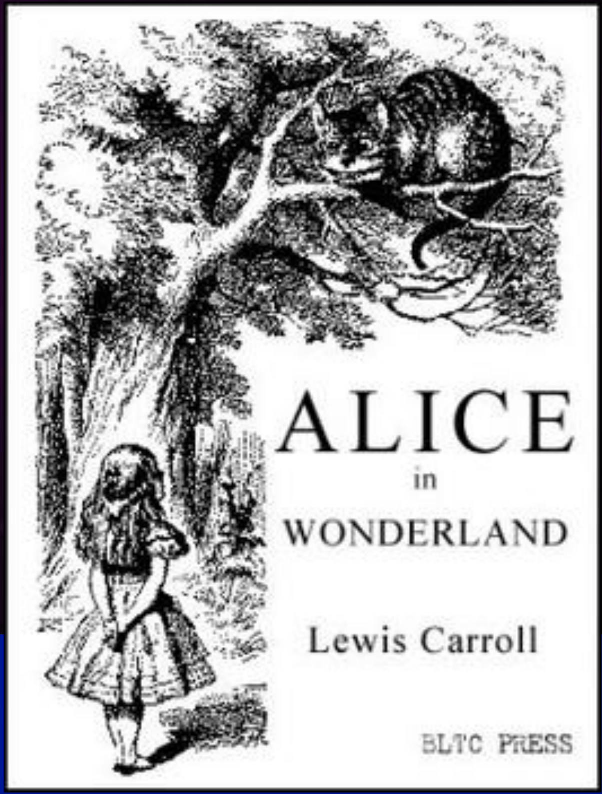
Announcements

- Homework #10 is due today
- Talk on Saturday “Hidden Galaxies Behind the Milky Way” by Trish Henning (UNM) at 7pm in SMLC
- Extra credit is due Saturday, Dec 10
- Review for test #4 on Monday Dec. 12 11:00am
- Test #4 on Tuesday, Dec 13 7:30 – 8:45am

