Dynamical evolution of two associated galactic bars

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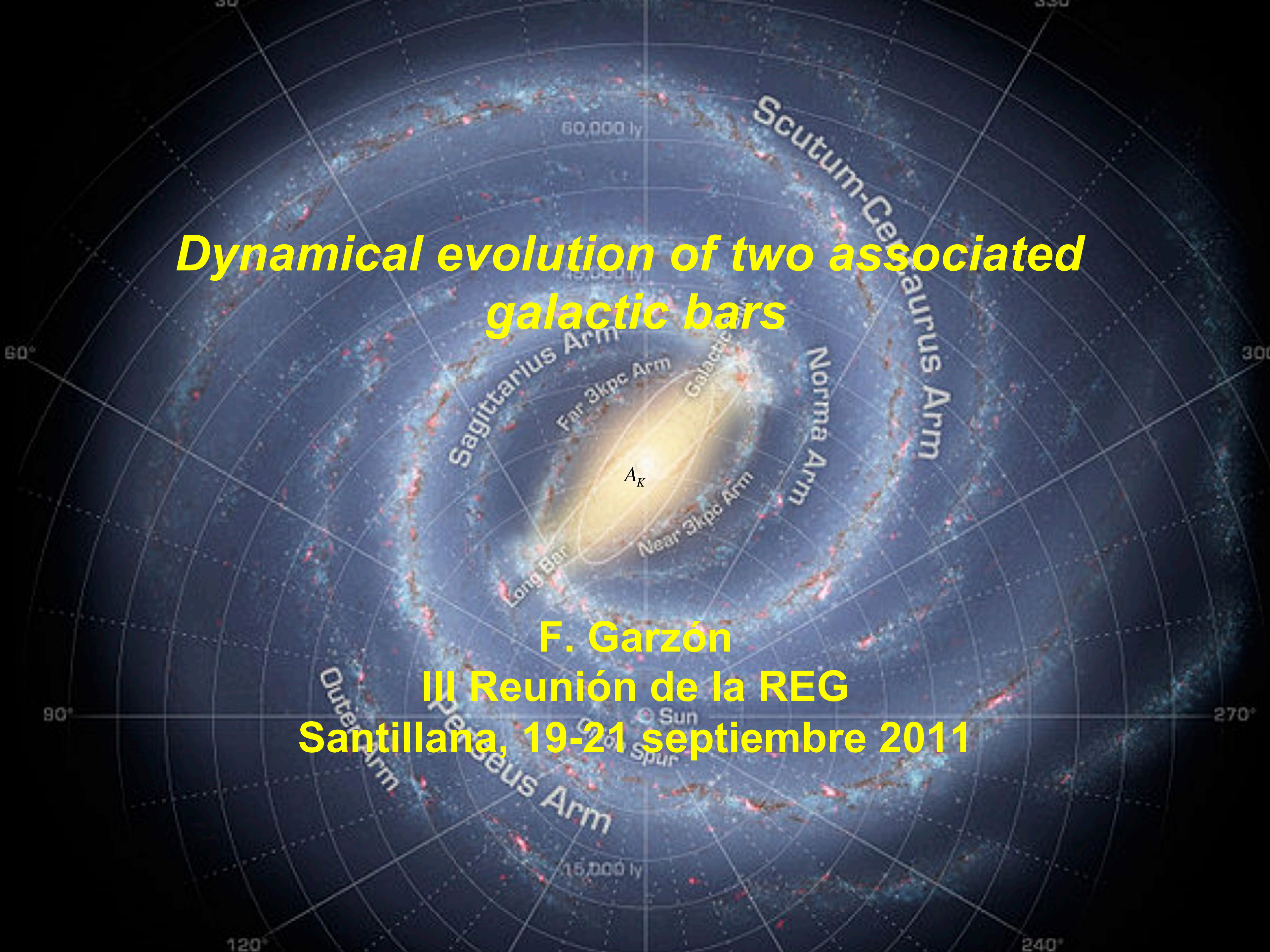
Santillana, 19-21 septiembre 2011



Motivation

- Double bar galaxies are common in nature
  - Roughly 20% of S0--Sb galaxies are double-barred (rarer in later types)
  - Inner bars ~ 500 pc in radius (~ 12% the size of outer bars)
  - sizes range from ~ 100 pc to > 1 kpc (Erwin, 08)
- The evolution and formation of such double-barred galaxies is still not well understood (Debattista & Shen, 07)
- The MW might be double-barred:
  - debate on the detailed morphology of the central region
    - boxy bulge + long thin (in-plane) bar
    - bulge + pseudo bulge
    - ellongated boxy bulge
    - …
- Study case: analytical treatment of the secular evolution of two such bodies, which oscillate with respect each other.
  - without geometrical deformation
  - with deformation described as Jacobi and pseudo-jacobi ellipsoids

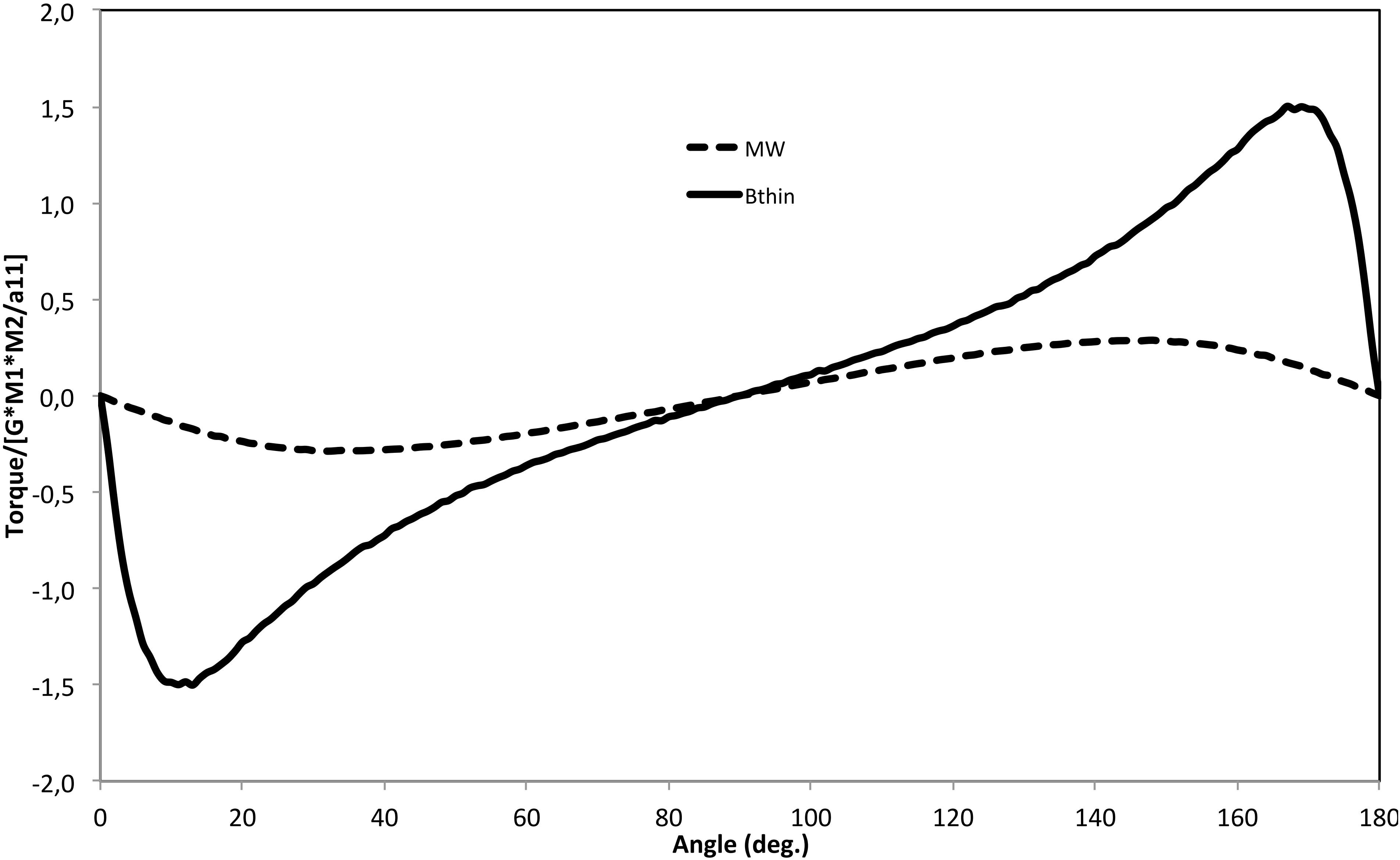
Formalism

$$\vec{\tau}_T = \vec{\tau}_1 + \vec{\tau}_2 = 0 \qquad \vec{\tau}_T = \frac{d\vec{L}_T}{dt} \qquad \vec{\tau}_i = \frac{d\vec{L}_i}{dt} \qquad \vec{L}_i = I_i \vec{\Omega}_i$$

$$\Delta\ddot{\phi} = (\dot{\Omega}_2 - \dot{\Omega}_1) = \left(\frac{1}{I_2} + \frac{1}{I_1}\right)\tau_2(\Delta\phi) - \frac{d\ln(I_2)}{dt}\Omega_2 + \frac{d\ln(I_1)}{dt}\Omega_1$$

