Cosmic Eschatology

When Do Things End?

What We Want to Know

- We have made a complete survey of the universe from the beginning up to now
- We would like to look at the future

- Three questions we'd like to answer:
- When will life on Earth become impossible?
- When will life as we know it become impossible? When does any life of which we can conceive become impossible?
- We will *not* consider human made disasters
  - Israel, Ukraine, etc.
- We will *not* consider disasters that don't wipe out civilization

- Time will be measured from *now*, not the beginning of the universe
  - Soon, it won't make any difference
- Mostly interested in getting the powers of ten right

Universe of Eternal Expansion

- We don't know what the dark energy is, but likely it is vacuum energy density
- It is *conceivable* that this energy density is unstable, but likely it is stable

- We'll assume the universe is made of vacuum energy density, which is eternally stable
- Starting in the near future, overall the universe will be completely dominated by the vacuum energy density ρ_Λ

- This means that in the future, the Friedman equation is

$$H^2 = \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho = \frac{8\pi}{3} G\rho_\Lambda$$

- We know that

$$H_0^2 \Omega_\Lambda = \frac{8\pi}{3} G\rho_\Lambda$$

- So we have

$$\frac{\dot{a}^2}{a^2} = H_0^2 \Omega_\Lambda$$

- Which has solution

$$\boxed{a(t) = a_0 e^{H_\Lambda t}}$$

- Where

$$\boxed{H_\Lambda^{-1} = 17.3\,\text{Gyr}}$$

$$H_\Lambda = H_0 \sqrt{\Omega_\Lambda} = (67.8 \text{ km/s/Mpc})\sqrt{0.692}$$

Killer Asteroids

- There will be several major changes in the universe in the future

- We'll go through a few at a time

- We know that giant asteroids have hit the Earth in the past
  - Dinosaurs wiped out 65 million years ago

- Such a large asteroid *could* make us extinct or destroy civilization

- No reason to believe there are not others
  - No major ones in < 1000 years
  - But we can't predict in the *long* term

- Given a long lead time, we could probably deal with them
  - Nudge them with rockets or other clever ideas
  - Deflect them with hydrogen bombs
  - Etc.

- If we don't, then this becomes an issue in about $t = 10^8 \text{ yr}$

- Giant asteroids
- Global warming
- Death of Sun
- Isolated universe
- Super galaxies
- No new stars
- Stars die
- Galaxies evaporate
- Matter decays
- Black holes decay

Runaway Global Warming

- The Sun is burning hydrogen to helium
- Over time, this causes the number of particles to decrease
- Which decreases the pressure ($P = k_B n T$)
- Which causes the Sun to shrink
- Which causes it to get hotter
- Which makes it burn faster
- Which increases the luminosity of the Sun

- Sun's luminosity has increased ~30% since it was born

- In about 900 million years the temperature will rise
- So that some ocean water evaporates
- Which is a greenhouse gas
- Which raises temperature some more
- Which eventually boils all the oceans
- And kills everyone

$$t = 10^9 \text{ yr}$$

- It is not inconceivable we can nudge the Earth in this time frame
  - Recall, we have a billion years to do it

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Death of the Sun

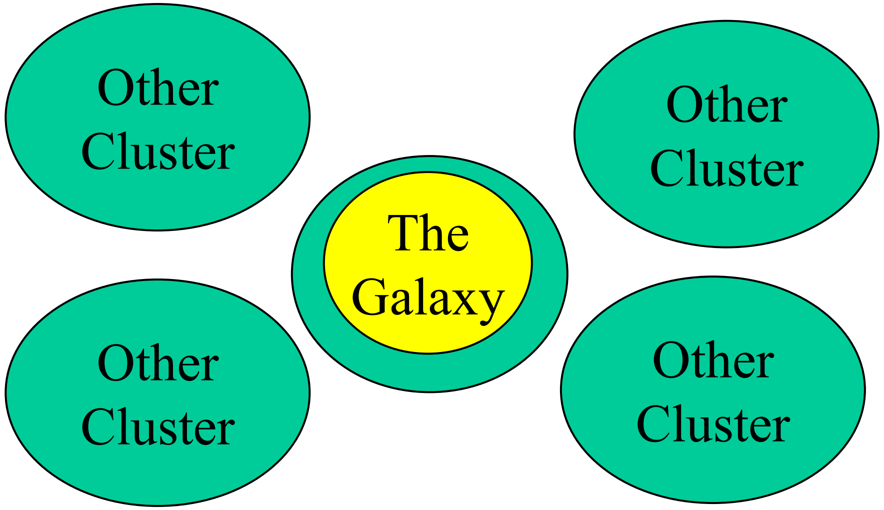
- The Sun is burning hydrogen to helium in its core
- It is not convective in its core, so it isn't getting any fresh fuel
- In approximately 5 billion years, the Sun will run out of fuel in its core

