Investigating the Dynamical Histories of Early-Type Galaxies

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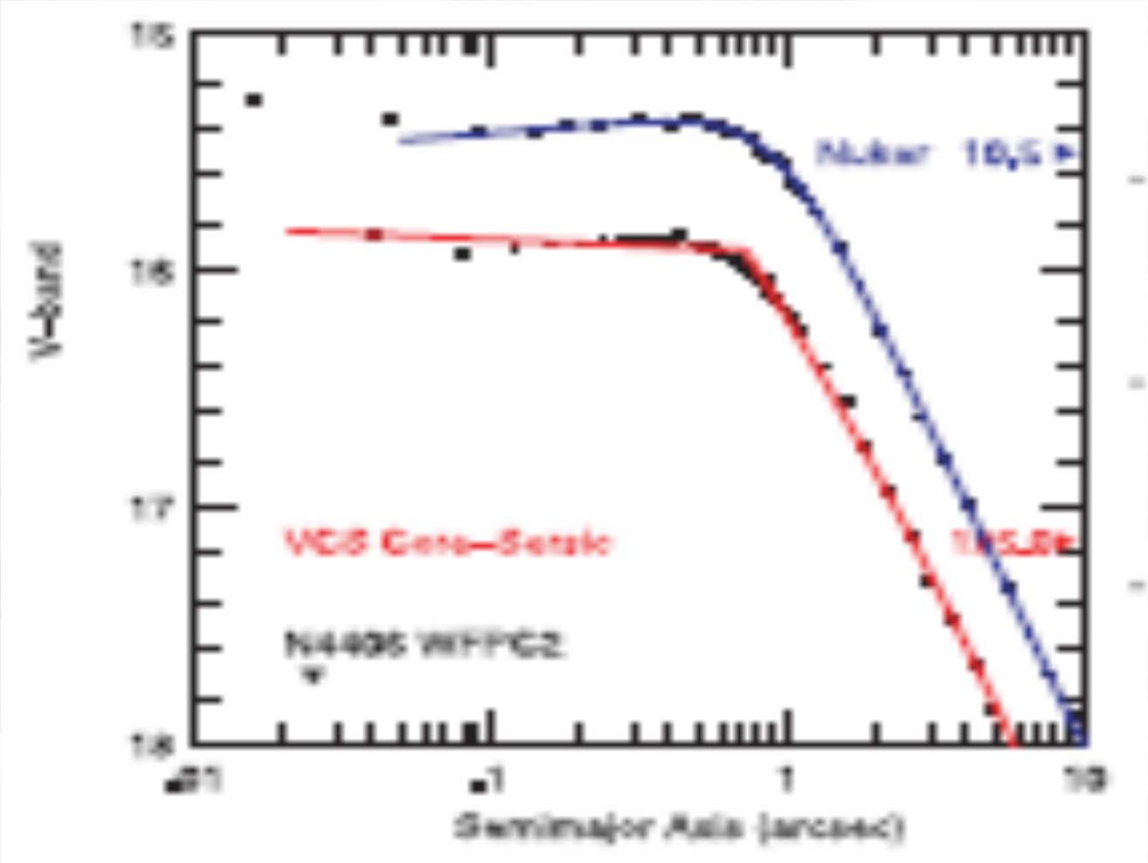
Early-Type Galaxies

- Formed by Mergers ?
- Dark Matter Profiles ?
- Supermassive Black Holes (SMBH) ?
- Core/Cusp Galaxies ?
- Binary Supermassive Black Holes (Binary SMBH) ?

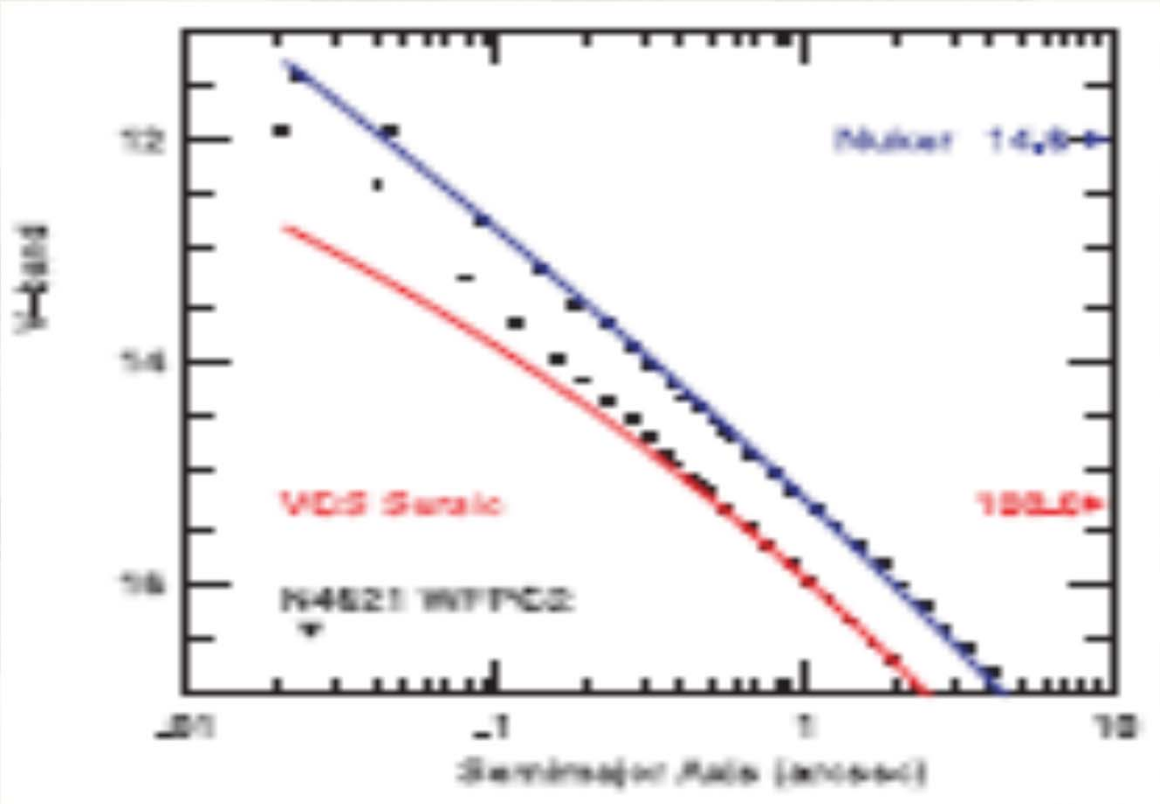
Core/Cusp Galaxies

- Core Galaxies are Early-type Galaxies with flat central brightness profile, called “cores’’
- Cusp Galaxies are those without flat parts

