Dynamical model of the Milky Way bar

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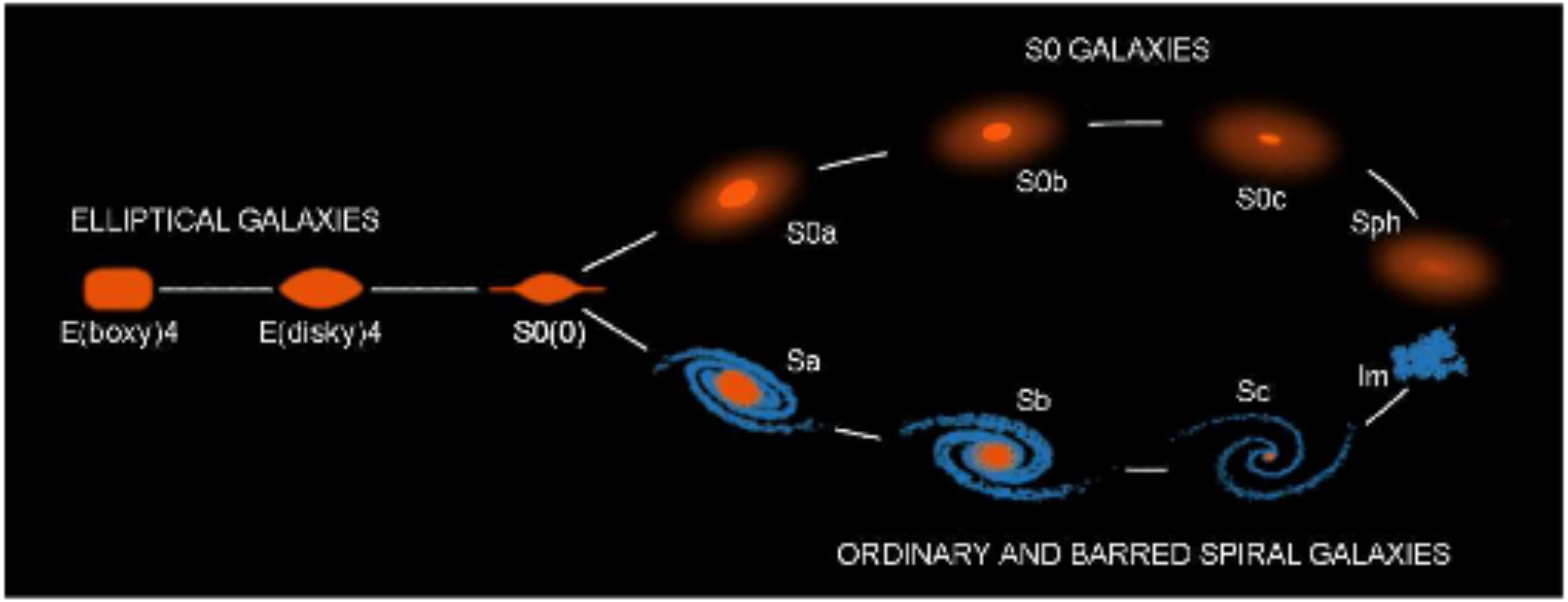
Outline

- Background
- Schwarzschild's orbit-superposition technique
- Results
- Future studies

