Directions:

- * is one point, ** is two, *** is three, etc.
- Some parts need multiple answers for full credit, but can receive partial credit which is specifically designated and bolded
- The total value of each question is given in parentheses
- Each question number is titled with the relevant topic that is it asking about
- For the math section, accept answers within 10% of the real answer.
 - This is not a strict rule, and usually teams will get an answer that is either really close or really far. If an answer is too close to judge at first glance, please use a calculator to check if it's an acceptable answer.
- When multiple answers are accepted, they are separated by a bolded "OR"
- For numerical answers in the DSO/theory section, a range of accepted values is given unless a specific number is required for credit

Section 1: DSOs/theory (65 pts)

- 1. Image 4 (SN UDS10Wil) (7)
 - a. *SN UDS10Wil OR SN Wilson
 - b. *Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
 - c. **Farthest known type Ia supernova
 - d. ***Gravitational lensing can magnify the object and affect its redshift measurement
- 2. Image 6 (M87) (5)
 - a. *87 **OR** M87
 - b. **VLBI OR Very Long Baseline Interferometry
 - c. **Fourier **OR** Fourier transform **OR** Fourier analysis
- 3. Image 2 (JKCS 041) (9)
 - a. *FITS **OR** Flexible Image Transport System
 - b. *~1.8
 - c. ***THREE OF: gravitational lensing; velocities of nearby galaxies orbiting the cluster; x-ray luminosity-mass relation; x-ray temperature-mass relation; gas mass fraction; local richness-mass relation; Sunyaev-Zel'dovich effect (1 pt. per correct answer)
 - d. ****Accept:** Inverse Compton scattering **OR** Sunyaev Zel'dovich effect; scattering of CMB photons can increase their energies and allow astronomers to measure pressure/density distribution of galaxy clusters.
 - e. **~10^{14.4}-10^{14.5} M $_{\odot}$ OR ~2.5*10¹⁴-3.2*10¹⁴ M $_{\odot}$
- 4. Image 1 (Bullet Cluster) (7)

- a. *Image 1
- b. *Two-cluster merger
- c. *Dark matter
- d. **~3000km/s
- e. **MOND **OR** Modified Newtonian Dynamics
- 5. Image 8 (3C273) (6)
 - a. *Image 8
 - b. *Approximately 1/10 the speed of light, or ~30,000km/s
 - c. *-26.7
 - d. *The Sun
 - e. **Reverberation mapping
- 6. Image 5 (GOODS-S 29323) (10)
 - a. *GOODS-S 29323
 - b. *Stars **OR** (less massive) black holes
 - c. **The simulation would take too long if a better resolution was used **OR** we are only interested in the overall flow of the system.
 - d. **More likely (1 pt.); higher opacity prevents localized cooling. Cooling on smaller scales can lead to fragmentation of the cloud into stars and smaller black holes. (1 pt.)
 - e. **~1*10⁸-2*10⁹ M_{\odot}
 - f. **Yes, reasonable (1 pt.); More massive (1 pt.)
- 7. Image 7 (PSS 0133-0400) (11)
 - a. *Image 7
 - b. *Standard candle OR standard ruler
 - c. **Baldwin effect
 - d. **Nearby cloud of hot gas **OR** accretion disk
 - e. **3 times OR third ionization state (1 pt.); ~154.9nm (1 pt.)
 - f. ***Lyman-alpha forest
- 8. Image 3 (H2356-309) (10)
 - a. *H2356-309
 - b. **Sculptor Wall
 - c. **Blazar (1 pt.); BL Lacertae OR BL Lac (1 pt.)
 - d. *The material in the jet is traveling close to the speed of light
 - e. **Synchrotron radiation **OR** magneto-bremsstrahlung radiation **OR** bremsstrahlung radiation
 - f. ******This is due to aberration **(1 pt.)**; The energy from the jet appears to be emitted along its line of motion **(1 pt.)**

Section 2: Math (60 pts.)

- 1. Orbits (13)
 - a. *.147 AU
 - b. **.251 AU (1 pt.); .044 AU (1 pt.)
 - c. $*7.59*10^{24} \text{ m}^3$
 - d. *3.14*10⁻⁴ AU **OR** .000314 AU
 - e. **1.029
 - f. *Tidal OR tidal force OR tidal interaction
 - g. **Circular orbit
 - h. **33100 times more significant
 - i. *Yes; if answered "no," draw a sad face but still give the point. Must be answered to receive point
- 2. Galaxy cluster (11)
 - a. *0.0666
 - b. **19300 km/s
 - c. *276 Mpc
 - d. **16300 km/s
 - e. *233 Mpc
 - f. **5.49*10¹⁵ M_{\odot}
 - g. $*5.49*10^{13} L_{\odot}$
 - h. *Dark matter
- 3. Galactic mass (8)
 - a. **6.75
 - b. **0.719
 - c. **Since the ratio is in fact larger than expected based on stellar density, then the mass ratio must be larger than expected, meaning that there is more unobserved mass (dark matter) concentrated further out in the galaxy.
 - d. **Lower (1 pt.); a galaxy cluster includes all the mass between galaxies which is comprised of more dark matter than what is confined by the optical radius of a galaxy (1 pt.)
- 4. Sèrsic (10)
 - a. $*0.189 I_e$
 - b. $*2.30 I_e$
 - c. $*0.234 I_e$
 - d. $\ *3.39 \ I_e$
 - e. **Spiral galaxy
 - f. *Higher
 - g. *.897
 - h. **Black holes and galaxies evolve concurrently/together.
- 5. G-waves (18)
 - a. *Transverse

- b. **Quadrupole
- c. **2 (1 pt.); 2 (1 pt.)
- d. *199W
- e. **4.68 billion years (1 pt.); 8.47*10²⁵ billion years (1 pt.)
- f. **4.68*10⁻¹⁸ billion years (1 pt.); 8.47*10⁷ billion years (1 pt.)
- g. *****Accept:** (mention of) Dynamical friction (**2pts.**) **OR** black holes transfer energy to nearby stars (**1 pt.**); below 1 parsec, the density of stars is not high enough for energy to be effectively transferred in the same way (**1 pt.**)
- h. *****1.2% the speed of light **OR** 0.012c **OR** 0.012