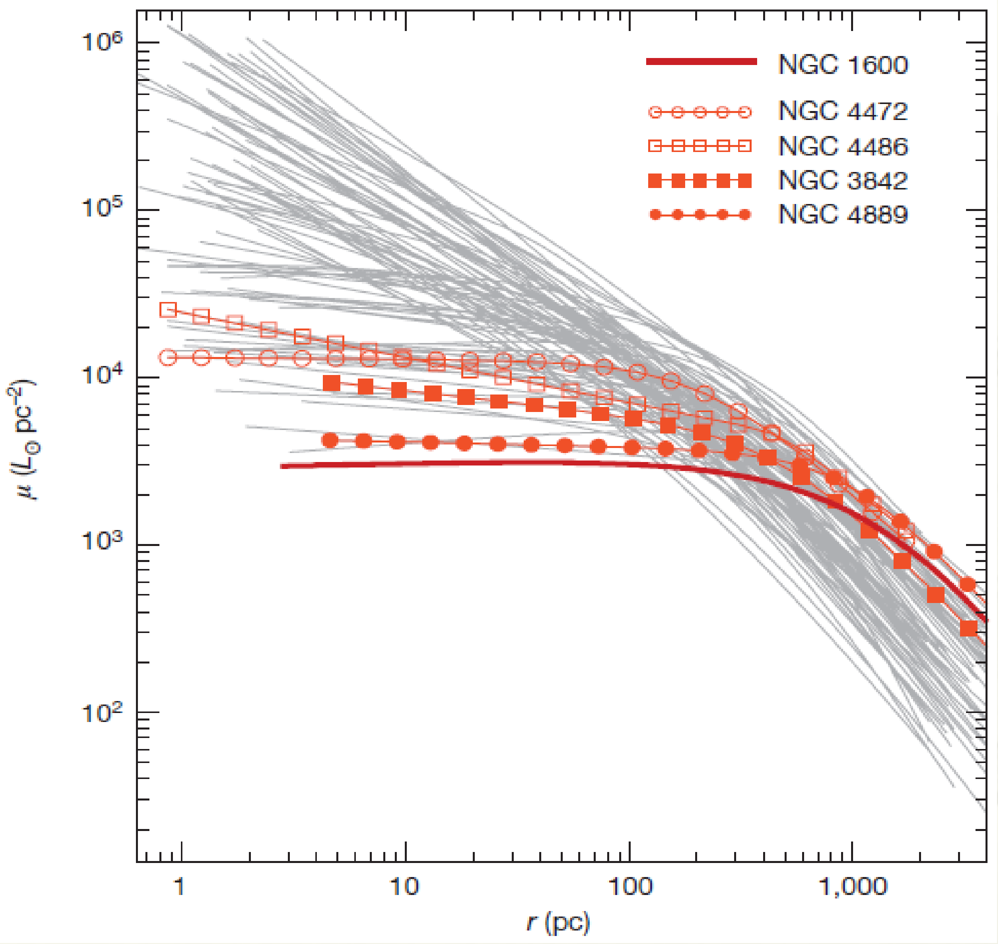
Brightness Profile with a Core



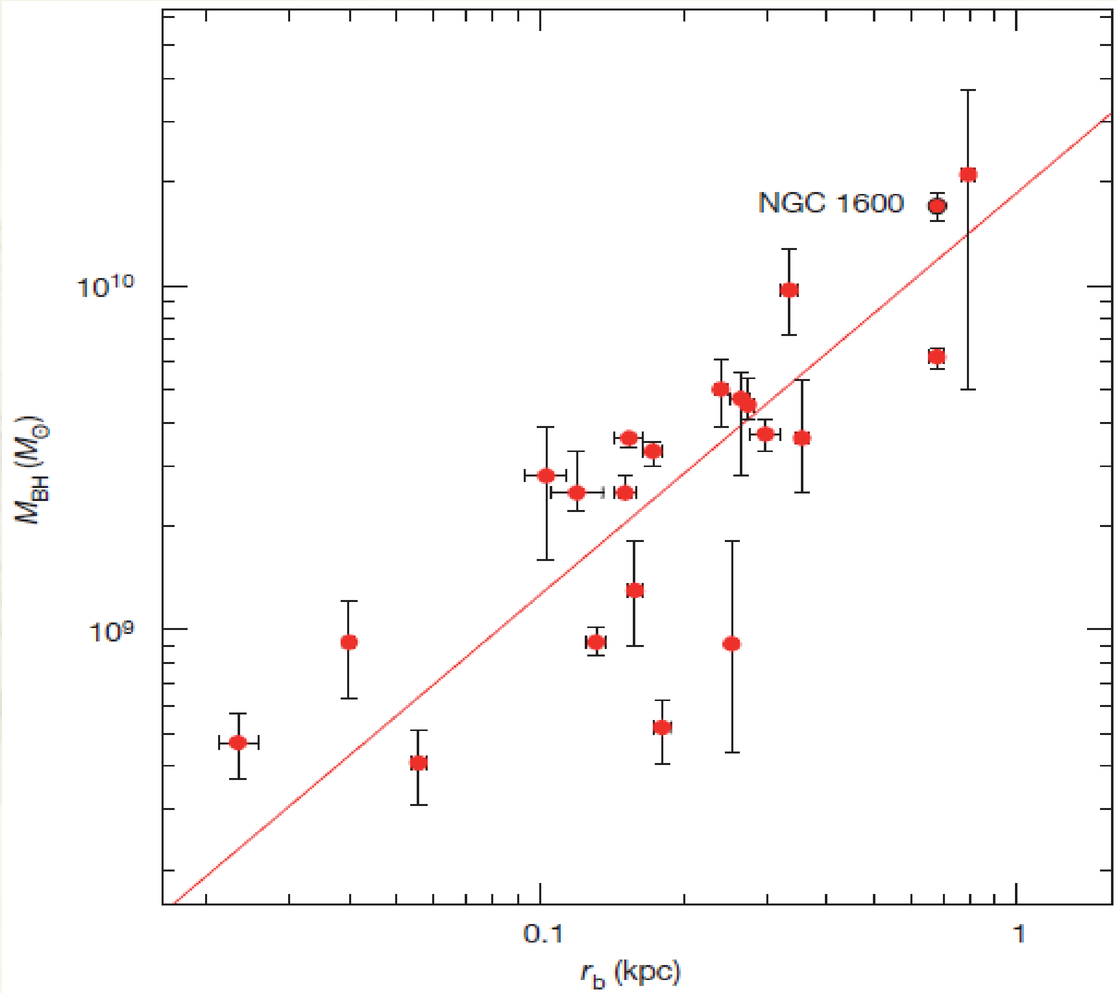
Brightness Profile without a Core



NGC 1600


NGC 1600
NGC 4472
NGC 4486
NGC 3842
NGC 4889
10^6
10^5
10^4
10^3
10^2
μ ($L_\odot$ pc^{-2})
1
10
100
1,000
r (pc)

Black-hole Mass vs Core Radius



The Equilibrium Modeling

- Searching an equilibrium that could fit observational data
- Schwarzschild Method
- An orbit-based method
- Tuning orbit weights to fit observations
- Only one black hole can be considered
- No information on dynamical evolution

Our Particle-Based Approach

$$\frac{d^2x(t)}{dt^2} = -\frac{\partial\Phi(x,y,z,t)}{\partial x}$$
$$\frac{d^2y(t)}{dt^2} = -\frac{\partial\Phi(x,y,z,t)}{\partial y}$$
