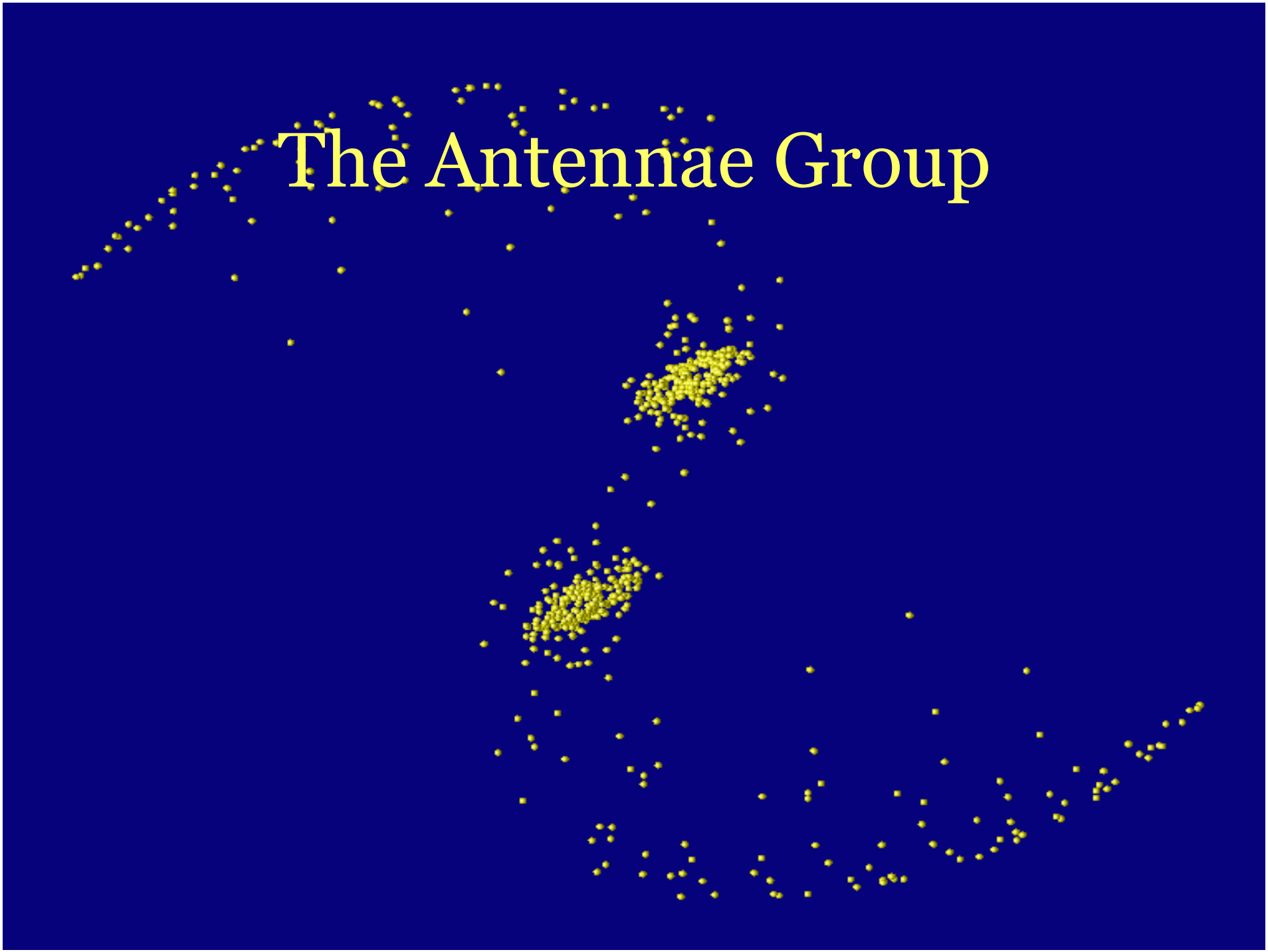
The Antennae Group



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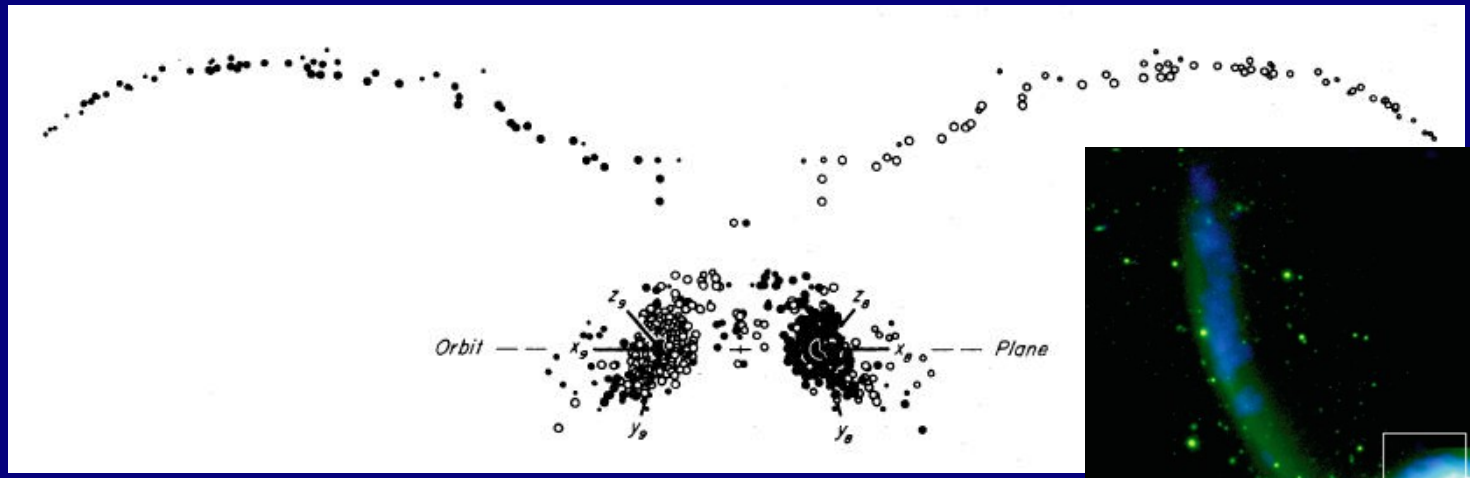
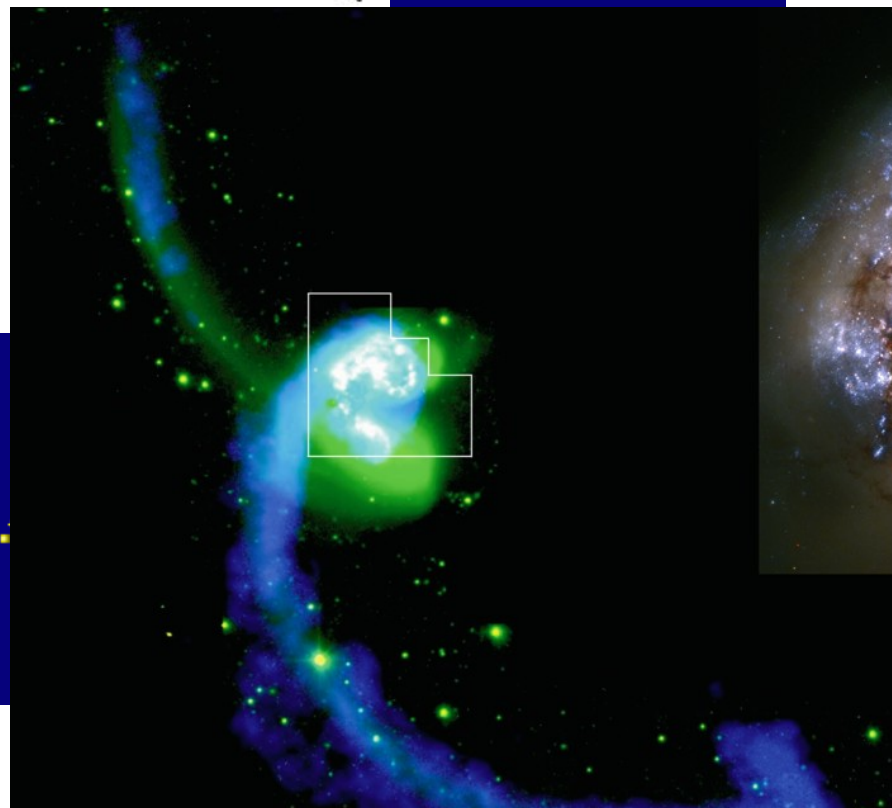
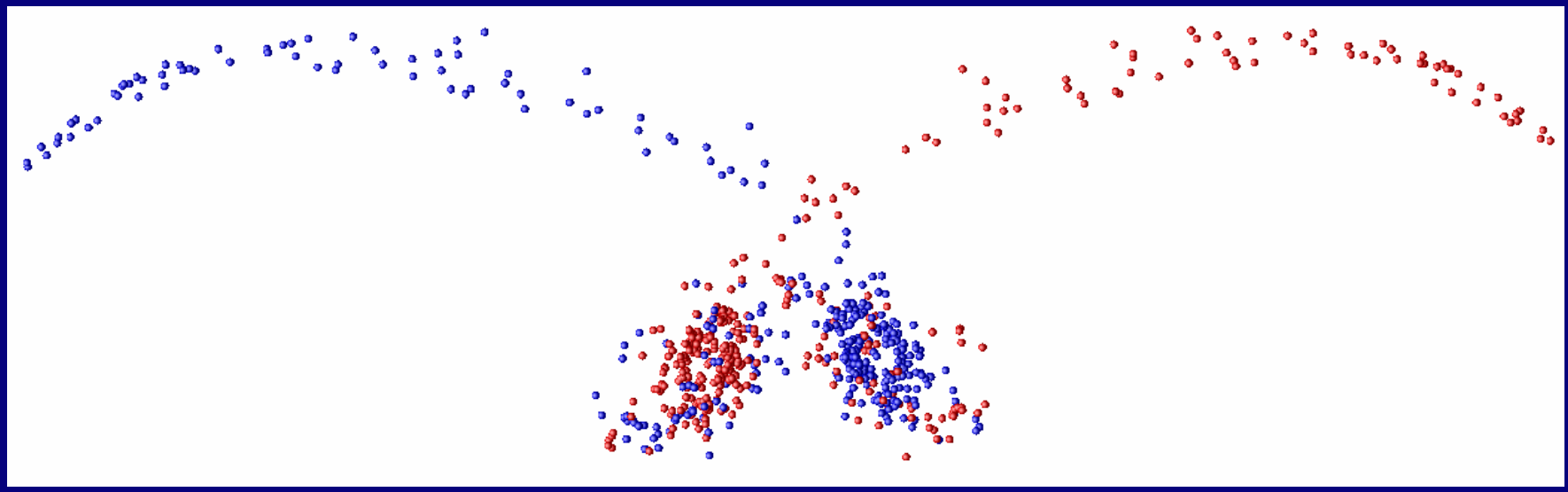
Toomre and Toomre

- 1972 – T&T set out to model galaxies NGC-4038/9 (i.e. the antennae) and were able to successfully produce an accurate rendering using a fourth order Runge-Kutta integration method.