$$t = 5\times10^9 \text{ yr}$$

- It undergoes a transition and gradually becomes a red giant
- The Sun will expand and eat Mercury and Venus
- Earth probably won't be consumed, but it will melt
- Even if we maneuver the Earth a little farther from the Sun, we only have a few hundred million years before the Sun dies and becomes a white dwarf
- Probably a good time to leave for other stars

Isolated Universe and Super Galaxies

- Lots of galaxy clusters and groups in the current universe
- Due to exponential expansion, all distant clusters are moving away from us
- From Hwk O, local group is isolated in $t = 10^{11}$ yr
- Last CMBR photon in 10^{12} yr
- In the Local Group, we know that Milky Way and Andromeda will merge in about 10^{10} years or so
- Other clusters have similar collisions
- Eventually, all of the galaxies in a cluster will merge
- This takes about $t = 10^{12}$ yr



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The Last Stars Are Born

- Milky Way is currently manufacturing stars at a rate of about 1 $M_\odot$/yr
- The gas present in the galaxy is about $10^{10}\,M_\odot$
- If this rate were constant, the gas would last 10^{10} yr
- But there is evidence it is slowing down, and will continue to slow down in the future

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- Best estimate: last stars will be born around $t = 10^{14}\ \text{yr}$
- A mere 10^{10} years later, solar-mass stars die

- To survive in our present form, we will have to live near low mass stars

The Last Stars Die

- Solar mass stars die in about 10^{10} yr
- Lower mass stars have less fuel, but …
- They are much less luminous
  - Burning fuel slower
- They have convection
  - Brings fresh hydrogen to the core
  - Uses 100% of their available fuel

- But stars less than about 0.085 $M_{\odot}$ do not undergo fusion
  - So they aren't stars
- At 0.085 $M_{\odot}$, stars live a long time, but not forever
  - Homework X

$$t = 10^{14} \text{ yr}$$

- The universe will consists only of white dwarfs, neutron stars, black holes, and objects smaller than stars (planets or brown dwarfs)

- At this point, we may be living in space and surviving on fusion power

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Galaxies Evaporate and Coalesce (1)

- Stars almost never collide, but they *do* undergo close encounters
- This causes them to change their velocities

$$\left|\Delta \mathbf{v}\right| = \frac{2GM}{vb}$$

- The velocity change is as large as the velocity itself if

$$b = \frac{2GM}{v^2}$$

- For example, for a 0.3 $M_\odot$ object colliding at a relative speed of 30 km/s (typical relative velocity of stars), we find

$$b = \frac{2(0.3)\left(6.674\times10^{-11}\ \text{m}^3/\text{kg/s}^2\right)\left(2\times10^{30}\ \text{kg}\right)}{\left(30\ \text{km/s}\right)^2} = 10^{11}\ \text{m} = 3\times10^{-6}\ \text{pc}$$

- Hence each star represents a "target" of area

$$\sigma = \pi b^2 = 3\times10^{-11}\ \text{pc}^2$$

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Galaxies Evaporate and Coalesce (2)

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$$\sigma = 3\times10^{-11}\ \text{pc}^2$$

- The general formula for rates of collisions is: $\Gamma = n\sigma(\Delta v)$
- Local density of stars is $n = 0.1\ \text{pc}^{-3}$
- Use 30 km/s for relative velocity

$$\Gamma = \left(0.1\ \text{pc}^{-3}\right)\left(3\times10^{-11}\ \text{pc}^2\right)\left(30\ \text{km/s}\right)\cdot\frac{3\times10^{7}\ \text{s/yr}}{3\times10^{13}\ \text{km/pc}}$$

$$\Gamma = 10^{-16}\ \text{yr}^{-1}$$

- Each star "collides" with one other star every 10^{16} yr
- Velocity randomly increases or decreases by about 30 km/s
- With a random walk, this velocity will reach 600 km/s (escape velocity) after $20^2 = 400$ collisions
- So after 10^{19} yr, each star has a chance to "evaporate" and leave the galaxy

