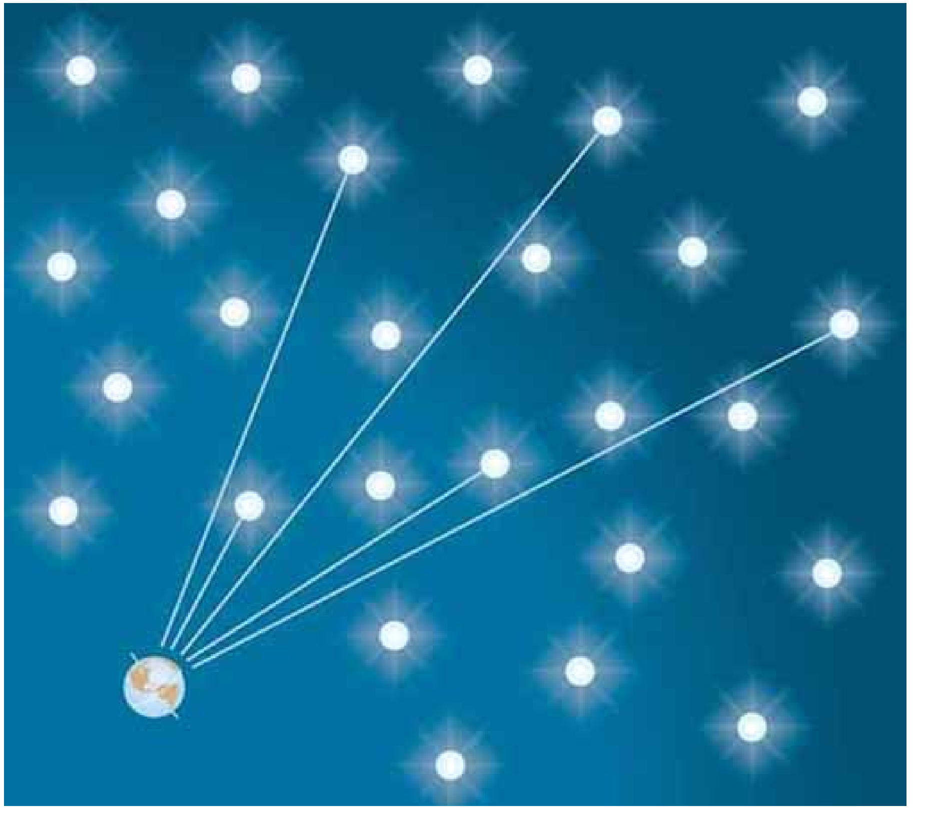
Outline

- Go over AGN problem, again, should be rotating BH
- Go over problem 6.6
- Olber's paradox
- Distances
  - Parallax
  - Distance ladder
  - Direct checks

Why is the night sky dark? (Olber's Paradox 1826)

- Or what is the temperature of the sky?
- Assume universe is static, infinite, and full of stars like the Sun.
- Then every ray extending out from the Earth will eventually intersect a star.
- So, the brightness of the sky at that point will be determined by the surface brightness of that star.
- But surface brightness is independent of distance, so the whole sky should be as bright as the Sun.
- Night sky is dark, so at least one assumption must be incorrect.



Uniformity of the Universe

We made the implicit assumption that the universe is homogeneous.

To do cosmology we assume that:

- Universe is homogeneous
  - Matter/energy is distributed evenly
  - Laws of physics are same everywhere