Morphological classification of galaxies



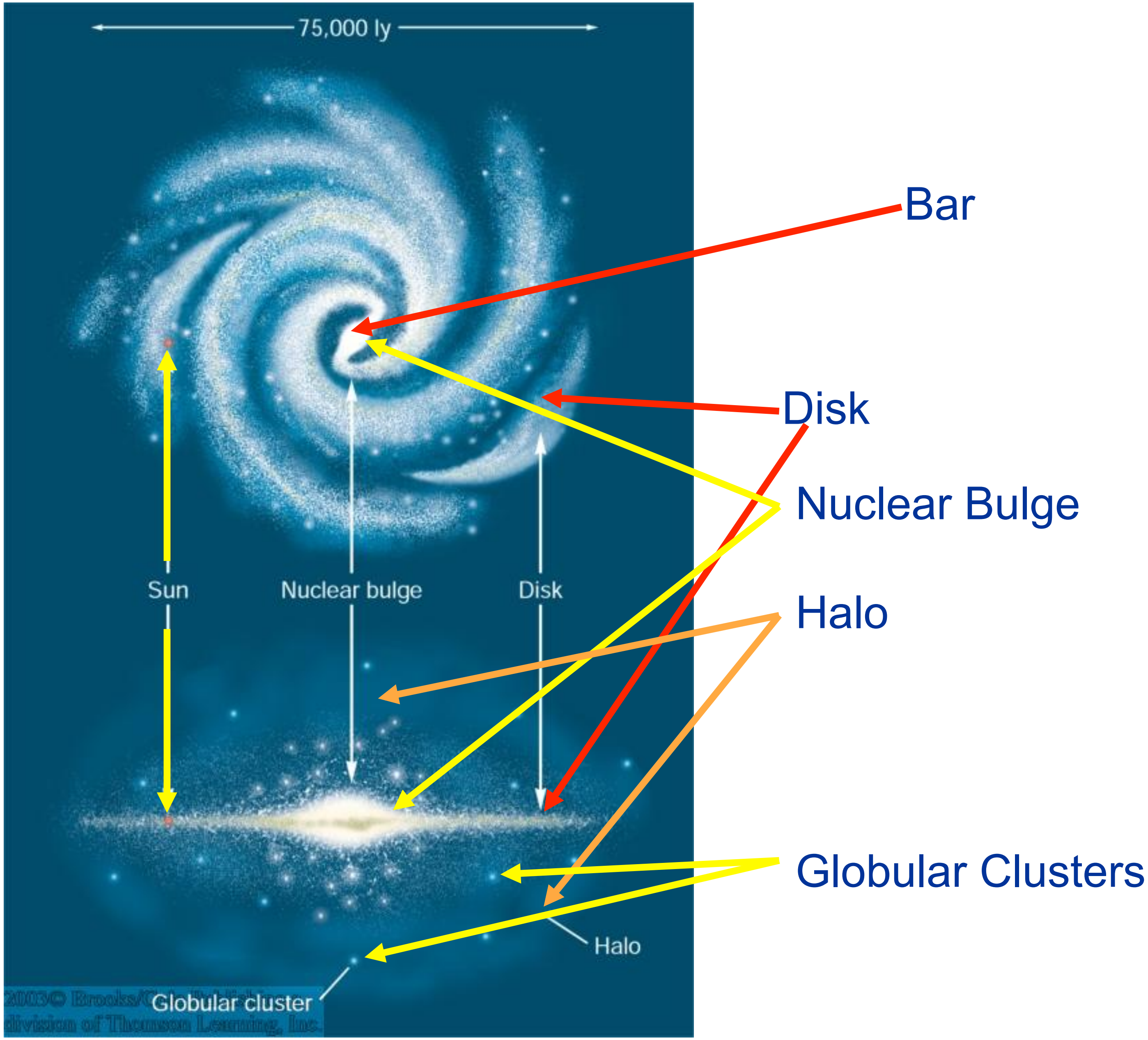
Kormendy & Bender 2012

Why do we want to study the bar region

- Bar is main driver for the secular evolution of disc galaxies
- Pushes mass from the bar region to the center where it creates a a central mass concentration
- Drives the angular momentum exchange within a disc galaxy.
- The strength of the bar correlates well with the amount of angular momentum exchanged

(Athanassoula 2003)