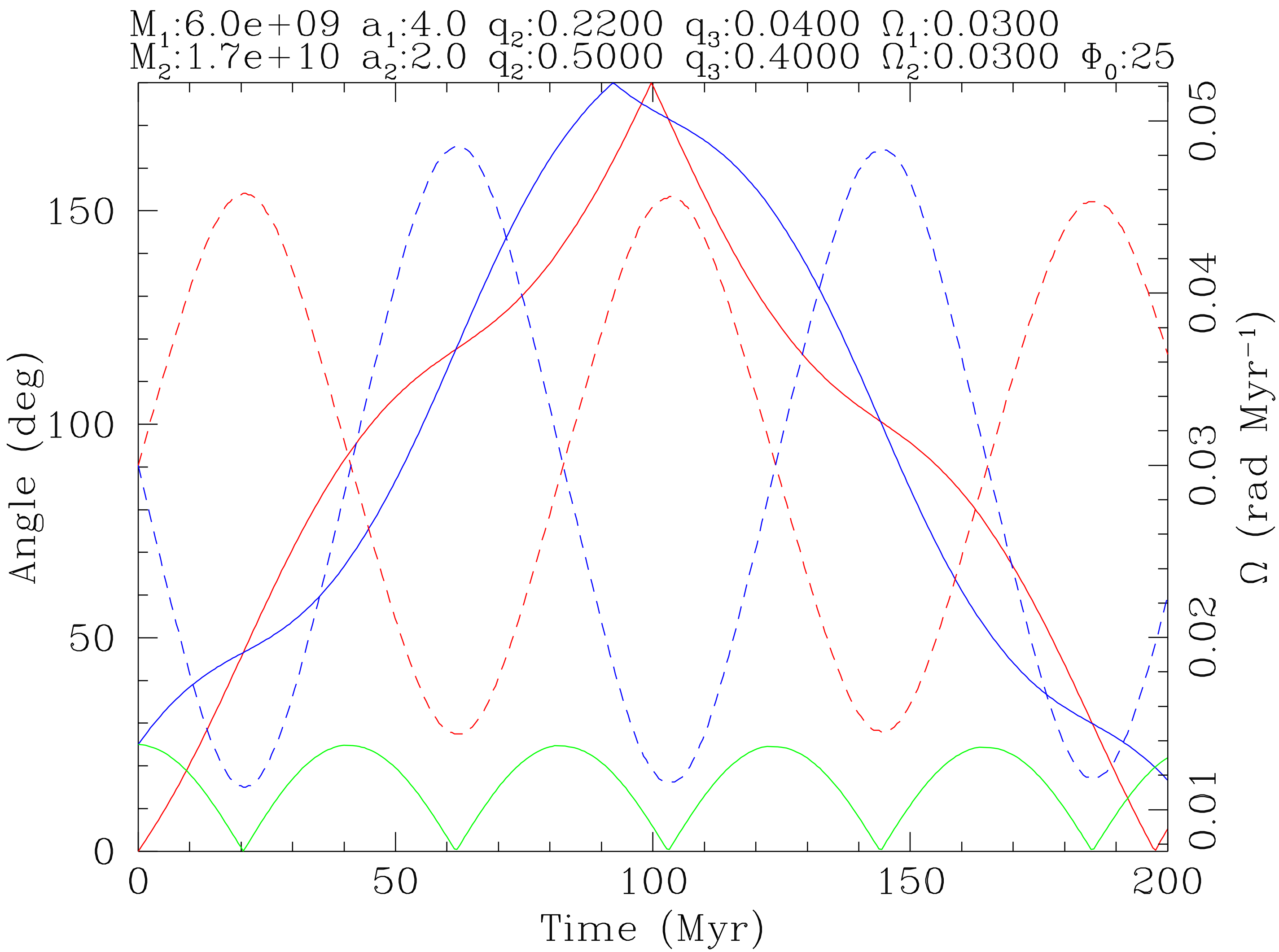
$$\tau_j(\Delta\phi) = \int_{Vj} dV \rho_j F_{\phi,i}(\vec{r})R$$

Torque



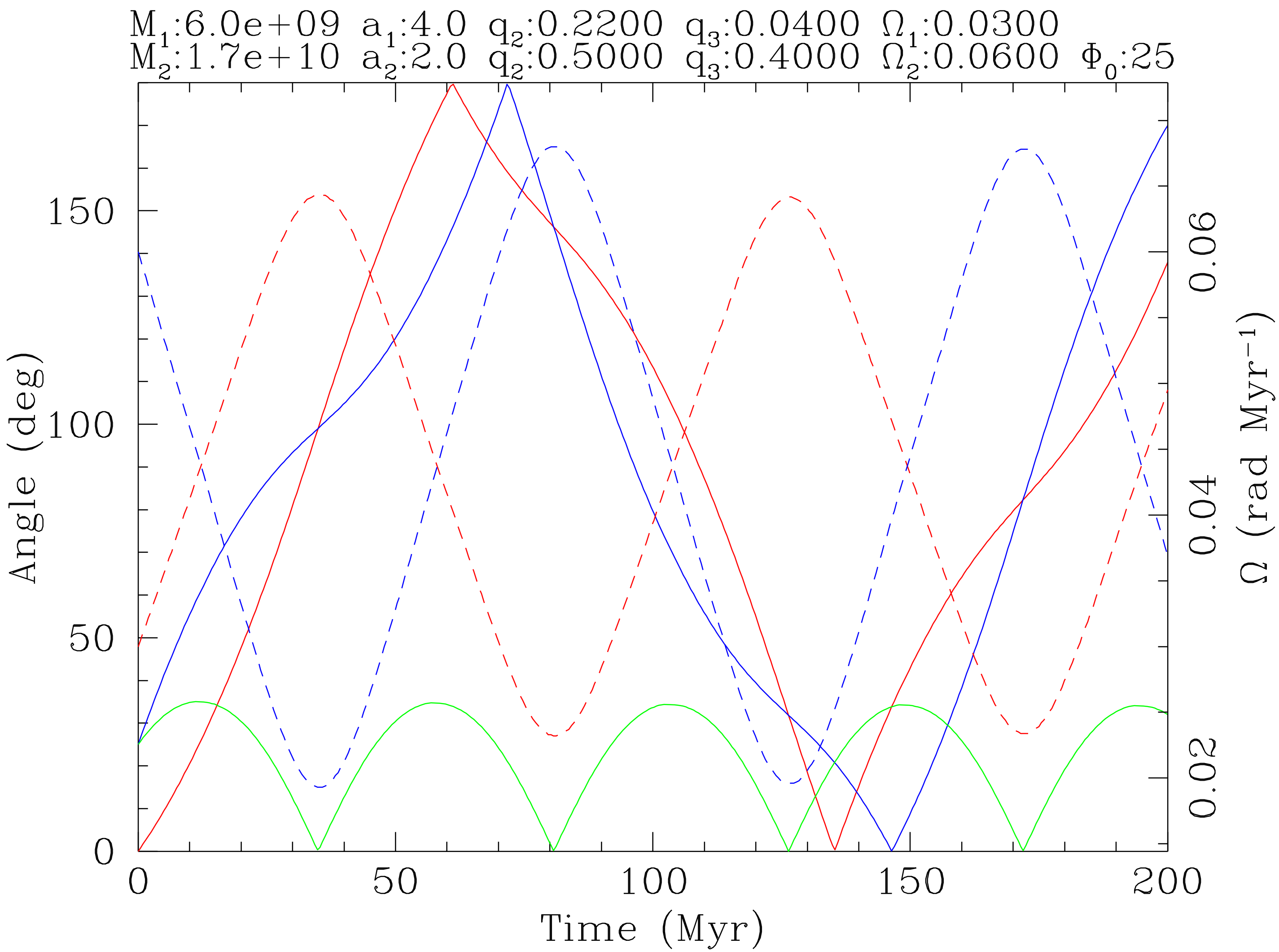
2,0
1,5
1,0
0,5
0,0
-0,5
-1,0
-1,5
-2,0
Torque/[G*M1*M2/a11]
0
20
40
60
80
100
120
140
160
180
Angle (deg.)
MW
Bthin