$$\frac{d^2z(t)}{dt^2} = -\frac{\partial\Phi(x,y,z,t)}{\partial z}$$

Total Potential $\Phi(x, y, z, t)$

- For realistic n-body simulation, total potential is updated at each time step
- Our method here:

$$\Phi(x, y, z, t) = U_G(x, y, z) + U_{BH}(x, y, z, t)$$

where U_G is the galactic potential

U_{BH} is the potential from SMBH (fixed)

or Binary SMBH (time-dependent)

NGC1399

Major Processes

- Step 1: Searching Best Inner Mass Model with one SMBH
- Step 2: Searching Best Total Mass Model with one SMBH
- Step 3: Consider Binary SMBH
- Step 4: Consider Axis-Symmetric Stellar Part

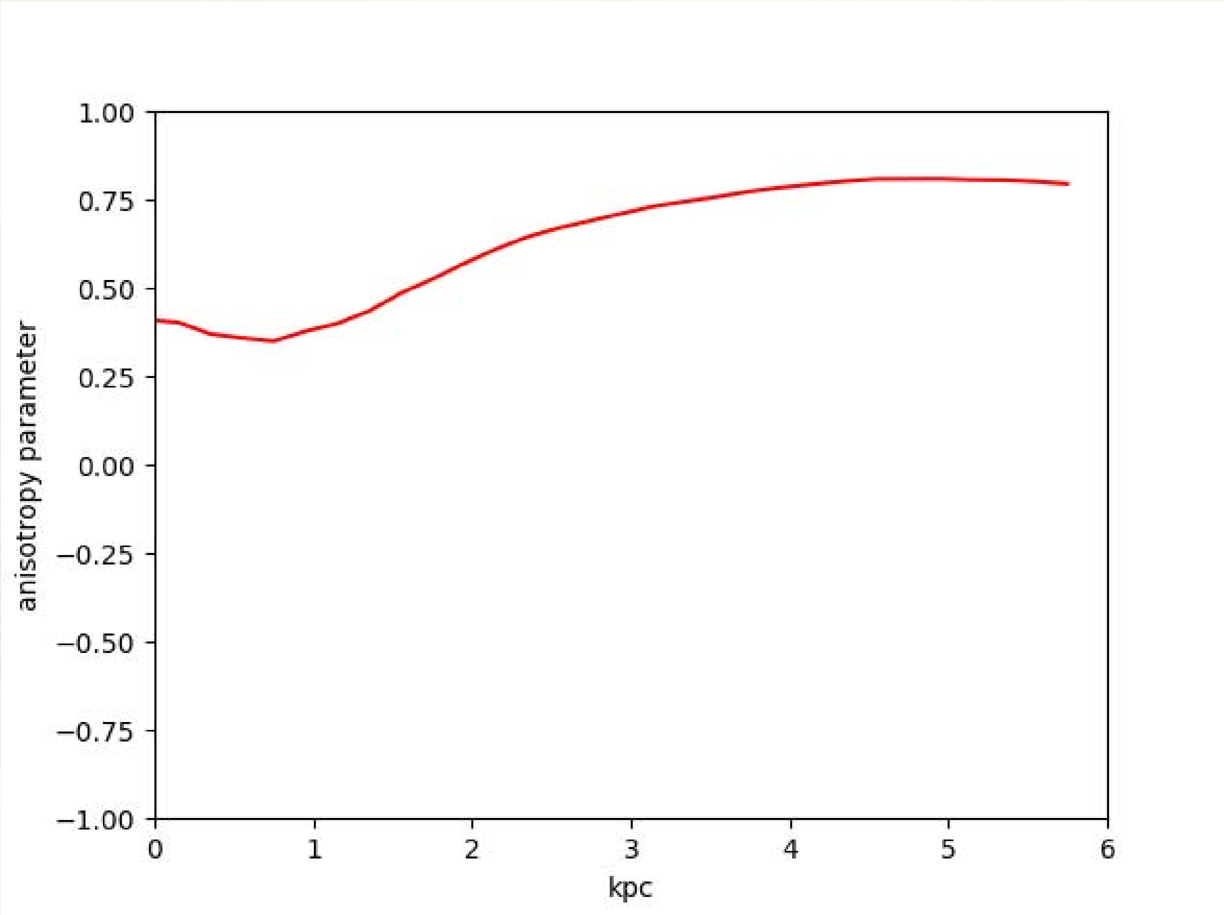
Stars' Initial Positions (10^6 Particles)

