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Questions & Answers for part 4

1. How many close encounters will the MW and M31 experience in the future?

Visually, the graph shows that there are only **three major close encounters** between the MW and M31. By refining the **threshold criteria**—setting a **separation range between 1 kpc and 50 kpc** and ensuring that each encounter follows a **significant drop from the previous peak**—the code accurately isolates these **three key crossover points** before the MW and M31 eventually merge.

2. How is the time evolution of the separation and relative velocity related?

The **separation and relative velocity of the galaxies are inversely proportional**. As the **separation decreases**, the **relative velocity sharply increases**, reaching a peak at pericenter. Conversely, as the galaxies move apart, their relative velocity declines, following a **cyclical pattern**.

For **MW and M31**, this process repeats until the galaxies eventually **merge**, at which point both the separation and velocity approach a steady state near zero.

For **M33 and M31**, the dynamics are different—**M33's orbit is more extended**, and while it undergoes repeated close passes, it does not immediately settle into a merger. The inverse proportionality between separation and velocity remains consistent, supporting the expected **gravitational dynamics of interacting galaxies**.

3. When do M31 and the MW merge? What happens to M33's orbit when they merge?

The **final recorded snapshot (t ≈ 11.43 Gyr)** shows a separation of **∼1.43 kpc**, indicating a near-complete merger. Analysis of the **separation falling below 10 kpc** shows repeated close passes starting around **5-6 Gyr**, ultimately stabilizing into a merger phase between **6-8 Gyr**. After **∼10 Gyr**, the MW and M31 remain within **1-2 kpc of each other**, effectively behaving as a single system.

Regarding **M33**, its orbit remains **tens of kpc away**, continuing to oscillate between **apocenters and pericenters**. However, after the MW-M31 merger, **M33's orbital decay continues**, suggesting it will eventually merge into the newly formed system over a longer timescale.

4. BONUS: What is the decay rate of M33's orbit after 6 Gyr? If constant, how long until M33 merges with MW+M31?

Analysis of M33's **apocenters after 6 Gyr** shows a gradual **orbital decay**:

- **t = 7.50 Gyr**, r = **108.76 kpc**
- **t = 8.93 Gyr**, r = **89.08 kpc**
- **t = 10.07 Gyr**, r = **77.42 kpc**
- **t = 11.07 Gyr**, r = **70.71 kpc**

The **approximate decay rate** (change in apocenter per Gyr) is calculated as **13.77 kpc/Gyr**.

If this rate remains **constant**, then for M33 to decay from **75 kpc** to merger (assuming a final radius near **0 kpc**), it would take approximately **5.45 Gyr** to fully merge with the MW-M31 remnant.