Rigid Bars



M1:6.0e+09 a1:4.0 q2:0.2200 q3:0.0400 Ω1:0.0300
M2:1.7e+10 a2:2.0 q2:0.5000 q3:0.4000 Ω2:0.0300 Φ0:25
Angle (deg)
Time (Myr)
Ω (rad Myr⁻¹)
0
50
100
150
200
0.01
0.02
0.03
0.04
0.05

Rigid Bars



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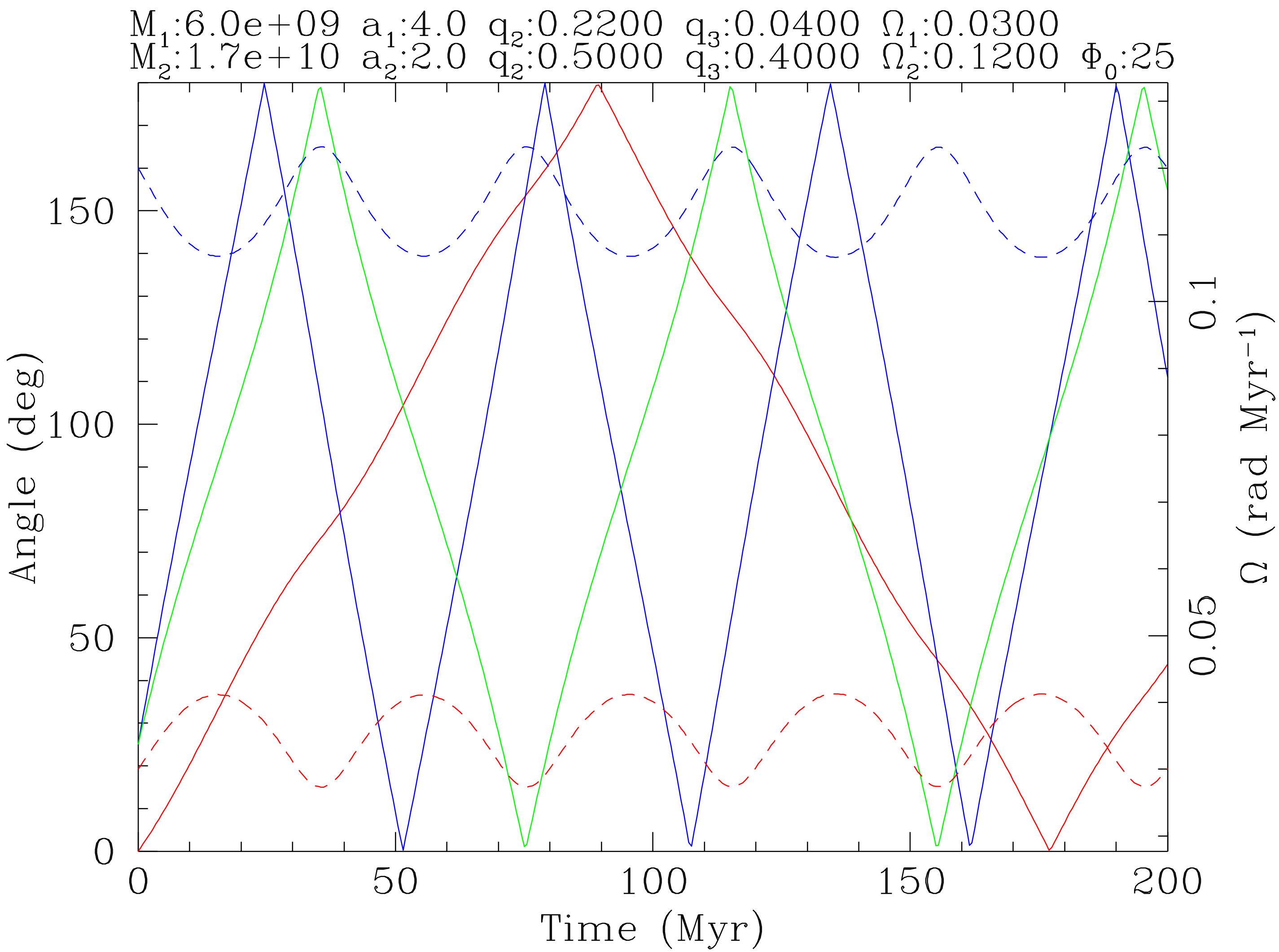
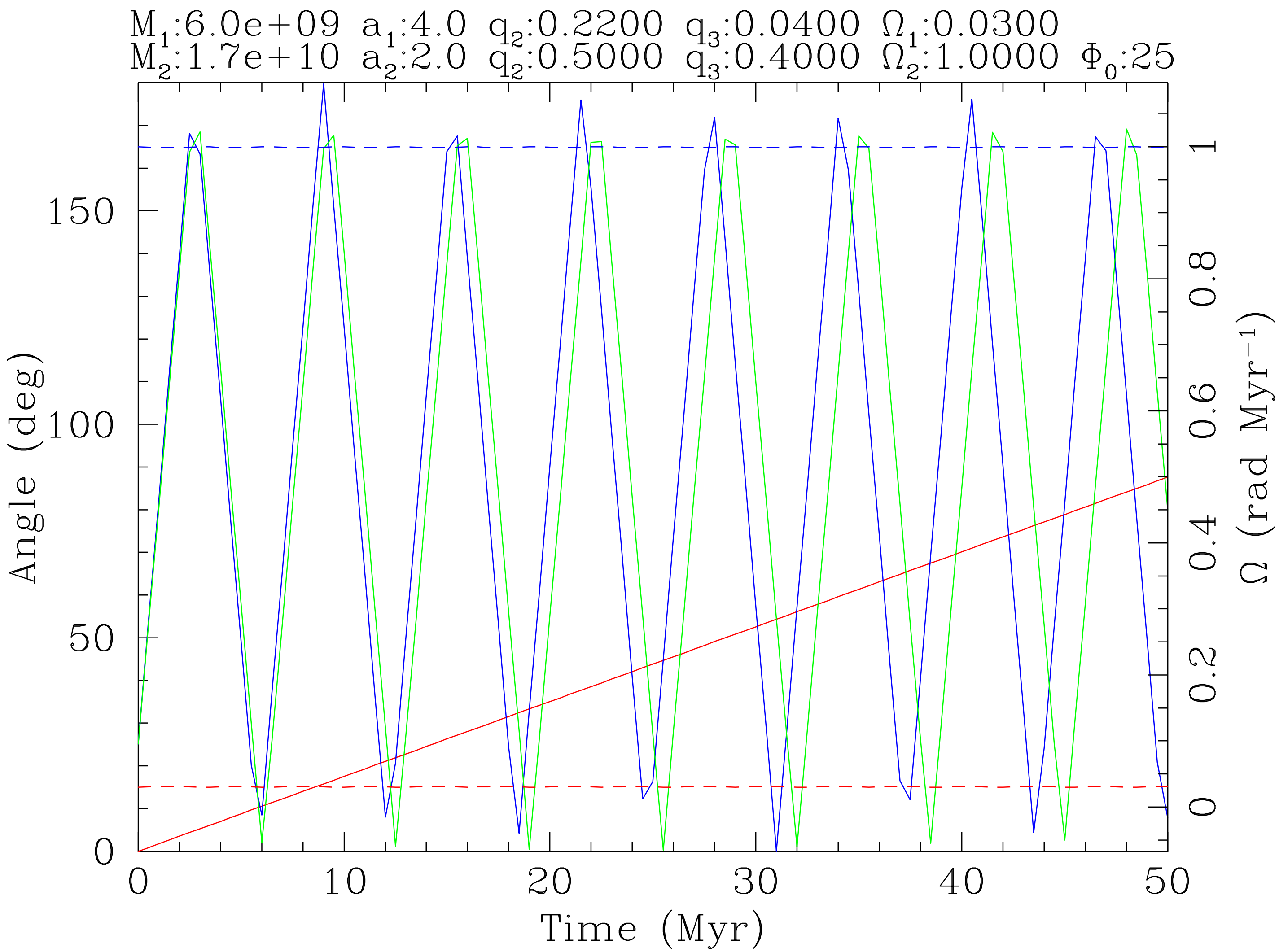
M2:1.7e+10 a2:2.0 q2:0.5000 q3:0.4000 Ω2:0.0600 Φ0:25
Angle (deg)
0
50
100
150
0
50
100
150
200
Time (Myr)
Ω (rad Myr⁻¹)
0.02
0.04
0.06