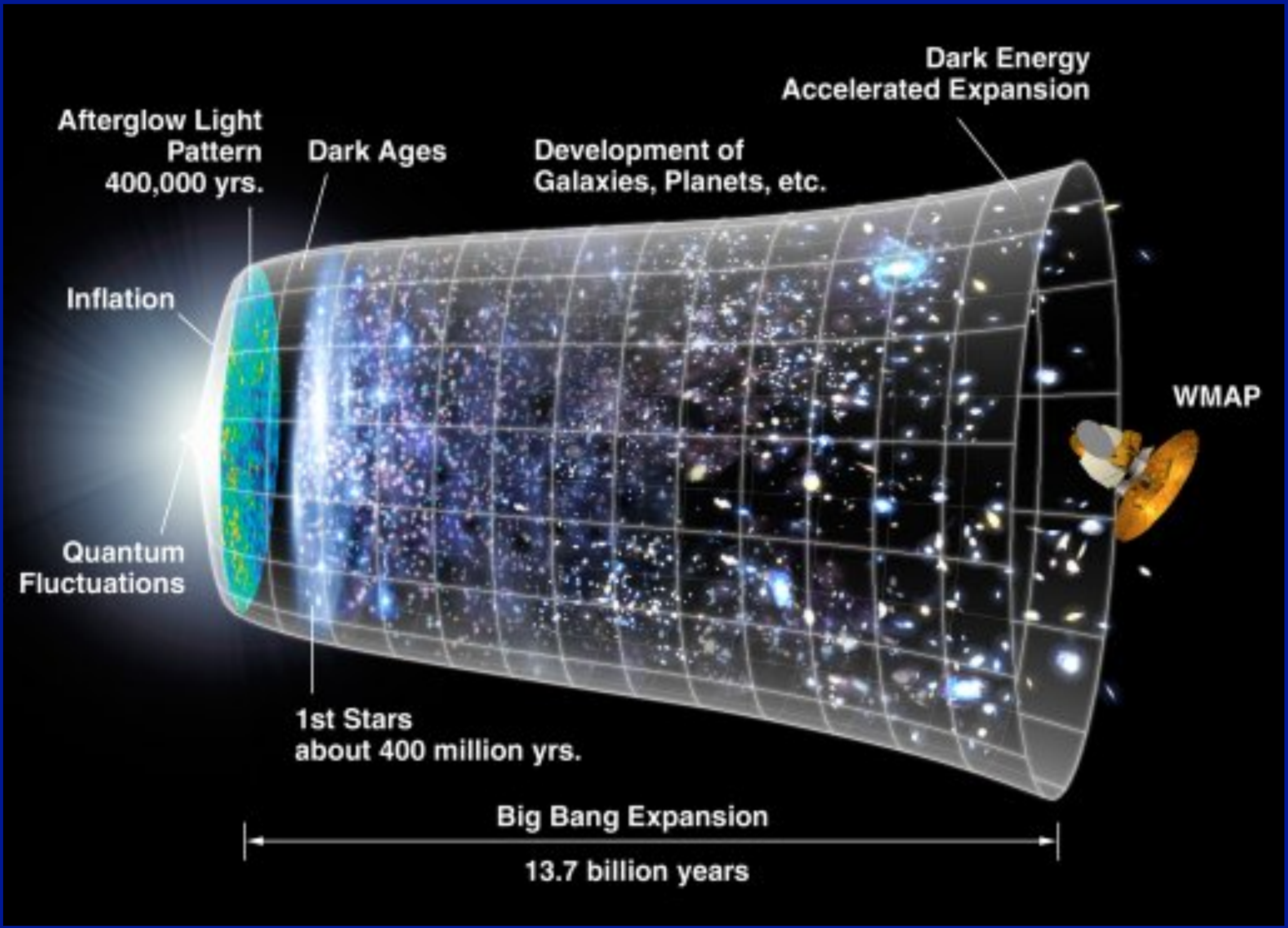
The Cheshire Cat Cluster

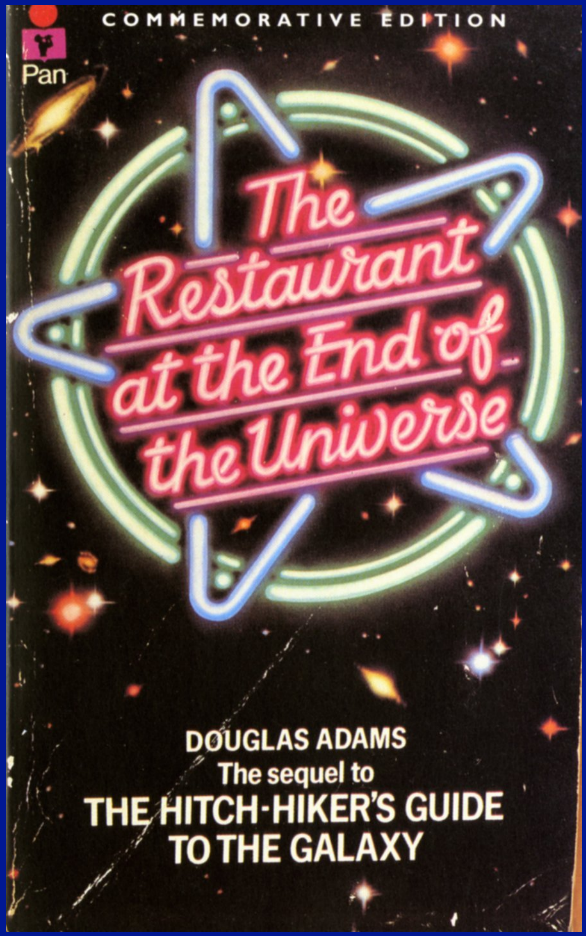


Purple: Chandra X-ray image, White: optical image

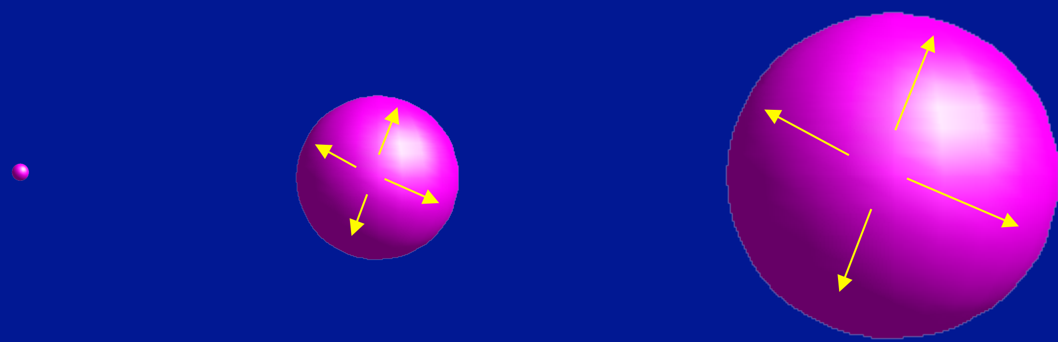
The End of the Universe

How will the Universe end? Is this the only Universe? What, if anything, will exist after the Universe ends?





Universe started out very hot (Big Bang), then expanded:

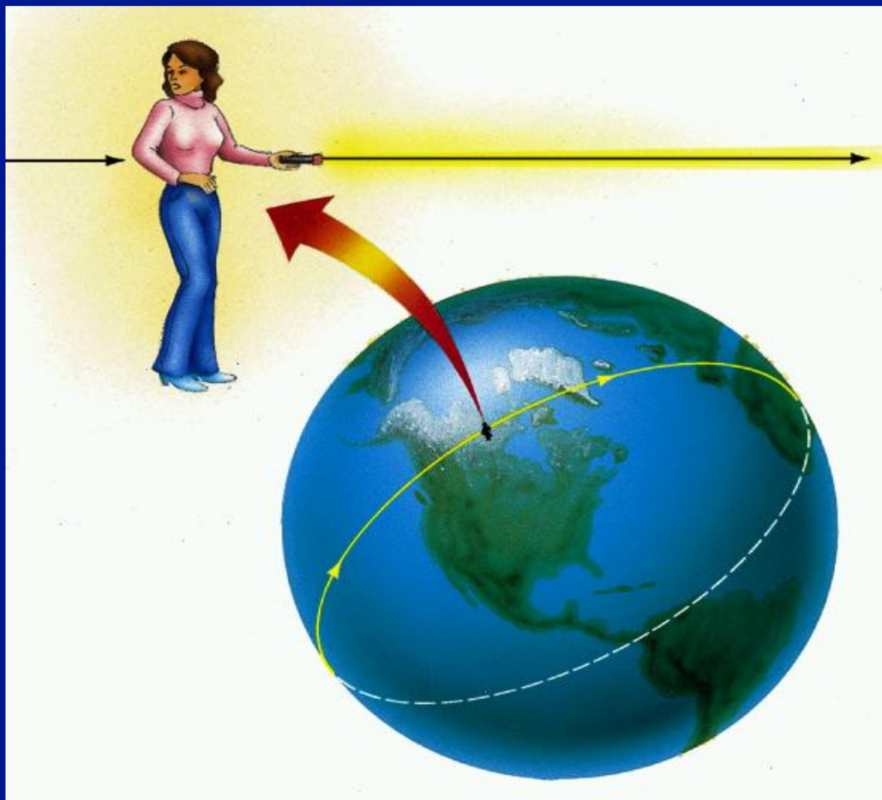


How it ends depends on the geometry of the Universe:

The Geometry of Curved Space

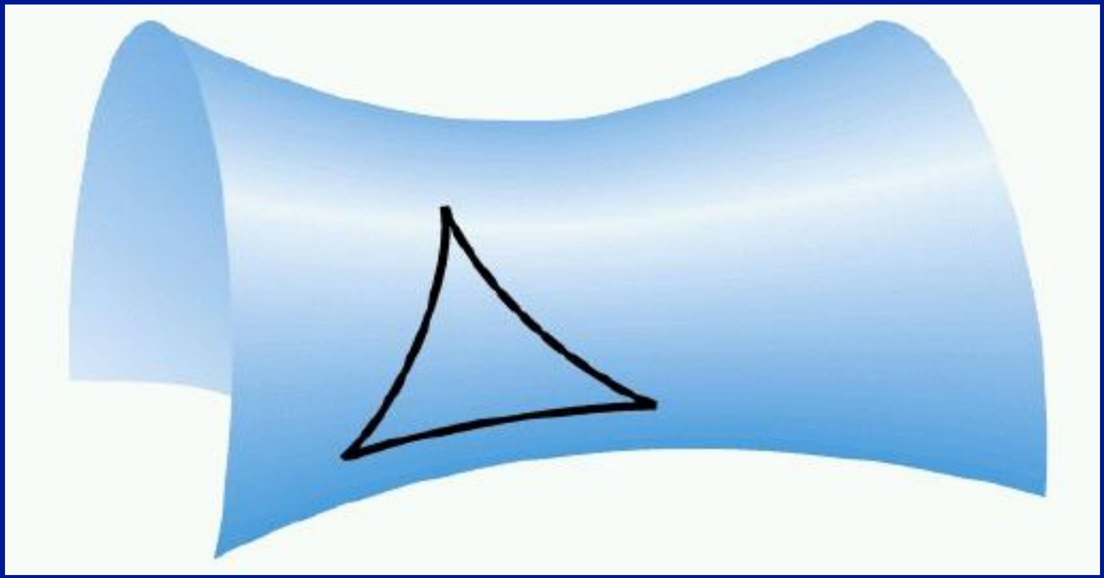
Possibilities:

1) Space curves back on itself (like a sphere). "Positive" curvature.



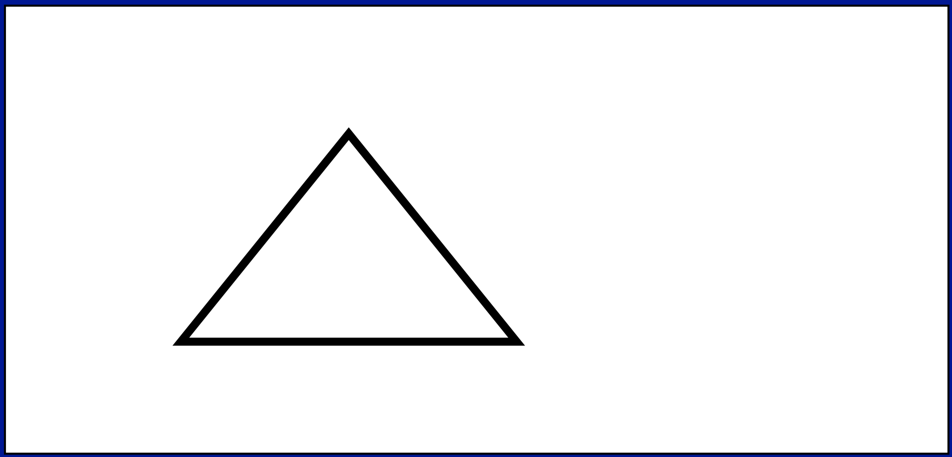
Sum of the Angles > 180

2) More like a saddle than a sphere, with curvature in the opposite sense in different dimensions: "negative" curvature.