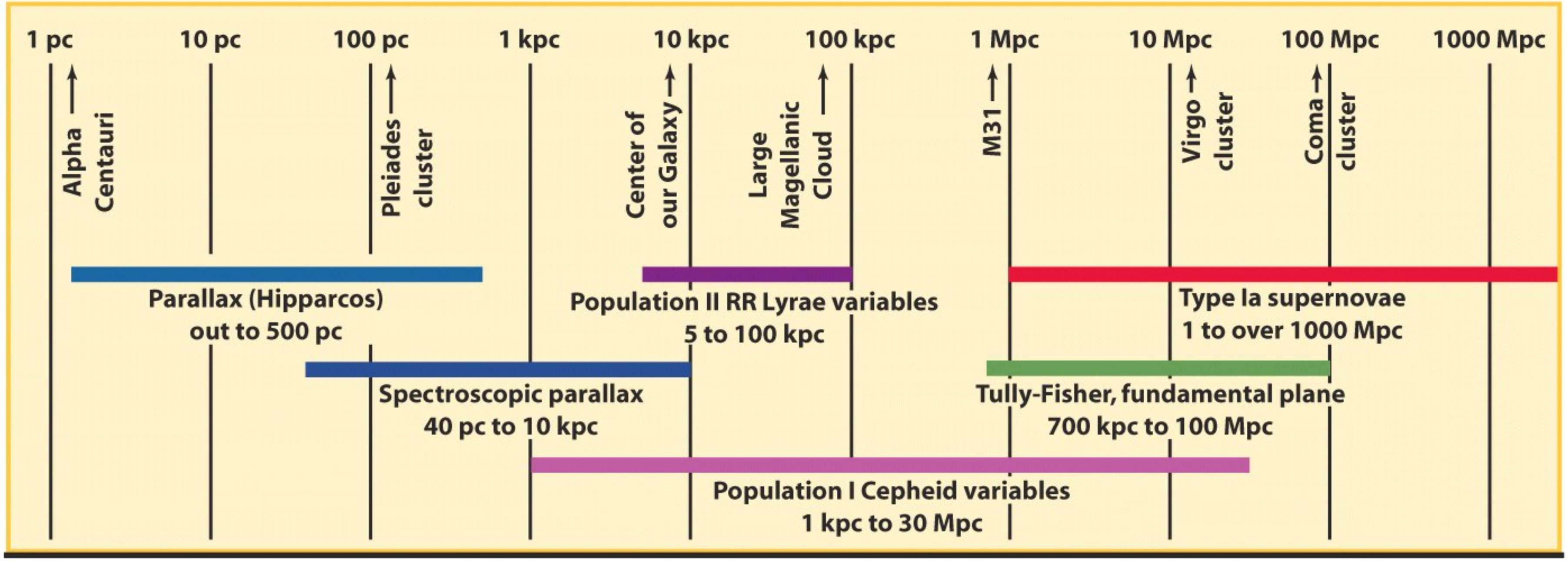
- How can we test this?

How can we test homogeneity?

- Does the Universe look the same in all directions? (Isotropy)
- Are the spectral lines from atoms the same in distant galaxies?
- Do the same laws of gravity apply in other galaxies?