Rigid Bars



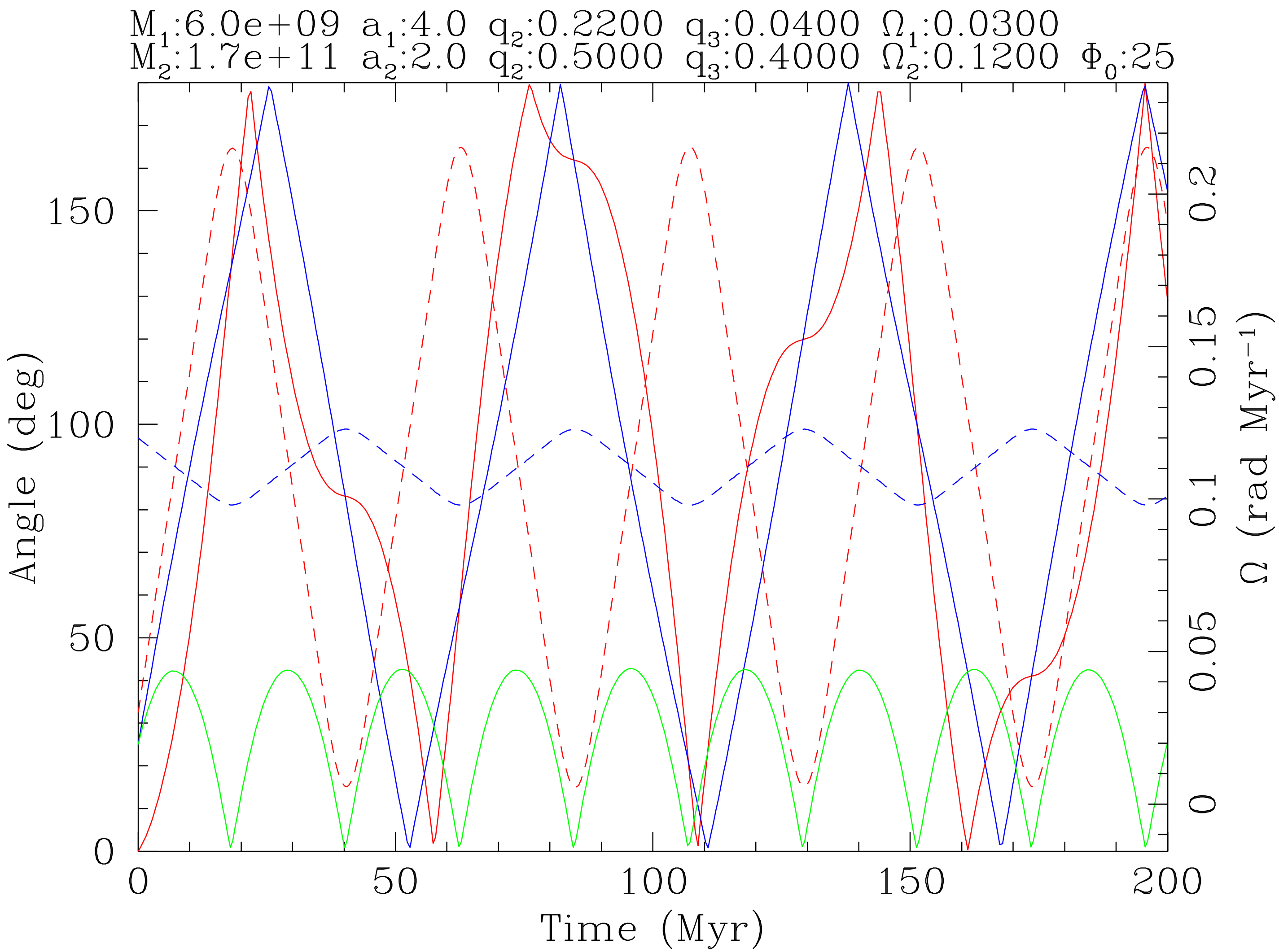
M1:6.0e+09 a1:4.0 q2:0.2200 q3:0.0400 Ω1:0.0300
M2:1.7e+10 a2:2.0 q2:0.5000 q3:0.4000 Ω2:0.1200 Φ0:25
Angle (deg)
Ω (rad Myr⁻¹)
Time (Myr)
0
50
100
150
200
0.05
0.1

Rigid Bars

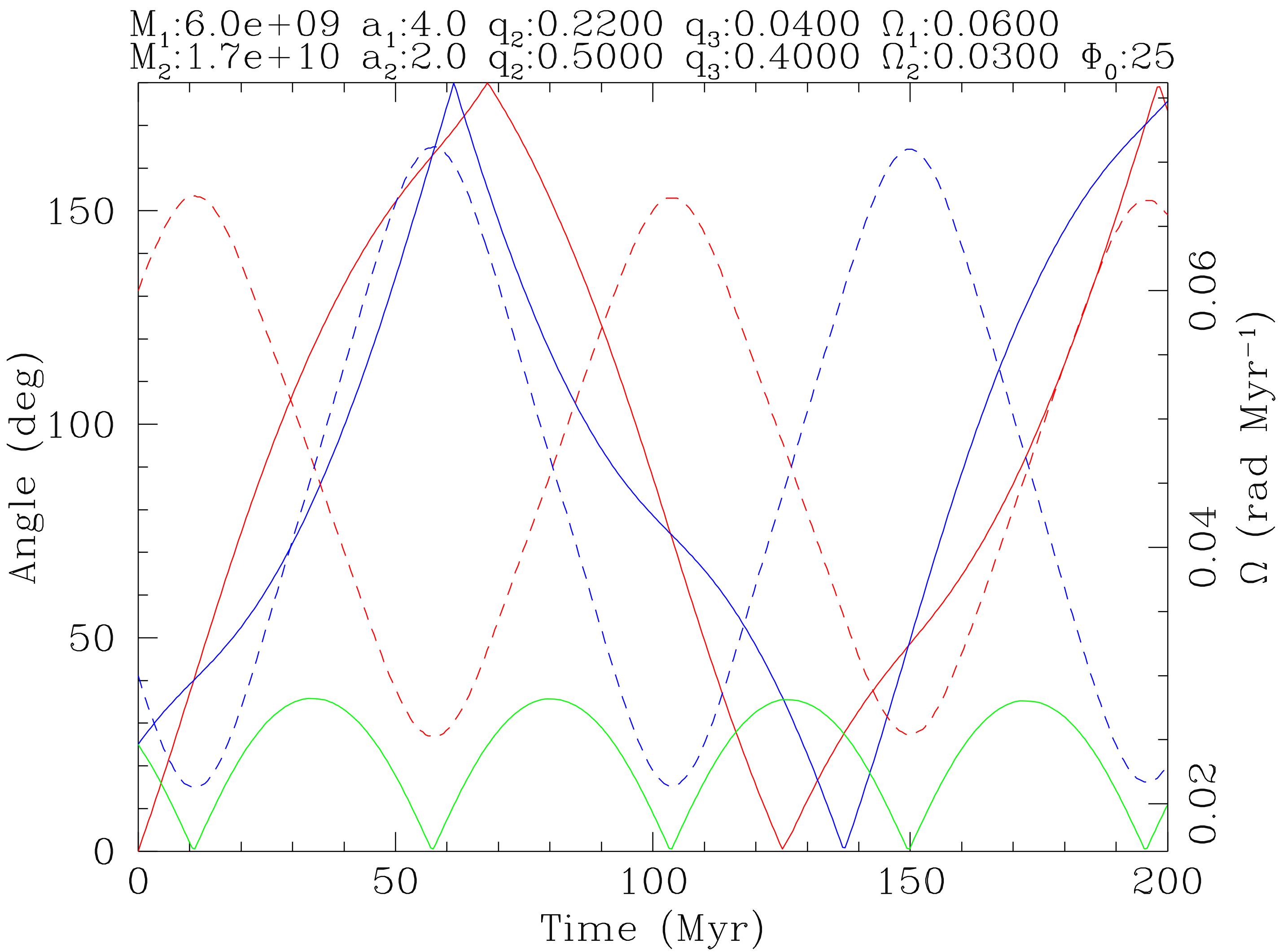


M1:6.0e+09 a1:4.0 q2:0.2200 q3:0.0400 Ω1:0.0300
M2:1.7e+10 a2:2.0 q2:0.5000 q3:0.4000 Ω2:1.0000 Φ0:25
Angle (deg)
Ω (rad Myr−1)
Time (Myr)
0
50
100
150
0
10
20
30
40
50
0
0.2
0.4
0.6
0.8
1

Rigid Bars


M1:6.0e+09 a1:4.0 q2:0.2200 q3:0.0400 Ω1:0.0300
M2:1.7e+11 a2:2.0 q2:0.5000 q3:0.4000 Ω2:0.1200 Φ0:25
Angle (deg)
Time (Myr)
Ω (rad Myr⁻¹)
0
50
100
150
200
0.05
0.1
0.15
0.2