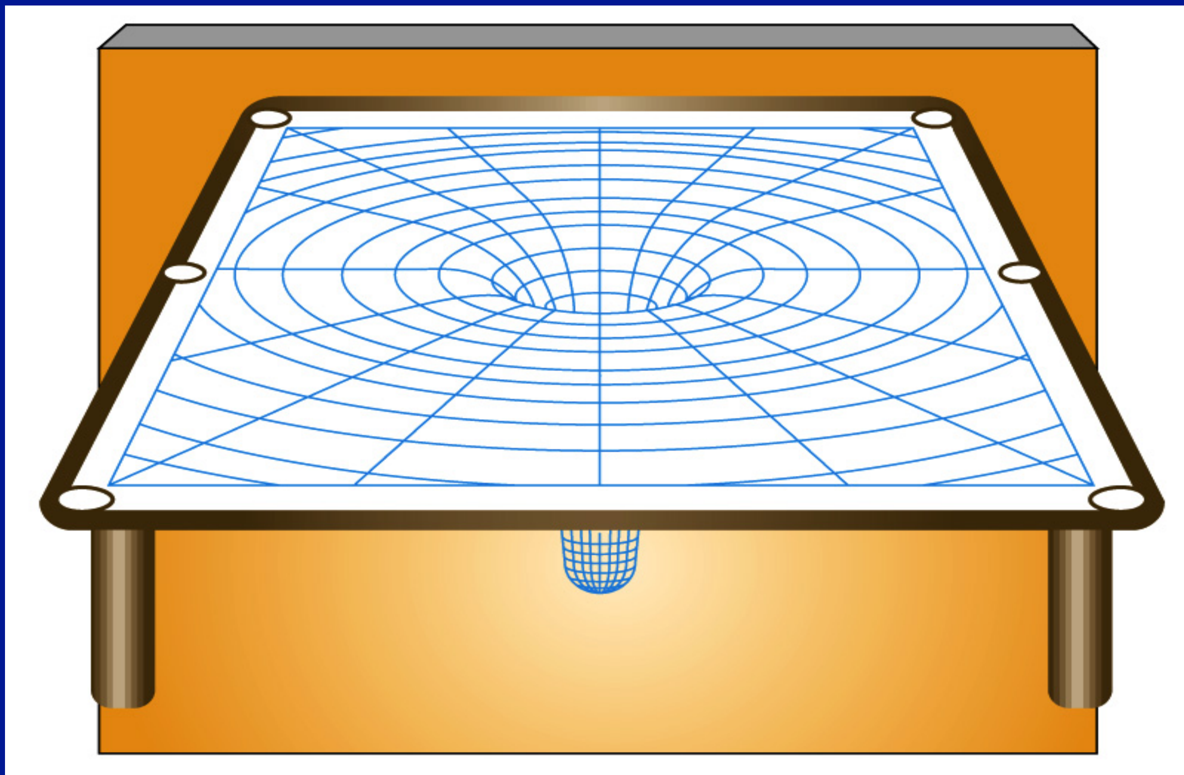
Sum of the Angles < 180

3) A more familiar flat geometry.



Sum of the Angles = 180

We saw that a black hole affects the geometry of space around it.



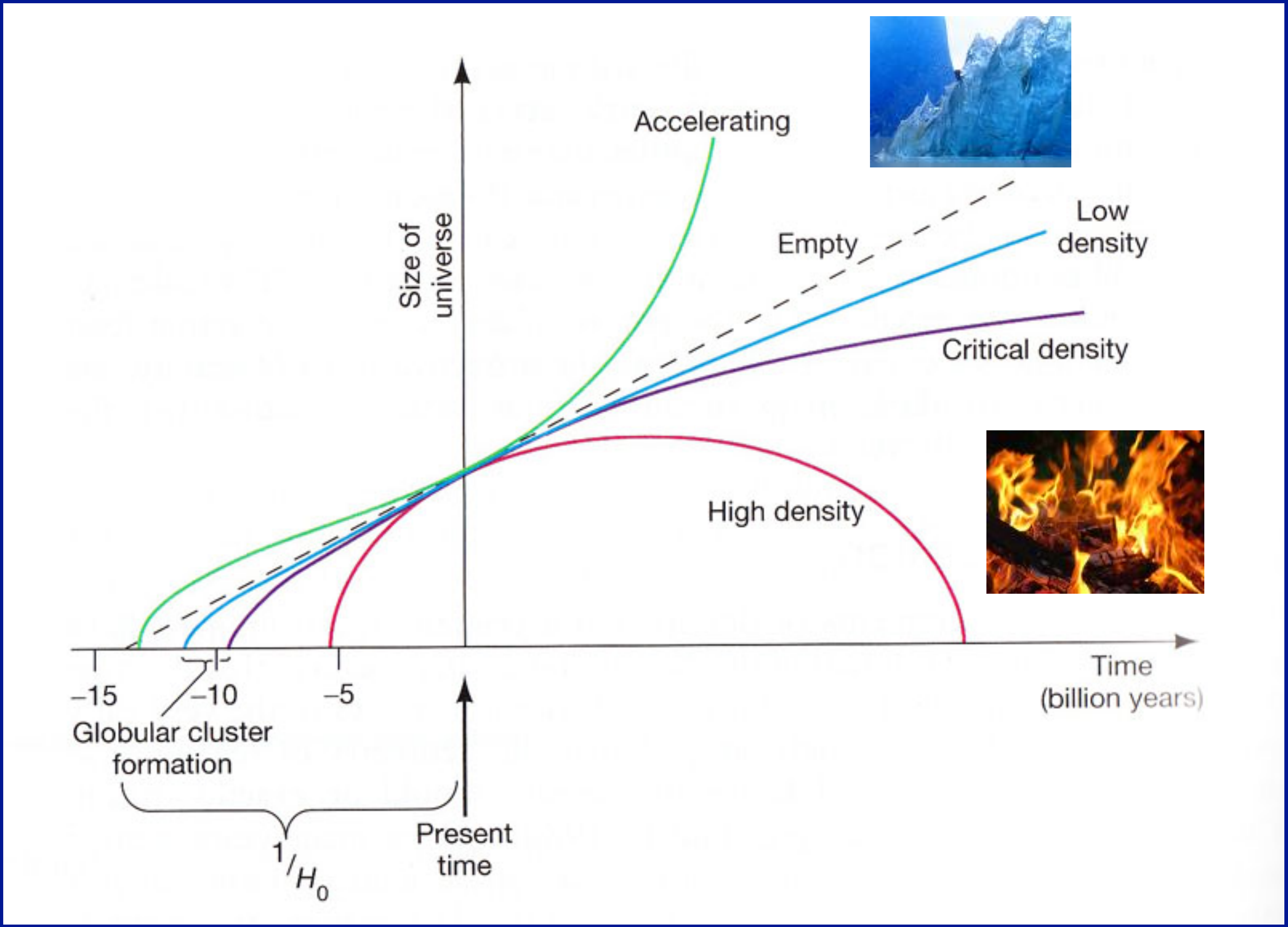
Likewise, the geometry of the universe depends on the total mass and energy of the universe (including dark energy). There is a critical amount, which if exceeded, implies positive curvature, and if not met, implies negative curvature. If right at the critical amount, get flat universe. Latest measurements imply <u>flat</u> universe.

