### Disk Galaxies & Galactic Interactions

Chemical evolution High-speed encounters Tidal stripping Dynamical friction

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University of Rochester

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# Metallicity-Luminosity relation



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# Metallicity gradients



Belfiore et al. (2017)

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### **Collisionless interactions**

Particle *q* experiences a tidal force per unit mass from *P* equal to

$$ec{F}_{ ext{tid}}(ec{r}) = -
abla \Phi_P(ec{R} - ec{r} ert) + 
abla \Phi_P(ec{R})$$

The rate of change of energy gained by q as a result of this encounter is

$$\frac{dE_q}{dt} = \vec{v} \cdot \vec{F}_{\rm tid}(\vec{r})$$



# Impact of a collisionless interaction

- Take  $\tau_{\text{tide}}$  to be the time it takes for the tide to rise, and  $\tau_{\text{enc}} \simeq \frac{R_{\text{max}}}{V}$  is the duration of the encounter, then when
- $\tau_{\rm enc} \gg \tau_{\rm tide}$  the effects of the approach and encounter cancel, resulting in no net energy change.
- $\tau_{\rm enc} \lesssim \tau_{\rm tide}$  the body lags behind the interaction, resulting in a torque on the system and a transfer of energy between the two bodies.

Galaxies and dark matter halos are both collisionless systems, so  $\tau_{\text{tide}} \sim \frac{R}{\sigma}$ .

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## High-speed encounters

In a coordinate system centered on *S*, the tidal force per unit mass is

$$\vec{F}_{\rm tide}(\vec{r}) = \frac{GM_P}{R^3} (2x'\hat{x} - y'\hat{y} - z'\hat{z})$$

Transforming back into (x, y, z) and integrating

$$\vec{F}_{\text{tide}} = \frac{d\vec{v}}{dt}$$

we find that

$$\Delta \vec{v} = \frac{2GM_P}{v_P b^2} (-x\hat{x} + y\hat{y})$$

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### Aside: The virial theorem

For gravitationally bound systems in equilibrium, the total energy is always equal to half of the time-averaged potential energy:

$$\langle E 
angle = rac{1}{2} \langle U 
angle$$

Since  $\langle E \rangle = \langle K \rangle + \langle U \rangle$ ,

$$\langle E \rangle = -\langle K \rangle$$
  
 $\langle K \rangle = -\frac{1}{2} \langle U \rangle$   
 $\langle U \rangle = -2 \langle K \rangle$ 

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### Tidal radius

Ignoring the orbital motion of the satellite, its tidal radius is

$$r_t = \left(\frac{m}{2M}\right)^{1/3} R$$

Accounting for the centripetal acceleration due to the satellite being in orbit, the tidal radius is

$$r_t = \left(\frac{\frac{m}{M}}{3 + \frac{m}{M}}\right)^{1/3} R$$

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### Tidal streams Magellanic Stream (ESA/Hubble)



## Tidal streams

#### Sagittarius Stream (S. Koposov & SDSS-III)



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# Tidal trails

Antennae Galaxies (NGC 4038 & NGC 4039)



# Dynamical friction

When an object of mass  $M_S$  moves through a large collisionless system whose constituent particles (field particles) have mass  $m \ll M_S$ , it experiences a drag force — dynamical friction.

Dynamical friction transfers the orbital energy of the satellite galaxy (and dark matter subhalos) to the dark matter particles that make up the host halo, causing the satellite (subhalo) to drift to the center of the potential well, where it can ultimately merge with the central galaxy (galactic cannibalism).

#### Intuitive picture 1: Equipartition

Two-body encounters move systems towards equipartition

$$m_1 \langle v_1^2 \rangle = m_2 \langle v_2^2 \rangle = m_3 \langle v_3^2 \rangle$$

Initially,  $v_S^2 \sim \langle v_{\text{field}}^2 \rangle$  and  $M_S \gg m$ , so the subject mass will (on average) lose energy to the field particles, slowing down. Dynamical friction is a manifestation of mass segregation.

# Dynamical friction

#### Intuitive picture 2: Gravitational wake

The moving subject mass perturbs the distribution of field particles, creating a trailing density enhancement ("wake"). The gravitational force of this wake on  $M_S$  slows it down.

