Class 16:

**Special topic**: Binary supermassive black holes, and black hole mergers

- The behavior of the central black holes during galaxy collisions/mergers
- The “final parsec problem”
- Black hole mergers and gravitational waves
- Can we find evidence for binary black holes today?

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I : Galaxy collisions and the behavior of black holes

- Suppose two galaxies collide/merge and each one contains a central supermassive black hole... what happens to these black holes?
  - At first, cores of each of the galaxies are orbiting each other... they merge due to process known as **dynamical friction**.
  - The two black holes are now on wide-ranging orbits within merged core... they sink towards center again due to dynamical friction
  - Eventually, the two black holes get close enough that their motion is dominated by gravitational field of the other black hole... form a **binary black hole**
Motion of black holes leaves a “wake” of stars and gas in their trail... the gravitational tug of this wake on the black hole then removes energy and angular momentum from blackhole orbit (dynamical friction)

**Dynamical friction**

Consider a mass, $M$, moving through a uniform sea of stars. Stars in the wake are displaced inward.

This results in an enhanced region of density behind the mass, with a drag force, $F_d$, known as dynamical friction.
II : Black hole binaries and the “final parsec problem”

- Dynamical friction causes black holes to “sink” to the center of the merged galaxy and form binary... what then?
  - Dynamical friction continues to operate and causes binary to shrink
  - Once black holes are about ~1pc apart, this process becomes ineffective [anyone figure out why?]
  - BUT SOMEHOW, binary continues to shrink
  - Once black holes are about 0.01pc apart, the gravitational waves that they are producing become effective at removing energy and angular momentum from orbit in a reasonable timescale
  - As black holes get close, they move faster, they emit stronger gravitational waves, and the binary shrinks at a faster rate
  - Eventually, the black holes merge...
III : Black hole mergers and gravitational waves...

- **Enormous** amounts of energy are released in this merger!
  - [*Let’s estimate power on board...*]
  - For a brief time, the power output from a merging supermassive black hole exceeds that of **all of the stars in the observable Universe combined!**
  - But, this energy is released as gravitational waves... can we see this?
  - That is the goal of LISA (Laser Interferometric Space Antenna)... a joint NASA/Europe project (launch ~2020).

*Baker et al. (2006; gr-qc/0602026)*
There’s also ground-based attempts to see gravitational waves (LIGO)... what’s the difference?

- **LIGO** - detects high frequency GWs
  - Final stages of merging neutron star binaries
  - Final stages of stellar mass BHs merging with other stellar mass BHs or neutron stars
  - (Possibly) core collapse supernovae

- **LISA** - detects lower frequency GWs
  - Merging supermassive black holes
  - Infall of a stellar-mass BH or neutron star into a supermassive black hole
  - Galactic Binary star system (esp. binary white dwarfs)
IV : Finding binary black holes today...

- If any of this is correct, we should see binary black holes in some fraction of galaxies (i.e., where we catch them before they’ve merged)
- In fact, it’s proving pretty tough to find them...
  - A couple of nice examples of “pre-binary” black holes are known
  - Evidence for real black hole binaries is more indirect and controversial
NGC6240, Credit: HST/Chandra/MPIEP
V: Other phenomena associated with merging black holes...

- Black hole kicks
  - When BHs merge, gravitational radiation can carry away linear momentum... final black hole is given a “kick”
  - Normally few×100km/s... but can reach 4000km/s
  - Can produce off-center/moving AGN, flares from kicked accretion disk, hyper compact star clusters...

- Effect of mass loss on accretion disk
  - At moment of merger, gravitational radiation can carry away ~5% of rest-mass energy
  - Disk suddenly feels different gravitational force... get a diskquake!