Fire and Ice (1920)

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 I had to perish twice,
I think I know enough of hate
To know that for destruction ice is also great
And would suffice.

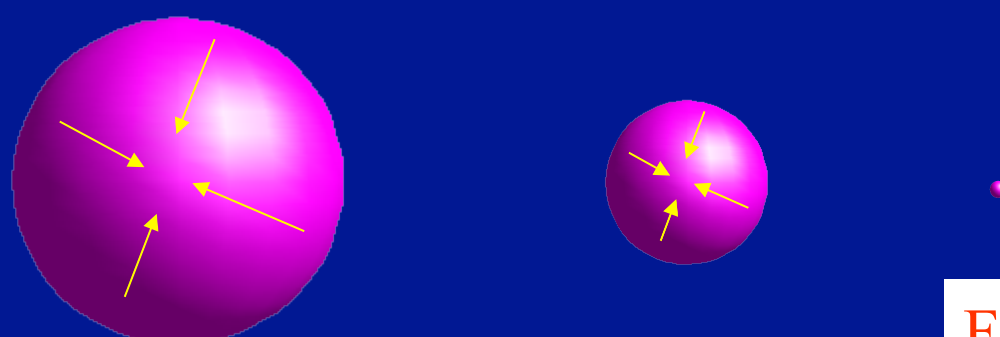
Robert Frost

The Geometry of the Universe determines its fate



Case 1: high density Universe, spacetime is positively curved

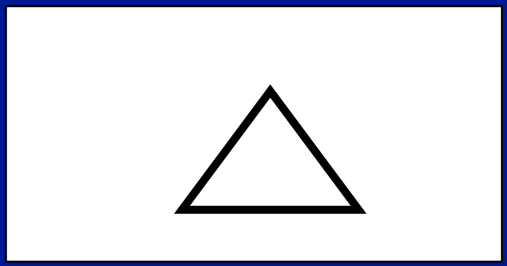
Result is

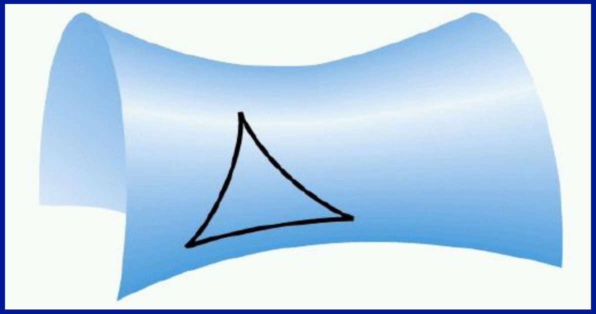


"Big Crunch"

Fire

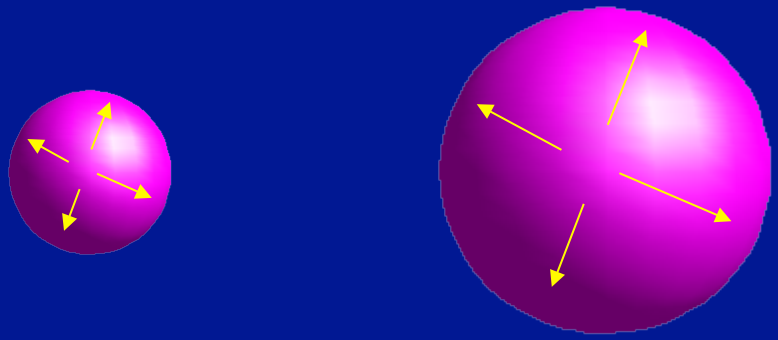
Cases 2 or 3: open Universe (flat or negatively curved)