Rigid Bars



M1:6.0e+09 a1:4.0 q2:0.2200 q3:0.0400 Ω1:0.0600
M2:1.7e+10 a2:2.0 q2:0.5000 q3:0.4000 Ω2:0.0300 Φ0:25
Angle (deg)
Time (Myr)
Ω (rad Myr⁻¹)
0
50
100
150
200
0.02
0.04
0.06

Formalism for deform. bars

$$\vec{\tau}_T = \vec{\tau}_1 + \vec{\tau}_2 = 0 \qquad \vec{\tau}_T = \frac{d\vec{L}_T}{dt} \qquad \vec{\tau}_i = \frac{d\vec{L}_i}{dt} \qquad \vec{L}_i = I_i \vec{\Omega}_i$$

$$\ddot{\Delta\phi} = (\dot{\Omega}_2 - \dot{\Omega}_1) = \left(\frac{1}{I_2} + \frac{1}{I_1} \right) \tau_2(\Delta\phi) - \frac{d \ln(I_2)}{dt} \Omega_2 + \frac{d \ln(I_1)}{dt} \Omega_1$$

$$\tau_j(\Delta\phi) = \int_{Vj} dV \rho_j F_{\phi,i}(\vec{r}) R$$

$$\Longrightarrow \quad \dot{\Omega}_i = \tau_i(\Delta\Phi) \left(I_i + \frac{\mathrm{d}I_i}{\mathrm{d}\Omega_i} \Omega_i \right)^{-1}$$

$$\Longrightarrow \quad \dot{\Omega}_i = \frac{\tau_i(\Delta\Phi)}{I_i} \left(1 + \frac{2\Omega_i}{a_{1i}} \frac{\partial a_{1i}}{\partial \Omega_i} + \frac{2 q_{2i} \Omega_i}{1 + q_{2i}^2} \frac{\partial q_{2i}}{\partial \Omega_i} \right)^{-1}$$

If Jacobi…

$$a_2 = a_1 a_3 \left[\frac{A_3}{A_3 a_3^2 - (A_1 - A_2) a_1^2} \right]^{1/2} \qquad q_2 = q_3 \left[\frac{A_3}{A_3 q_3^2 - (A_1 - A_2)} \right]^{1/2}$$

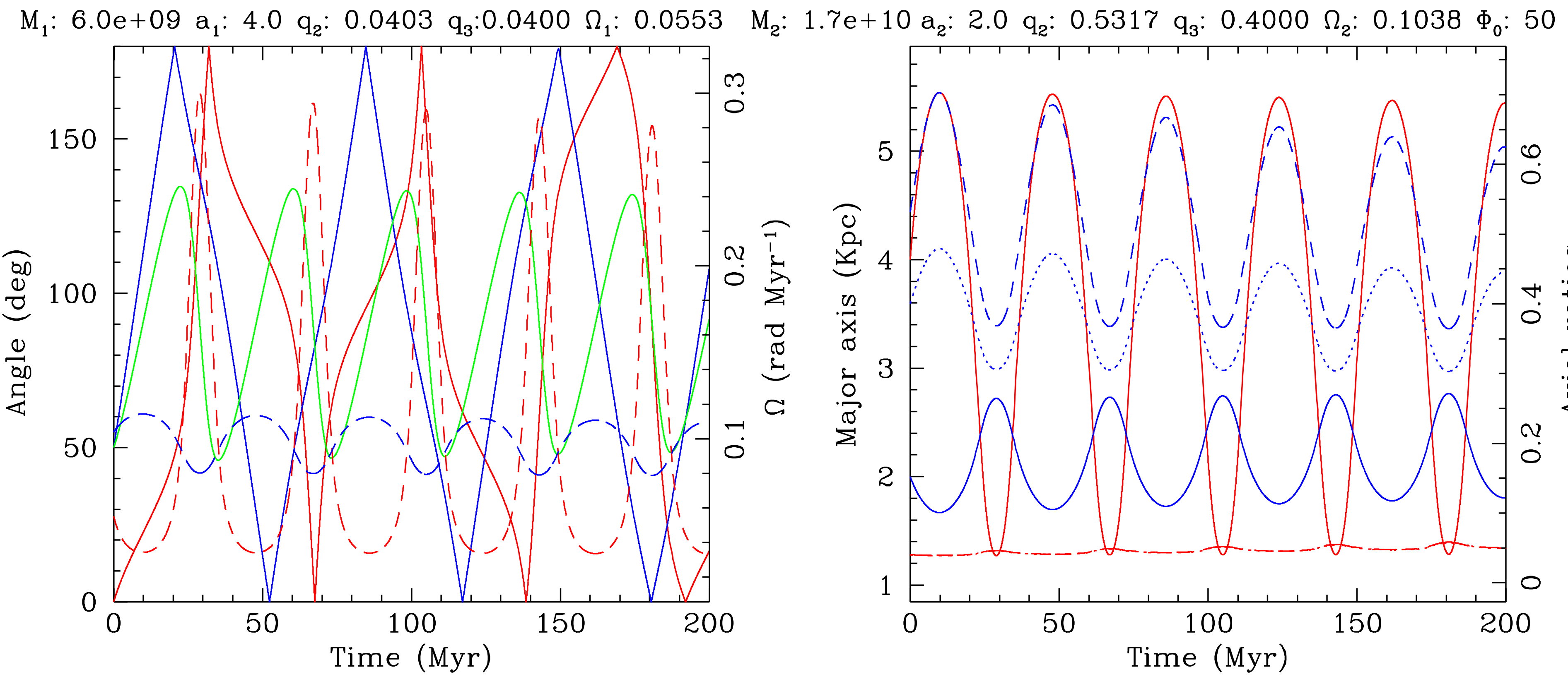
$$a_3 = a_1 a_2 \left[\frac{A_1 - A_2}{A_3 (a_2^2 - a_1^2)} \right]^{1/2} \qquad q_3 = q_2 \left[\frac{A_1 - A_2}{A_3 (q_2^2 - 1)} \right]^{1/2}$$

$$\Omega^2 = \frac{3}{2} \frac{GM}{a_1 a_2 a_3} \frac{a_1^2 A_1 - a_2^2 A_2}{(a_1^2 - a_2^2)} \qquad \Omega^2 = \frac{3}{2} \frac{GM}{a_1^3 q_2 q_3} \frac{A_1 - q_2^2 A_2}{(1 - q_2^2)}$$

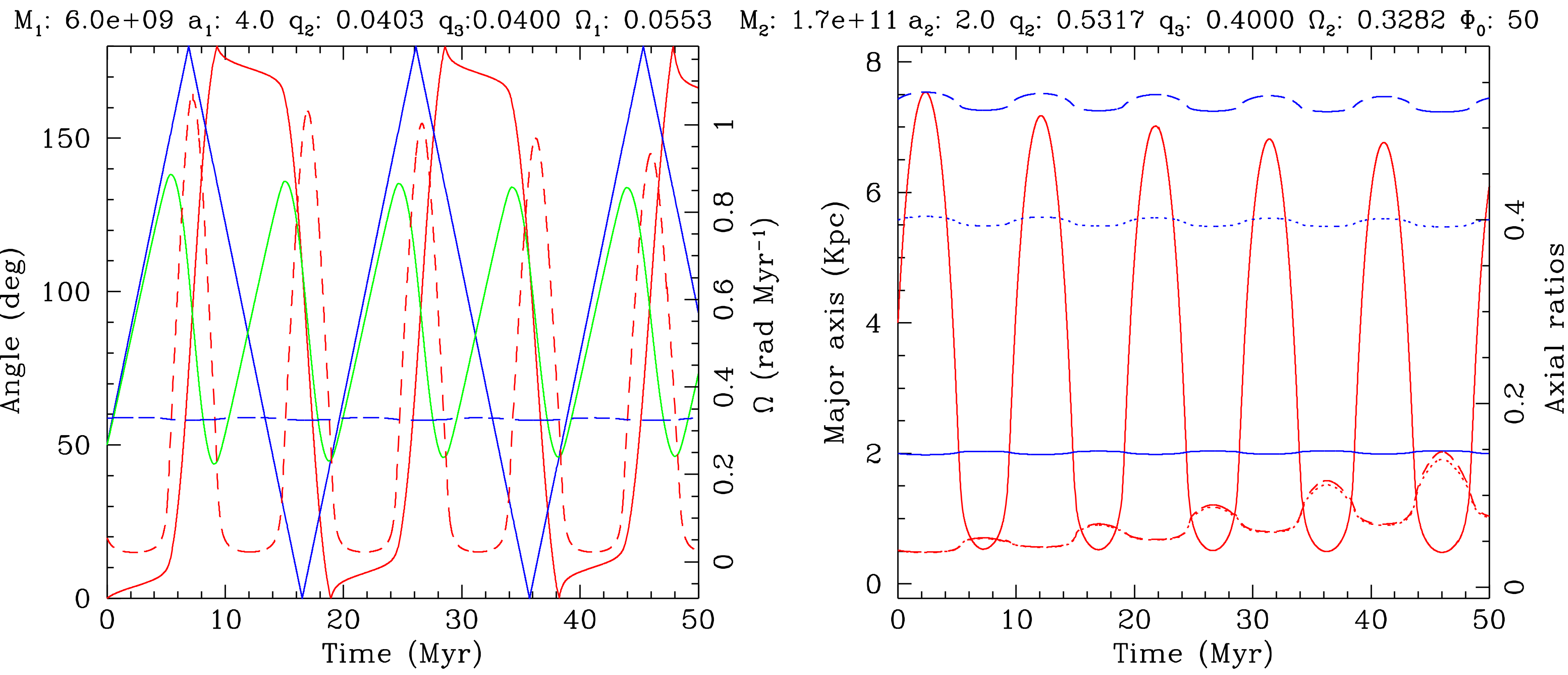
$$\dot{\Omega}_i = \tau_i(\Delta\Phi) \left[I_i \left(\frac{2 q_{2,i} \Omega_i}{1 + q_{2,i}^2} \frac{\partial q_{2,i}}{\partial \Omega_i} - \frac{1}{3} \right) \right]^{-1}$$