Milk Way Galaxy-A typical barred spiral galaxy



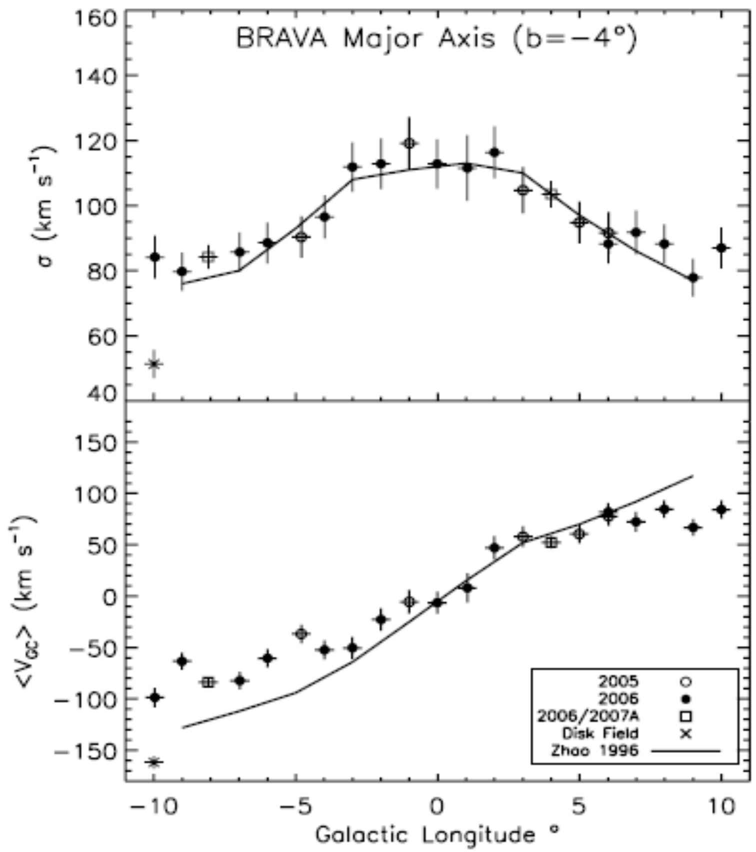
Background I: Observations

- The finding of the bar (de Vaucoulerus 1964), 21-cm observations
- A clear detection of the triaxial bar by Blitz & Spergel (1991) form the infrared balloon observations
- COBE confirms the bar with a bar angle ~20^o (Weiland 1994)
- Recently observations:

  2MASS, OGLE, HST, BRAVA, APOGEE
- Some density models have been constructed by the star counts and surface brightness, also some N-body models

Background II: dynamical model

- Zhao (1996) used the Schwarzschild's method constructed a self-consistent model
- Hafner et al.(2000) proper motion
- Small number of kinematics are used



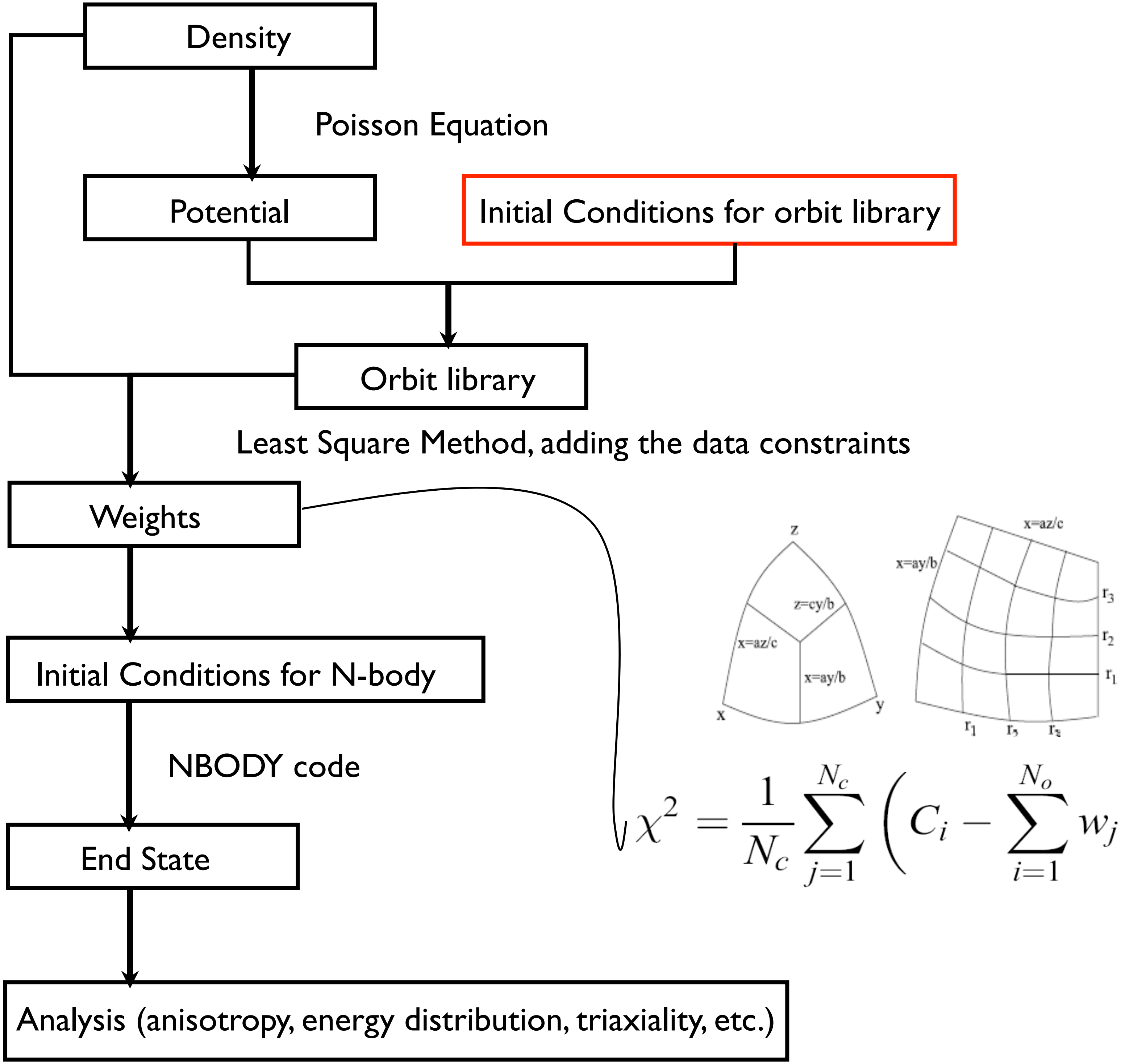
Four modeling methods

- Schwarzschild's orbit-superposition technique (Schwarzschild 1979)
- Made-to-measure (Syer & Tremaine 1996)
- Torus (McMillan & Binney 2008)
- N-body