Current measurements favor an open Universe

Result is infinite expansion



Ice

The Five Ages of the Universe

1) The Primordial Era

2) The Stelliferous Era

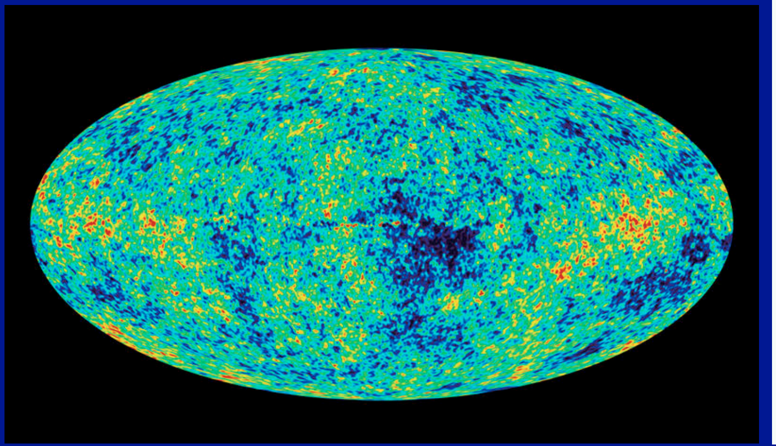
3) The Degenerate Era

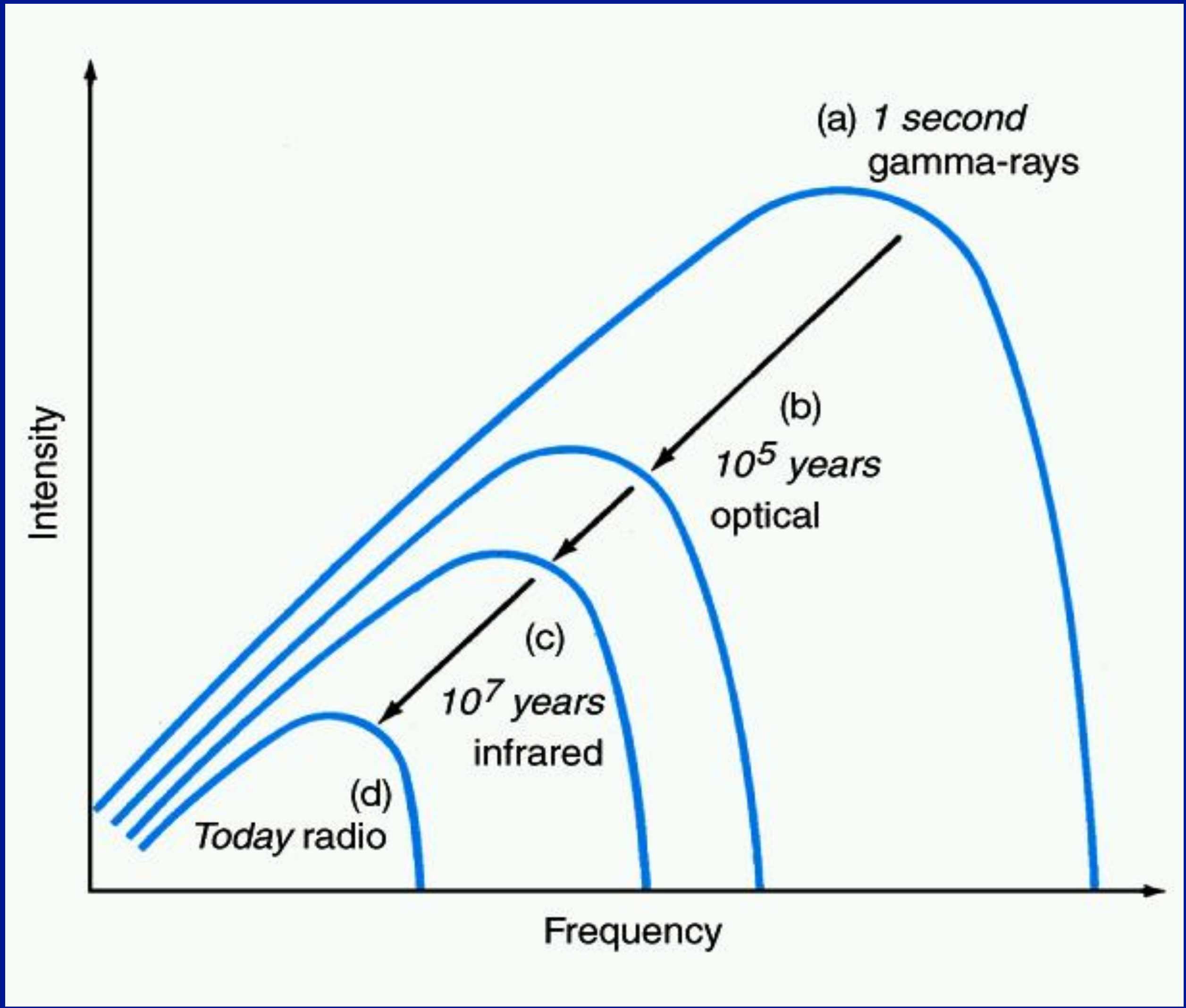
4) The Black Hole Era

5) The Dark Era

1. The Primordial Era: 10^{-50} - 10^{5} y

Something triggers the Creation of the Universe at t=0

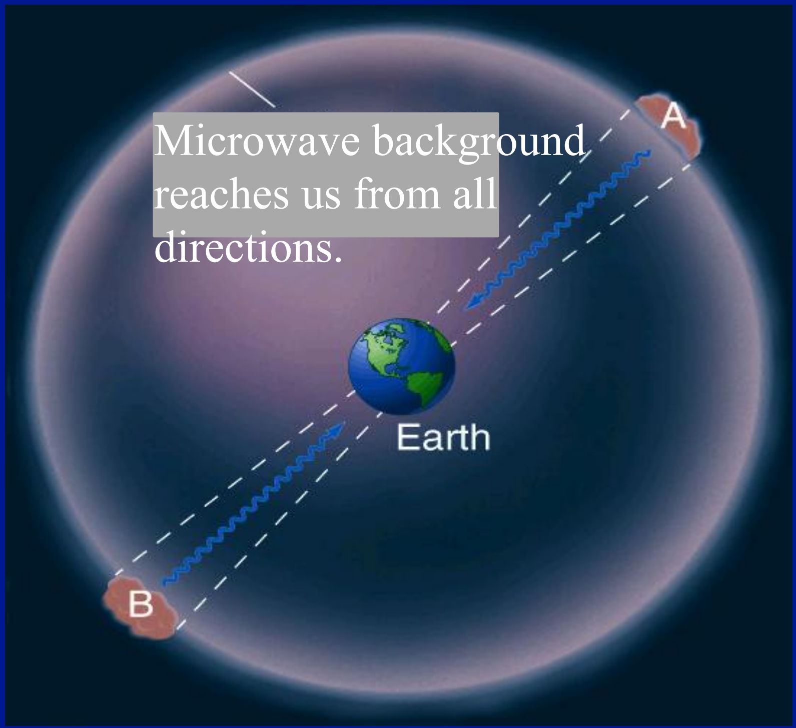




The Early Universe

Inflation

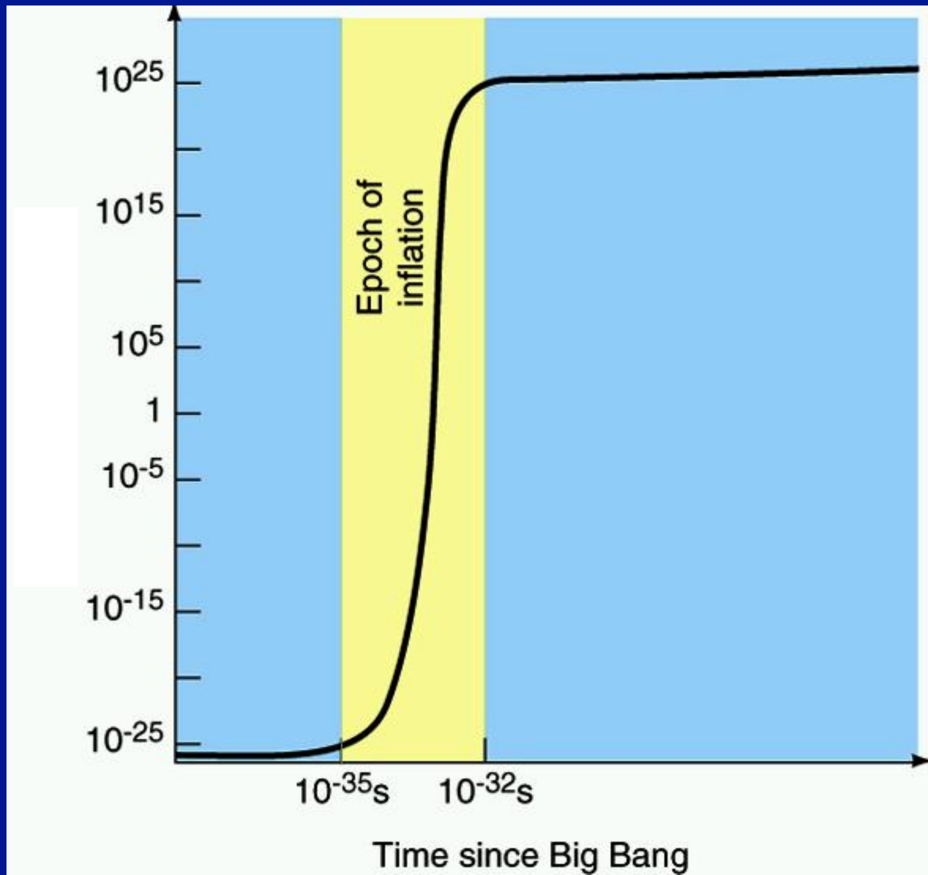
A problem with microwave background:



Temperature of background in opposite directions nearly identical. Yet even light hasn't had time to travel from A to B (only A to Earth), so A can know nothing about conditions at B, and vice versa. So why are A and B almost identical? This is "horizon problem".