$$\rho_{\rm star} = \rho_c^* \left\{ 1 + \left(\frac{r}{r_{sb}} \right)^2 \right\}^{-1.5}$$

where r_{sb} = 0.202 or 1.0

(2 values)

Stars' Initial Velocities (Anistropy Parameter)



The Inner Galactic Profile

$$\rho_g = \rho_c \left(\frac{r}{r_{mb}}\right)^{-\gamma} \left\{1 + \left(\frac{r}{r_{mb}}\right)^{\alpha}\right\}^{\frac{\gamma-\beta}{\alpha}}$$

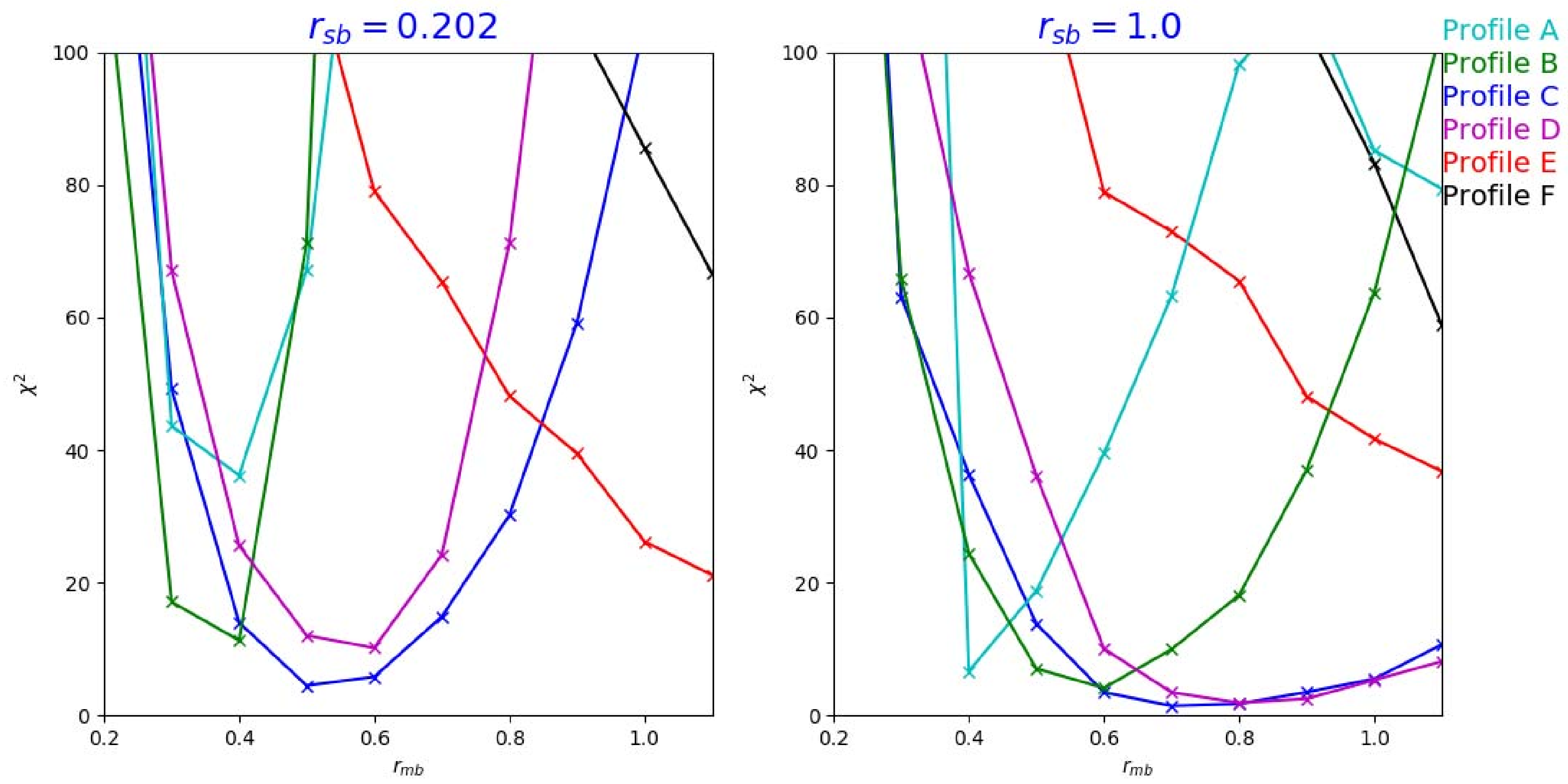
6 sets of α, β, γ *(see next slide)*

where r_{mb} is 0.202, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1 (10 values)