First three ones are fixed potential

The aim of our studies

- Using the Schwarzschild's orbit-superposition technique to construct the self-consistent model of the Galactic bar
- In model constraints, we add the current available data (BRAVA).



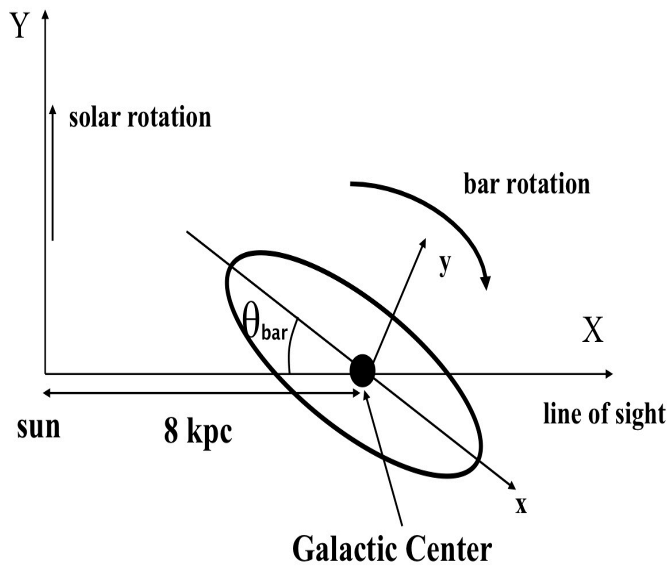
$$\chi^2 = \frac{1}{N_c}\sum_{j=1}^{N_c}\left(C_i - \sum_{i=1}^{N_o} w_j O_{ij}\right)^2.$$

Model of the Milky Way

- Bar + bulge

$$\rho(x,y,z) = \rho_0 \left[\exp\left(-\frac{s_b^2}{2} \right) + s_a^{-1.85} \exp(-s_a) \right]$$

$$s_b^4 = \left[\left(\frac{x}{a} \right)^2 + \left(\frac{y}{b} \right)^2 \right]^2 + \left(\frac{z}{c} \right)^4,$$