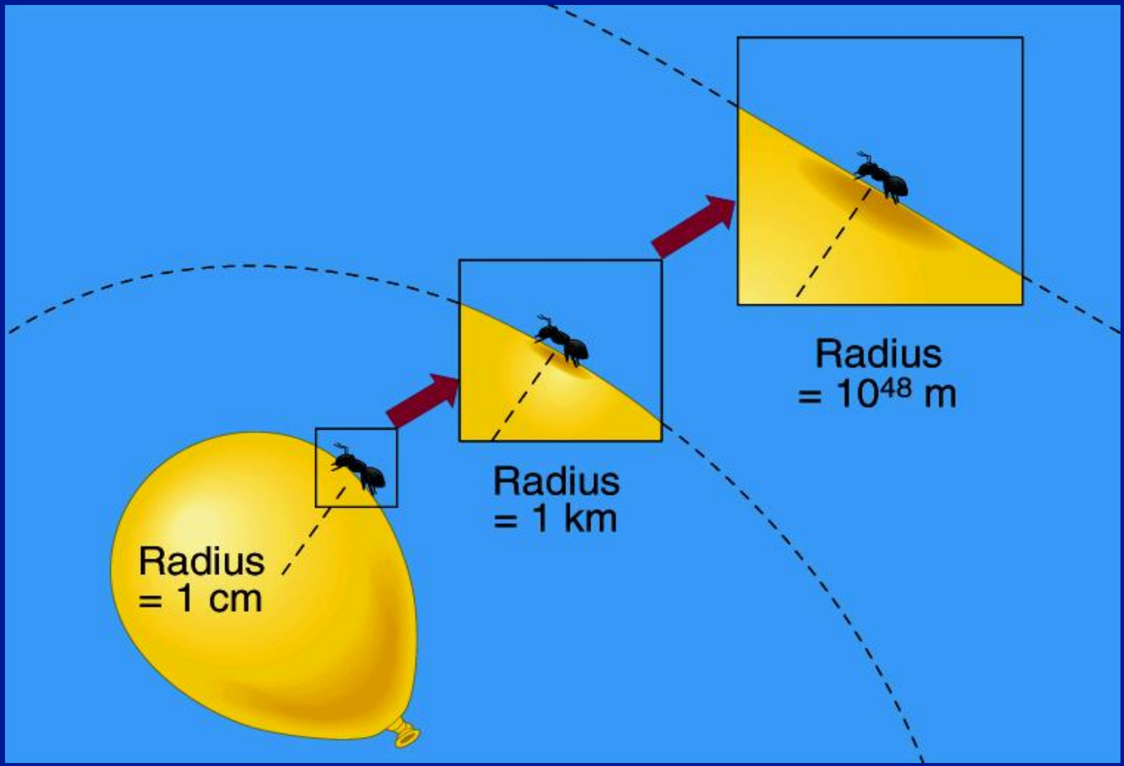
Solution: Inflation. Theories of the early universe predict that it went through a phase of rapid expansion.

Separation between two points (m)



If true, would imply that points that are too far apart now were once much closer, and had time to communicate with each other and equalize their temperatures.

Inflation also predicts universe has flat geometry:



Microwave background observations seem to suggest that this is true.

Clicker Question:

What is the temperature of the microwave background now, 14 billion years after the Big Bang that produced it?

A: 0.27 K

B: 2.7 K

C: 27 K

D: 270 K

Clicker Question:

What is the fate of a closed, high density Universe?

A: Can’t get started, no Big-Bang is possible.

B: It expands forever

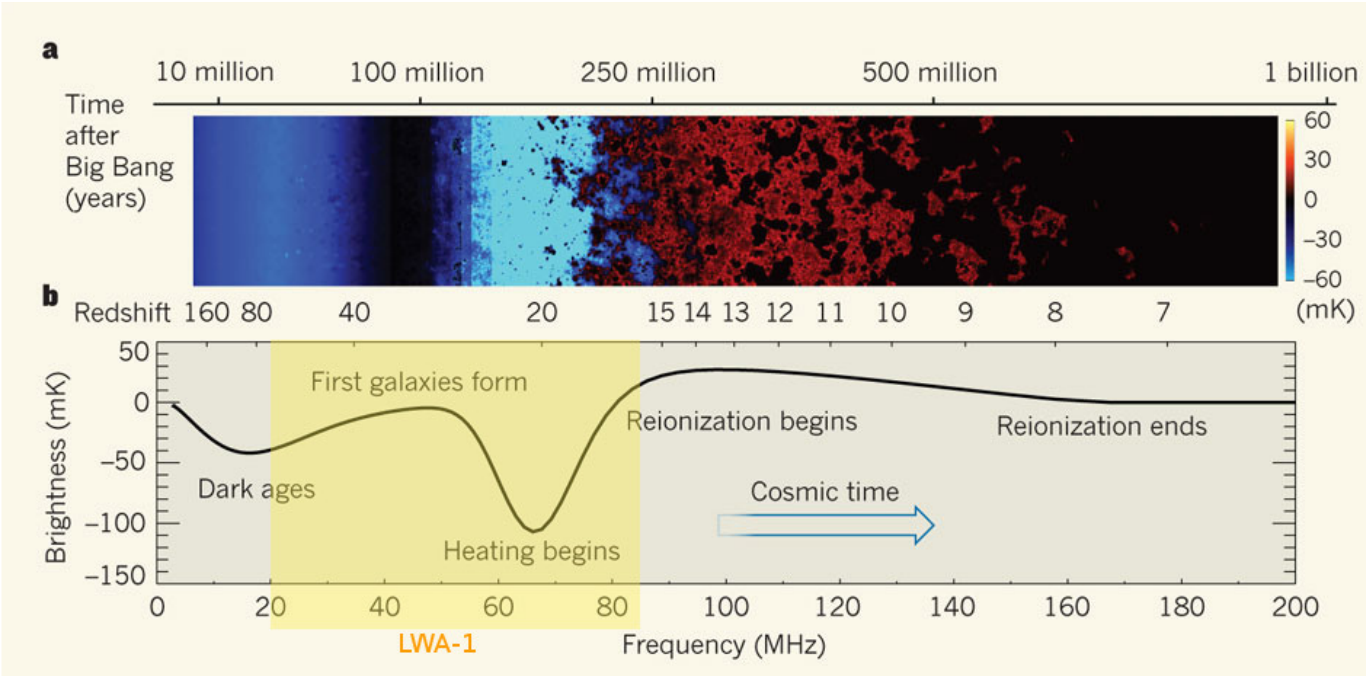
C: It expands for a while, stops, then contracts to a “Big Crunch”

D: It oscillates between expansion and contraction.

2. The Stelliferous Era: 10^6 - 10^{14} y

Now = 13.8 billion years ~ 10^{10} y

LWA 1 Science Program: Dark Ages



The predicted brightness temperature of the 21cm line from the HI gas is displayed as a function of time, redshift & frequency.

