Formation and Structure of Luminous Ellipticals with Central Massive Black Holes

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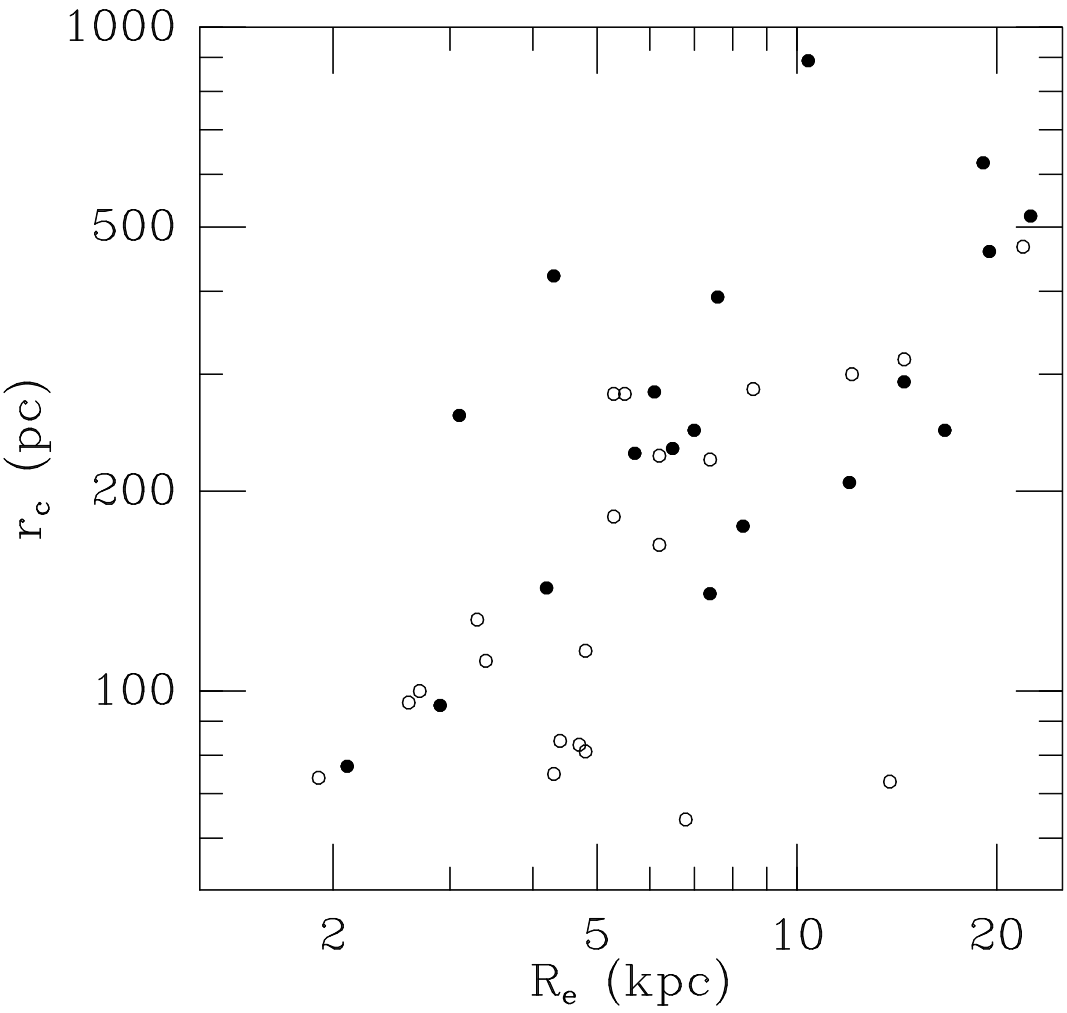
What's the problem?

The central structure of ellipticals has been a mystery

The pre-HST view (Data from Lauer 1985)