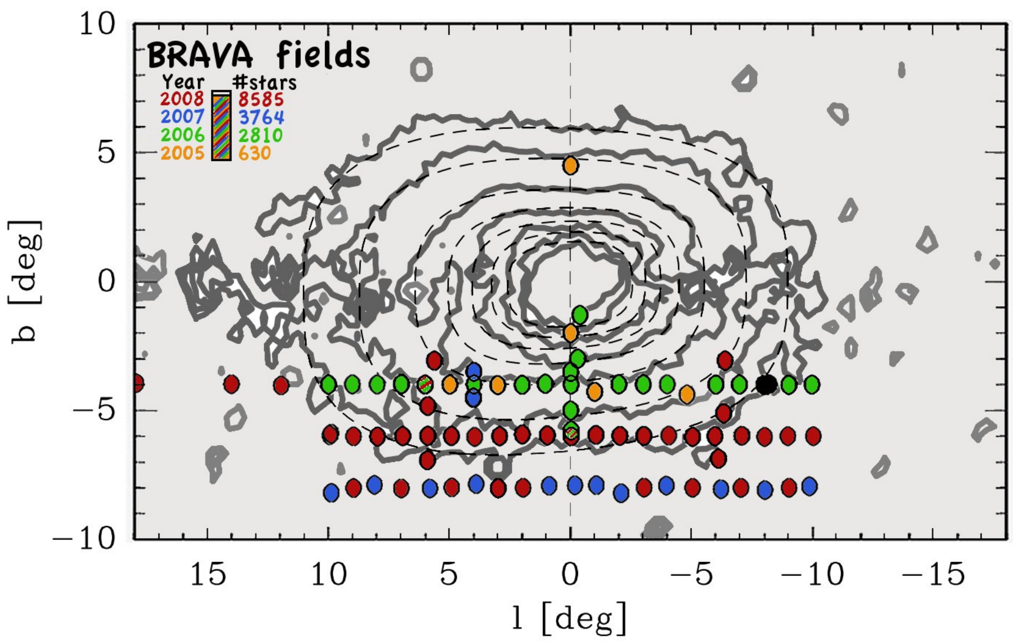


- Miyamoto-Nagai disk

$$D^2 = x^2 + y^2 + [a_{MN} + (z^2 + b_{MN}^2)^{1/2}]^2,$$

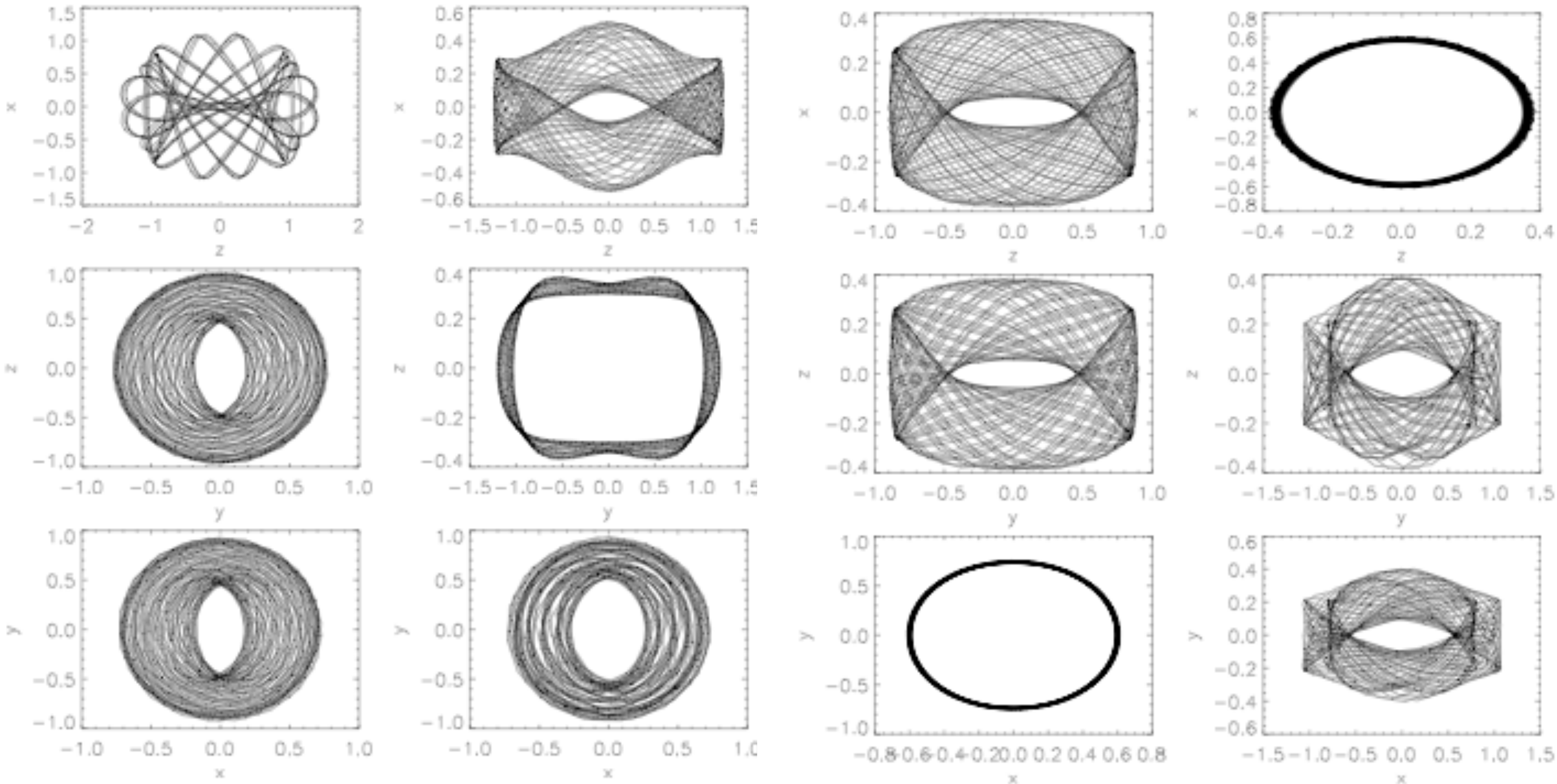
BRAVA data
(Bulge Radial Velocity Assay)

- ~10,000 M stars
- The velocity error is ~5km/s
- The data has been released by http://brava.astro.ucla.edu/data.htm



Cerro Tololo Inter-American Observatory 4 m Hydra multiobject spectrograph.