1972 → 2006

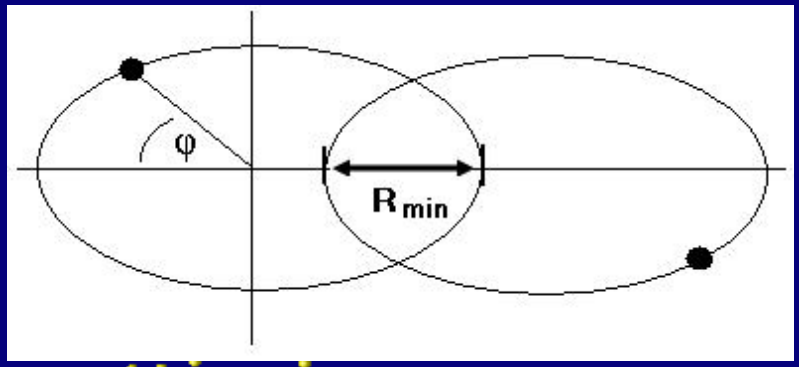


Kepler problem

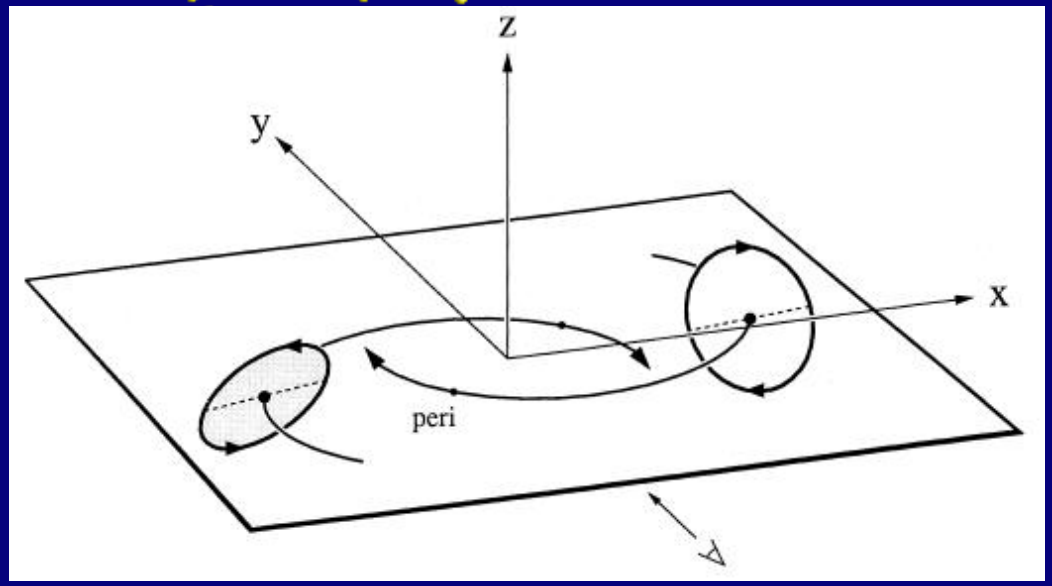
$$\mathbf{r}_1 = \frac{m_2}{m_1 + m_2} r(\phi)\hat{\mathbf{r}} \qquad v_r = -\varepsilon \sqrt{\frac{G(M_1 + M_2)}{R_{\min}(1+\varepsilon)}} \sin\phi$$

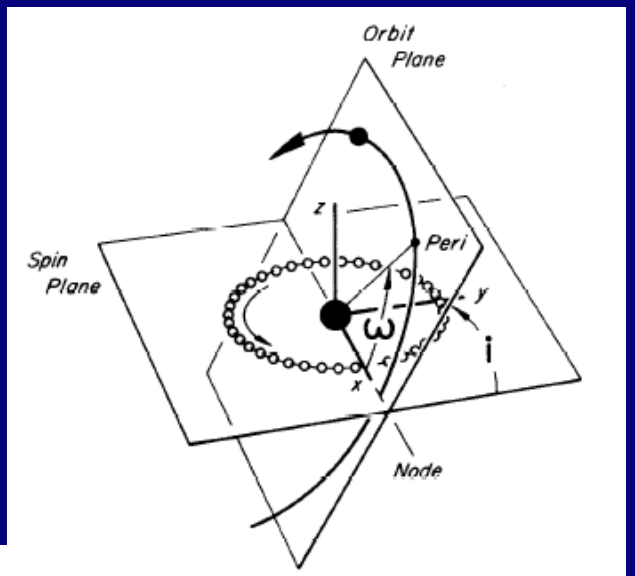
$$\mathbf{r}_2 = -\frac{m_1}{m_1 + m_2} r(\phi)\hat{\mathbf{r}} \qquad v_\phi = \sqrt{\frac{G(M_1 + M_2)}{R_{\min}(1+\varepsilon)}} (1 - \varepsilon\cos\phi)$$

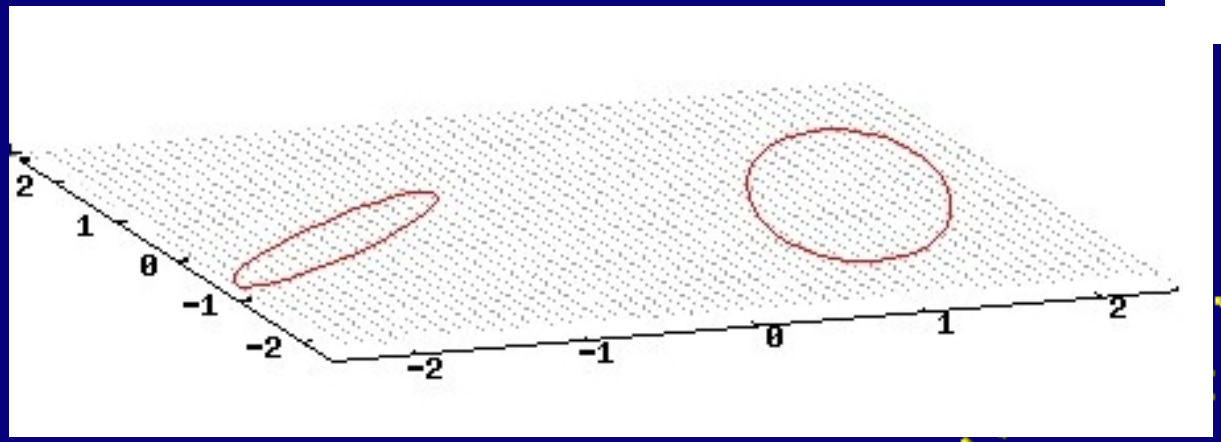
$$r(\phi) = \frac{R_{\min}(1+\varepsilon)}{1 - \varepsilon\cos\phi}$$



Geometry

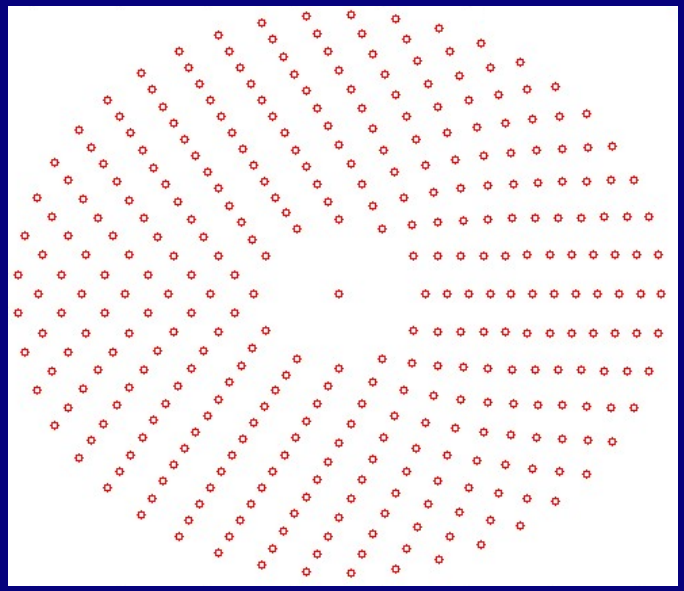






Galaxy Setup

- We filled 12 concentric rings of radii $0.2R_{min}$ to $0.75R_{min}$ with a step of $0.05R_{min}$, with each ring having 3 more particles than the previous
- Particles given initial velocity to maintain a circular orbit.
- Softening: $\varepsilon = 0.2$



$$\frac{v_0^2}{r} = \frac{GM}{r^2 + \varepsilon^2} \Rightarrow v_0 = \sqrt{\frac{GMr}{r^2 + \varepsilon^2}}$$