Table of 6 Profiles

Profile	α	β	γ	$\rho_g(r)$
A	2	3	0	$\rho_c \left\{1 + \left(\frac{r}{r_{mb}}\right)^2\right\}^{-1.5}$
B	2	5	0	$\rho_c \left\{1 + \left(\frac{r}{r_{mb}}\right)^2\right\}^{-2.5}$
C	1	4	1	$\rho_c \left(\frac{r}{r_{mb}}\right)^{-1} \left\{1 + \frac{r}{r_{mb}}\right\}^{-3}$
D	2	5	1	$\rho_c \left(\frac{r}{r_{mb}}\right)^{-1} \left\{1 + \left(\frac{r}{r_{mb}}\right)^2\right\}^{-2}$
E	1	4	2	$\rho_c \left(\frac{r}{r_{mb}}\right)^{-2} \left\{1 + \frac{r}{r_{mb}}\right\}^{-2}$
F	1	6	2	$\rho_c \left(\frac{r}{r_{mb}}\right)^{-2} \left\{1 + \frac{r}{r_{mb}}\right\}^{-4}$

2 x 6 x10 Cases run for 10 dynamical times



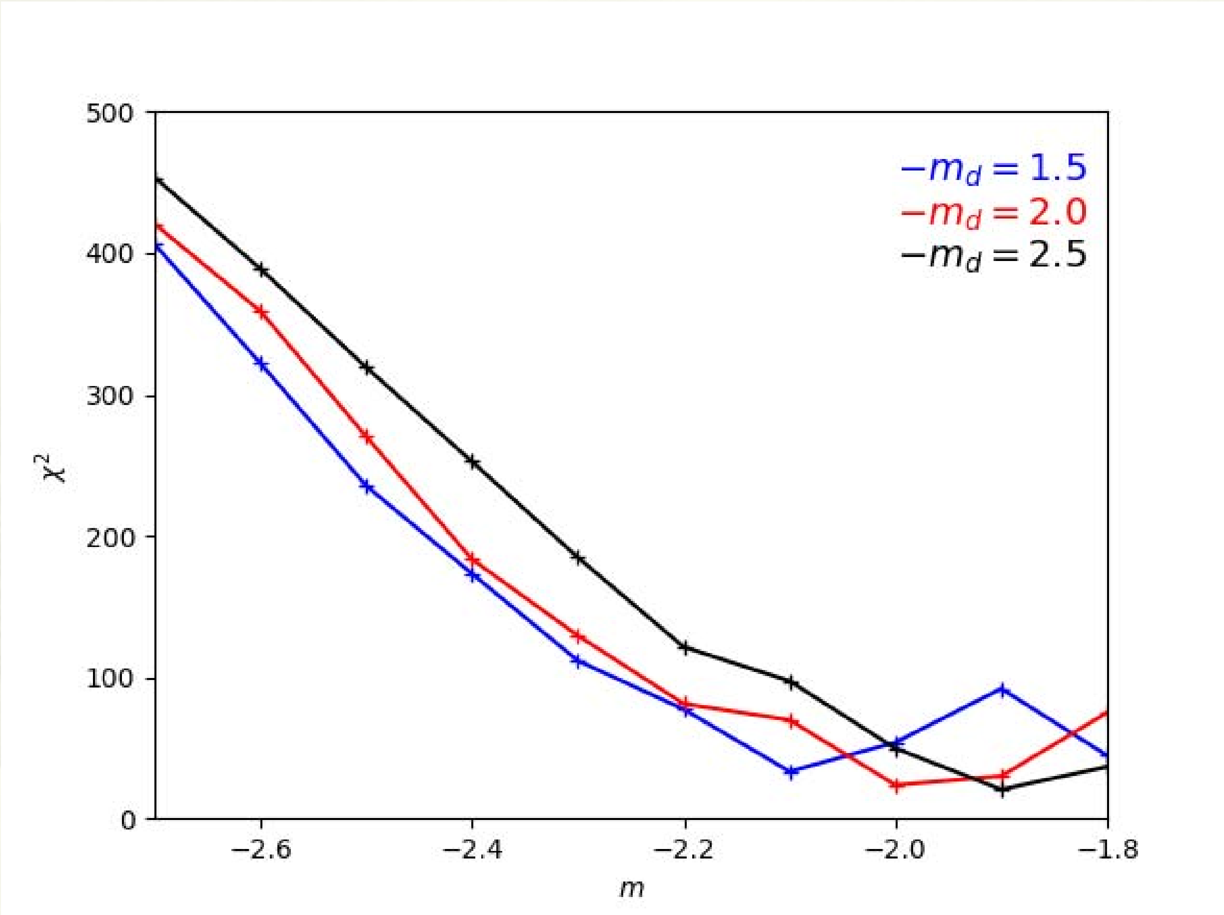
The Total Galactic Profile

$$\rho(r) = \begin{cases} \rho_{\mathrm{g}}(r) & \text{if} \quad r \leq m_d \\ cr^m & \text{if} \quad r > m_d \end{cases}$$