Some typical regular orbits



Models with different parameters

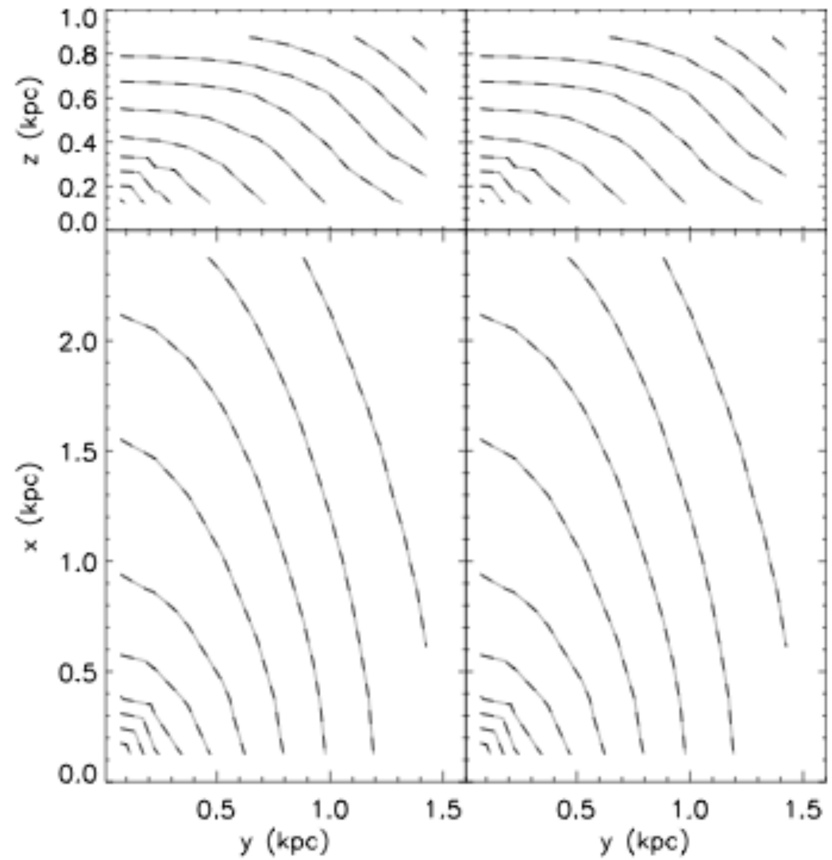
model ID	Ω_p (km s^{-1} kpc^{-1})	M_d (M_{bar})	θ_{bar} (°)	χ^2
1	40	2.25	13.4	331
2	40	2.25	20	328
3	40	2.25	30	430
4	40	5	13.4	359
5	40	5	20	393
6	40	5	30	438
7	40	8	13.4	851
8	40	8	20	902
9	40	8	30	843
10	50	2.25	13.4	363
11	50	2.25	20	340
12	50	2.25	30	272
13	50	5	13.4	297
14	50	5	20	279
15	50	5	30	284
16	50	8	13.4	606
17	50	8	20	633
18	50	8	30	561
19	60	2.25	13.4	456
20	60	2.25	20	444
21	60	2.25	30	379
22	60	5	13.4	308
23	60	5	20	293
24	60	5	30	298
25	60	8	13.4	403
26	60	8	20	354
27	60	8	30	344
28	80	2.25	13.4	314
29	80	2.25	20	374
30	80	2.25	30	371
31	80	5	13.4	319
32	80	5	20	398
33	80	5	30	273
34	80	8	13.4	379
35	80	8	20	352
36	80	8	30	467

