Final Exam will be in this room 1:30-4:00, Wednesday May 7

Robyn will hold a review session in G131 Monday, May 5, from 5 to 6pm

Will do FCQ’s today.

Website
http://casa.colorado.edu/~wcash/APS1120/APS1120.html
Quasar Absorption Lines

- **3C 273** $z=0.158$
- **Q1422+2309** $z=3.62$
The Intergalactic Medium
Intergalactic Medium

70% of the regular matter in the universe is between the galaxies

Was probably neutral, then re-ionized

Somehow got oxygen and other heavy elements.

We didn’t know it was there 20 years ago.

Still don’t have any clue how it works.

Cutting edge of research.
The Cosmic Web
Structure of the Universe

Where is the center of the Universe?

Where are the edges?

What happens if you fly to the edge and stick your finger through?

Newtonian Universe must be infinite.

**Cosmological Principle:** The Universe is Everywhere the Same (when averaged over grand scale)
Classical Universe

- Euclidean Geometry
- Infinite in Extent
- Matter may or may not be everywhere
- Universe infinitely old
  - always been here, always will be

- Expansion still possible
  - \(2 \times \infty = \infty\)
Cosmological Principle

• Cosmological Principle applied to expanding Euclidean Universe
• New matter must be formed of nothing to keep density everywhere the same.
Olber’s Paradox

If universe is infinite with stars everywhere, then there an infinite number of stars.

Any line of sight will eventually intersect the surface of star. Sky would be as bright as the surface of the Sun.

Well it isn’t. So why not?
Universe Must Change

Answer to Olber’s Paradox:

Universe must change:

Space:  ie  the stars stop
   This was the answer until mid 20th Century

Time:  Universe hasn’t always been here, so can’t see forever.
   Discovery of Big Bang leads us to this answer.
General Relativity

• GR provided an answer
• The presence of matter warps space in on itself.
• Space is actually DEFINED by the presence of the matter in it!!!
• Solves the edge problem
• But geometry is no longer Euclidean
Geometry of Universe

There's no path out!

Space Curves in on itself
Curved Space

There is no “edge” but the volume is finite.

Surface of Earth has no end, but it is finite.
Expands and falls back

Universe starts as pinprick

Expands.

But its below escape velocity.

Hits maximum size.

Then shrinks

The End is the “Big Crunch”
Negatively Curved Universe

It's warped so it cannot close back on itself.

Is infinite in extent.
Open vs Closed

Universe is either open or closed.

If closed: Positive Curvature
            Finite Mass
            Finite Lifetime
            Finite Volume

If open:   Negative Curvature
            Infinite Mass
            Infinite Volume
            Infinite Lifetime  That’s INFINITY Folks!!!

Astronomers have prejudice in favor of closed universes.

All measurements have been inconclusive. We live near the edge!
Critical Density

• Whether Universe is open or closed depends on the average DENSITY of matter.
• Above $10^{-29}$ g/cc the universe is closed
• Below $10^{-29}$ g/cc the universe is open
• We are very close to that density
• Coincidence?

$\rho_{\text{crit}}$ is about 1 atom per liter
History and Fate of Universe

Universe is one of these (maybe).
Best Guess Size

• Diameter of Universe is about $10^{24}$ times larger than the part we can see.
• That makes the volume $10^{72}$ times larger.
• But still finite

• How big is $10^{72}$?
Heat Death of Universe

• If universe is open, then it will last forever
• But stars will all burn out $10^{14}$ years
• Protons decay $10^{31}$ years
• Orbits will decay into black holes at center of the galaxies $10^{60}$ years
• Giant black holes evaporate $10^{100}$ years

• Nothing left but redshifting photons
More on Infinite Universe

• If Cosmological Principle holds and universe is infinite, there’s infinite mass.
• Infinite Planets
• Infinite Earth-like planets
• Infinite planets just like you.
• Infinite You’s

• Far away: About $10^{10^{118}}$ meters away