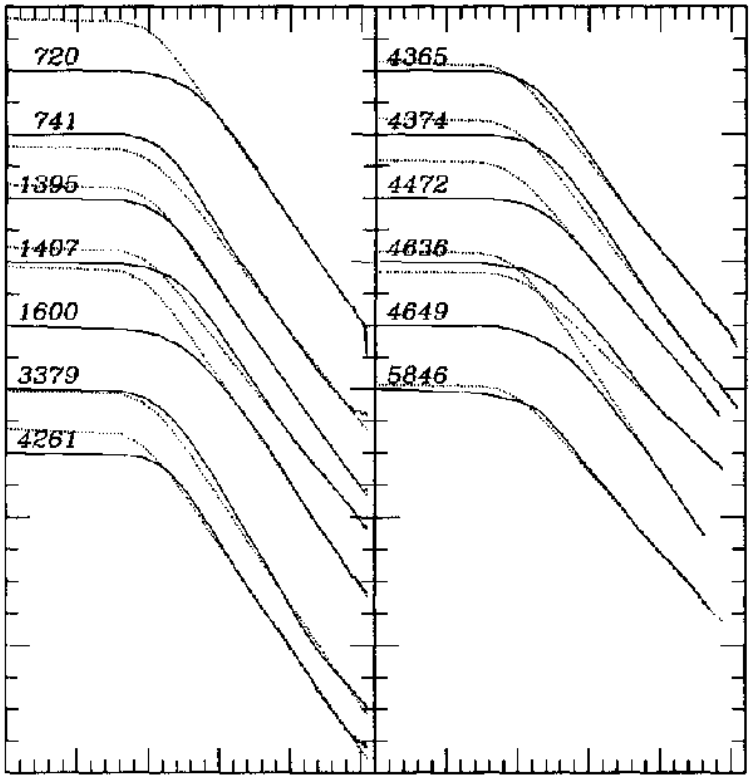


- Ellipticals have cores
- $r_c \propto R_e$

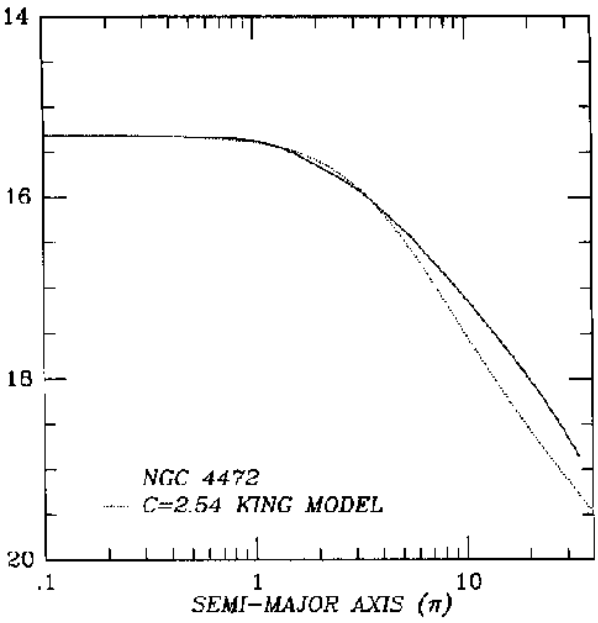
Cores of Ellipticals

Lauer 1985

The cores of the class I galaxies also appear to be well resolved ...



a typical example of the poor agreement with King models...



Theories predict...

- No core (isothermal cusps) — dissipational collapse
- r_c = const. — merging

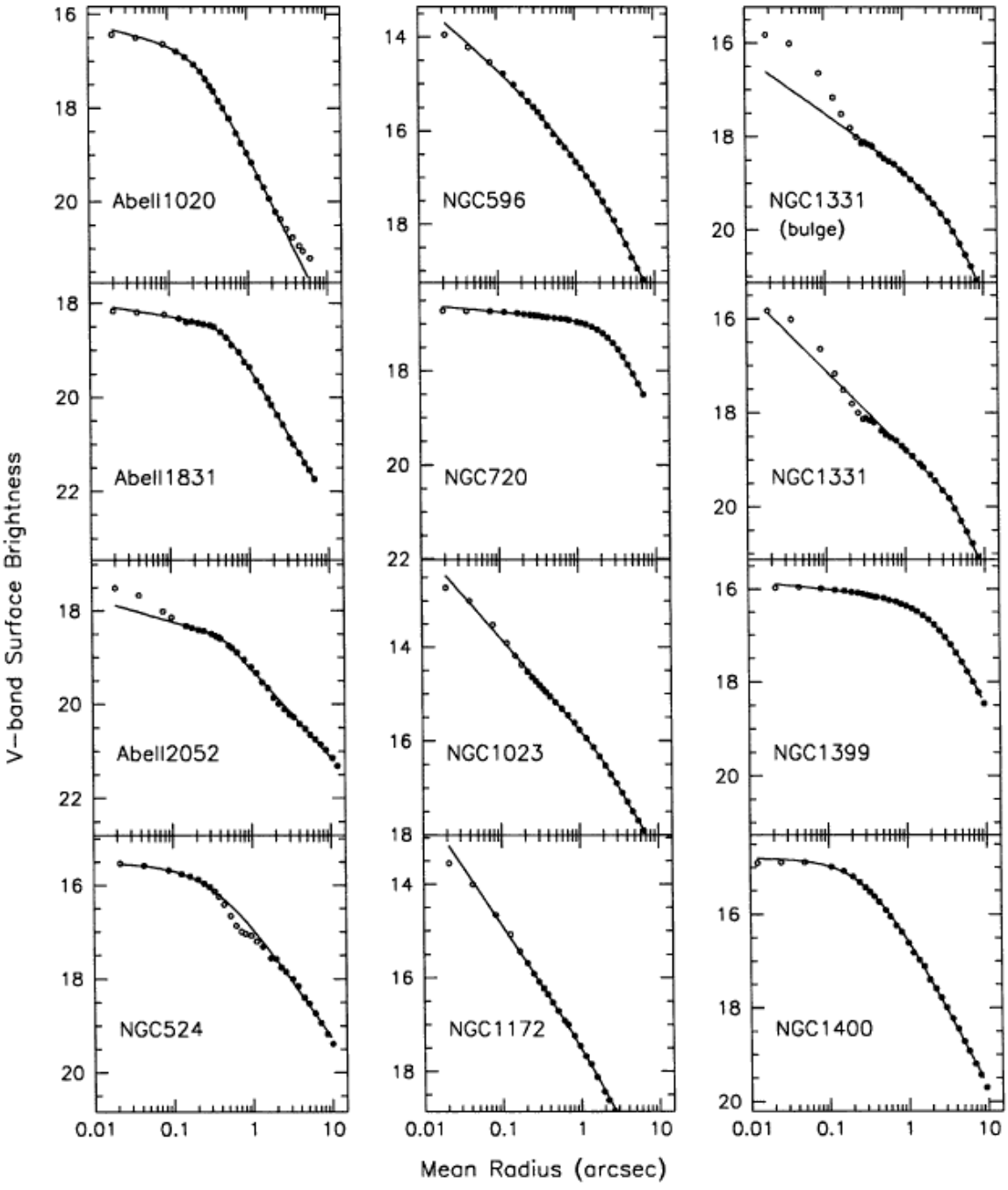
No theory predicts large cores.

Massive central BHs did not help

- Thermal evolution (Bahcall & Wolf 1976) forms $\rho \propto r^{-7/4}$
- Adiabatic growth of the central BH (Young 1980) forms $\rho \propto r^{-3/2}$

The HST view — Cores are not.