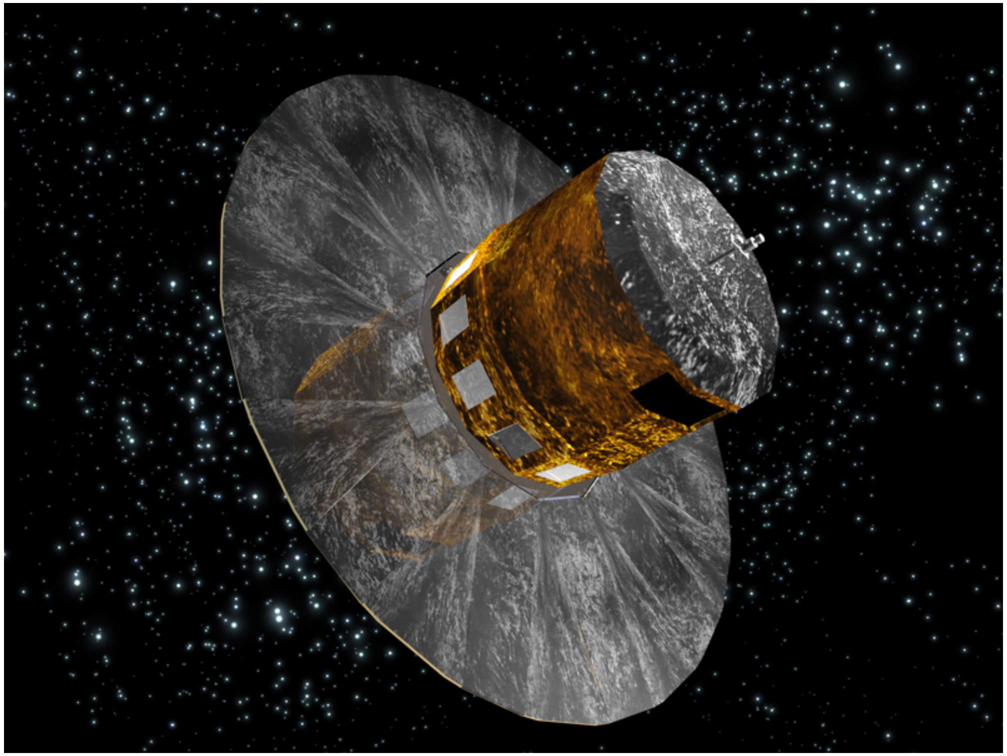
Distances

- Distances start with parallax of nearby stars and work outwards in a "distance ladder".
- Each step is used to calibrate the next.



Parallax

- Best current parallax measurements come from Hipparcos satellite.
  - 120,000 stars with 1 milliarcsecond accuracy.
- Now Gaia is operating
  - goal is observe 10^9 stars
  - 2×10^7 to 10% accuracy as far as the Galactic center
  - 2×10^6 to 1% accuracy