where m_d = 1.5, 2.0, 2.5

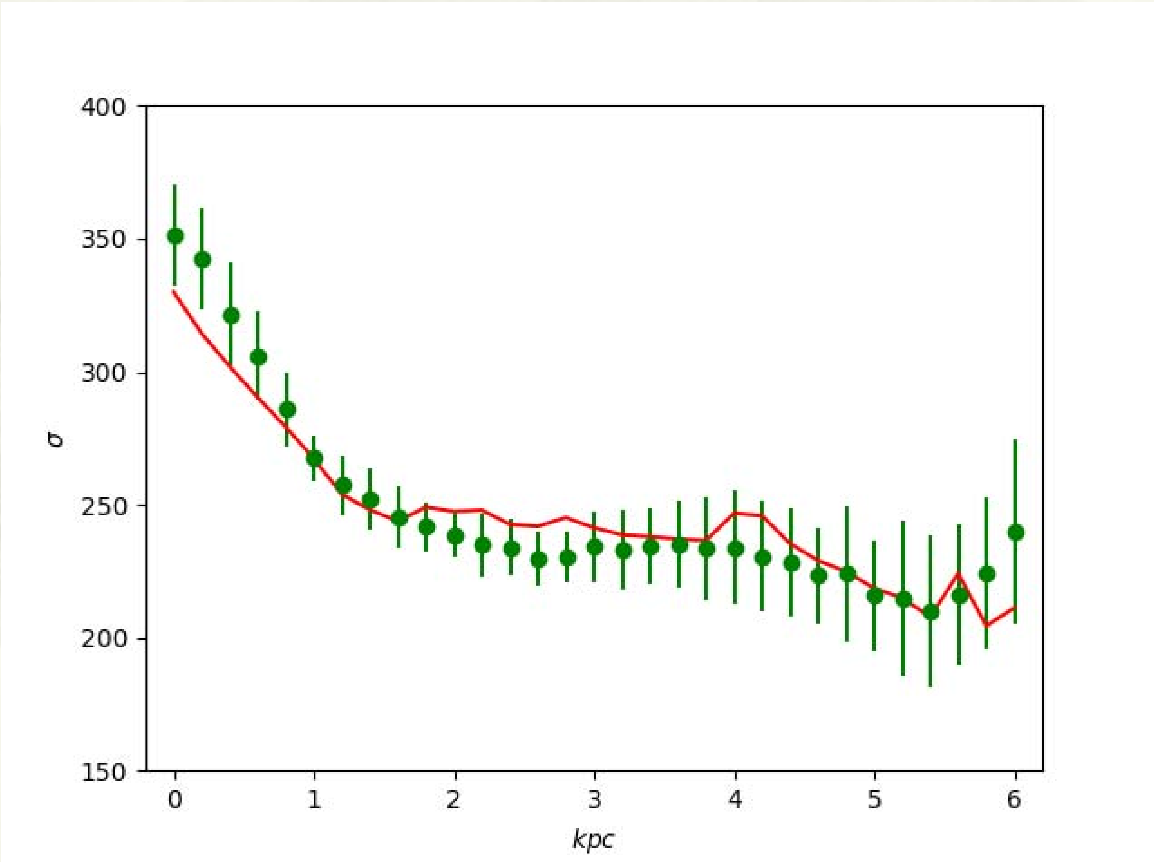
power index m = -2.7, -.2.6, -2.5, -2.4, -2.3,
-2.2, -2.1, -2.0, -1.9, -1.8