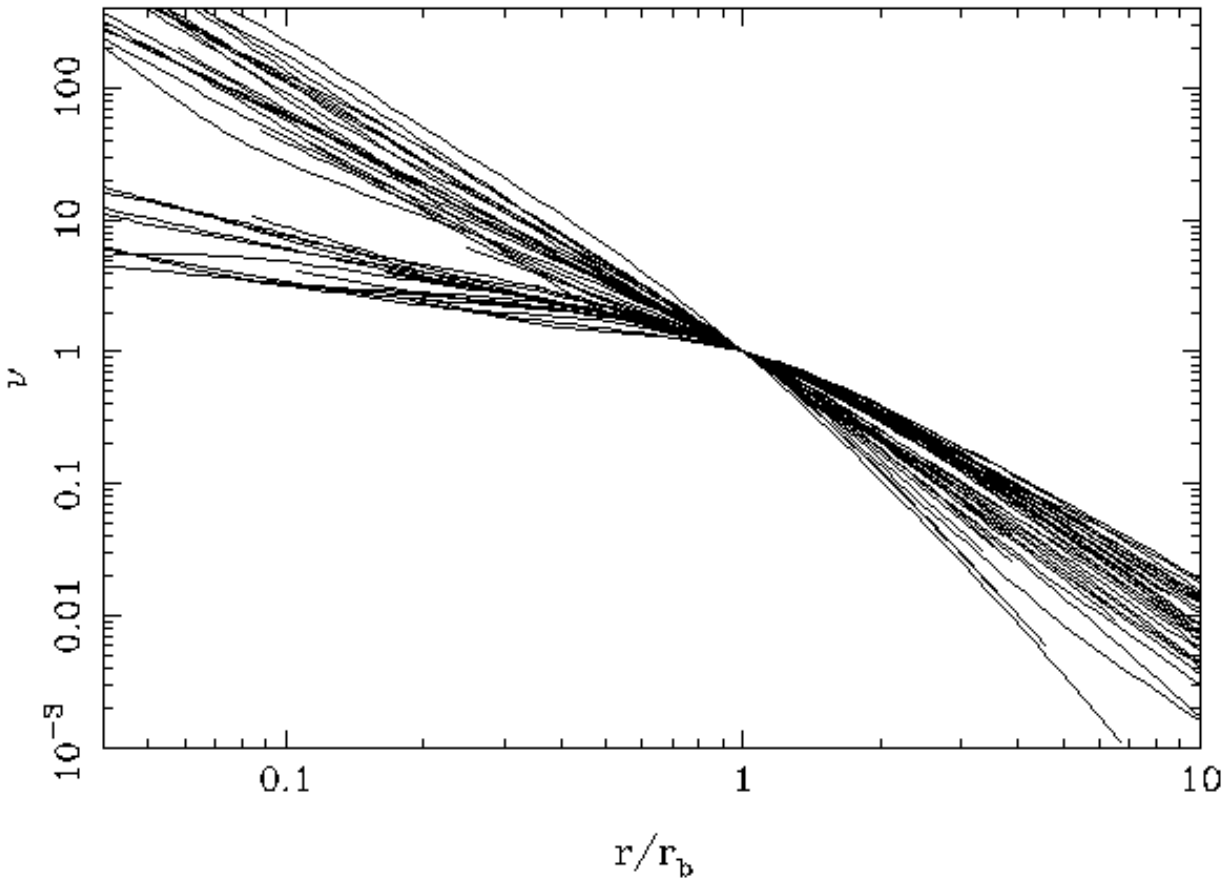
Byun et al. (1996)



No observed elliptical showed a real core...

Deprojected profiles.

Gebhardt et al (1996)



- Cuspy galaxies — $\rho \propto r^{-2}$
- Core (or "weak cusp") galaxies — $\rho \propto r^{-0.5 \sim -1}$

What have been recognized as "cores" are are all week cusps.

How these "weak cusp" ellipticals are formed?

Merging with central BH

— Simulation —

a) Let two galaxies with central BH merge with each other.

b) Take the remnant as the initial model and repeat the merging process

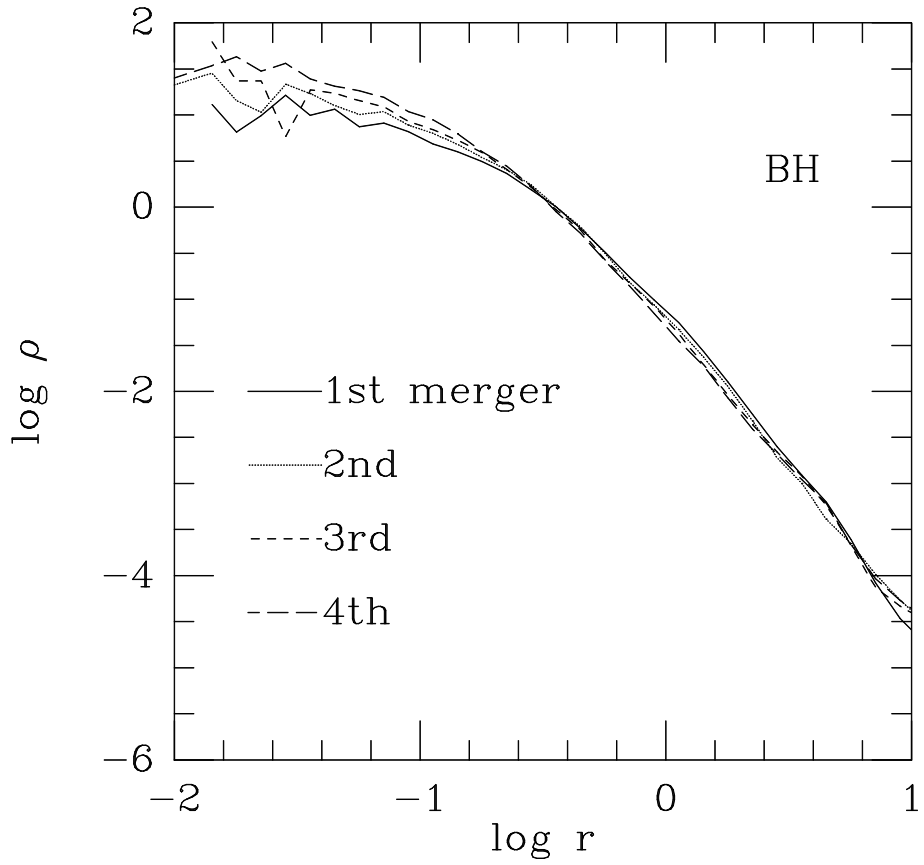
Initial conditions:
Isotropic King models with $W_c = 5, 7, 9$
$N = 32768 + 2$
$M_{BH} = 1/32 M_{gal}$ Parabolic orbit with $r_p = 1$ in the standard unit ($M = G = 1$, $E = -1/4$)