$$\frac{\partial q_{2,i}}{\partial \Omega_i} < 0$$

Evolution of deform. bars (J)

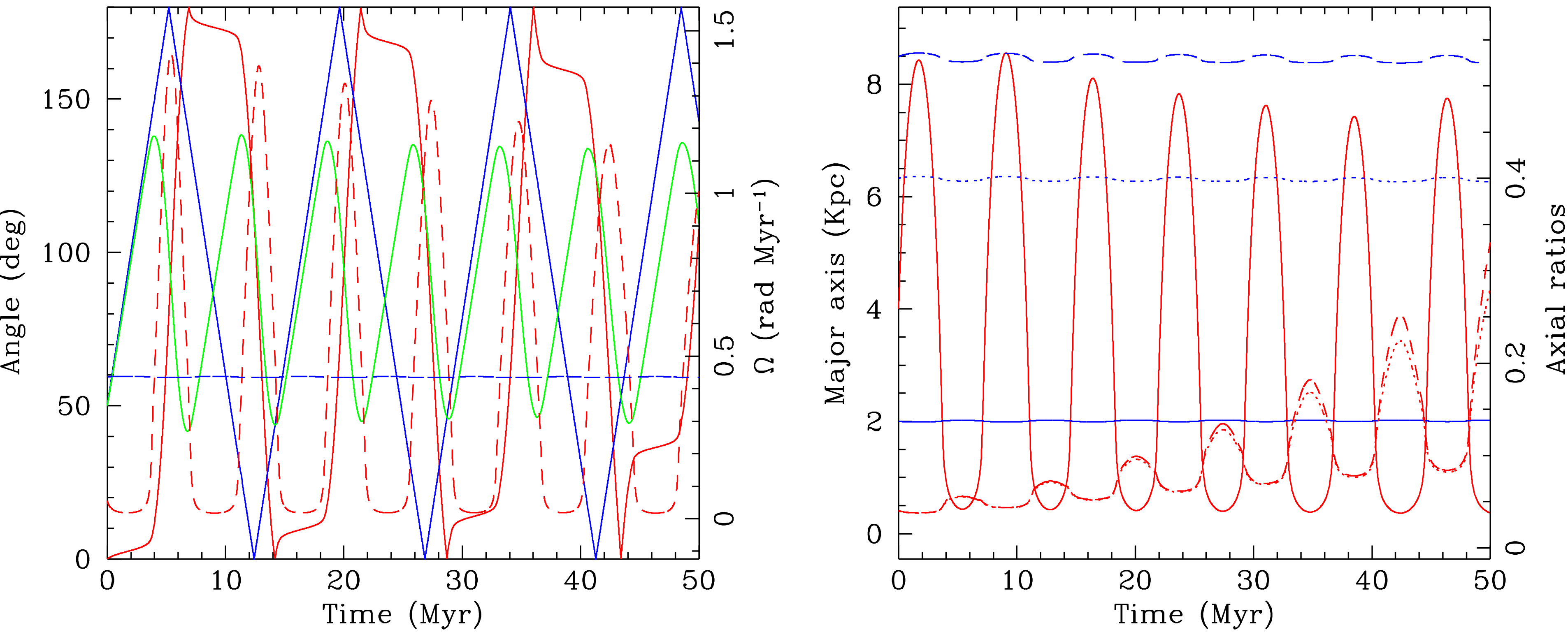


Evolution of deform. bars (J)

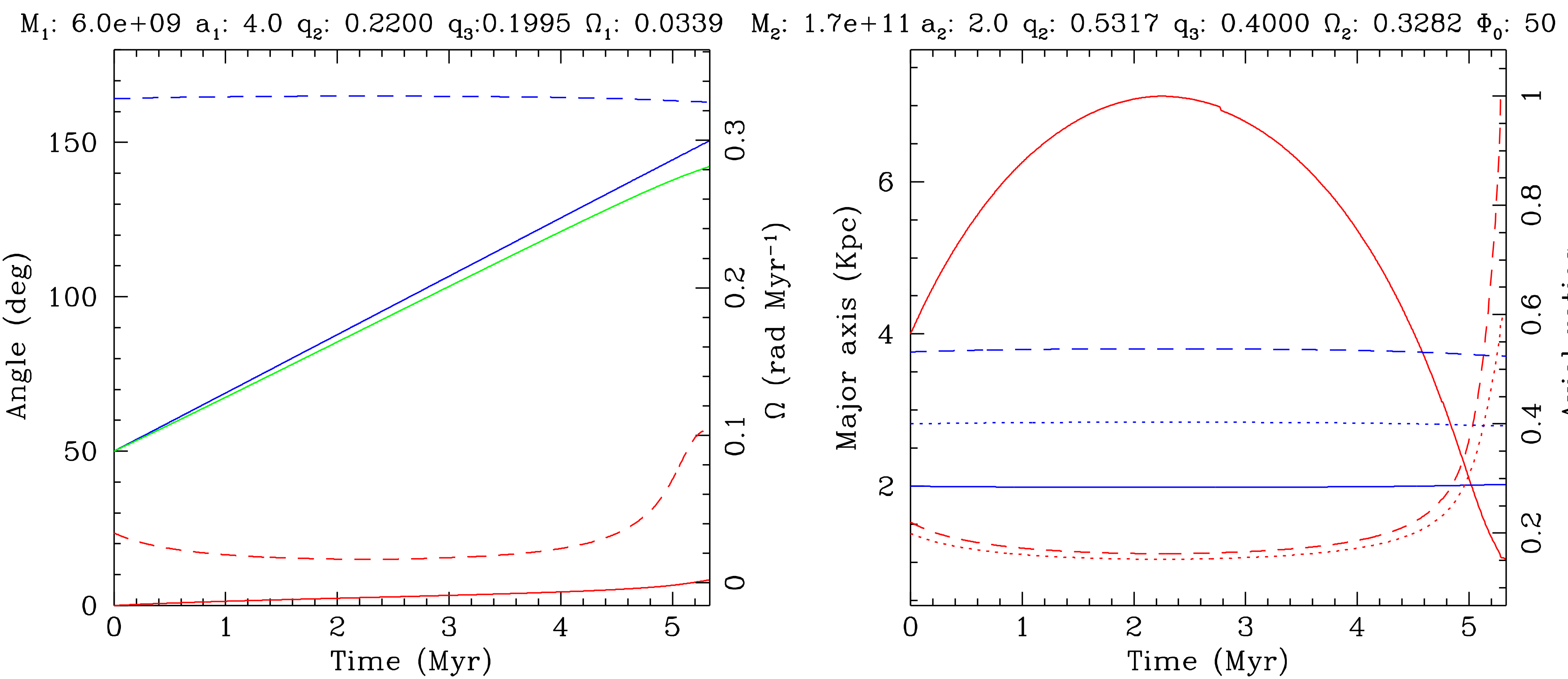


Evolution of deform. bars (J)

M_1: 6.0e+09 a_1: 4.0 q_2: 0.0403 q_3:0.0400 Ω_1: 0.0553 M_2: 3.0e+11 a_2: 2.0 q_2: 0.5317 q_3: 0.4000 Ω_2: 0.4360 Φ_0: 50



Evolution of deform. bars (J)