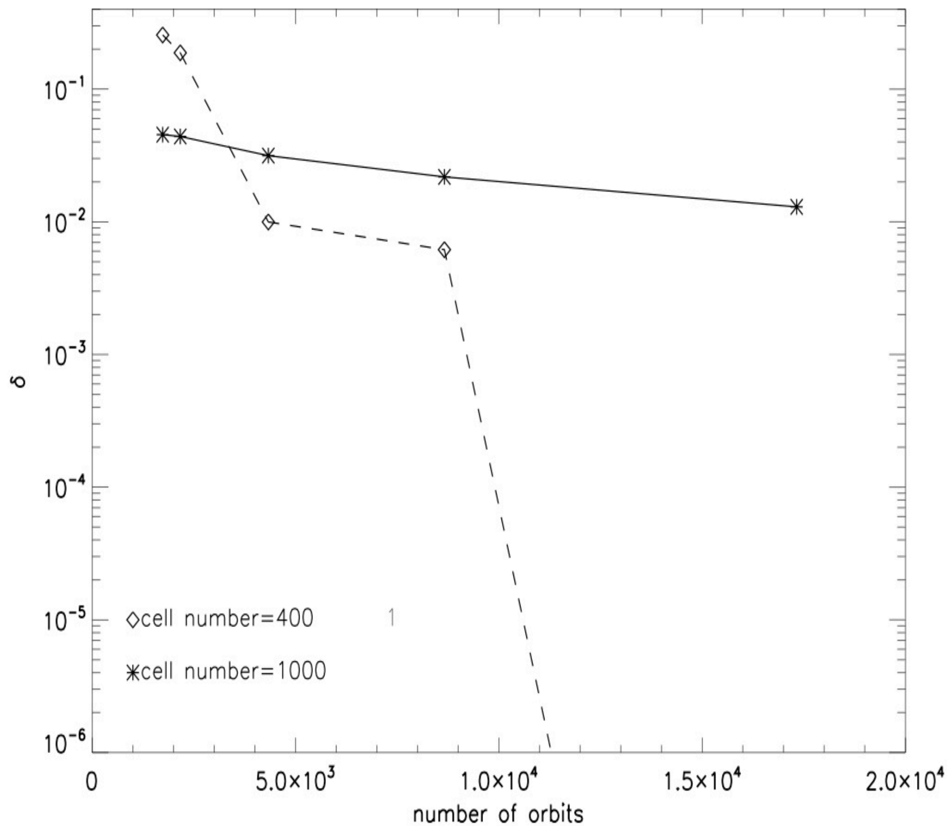
Self-consistency of the model

$$\Omega_p = -60 km/s/kpc$$

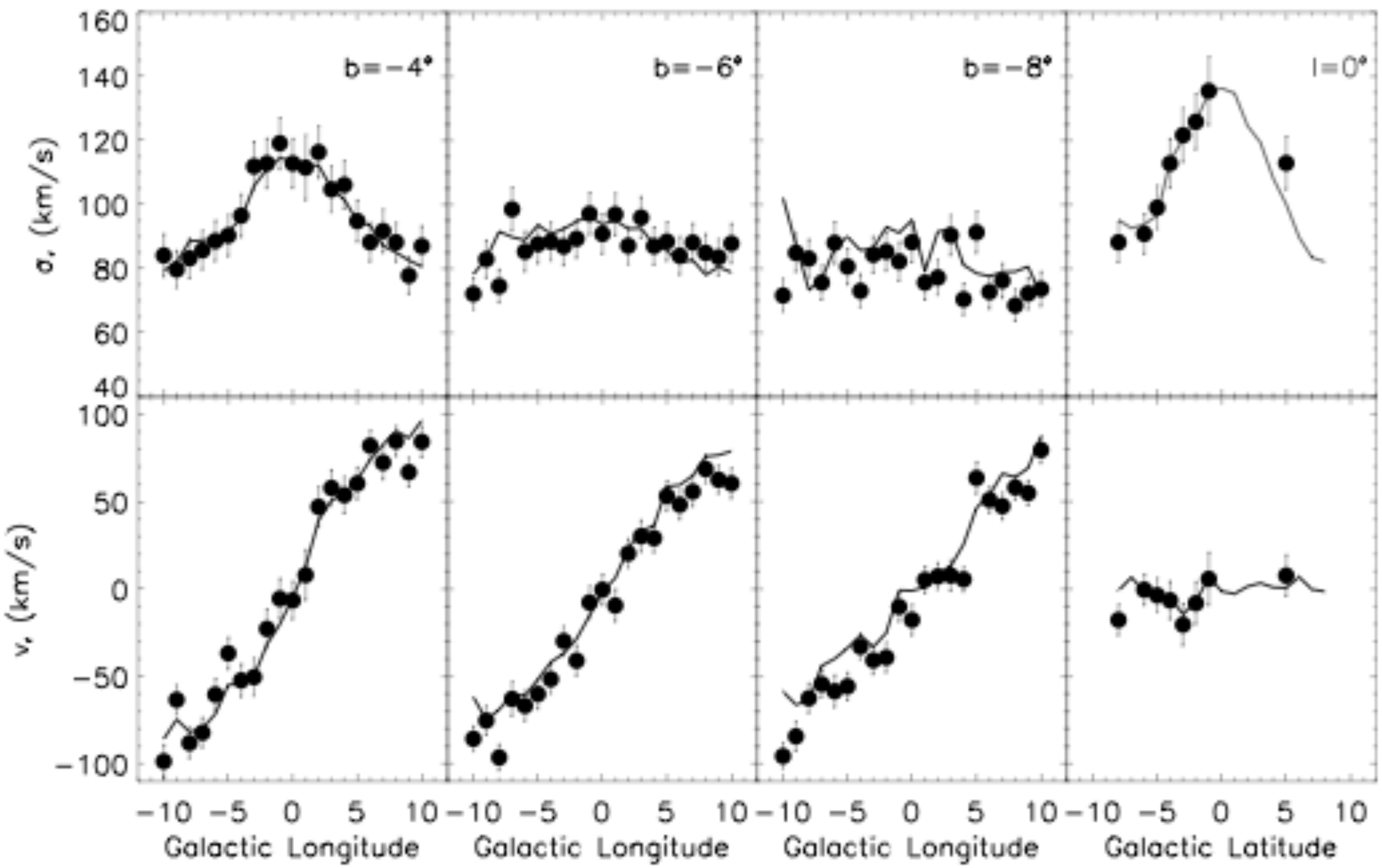
$$M_{disk} = 10^{11} M_{sun}$$

$$\theta_{bar} = 20^\circ$$





Best-fitting model



$$\Omega_p = -60 km/s/kpc$$

$$M_{disk} = 10^{11} M_{sun}$$

$$\theta_{bar} = 20^{\circ}$$

arXiv:1209.0963, Wang et al. 2012

Proper motion & Stability

Field	(l,b)	σ_l	σ_b	Ref.
	(°)	(mas yr^{-1})	(mas yr^{-1})	
Baade's Window	(1,-4)	3.2 ± 0.1	2.8 ± 0.1	Spaenhauer et al. (1992)
Baade's Window	(1,-4)	3.14 ± 0.11	2.74 ± 0.08	Zhao et al. (1996)
Baade's Window	(1.13,-3.77)	2.9	2.5	Kuijken & Rich (2002)
Baade's Window	(1,-4)	2.87 ± 0.08	2.59 ± 0.08	Kozłowski et al. (2006)
Baade's Window	(0.9,-4)	3.06 ± 0.11	2.79 ± 0.13	Soto et al. (2007)
Baade's Window	(1,-4)	3.13 ± 0.16	2.50 ± 0.10	Babusiaux et al. (2010)
Baade's Window	(1.13,-3.76)	3.11 ± 0.08	2.74 ± 0.13	Soto (2012) in preparation
Plaut's Window	(0,-8)	3.39 ± 0.11	2.91 ± 0.09	Vieira et al. (2007, 2009)
Sagittarius's Window	(1.25,-2.65)	3.3	2.7	Kuijken & Rich (2002)
Sagittarius's Window	(1.27,-2.66)	3.07 ± 0.08	2.73 ± 0.07	Kozłowski et al. (2006)