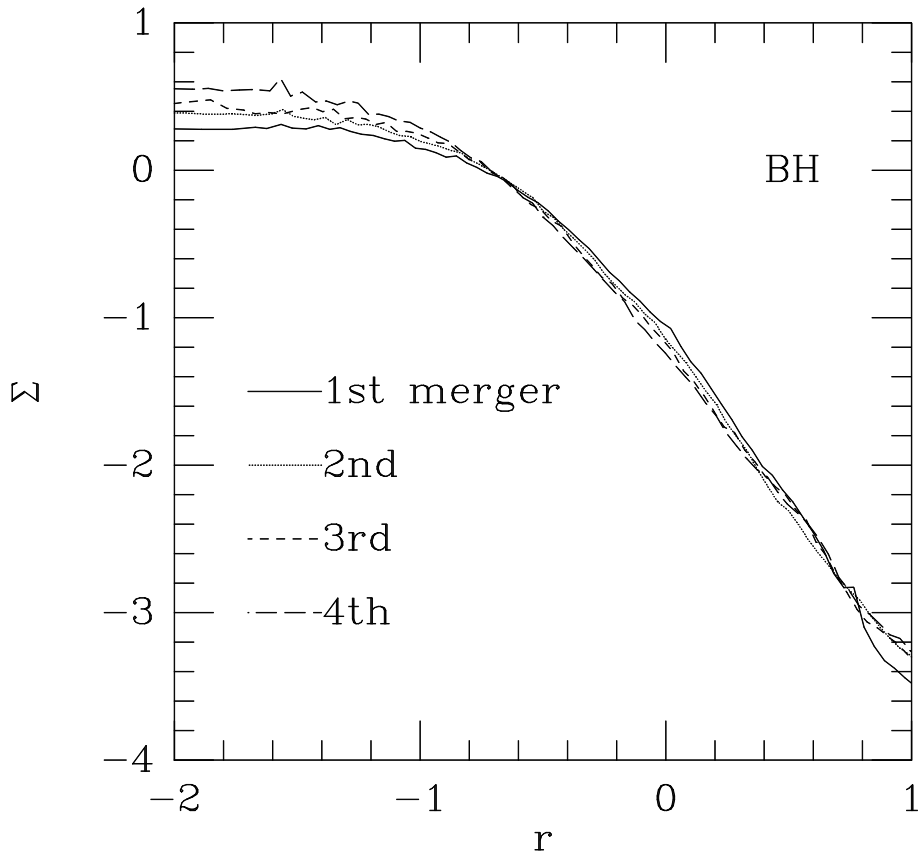
Some details

- Number of particles is halved after each simulation.
- Radius of the galaxy is scaled to the standard unit after each simulation
- calculation code: NBODY1 on GRAPE-4
- CPU time 10-20 hours per run