Figure 1 from Pritchard & Loeb, 2010 Nature 469 772

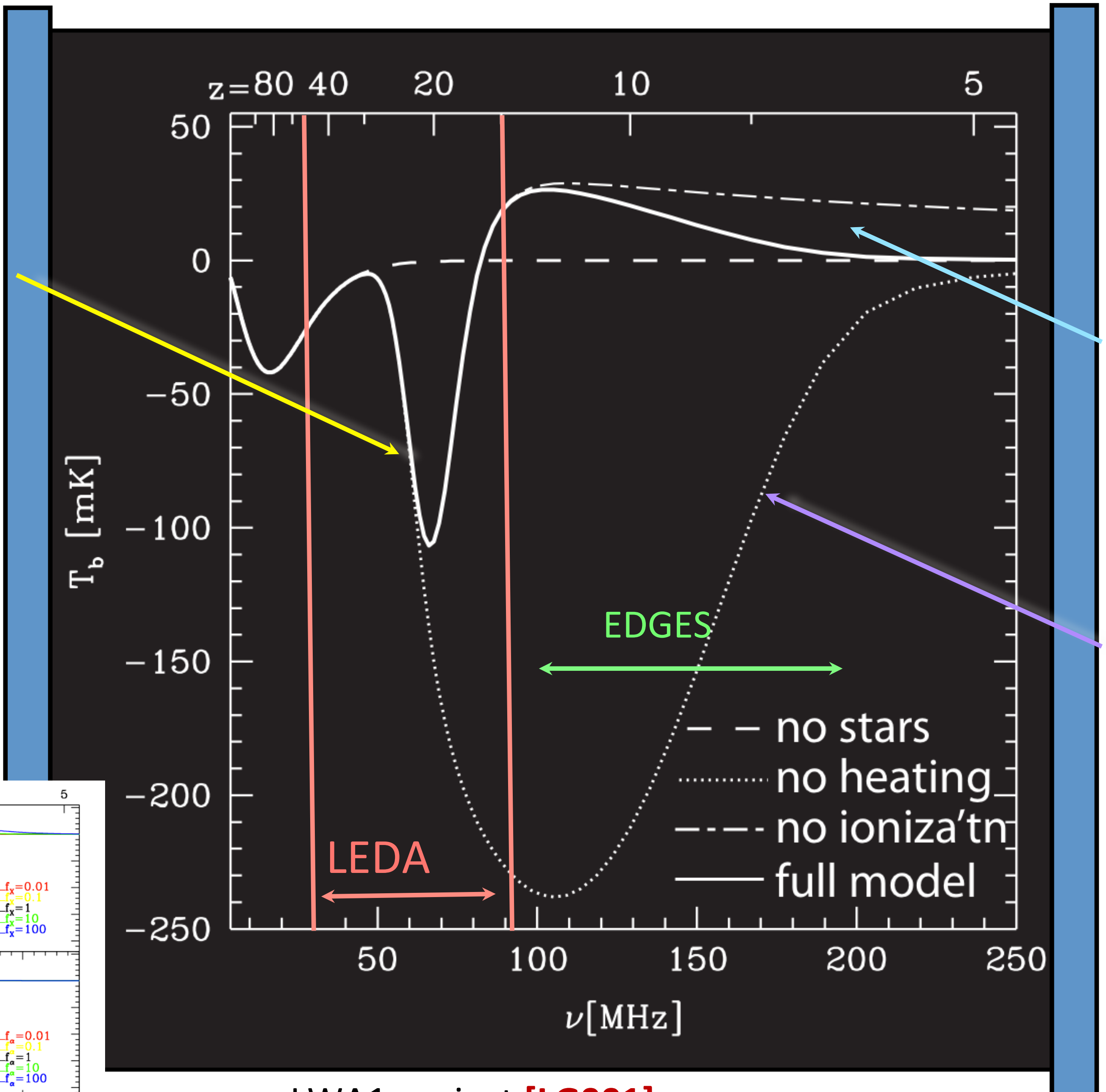
The Dark Ages through Cosmic Dawn encompasses the formation of the 1st galaxies & black holes. LWA1 offers a unique window into this era.

- ***LEDA*** (Large Aperture Experiment to detect the Dark Ages) :
  - Probe thermal history & Lyα output of 1st stars & galaxies by characterizing HI trough – only means to detect IGM @ z >15
  - New correlator, total power hardware & data reduction pipeline

LWA Long Wavelength Array

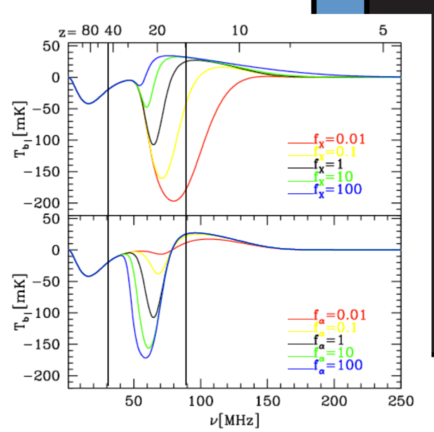
LEDA: Inference

Lyman-α photon production (likely from stars) determines magnitude of decoupling from the dashed curve



Production of ionizing photons determines the difference between dash-dot and solid curves

Case where IGM not reheated prior to reionization. It takes just 10^{-3} eV per baryon to significantly change this curve.



LWA1 project **[LG001]**

Simulations

http://cita.utoronto.ca/~malvarez/visualization/

How Long do Stars Live?

A star on Main Sequence has fusion of H to He in its core. How fast depends on mass of H available and rate of fusion. Mass of H in core depends on mass of star. Fusion rate is related to luminosity (fusion reactions make the radiation energy).

So,

$$\text{lifetime} \quad \alpha \quad \frac{\text{mass of core}}{\text{fusion rate}} \quad \alpha \quad \frac{\text{mass of star}}{\text{luminosity}}$$

Because $\text{luminosity} \quad \alpha \quad (\text{mass})^3$,

$$\text{lifetime} \quad \alpha \quad \frac{\text{mass}}{(\text{mass})^3} \quad \text{or} \quad \frac{1}{(\text{mass})^2}$$

So if the Sun's lifetime is 10 billion years, the smallest 0.1 M_{Sun} star's lifetime is 1 trillion years.

How Long do Galaxies Live?

Only as long as they can continue to manufacture stars. To do that the galaxy needs gas.

So,

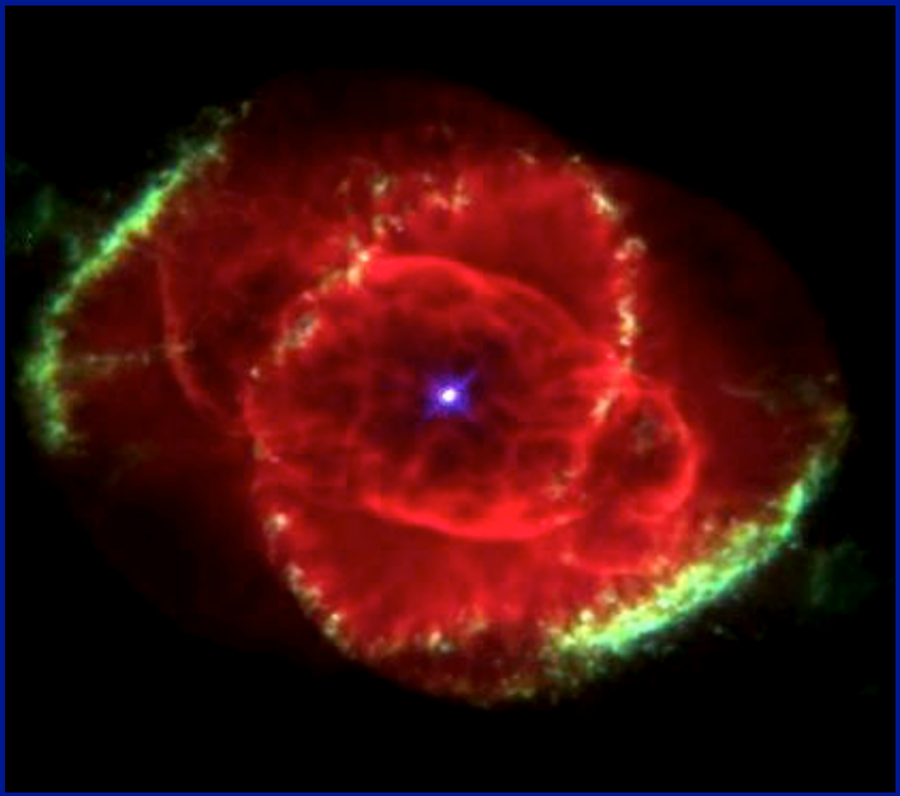
$$\text{lifetime} \quad \alpha \quad \frac{\text{Mass of gas}}{\text{star formation rate}} = \quad \text{10 billion years (for MW)}$$