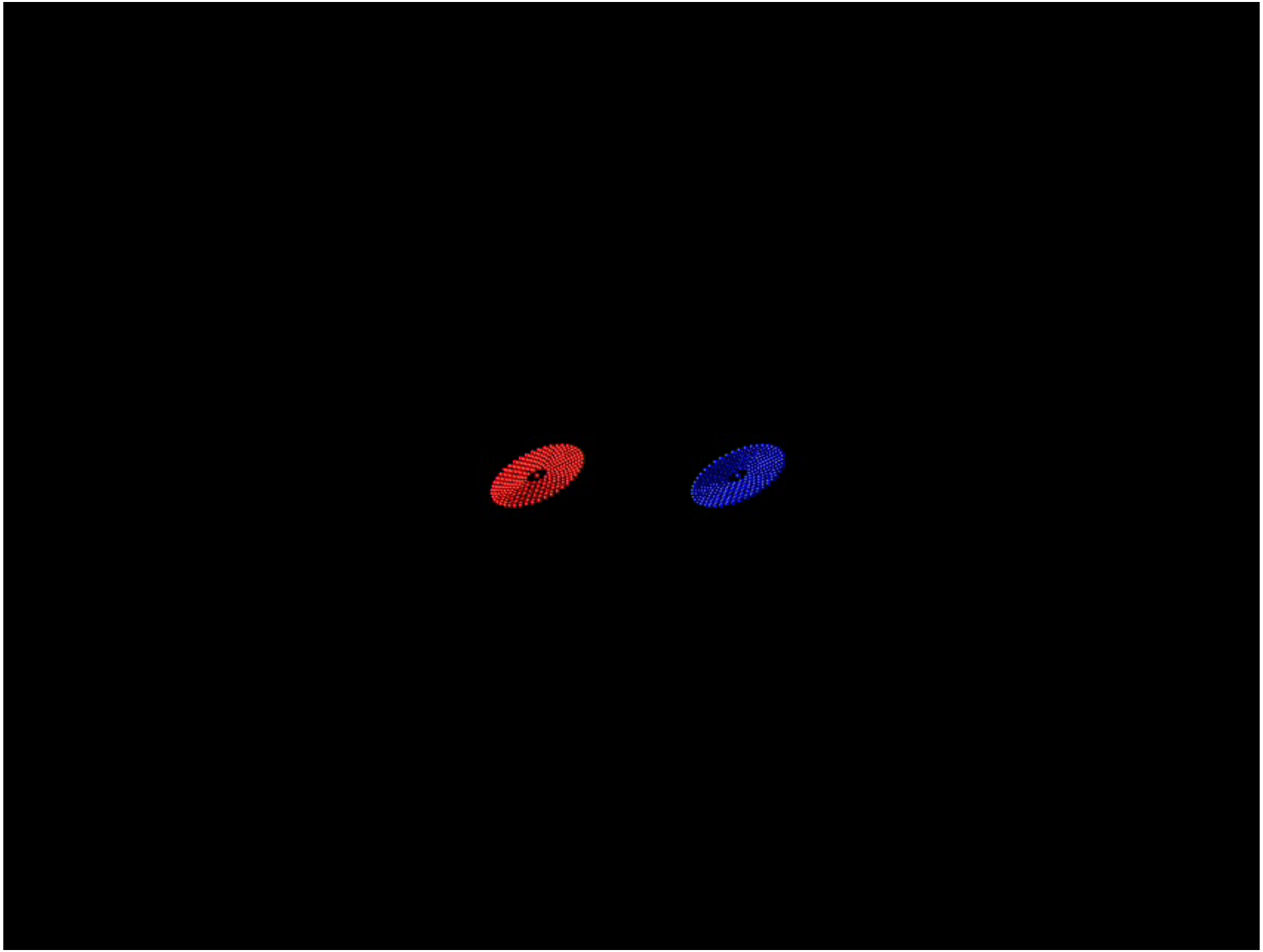
Restricted 3-Body

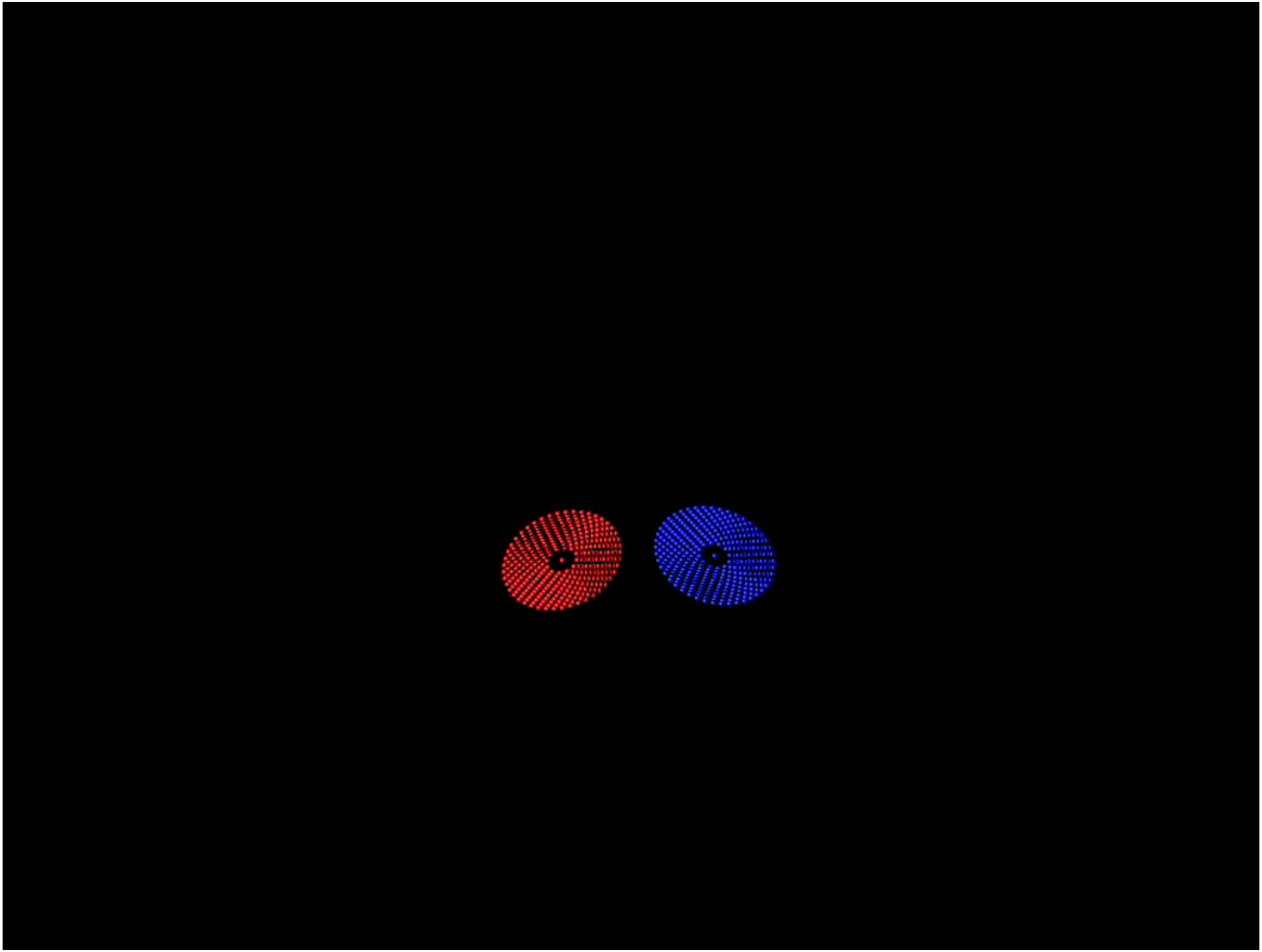
- Send satellite masses to 1.0 E-9 as compared to M = 1 for the center of mass.