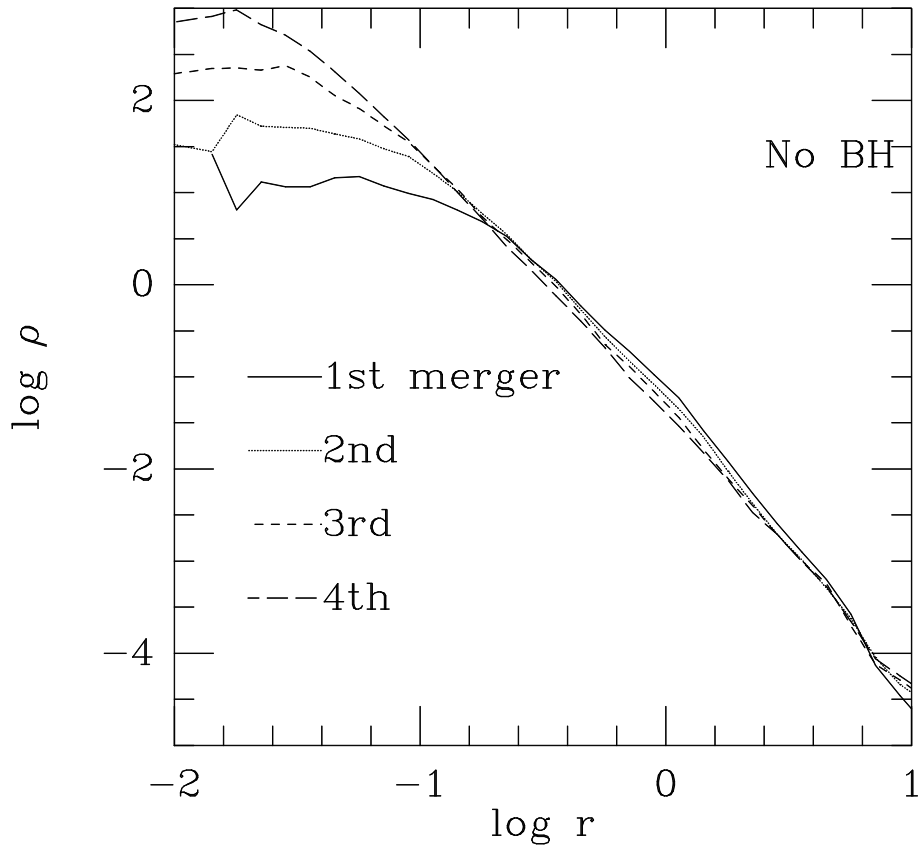
Density Profiles

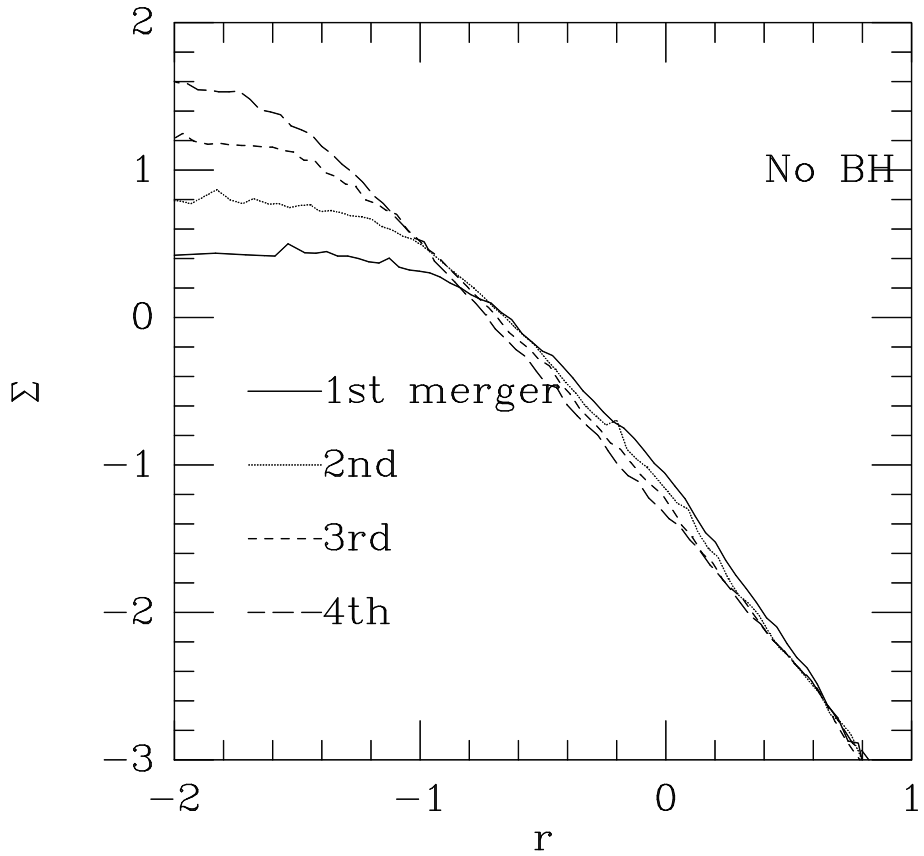
Makino & Ebisuzaki (1996)





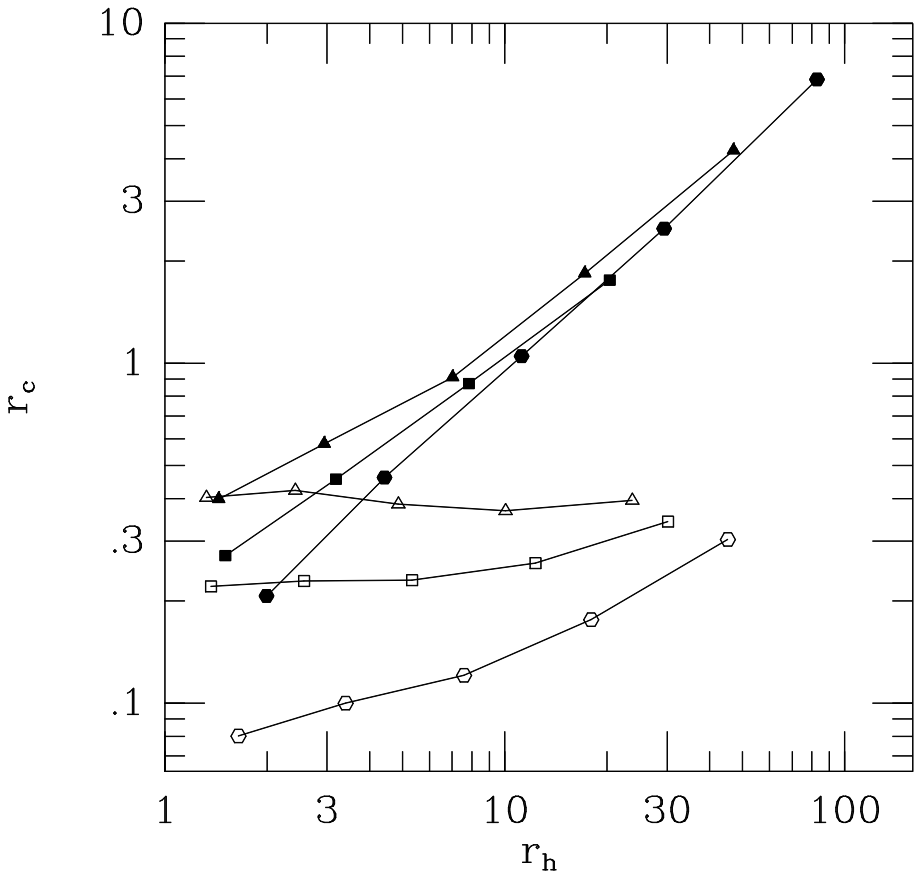
Without central BH...





Evolution of "Core radius"

The radius of the "weak cusp" region can be estimated using the standard estimation algorithm for core radius (Casertano and Hut 1985)



Open symbols : runs without BH
Filled : with BH

- All BH runs converge to $r_c/r_h = 0.08$.
- In non-BH runs, r_c/r_h decreases (or, r_c remains almost constant)