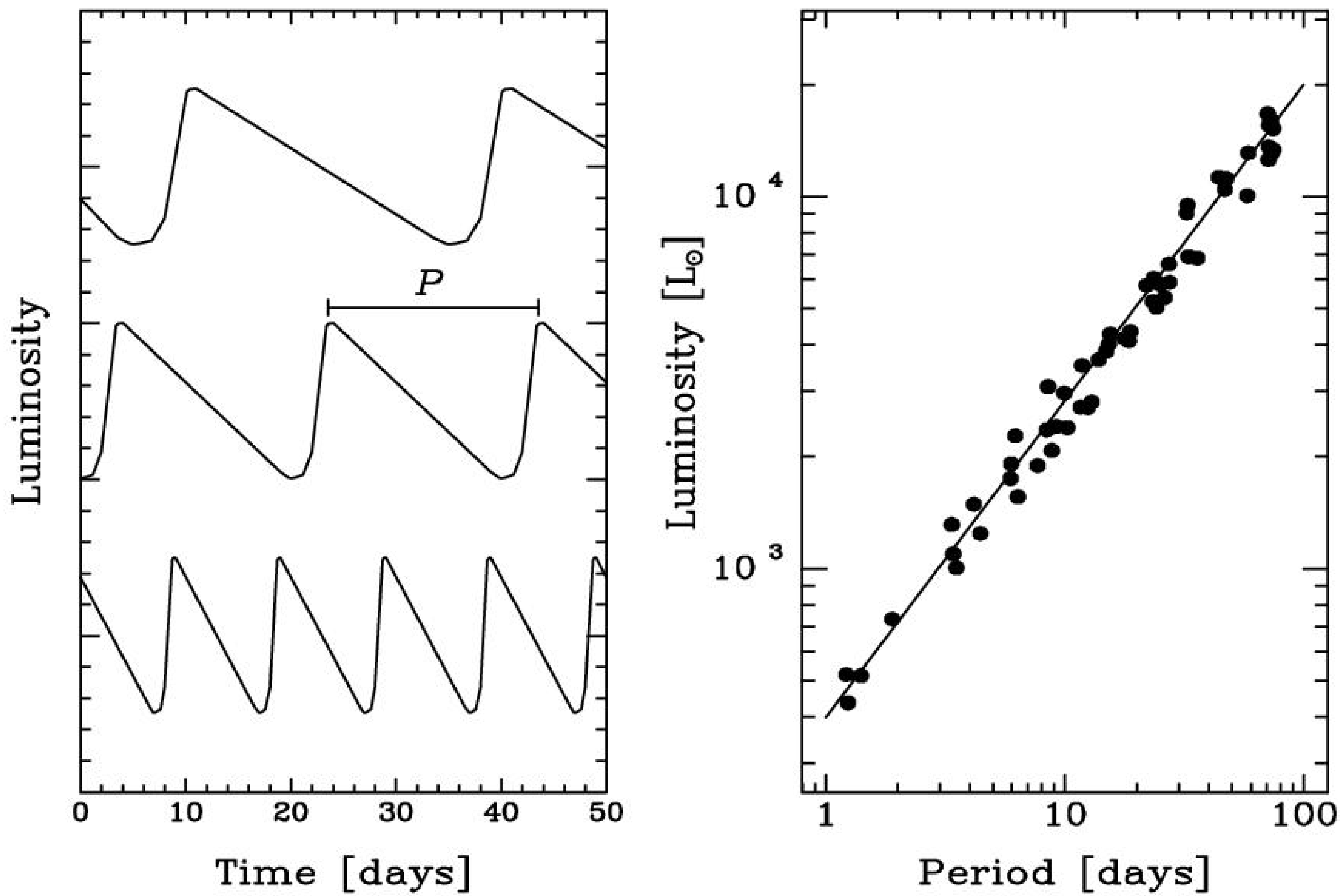


Distance Ladder

- Measure distance to nearby stars via parallax
  - Find luminosity $L = 4\pi D^2 f$, spectral type
  - Provides luminosity scale on HR diagram
- Observe a cluster of stars
  - Construct HR diagram
  - Apply luminosity scale using local calibration
  - Calculate distance $D^2 = 4\pi f/L$
- Find Cepheid variable stars in clusters
  - Calculate luminosity since distance to host cluster is measured
  - Measure period of brightness variations
  - Calibrate luminosity versus period relation for Cepheids

Cepheids

Pulsation period and average luminosity are well correlated.