$$\frac{GMm}{R_{\min}^2 + \varepsilon^2} \sim 10^{-9}$$

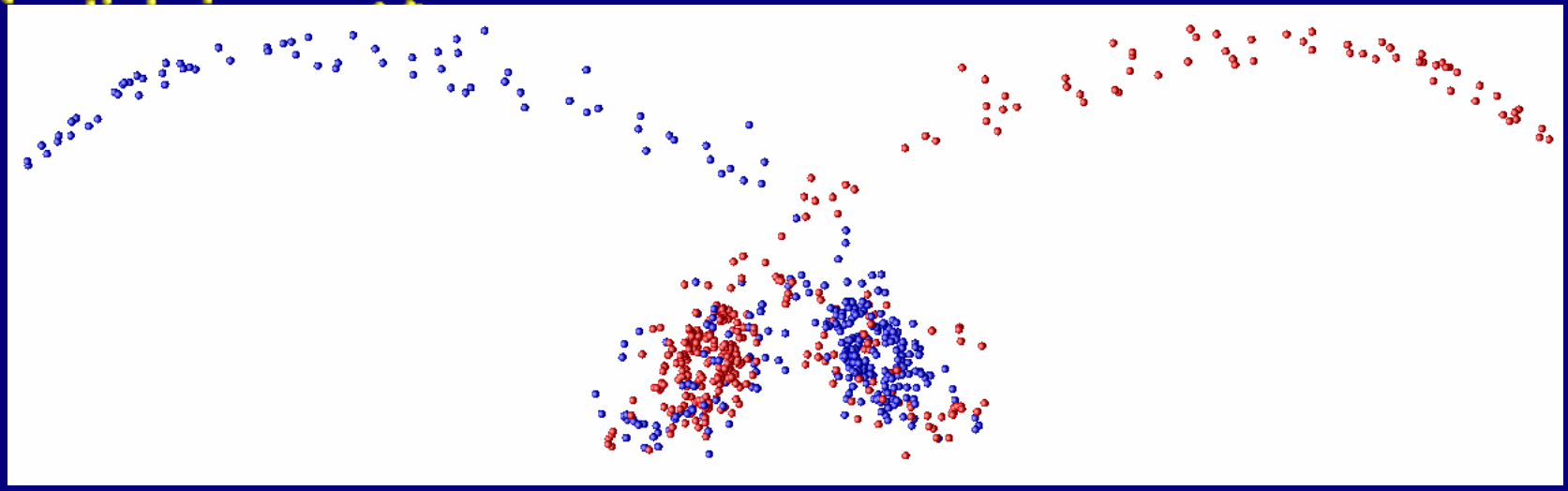
$$\frac{Gm^2}{r^2 + \varepsilon^2} \to \frac{Gm^2}{\varepsilon^2} \sim 10^{-15}$$

