range of disk potentials.

• Massive clumps do it quickly,
But produce very non-circular orbits.
Relevant to stellar halos, thick disks or outer disks?

• More numerous, low mass clumps can also do the job, but it takes longer. Also true of clumps in spirals (J. Sellwood), super-star clusters, large cloud complexes and nearby satellites. Many of these won't persist long enough to do it alone, but cumulative effects…

• In these latter cases there may be persistent 'broken' profiles.

• Accretion effects: ESH 2014 (ApJ accepted) find that halo accretion balancing SF can shrink the disk, but preserve the exponential profile.

• The universality of this process suggests a very generic mechanism. E.g., relaxation to an azimuthally blind, maximum entropy state, with $\Sigma \sim (1/r)\exp(-r/a)$.