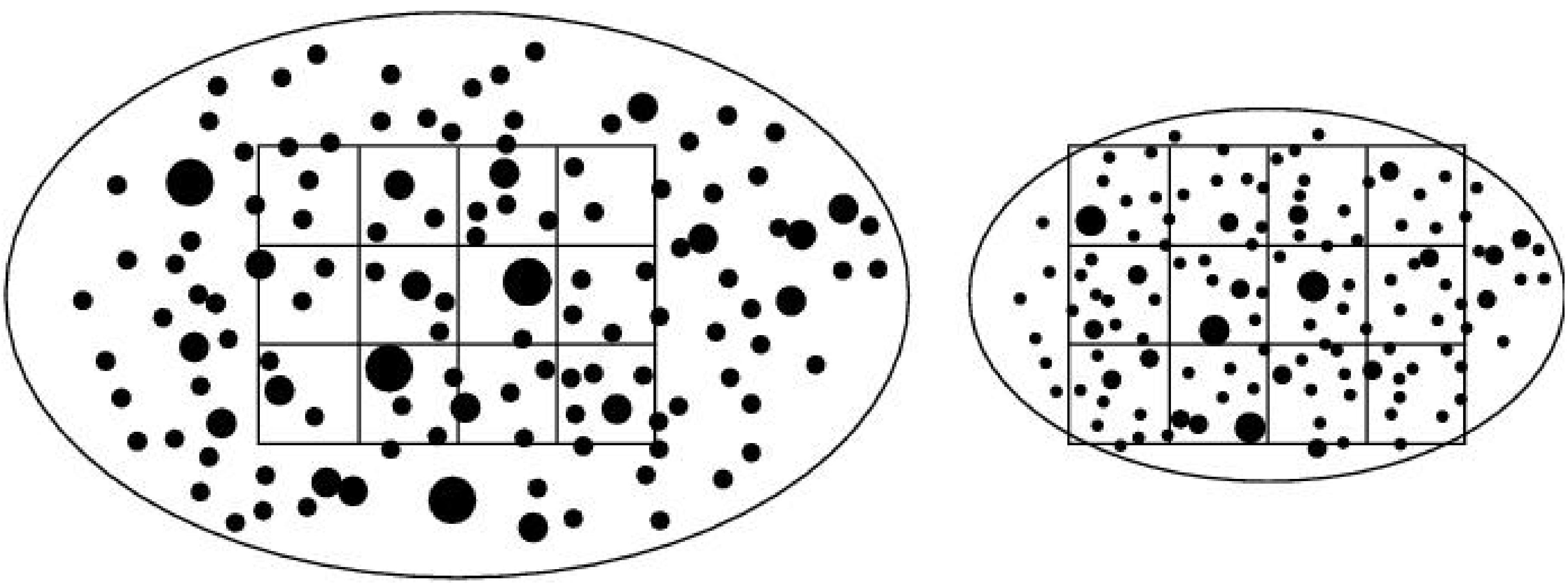


Distance Ladder

- Find Cepheid variable stars in nearby galaxies < 20 Mpc
  - Measure brightness variation period, use to find luminosity
  - Calculate distance $D^2 = 4\pi f/L$
  - This was a main motivation for building HST
- Look at galaxy members, see if any are "standard candles"
  - Globular clusters and planetary have similar peak luminosity in most galaxies
  - Calibrate luminosity distribution in galaxies with Cepheids
  - Use calibrated luminosity to measure distances to more distant galaxies (and ones without Cepheids).
- Look at galaxy properties to see if any correlate with luminosity
  - Tully-Fisher relation $L \sim v^{\alpha}$, where v = orbital at large radii (flat part)
  - Surface brightness fluctuations

Surface Brightness Fluctuations

- Fixed angular resolution corresponds to different physical size in galaxies at different distances
- Total light in each field ~ N = number of stars in field, fluctuations from field to field $\sigma \sim \mathrm{sqrt}(N)$.
- More stars in fields in more distant galaxies, so $N \sim D^2$.
- Thus, $\sigma \sim 1/D$.