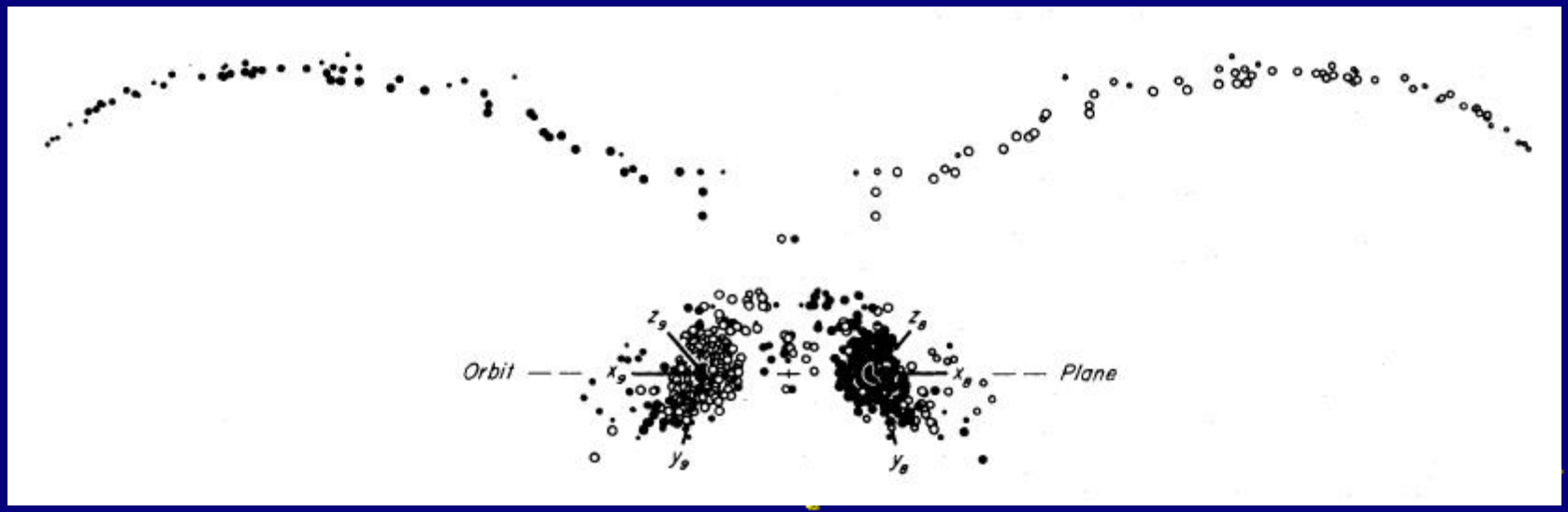
Our Results

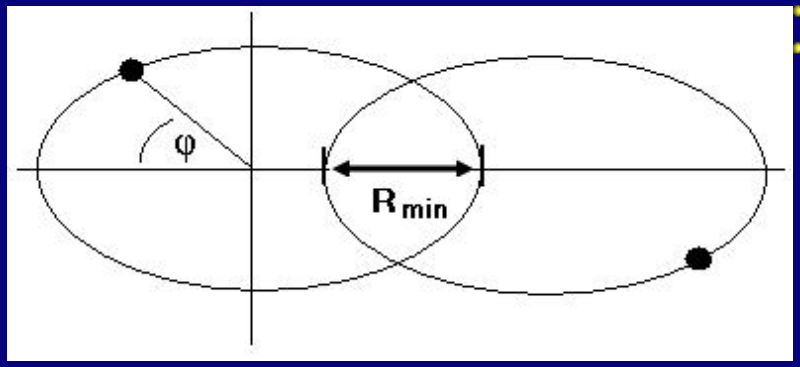




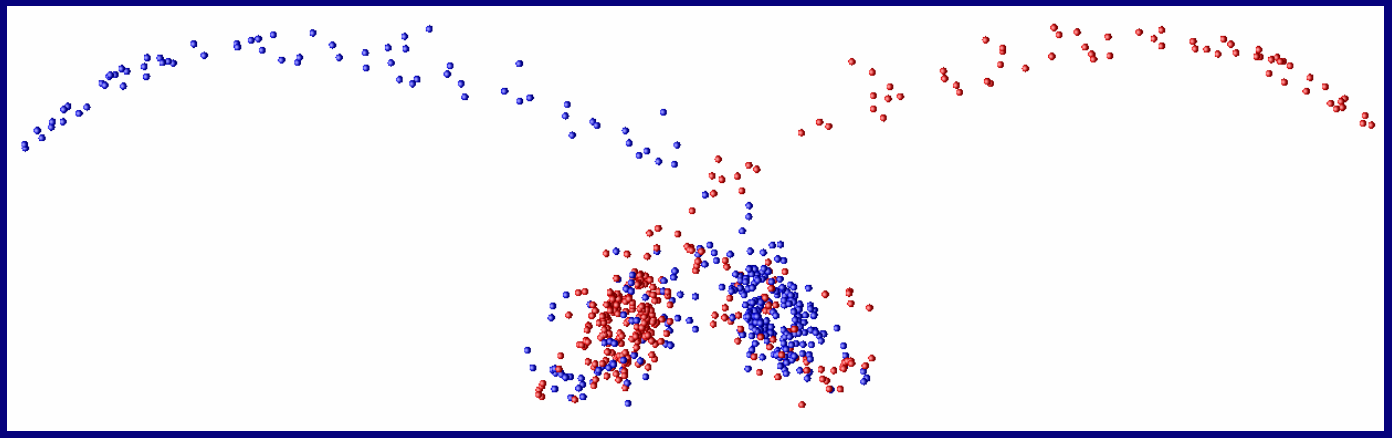
Comparison



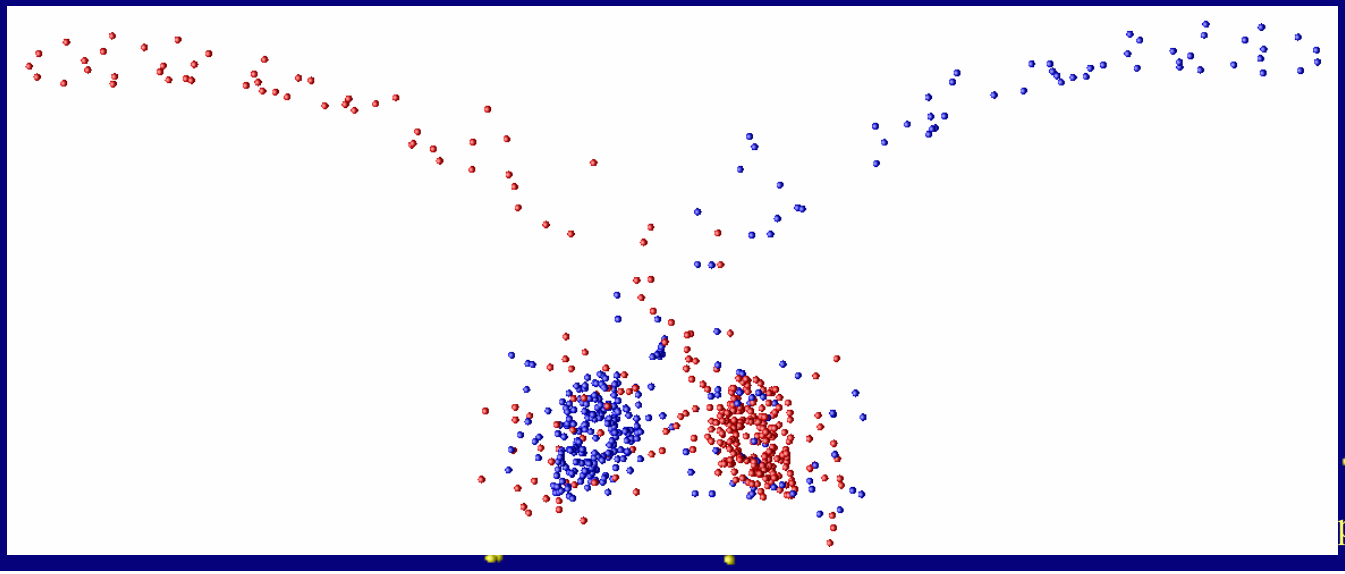




Orbit Plane