Simulation result summary

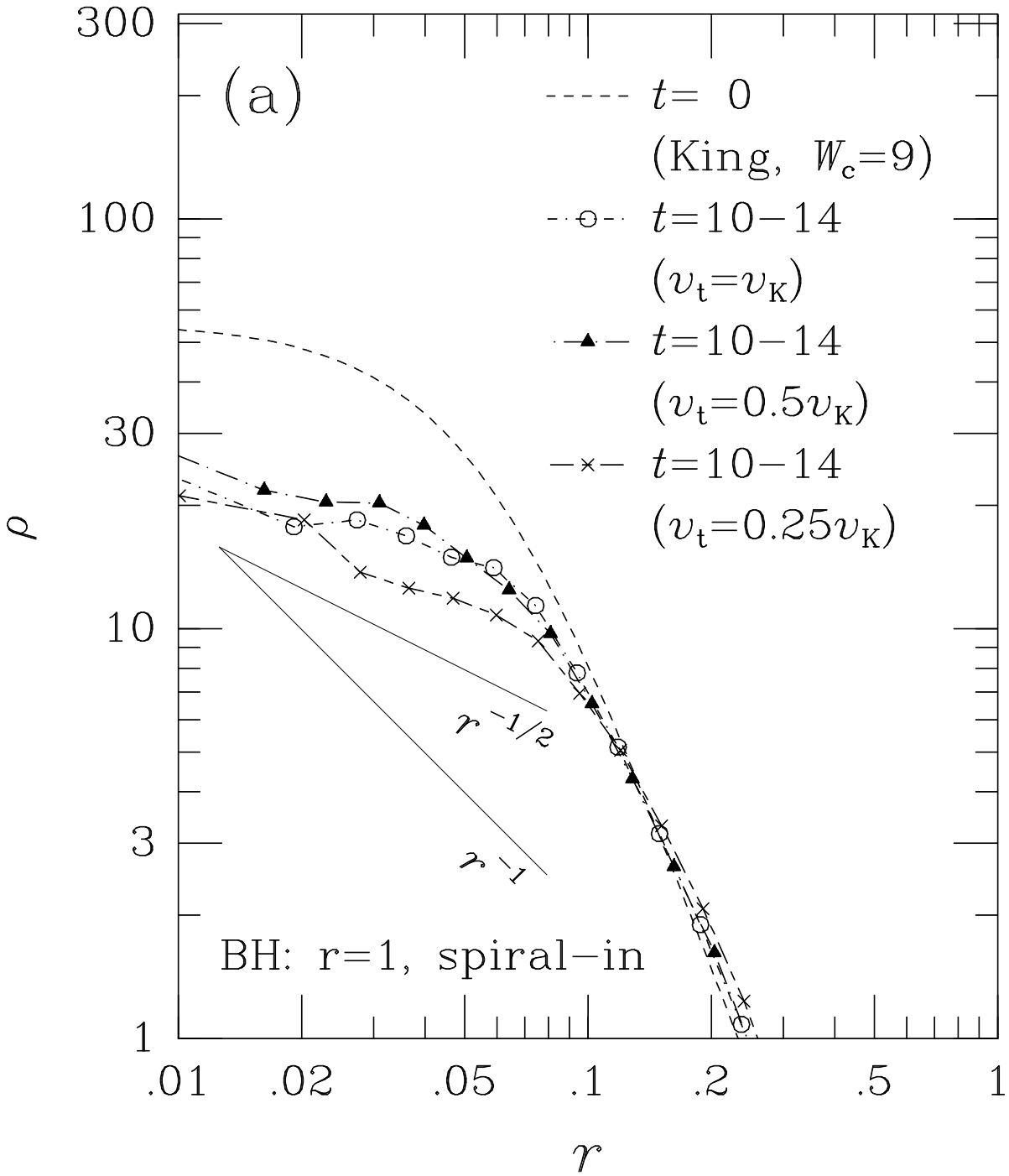
- Merging of galaxies with central BHs results in "weak cusps"
- $r_c/R_e \sim M_{BH}/M_g$

Seems to explain observation rather well.

What is the formation mechanism of "weak cusps"?