Galaxies Evaporate and Coalesce (3)

- So after 10^{19} yr, each star has a chance to "evaporate" and leave the galaxy

$$t = 10^{19}\ \text{yr}$$

- Where did this energy come from?
- The star exchanged kinetic energy with the other star it "collided" with
- Only those with the most kinetic energy get to leave
- The remaining stars, therefore, have *less* kinetic energy
  - Evaporative cooling

- Generally, the lower mass objects get tossed out
- The higher mass objects settle towards the middle, and get eaten by the black hole
- Eventually, all that is left is a super-massive black hole

- At this point, universe is one dead star, one brown dwarf, or one black hole

$$M = 10^{9} - 10^{11}\ M_{\odot}$$

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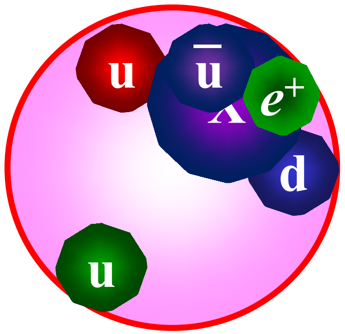
Matter Decays from GUTs

- In the standard model of particles physics, baryon number is conserved
  - Except for some minuscule non-perturbative effects
- In Grand Unified Theories (GUTs), there are massive *X* bosons that make the proton unstable
- Typical rates for such decays are suppressed because of the large mass of the *X* bosons



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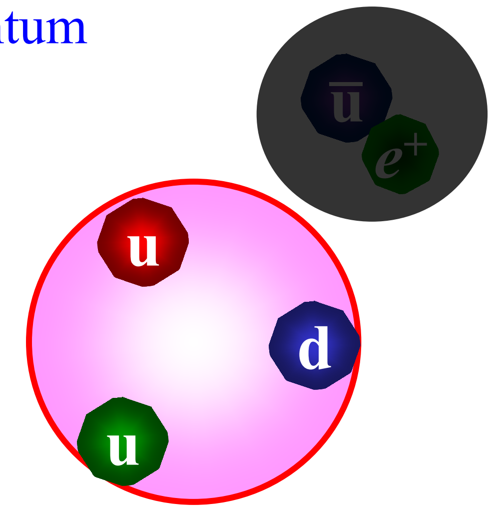
- We would expect $M_X \sim 10^{16}$ GeV/c^2 and typically $\alpha_X \sim 10^{-2}$, so

$$\Gamma \approx \frac{\alpha_X^2 m_p^5 c^2}{M_X^4 \hbar} \approx \frac{\left(10^{-2}\right)^2 \left(1 \text{ GeV}\right)^5 \left(10^9 \text{ eV/GeV}\right)}{\left(10^{16} \text{ GeV}\right)^4 \left(6.6\times10^{-16} \text{ eV}\cdot\text{s}\right)} \approx 1.5\times10^{-44} \text{ s}^{-1} \approx \left(2\times10^{34} \text{ yr}\right)^{-1}$$

- Direct measurements indicate decay rate is no higher than $\Gamma^{-1} > 2.4\times10^{34}$ yr
- So the shortest time for this to happen is about 10^{34} yr

Matter Decays from Virtual Black Holes

- We don’t have a quantum gravity theory, but …
- Black holes seem to ignore conservation laws
  - Other than charge, energy, angular momentum
  - The “no hair” theorem
- A quantum theory would probably allow creation of virtual black holes
  - Ignore baryon number conservation
  - Minimum mass $M_P = 10^{19}$ GeV