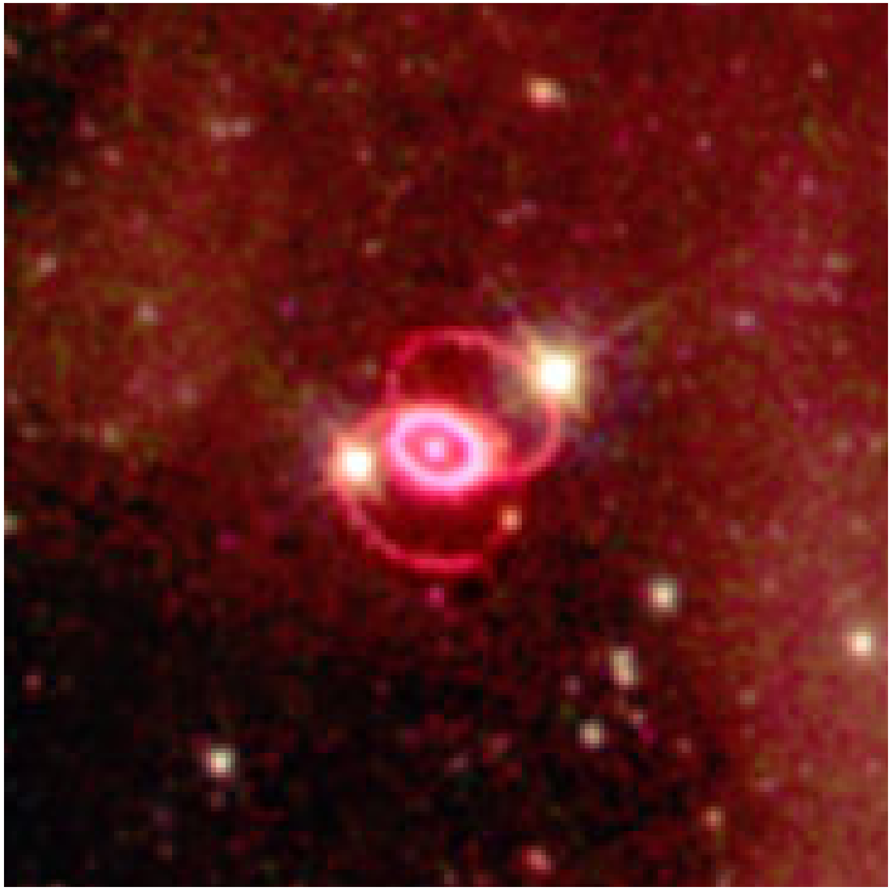
Distance Ladder

- Look for type Ia supernovae in galaxies with measured distances (Cepheid, globular cluster, PN, Tully-Fisher, SBF)
  - Calibrate luminosity of type Ia SN
  - Best calibration involves a correction for duration of SN
  - Use calibrated luminosity to measure distances to more distant galaxies that have type Ia SN.
- This provides the best distance measurements for individual galaxies out to ~1 Gpc.

Direct Distance Measurements

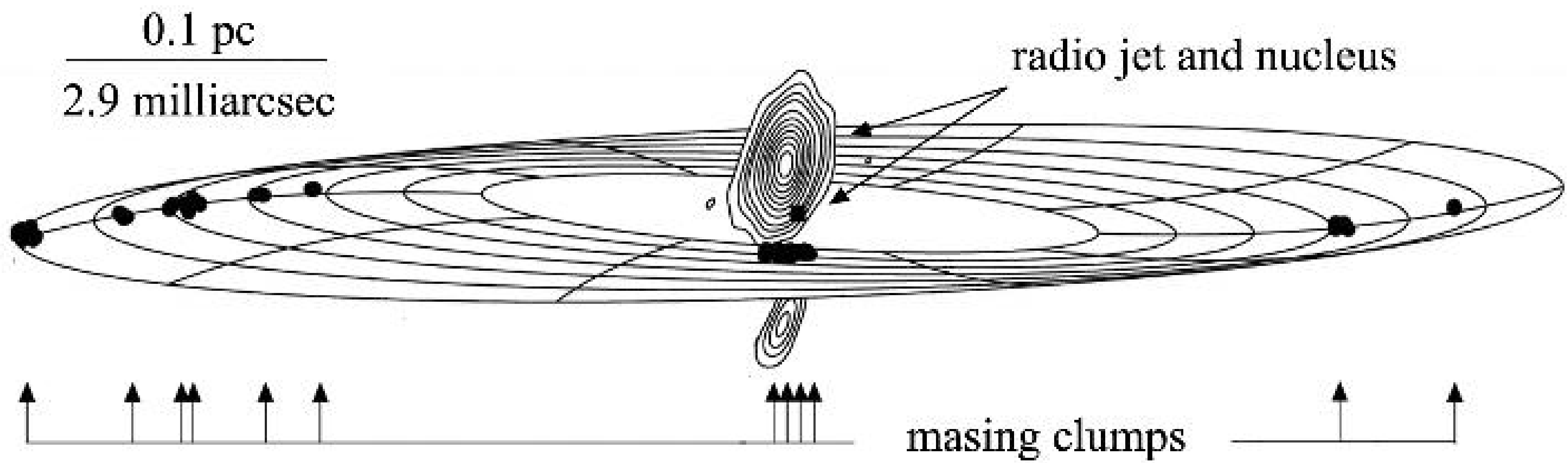
- Spectroscopic eclipsing binaries
  - Find size of stars from duration of eclipse and velocity curve
  - Find surface temperature of stars from spectra
  - Calculate $L = 4\pi r^2 \sigma T^4$.
  - Calculate distance $D^2 = 4\pi f/L$
- Works for local group galaxies
- Provides check on distance ladder out to ~ 1 Mpc.

Light Echo from SN1987A



- Rings are gas from SN progenitor.
- Rings lit up ~240 days after SN.
- Draw geometry on board.
- Provides check of distance to LMC.

Water masers around BH



- Clumps of molecular gas orbit supermassive black hole.
- Some clumps emit 22 GHz line from H_2O.
- Can precisely measure radial velocity of clump and position on sky.
- Solve for mass of BH and distance, if multiple clumps can be followed.

Homework

For next class: problem 7.1