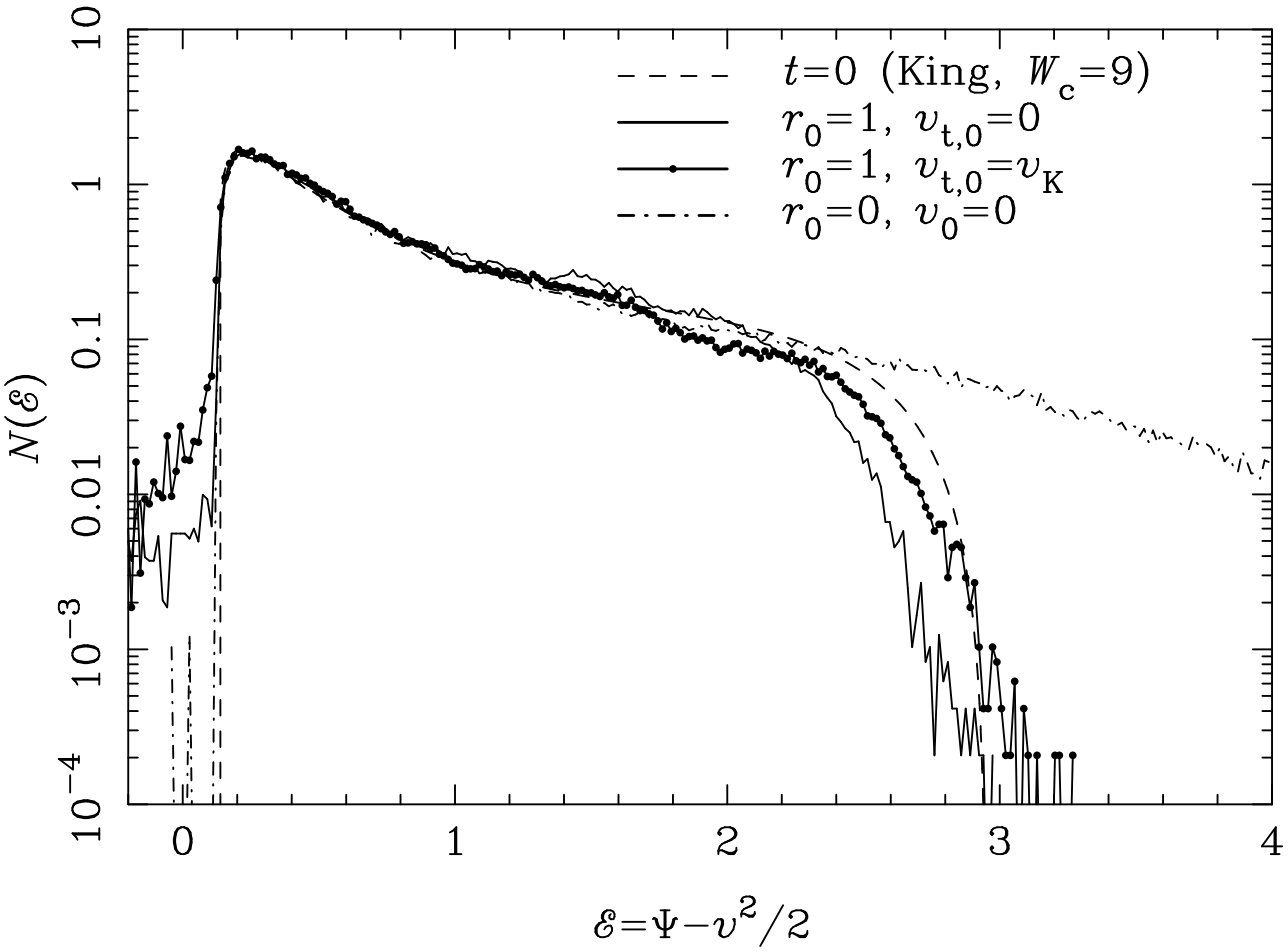
Simple Experiment

Let a BH fall down to the center of a spherical galaxy (Nakano and Makino 1999a)



The same weak cusp was formed, but WHY?

Energy distribution function



Energy distribution function is practically unchanged

↓

$N(\mathcal{E})$ becomes zero at finite $\mathcal{E}=\mathcal{E}_0$.
No star is strongly bound to the central BH.

↓

$f(\mathcal{E})(=N(\mathcal{E})/A(\mathcal{E}))$ also becomes zero at finite E.

Theory for the weak cusp

(Nakano and Makino 1999b)
$f(\mathcal{E}) \rightarrow \rho(r)$

$$\rho(r) = 4\pi \int_0^{\Psi(r)} f(\mathcal{E}) \sqrt{2\left[\Psi(r) - \mathcal{E}\right]} d\mathcal{E},$$

If $\Psi(r) > \mathcal{E}_0$, the above can be rewritten as

$$\rho(r) = 4\pi \int_0^{\mathcal{E}_0} f(\mathcal{E}) \sqrt{2\left[\Psi(r) - \mathcal{E}\right]} d\mathcal{E}.$$

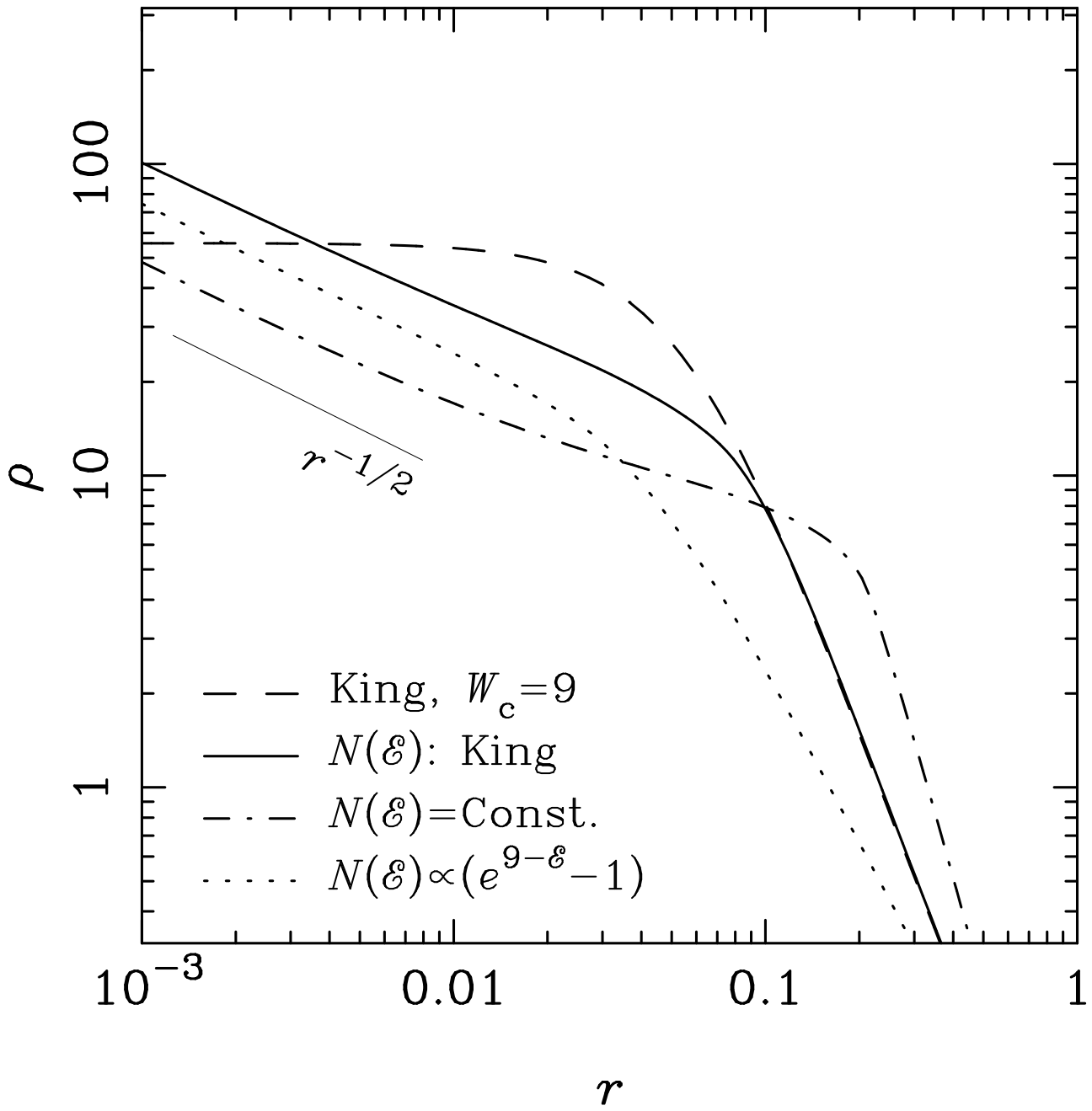
In the region $\Psi(r) > \mathcal{E}_0$, the right hand side can be expanded as

$$\rho(r) = 4\sqrt{2}\pi \sqrt{\Psi(r)} \int_0^{\mathcal{E}_0} f(\mathcal{E}) \left[1 - \frac{1}{2}\frac{\mathcal{E}}{\Psi(r)} + O\left(\left[\frac{\mathcal{E}}{\Psi(r)}\right]^2\right)\right] d\mathcal{E}$$

$$\rho(r) \propto \sqrt{\Psi(r)} \sim \sqrt{\frac{GM_{\rm BH}}{r}}.$$

Numerical example

- A self-consistent density profile for given $N(\mathcal{E})$.
- Gravitational field: self-gravity + central BH.
- Algorithm: Binney (1982)



Was this result already known?