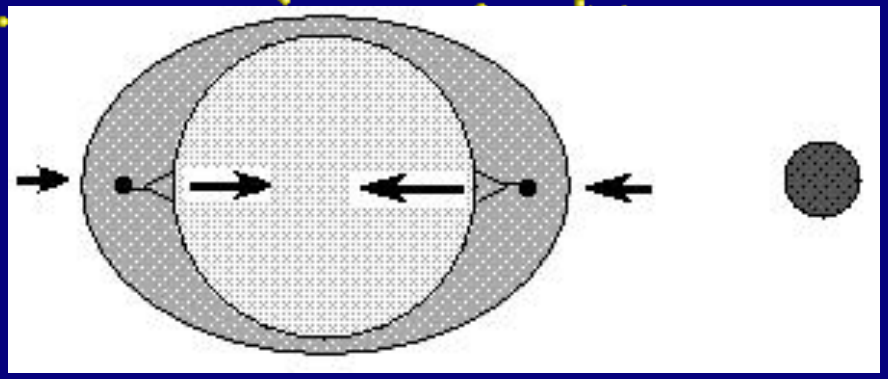


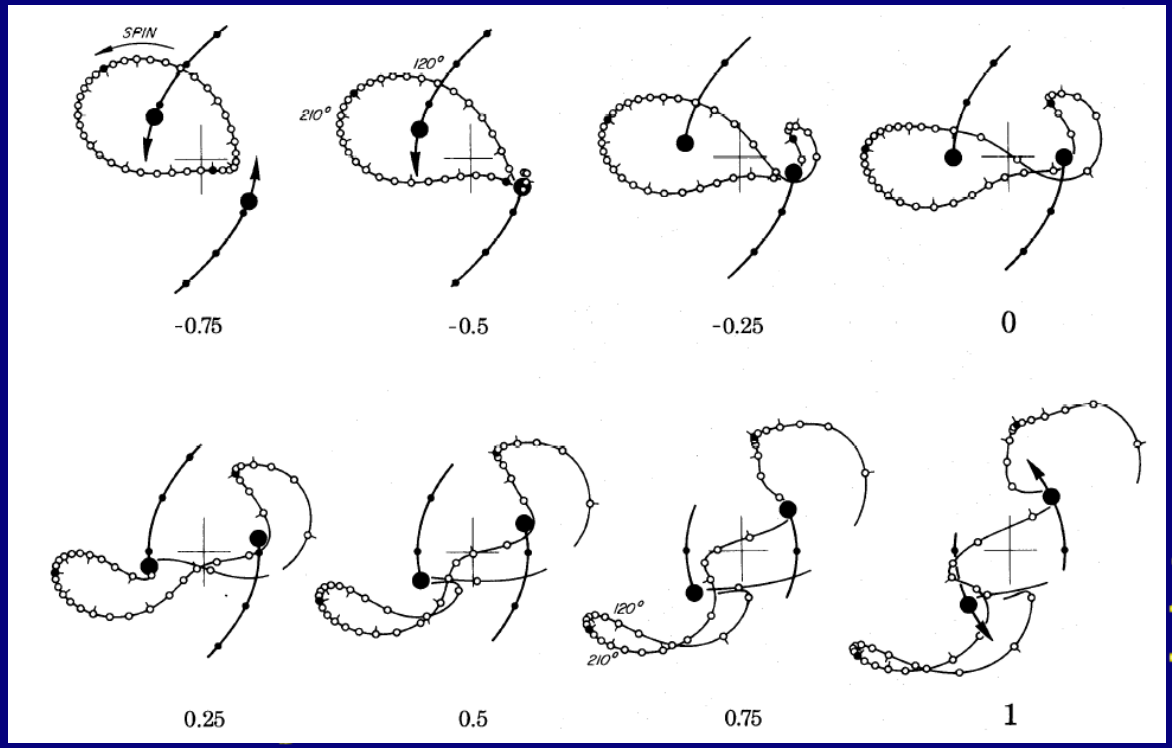
$\varphi = 0$

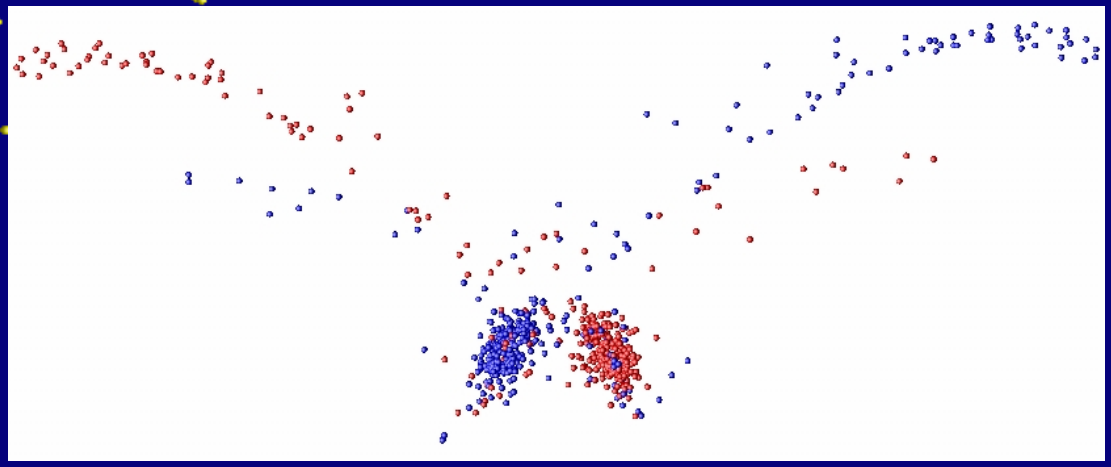


$\varphi = 2\pi/3$

Tidal Forces

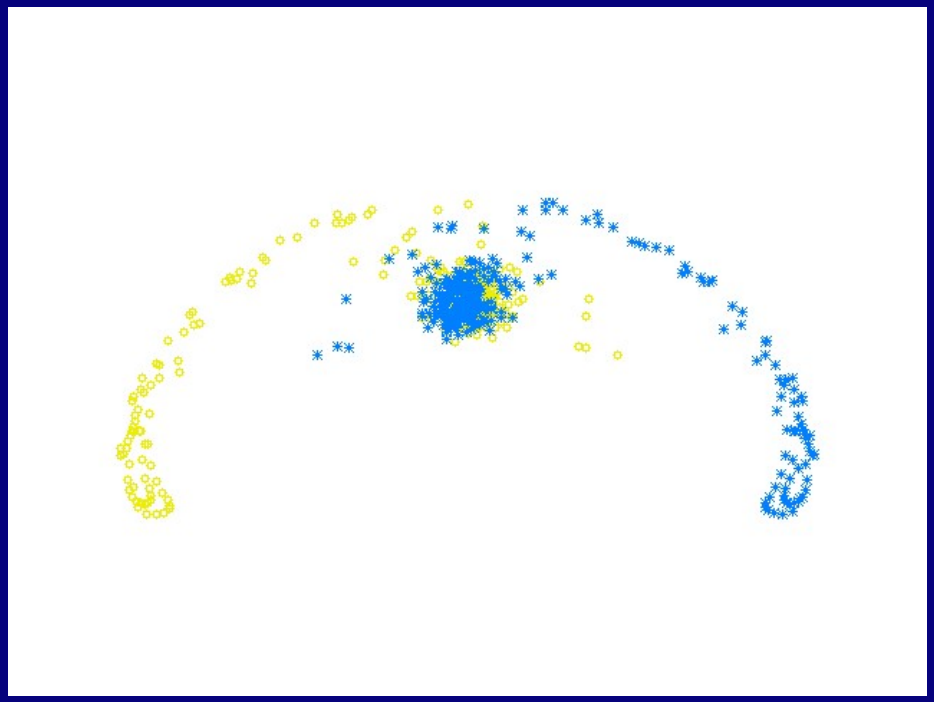


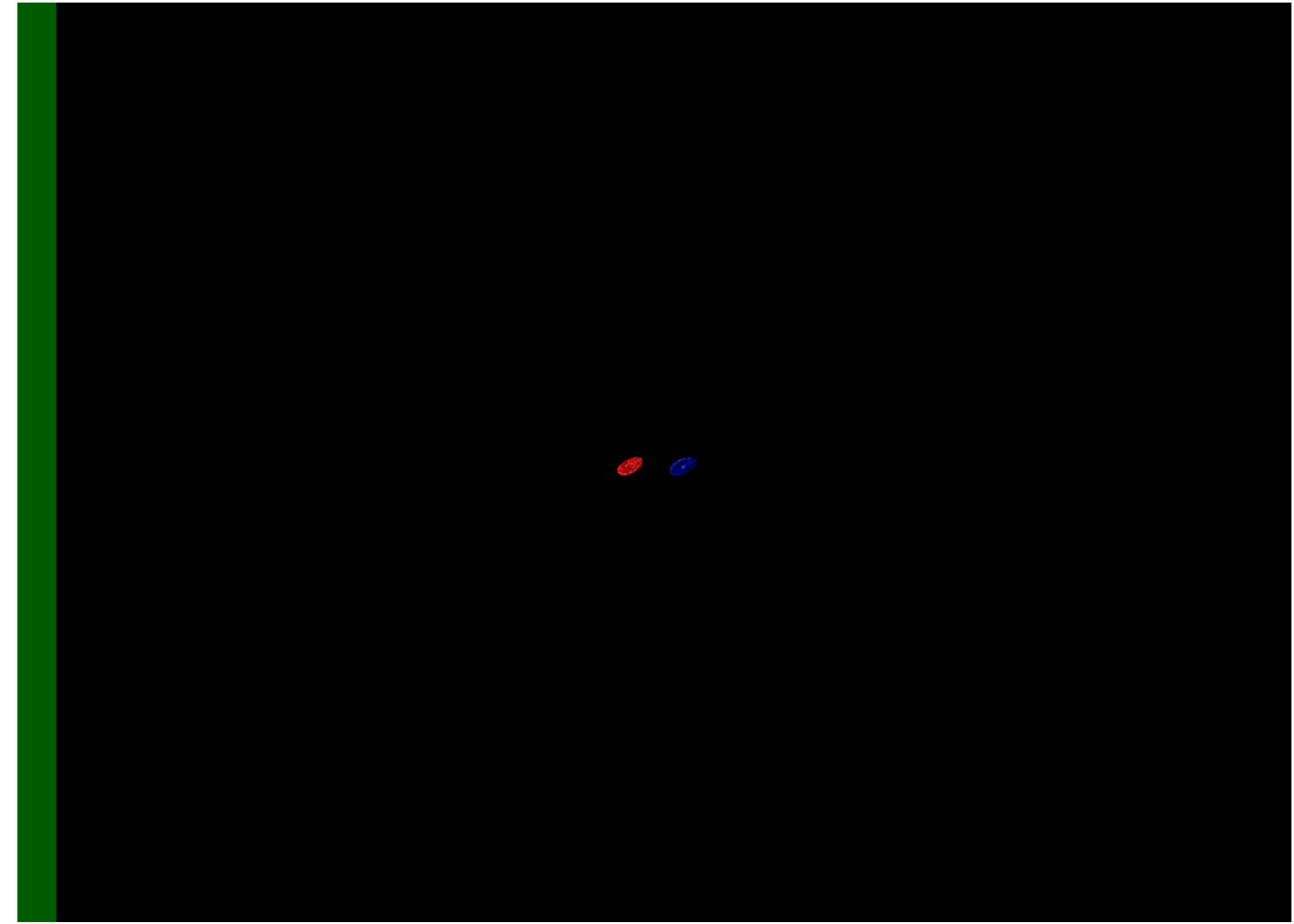




Dumbo

Extra tails





Next Step

- Asymmetry in NGC 4038/9 – differences in mass or size
- More realistic galaxy model
- Different integration tools – Tree Codes
- Check that conserved quantities are conserved