30 More Cases



The Best Case with one SMBH

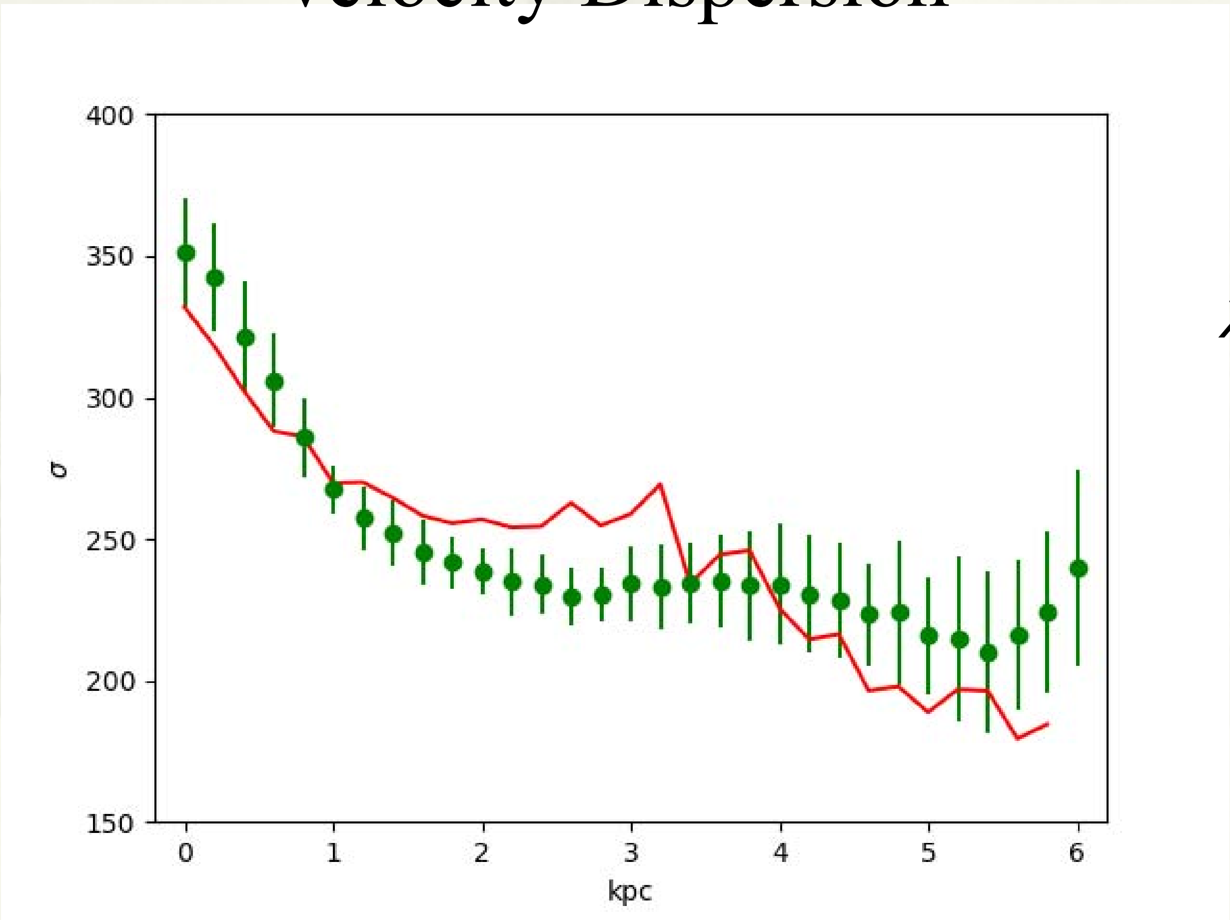
Velocity Dispersion



$\chi^2 = 20.91$

Binary SMBH

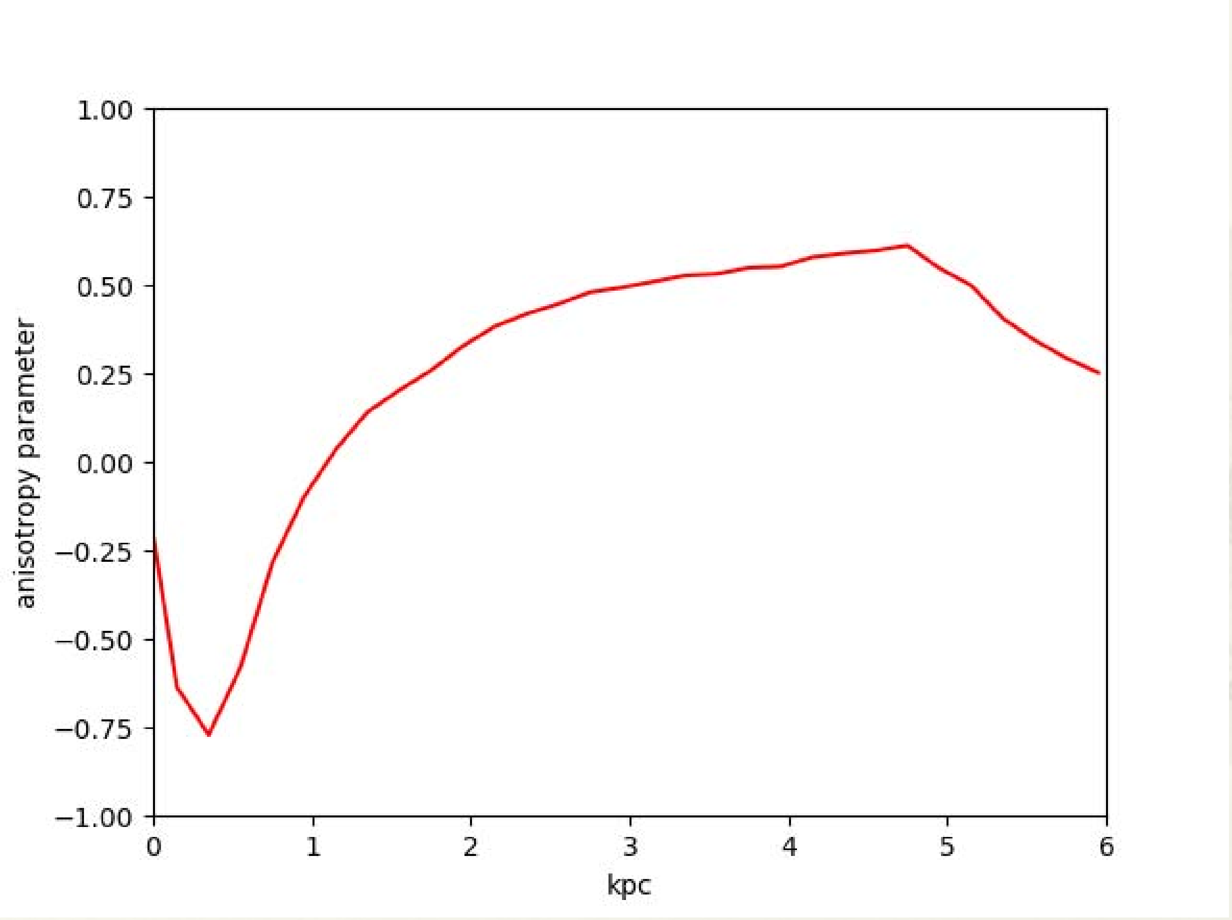
Velocity Dispersion



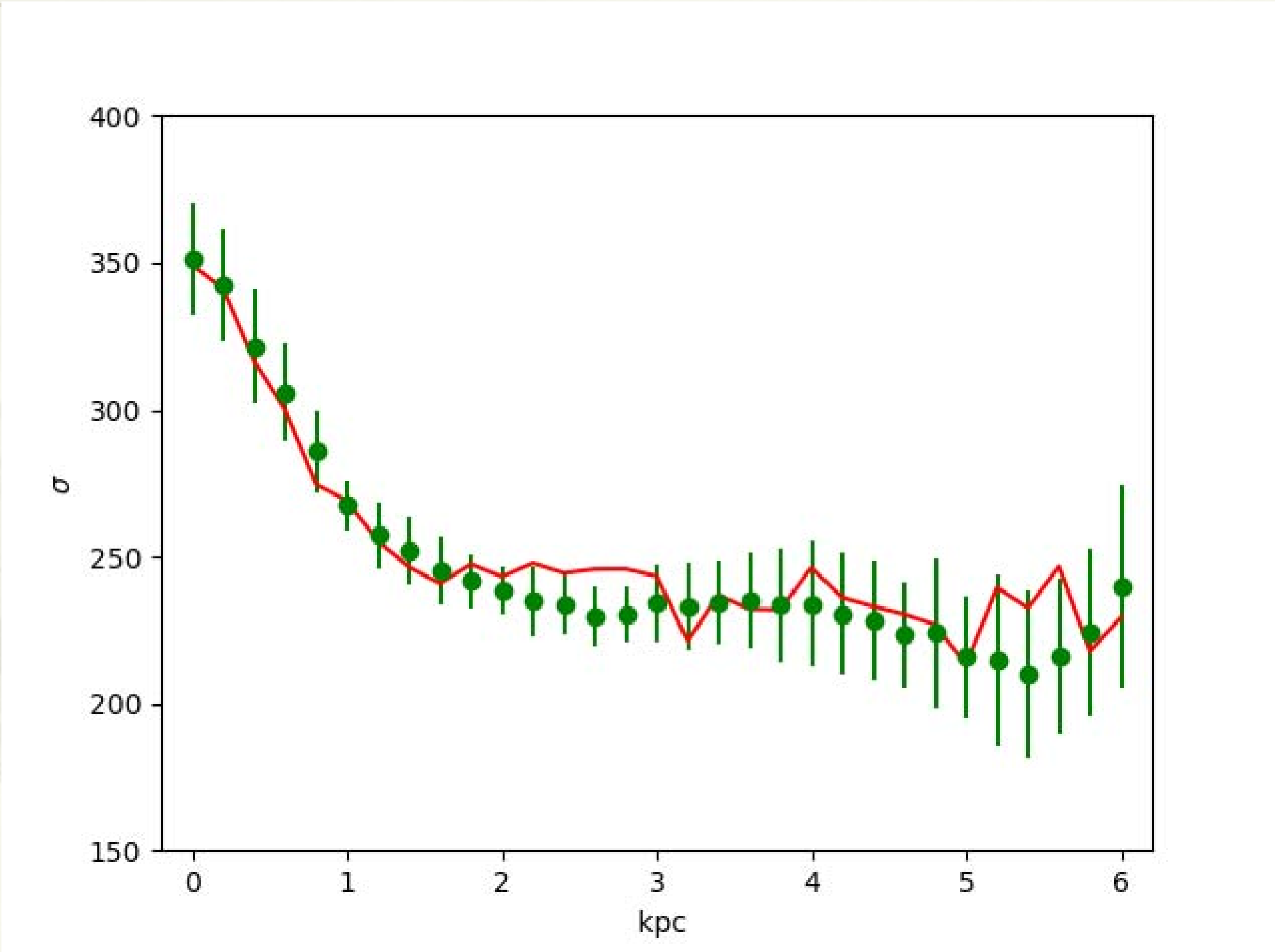
$$\chi^2 = 56.65$$

Spherical + Axis-Symmetric ?

Velocity Configuration

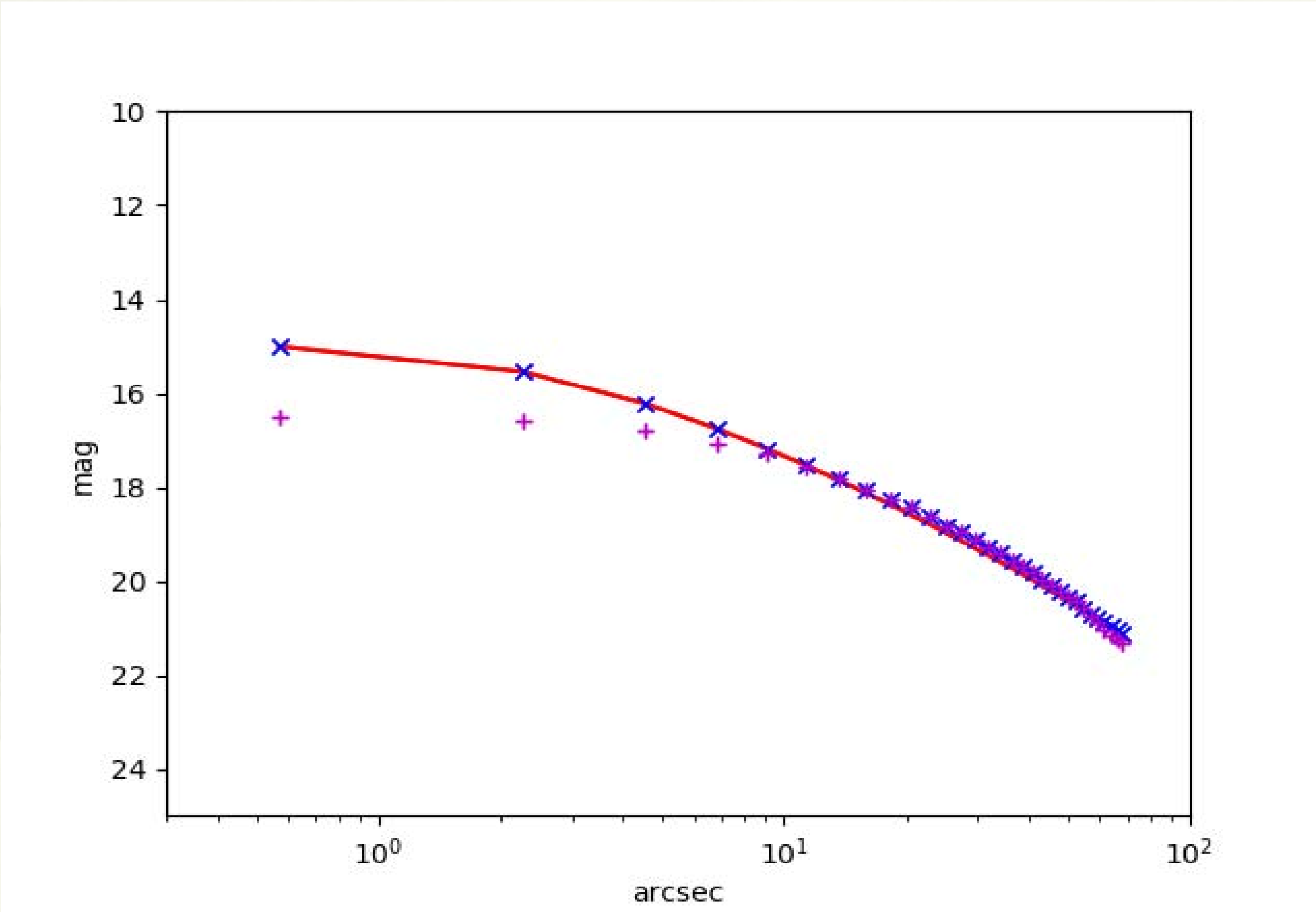


Velocity Dispersion



$$\chi^2 = 16.39$$

Surface Brightness



Results

- Through numerical surveys of important parameters, a mass model with central cusp is obtained
- The power index of central cusp is -1
- For stars, both the spherical part and the axis-symmetric part are necessary

Concluding Remarks

- The axis-symmetric part could be formed during the merging of two SMBHs

- Binary SMBH might have combined to be one SMBH by now, as our best model is the one with single SMBH