A message from Scott Tremaine:

> I have been reading your *very nice* paper with Nakano ... I thought I would point out that *this result was actually obtained in a simple form by Peebles* ...

Paper (conference talk) by Peebles (1972)

If a BH is placed at the center of the core of a stellar system with infinitely large core radius, the density around the center would be:

$$\rho \sim \rho_0 \sqrt{1 + GM/rE}$$

"A derivation is given in Zel'dovich and Novikov (1971), p. 434."

Reasoning: Phase space density conservation
Neighborhood of BH → high velocity → high density

— Only applicable to small BH embedded in large core

Our derivation is more general

- Does not require infinitely large core
- Does not require constant f

Fate of BH binary

BH binary

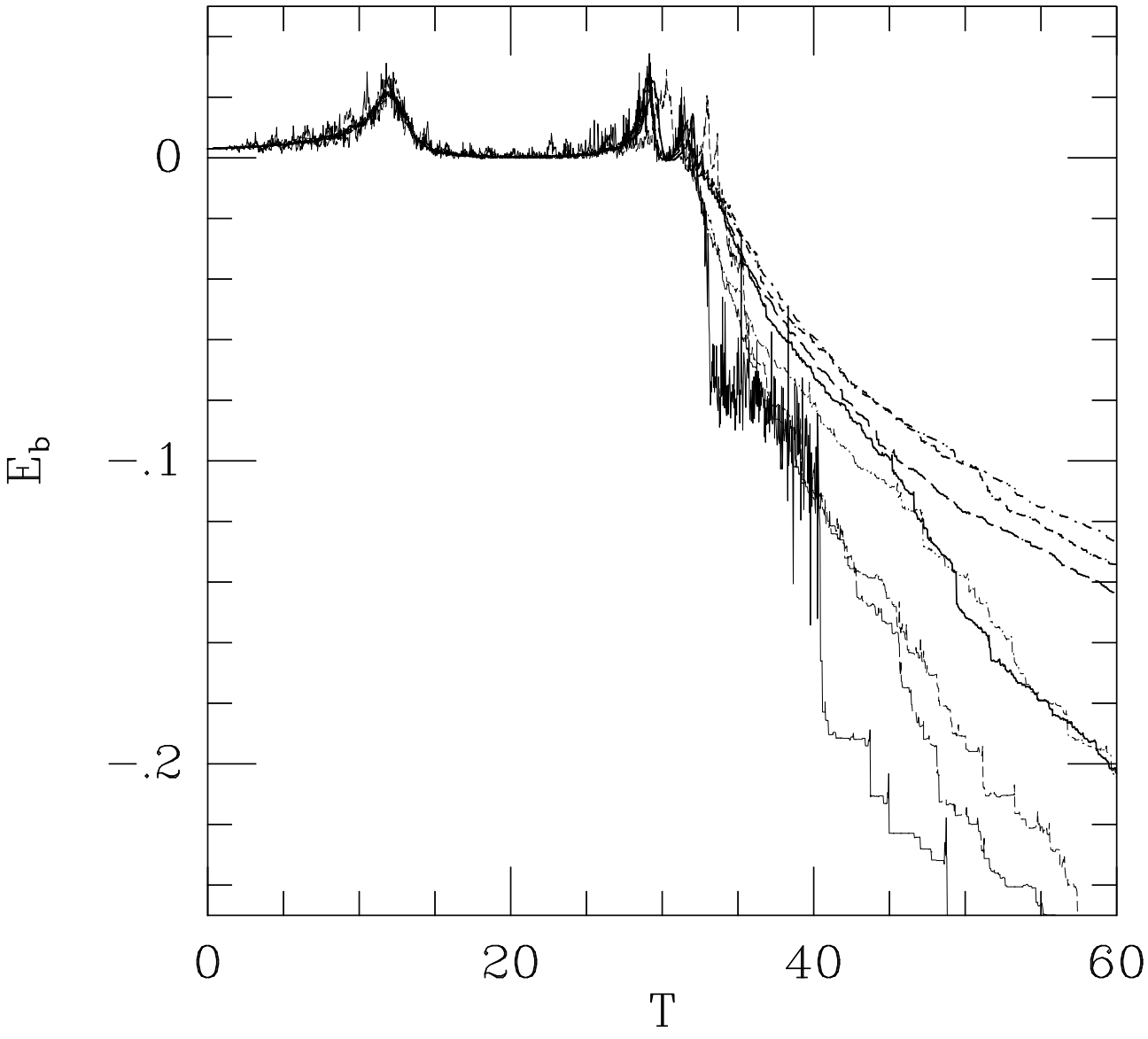
—shrink and finally merge?

—throw out all nearby stars and become stable?

Numerical studies (Makino 1997, Quinlan and Hernquist 1997)

— Evolution timescale depends on N (number of particles used)

—Extrapolation to large N: BHs do not merge within Hubble time



Result for N=2k — 256k

Summary

- We found the weak cusp is formed in merging of galaxies with massive BHs.
- The formation mechanism of the weak cusp is explained by simple analytical argument.
- Weak cusps are signatures of the merging of galaxies with BHs
- The merging timescale of BH binary is very long. Typical large ellipticals may host binary BHs.