Sagittarius's Window	(1.25,-2.65)	3.067	2.760	Clarkson et al. (2008)
Sagittarius's Window Window	(1.26,-2.65)	3.56 ± 0.08	2.87 ± 0.08	Soto (2012) in preparation
NGC 6558	(0.28,-6.17)	2.90 ± 0.11	2.87 ± 0.13	Soto (2012) in preparation
Baade's Window	(1,-4)	4.44	2.52	Model 23
Plaut's Window	(0,-8)	5.28	2.32	Model 23
Sagittarius's Window	(1,-3)	4.43	2.67	Model 23
NGC 6558	(0,-6)	4.46	2.36	Model 23

The bar is only stable within 0.5 Gyr

Regular orbit fraction

Orbit integrated time	1/4Hubble time	1/3Hubble time	1/2Hubble time	Hubble time
Regular orbit fraction	19.4%	18.7%	8.8%	7.1%
Irregular orbit fraction	80.6%	81.3%	91.2%	92.9%

Future studies

- Constructing a new density model of the bar and rerun the Schwarzschild's method

- Using the N-body simulation or some toy-models.

Shen 2010's model

Baade's Window	(1,-4)	3.28	2.38
Plaut's Window	(0,-8)	3.35	2.11
Sagittarius I	(1,-3)	3.33	2.47
NGC 6558	(0,-6)	3.26	2.17
Baade's Window	(1,-4)	3.72	2.58
Plaut's Window	(0,-8)	3.36	2.34
Sagittarius I	(1,-3)	3.63	2.58
NGC 6558	(0,-6)	3.52	2.28
Baade's Window	(1,-4)	4.44	2.52
Plaut's Window	(0,-8)	5.28	2.32
Sagittarius I	(1,-3)	4.43	2.67
NGC 6558	(0,-6)	4.46	2.36

Thank you!