The End of the Universe

Astronomy 101
Critical Density

• All galaxies *attract* each other via *gravity*.
  – Gravitational attraction *slows* the expansion.

• How it behaves depends on the *density*:
  – *High Density*: Expansion slows, stops, & reverses.
  – *Low Density*: Keeps expanding forever.

• Dividing Line = “*Critical Density*”
Density Parameter: $\Omega$

$$\Omega = \frac{\text{average density of Universe}}{\text{critical density}}$$

- $\Omega > 1$: High Density "Closed" Universe
- $\Omega = 1$: Critical Density "Open" Universe
- $\Omega < 1$: Low Density "Open" Universe
What is $\Omega$?

- **Observers:**
  - Best Estimate is $\Omega=0.1-0.3$ (or higher)
    - Hard to measure slowing of expansion rate.
    - Galaxies evolve in an (as yet) unknown way.
    - Problem of accounting for Dark Matter.

- **Theorists:**
  - (Some) would like $\Omega=1$, so introduce $\Lambda>0$
Closed Universe: $\Omega > 1$

- Gravity of all matter is enough to eventually overcome the expansion of the Universe:
  - Expansion slows to a maximum size & stops.
- Universe re-collapses:
  - Galaxies get closer together
  - Get a cosmological blueshift
  - Universe grows hotter & denser
  - Collapses in the Big Crunch
A Phoenix from the Ashes?

• After the Big Crunch, what then?
  – Nothing.
  – Another Big Bang creates a new Universe.

• Second Law of Thermodynamics:
  – Entropy increases in a closed system.
  – Next Big Bang starts with greater entropy.
  – Will expand for longer than previous one.
Open Universes: $\Omega < 1$ or $\Omega = 1$

- Universe keeps expanding forever.
- Gravity slows the expansion a little:
  - *Lower* the density, the *less* the expansion slows.
  - A Critical Density Universe slows to a stop at infinite time.
  - A Sub-critical Density Universe approaches a constant speed at infinite time.
Evolution of an Open Universe

• As the Universe expands:
  – Space between galaxy clusters widens.
  – Universe steadily cools down.
  – Expansion continues forever.

• Details depend on:
  – Stellar Evolution
  – Quantum Mechanics
Star Formation

• Present Time ($t \approx 10^{10}$ yrs):
  – Most stars are metal rich, and make more metals ejected in supernova explosions.
  – Next generation starts with a little less Hydrogen and more metals.
  – Some fraction of the star’s matter is locked up in stellar remnants: white dwarfs, neutron stars & black holes.
End of Star Formation

• $t=10^{14}$ years:
  – Successively more matter is locked up in stellar remnants, depleting the free gas reserves.
  – Cycle of star birth and death is broken.
  – Nuclear fuel is exhausted.
  – Red dwarfs burn out as low-mass white dwarfs
  – Remaining matter is locked up in black dwarfs, cold neutron stars, and black holes.
Solar System “Evaporation”

• $t=10^{17}$ years:
  – Weak gravitational encounters between stars are rare, but slowly disrupt orbiting systems:
  – Planetary systems get disrupted by stellar encounters and their planets scattered.
  – Wide binary systems are broken apart.
  – Close binary stars coalesce into single remnants.
Dissolution of Galaxies

• $t=10^{19}$ years:
  – Stellar remnants within galaxies interact over many many many orbits.
  – Some stars gain energy from the interaction and $\sim 90\%$ get ejected from the galaxy.
  – Others lose energy and sink towards the center.
  – These coalesce into a Supermassive Black Hole.
Dissolution of Matter?

• $t=10^{32}$ years:
  – Some GUTs theories predict that protons are unstable.
  – Protons decay into electrons, positrons, to neutrinos.
  – All matter not in Black Holes comes apart.
  – Current experimental limits on the proton decay time may be much larger than $10^{32}$ years.
Evaporation of Black Holes

• $t=10^{100}$ years:
  – Black Holes slowly evaporate by emitting particles and photons via Hawking Radiation.
  – Supermassive Black Holes evaporate completely one-by-one in a last final weak flash of gamma rays in $\sim 10^{100}$ years.

• The end of the epoch of organized matter
The Big Chill

• After black holes all evaporate:
  – Increasingly redshifted photons.
  – Universe continues to cool off towards a Radiation Temperature of absolute zero.
  – Only matter is a thin, formless gas of electrons, positrons, neutrinos.

• The end is cold, dark, and disordered...
Effects of Dark Energy and Dark Matter

• Dark Matter and Dark Energy are not well understood, but are major constituents of the Universe
  – Many experiments underway to characterize both
    • LHC
    • DES
    • LSST
    • JDEM
• Both can alter the fate of the Universe
• Dark Energy counteracts gravity though, increasing the expansion
  – Probably makes the Universe more likely to be open
Possible Fates of the Universe

- Very Open: $\Omega << 1$
- Closed: $\Omega > 1$
- Critical/Open: $\Omega = 1$

Distance Between Galaxies vs. Time

~100 Billion Years
“The opinion on which [fate of the Universe] is preferable cannot be classified as a debate in science, however, unless we can explain what point is served by the outcome of the debate.”

P.J.E. Peebles

*Principles of Physical Cosmology* (1993)
“Some say the world will end in fire. Some say in ice. From what I’ve tasted of desire I hold with those who favor fire. But if it had to perish twice, I think I know enough of hate To say that for destruction ice Is also great And would suffice.”

Robert Frost
Fire and Ice (1923)
“This is the way the world ends
This is the way the world ends
This is the way the world ends
Not with a bang but a whimper.”

T.S. Eliot

The Hollow Men (1925)
“It’s the end of the world as we know it
It’s the end of the world as we know it
It’s the end of the world as we know it
And I feel fine”

REM
(1987)
Summary:

• The Fate of the Universe depends on the density of matter.

• **Closed Universe:**
  – Enough matter to stop the expansion
  – Collapses in a “Big Crunch”

• **Open Universe:**
  – Expands forever
  – Ends in a cold, disordered state.