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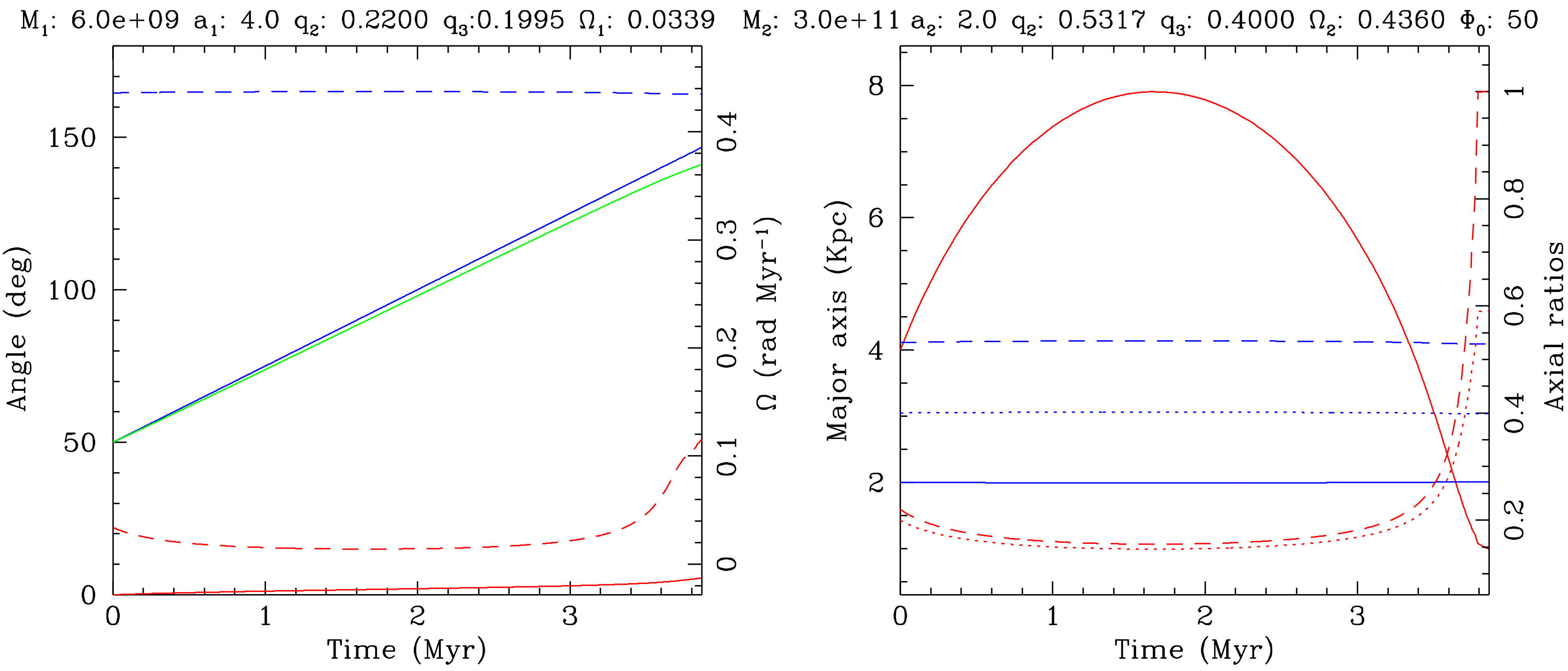
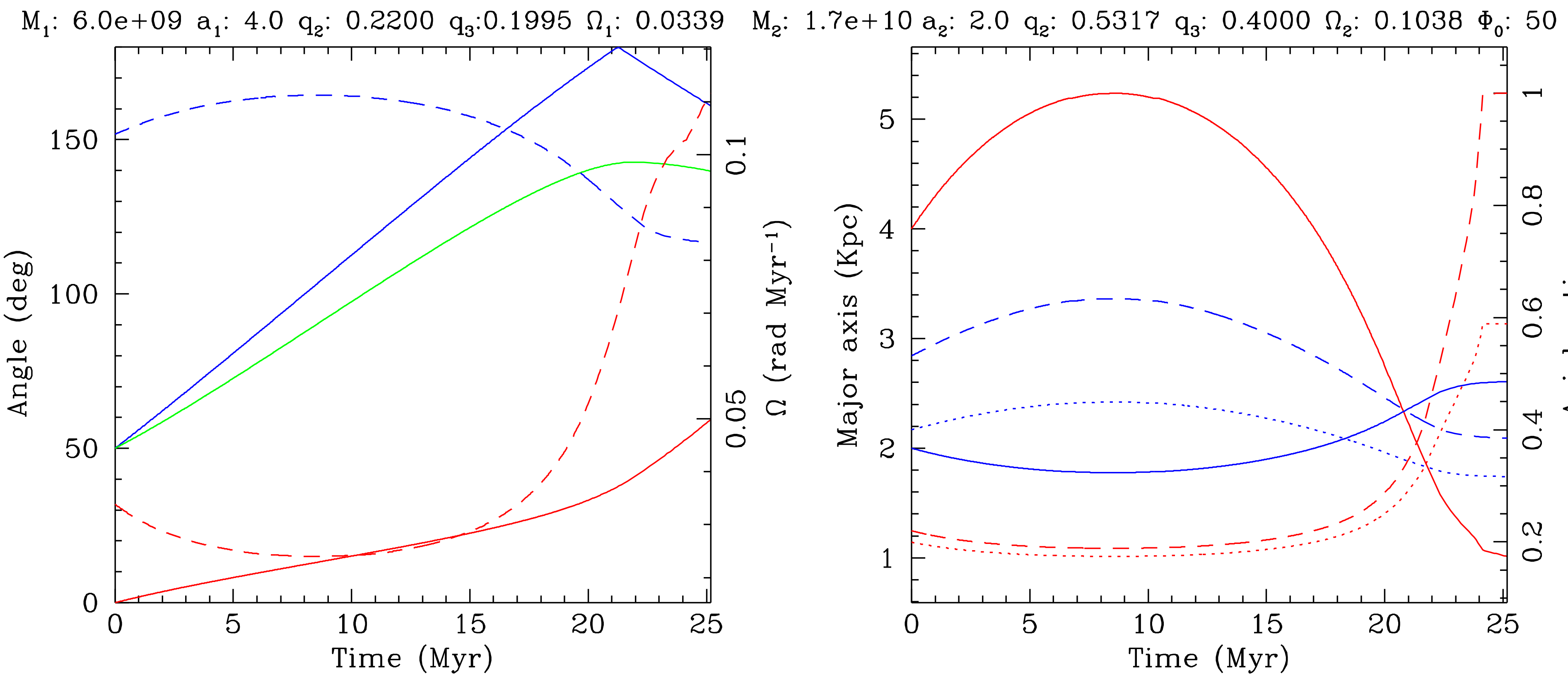


Evolution of deform. bars (J)



If pseudo-Jacobi

$$V(\vec{x}) = \frac{3}{4}\frac{GM}{a_1^3}\int_{u(\vec{x})}^{\infty}\left[1 - \sum_{j=1}^{3}\frac{x_j^2}{a_j^2+\mu}\right]\frac{d\mu}{\Delta(\mu)}$$

$$\Delta^2(\mu) = (1+\mu)(q_2^2+\mu)(q_3^2+\mu) \qquad \sum_{j=1}^{3}\frac{x_j^2}{a_j^2+u} = 1$$

$$V_i(\vec{x}) = -\frac{3}{4}\frac{GM_i}{a_{1i}^3}\left[A_i[u_i(\vec{x})]x^2 + B_i[u_i(\vec{x})]y^2 + C_i[u_i(\vec{x})]z^2\right]$$

$$A_i[u_i(\vec{x})] = \int_{u_i(\vec{x})}^{\infty}\frac{d\mu}{(1+\mu)\Delta_i(\mu)}$$

$$B_i[u_i(\vec{x})] = \int_{u_i(\vec{x})}^{\infty}\frac{d\mu}{(q_2^2+\mu)\Delta_i(\mu)}$$

$$C_i[u_i(\vec{x})] = \int_{u_i(\vec{x})}^{\infty}\frac{d\mu}{(q_3^2+\mu)\Delta_i(\mu)}$$