- A virtual black hole could, in a similar manner, result in baryon decay
- Calculation probably similar to before

$$\Gamma \approx \frac{\alpha_X^2 m_p^5 c^2}{M_P^4 \hbar} \approx \frac{\left(10^{-2}\right)^2 \left(1\ \text{GeV}\right)^5 \left(10^9\ \text{eV/GeV}\right)}{\left(10^{19}\ \text{GeV}\right)^4 \left(6.6\times 10^{-16}\ \text{eV}\cdot\text{s}\right)} \approx 1.5\times 10^{-56}\ \text{s}^{-1} \approx \left(2\times 10^{46}\ \text{yr}\right)^{-1}$$

$$\Gamma^{-1} < 10^{46}\ \text{yr}$$

- This gives us a likely upper limit on the decay rate

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Matter Decays Summary

- If GUTs are right, proton decay could be just around the corner $\Gamma^{-1} > 10^{34}\ \text{yr}$
- If GUTs are not right, there will probably still be proton decay with $\Gamma^{-1} < 10^{46}\ \text{yr}$
- All ordinary matter will probably disappear with time scale $t = 10^{34} - 10^{46}\ \text{yr}$
- This destroys white dwarfs, brown dwarfs, neutron stars
- Remaining stable particles are neutrinos, electrons (and positrons) and photons
- These plus black holes are all that is left
- Difficult to imagine how you still have life in this universe
- But there is still a source of energy available

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Hawking Radiation

- At this point, the universe contains some stellar black holes and galactic black holes

$$M_* = 10 - 100\,M_\odot\,,$$

$$M_g = 10^9 - 10^{11}\,M_\odot$$

- Are black holes truly eternal?
- Though we don't have a quantum theory *of* gravity, we can do particle physics calculations in the presence of black holes
- These indicate that the black holes *should* emit radiation called Hawking radiation
- A particle anti-particle pair appears spontaneously near a black hole
- One of them falls into the black hole
  - This one actually has negative energy
- The other escapes to infinity
- The black hole emits radiation at a temperature

$$k_B T_H = \frac{\hbar c}{4\pi R_s}$$

$$R_s = 2GM/c^2$$

$$T_H \propto M^{-1}$$

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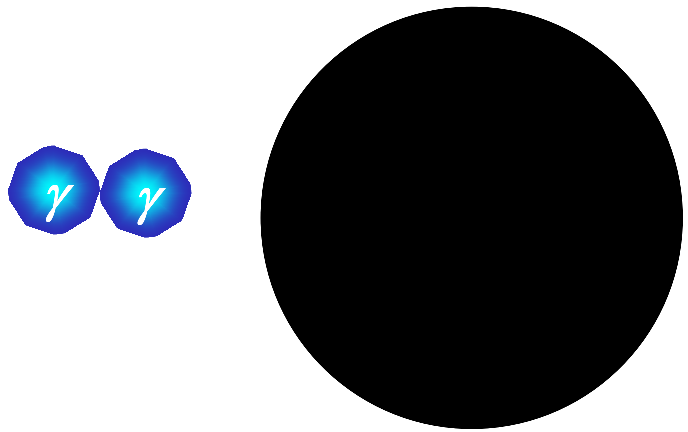

Back Reaction of Hawking Radiation

- Black holes will radiate from the event horizon at this temperature

$$k_B T_H = \frac{\hbar c}{4\pi R_s} \qquad R_s = \frac{2GM}{c^2}$$

- The actual calculations are more complicated than this, but naively, just use the Stefan-Boltzmann law

$$L = 4\pi R_s^2 \sigma T_H^4 \propto M^2 M^{-4} = M^{-2}$$

- Until we have a quantum theory of gravity, we don't know, but everyone assumes there is a back-reaction which causes the black hole to lose energy (decrease mass)

- The time it takes to completely disappear will depend on the mass

$$t \propto \frac{M}{L} \propto \frac{M}{M^{-2}} = M^3$$

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Time for Black Hole Evaporation

- Black holes will radiate from the event horizon at this temperature

$$M_* = 10 - 100\, M_\odot \,,$$
$$M_g = 10^9 - 10^{11}\, M_\odot$$

- You can get a pretty good approximation using formulas I gave you (homework X)

$$t \propto M^3$$

- For stellar mass black holes, it works out to about $t_* = 10^{70} - 10^{73}$ yr
- For galactic mass black holes, it is more like $t_g = 10^{94} - 10^{100}$ yr
- By 10^{100} yr, all black holes will be gone
- Any given region within a cosmic horizon will contain at most, one of the following:
  - Photon
  - Electron or positron
  - Neutrino
- With no energy source, difficult to imagine how intelligence could survive

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