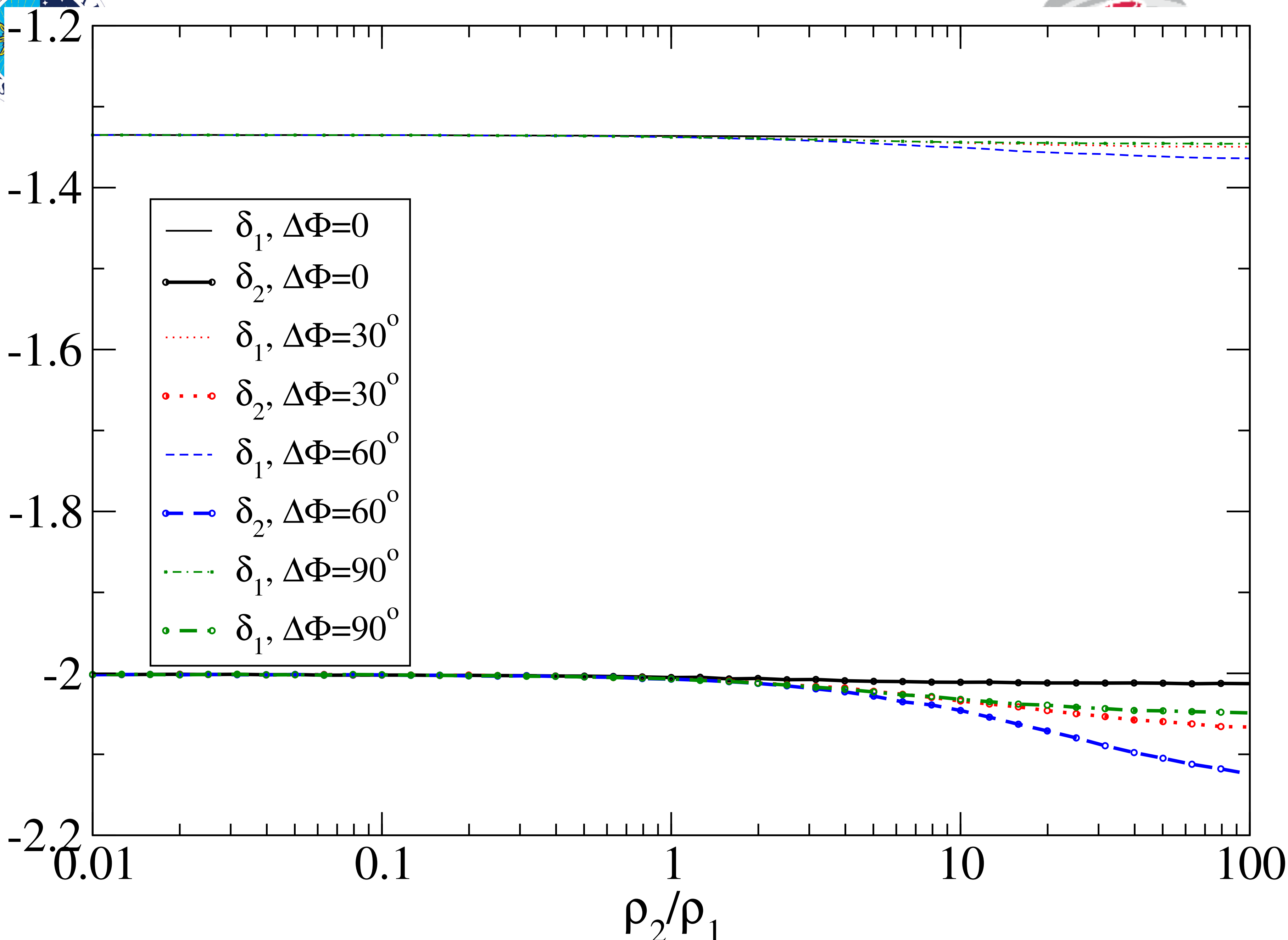
and…

$$V_i(\vec{x}_i)+V_j(\vec{x}_i)+\frac{1}{2}\Omega_i^2(x_i^2+y_i^2)=\text{constant}$$

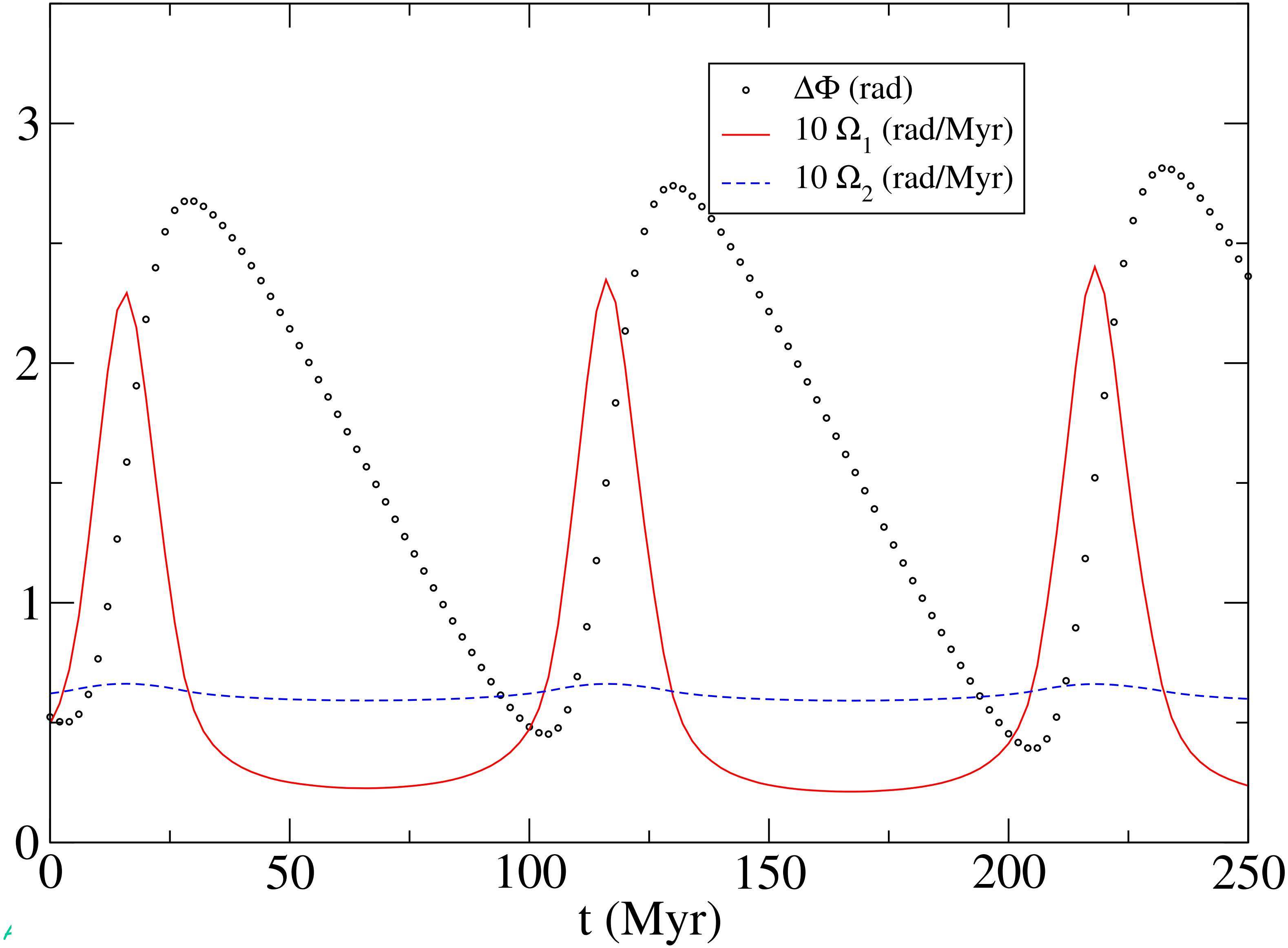
$$A_i[0]+D_{ji}\left[A_j[u_{ij1}]\cos^2(\Delta\Phi)+B_j[u_{ij1}]\sin^2(\Delta\Phi)\right]-E_i=$$
$$=q_{2i}^2\left\{B_i[0]+D_{ji}\left[A_j[u_{ij2}]\sin^2(\Delta\Phi)+B_j[u_{ij2}]\cos^2(\Delta\Phi)\right]-E_i\right\}=$$
$$=q_{3i}^2\left\{C_i[0]+D_{ji}C_j[u_{ij3}]\right\}$$

$$\dot{\Omega}_i=\frac{\tau_i(\Delta\Phi)}{I_i}\left(1+\frac{2\Omega_i}{a_{1i}}\frac{\partial a_{1i}}{\partial\Omega_i}+\frac{2q_{2i}\Omega_i}{1+q_{2i}^2}\frac{\partial q_{2i}}{\partial\Omega_i}\right)^{-1}$$

$$\delta_1\equiv(2\Omega_i/a_{1i})\times(\partial a_{1i}/\partial\Omega_i)$$
$$\delta_2\equiv\Omega_i\times(\partial q_{2i}/\partial\Omega_i)$$


-1.2
-1.4
-1.6
-1.8
-2
-2.2
0.01
0.1
1
10
100
ρ2/ρ1
δ1, ΔΦ=0
δ2, ΔΦ=0
δ1, ΔΦ=30o
δ2, ΔΦ=30o
δ1, ΔΦ=60o
δ2, ΔΦ=60o
δ1, ΔΦ=90o
δ1, ΔΦ=90o

Evol. of deform. bars (PJ)



Evol. of deform. bars (PJ)