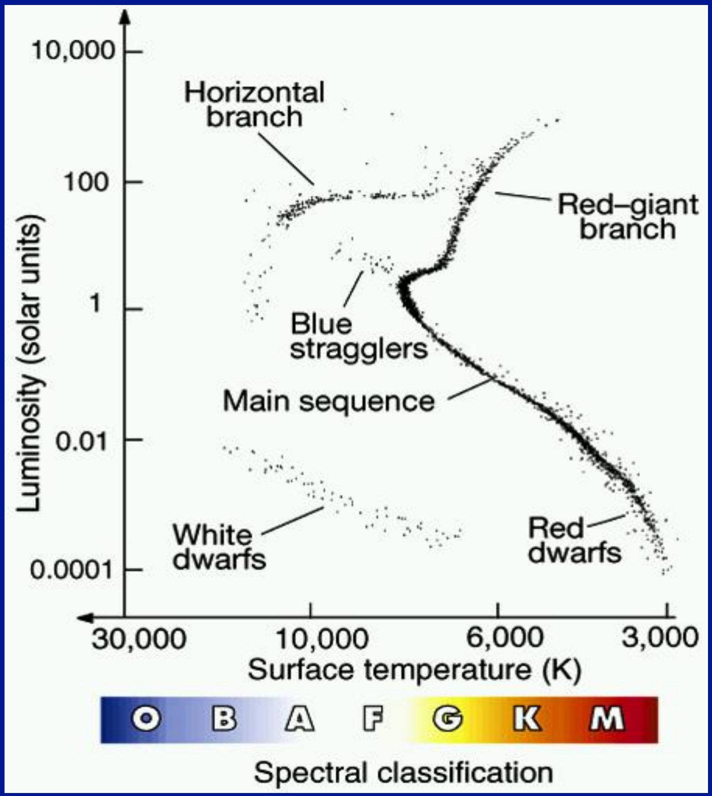
Galaxies with modest star formation rates can shine for perhaps 1 trillion years

3. The Degenerate Era: 10^{15} - 10^{39} y

Most stars leave behind a white dwarf

Mass between 0.1 and 1.4 M_sun





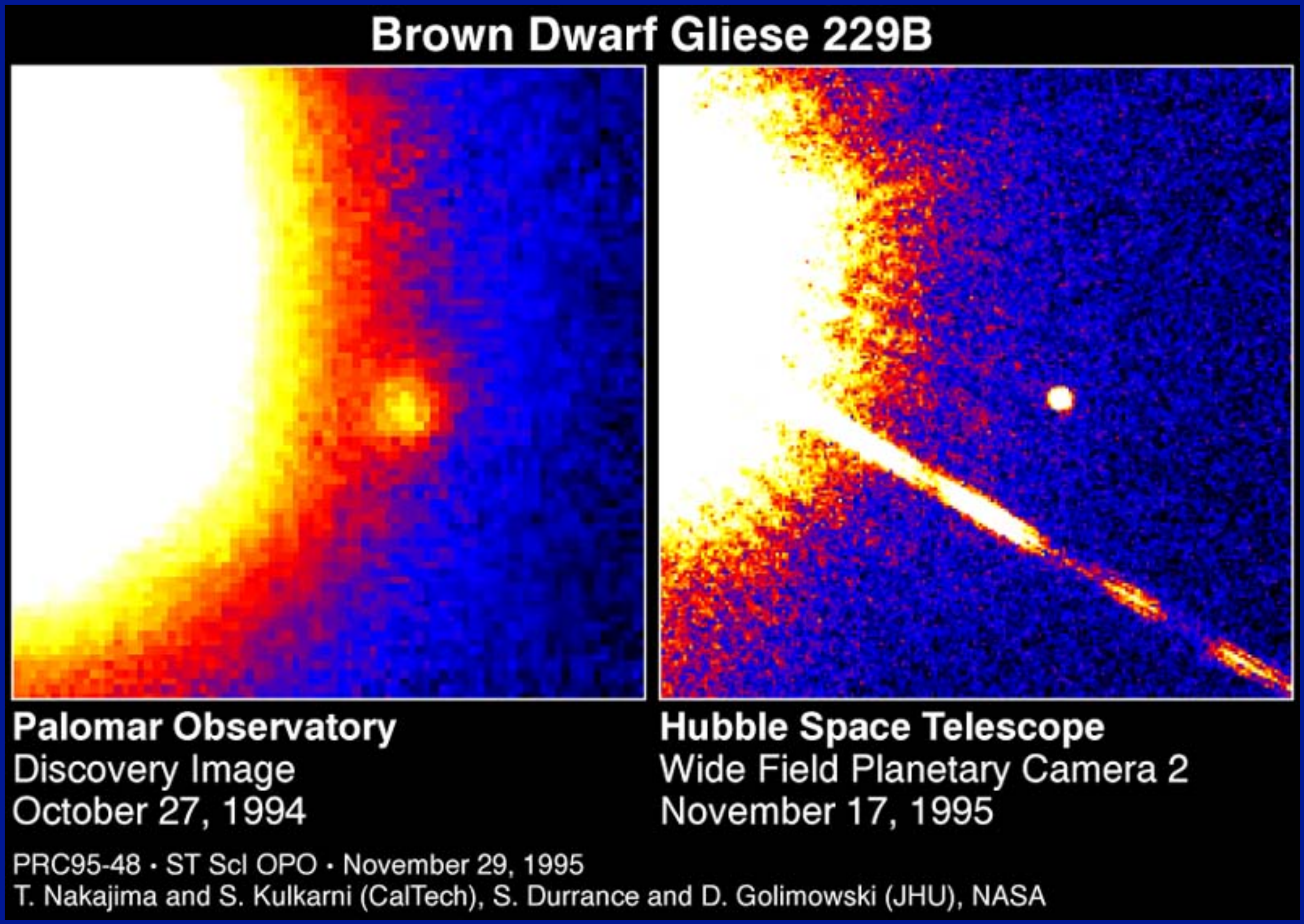
The Degenerate Era: 10^{15} - 10^{39} y

Some failed protostars never got hot enough to ignite hydrogen fusion:

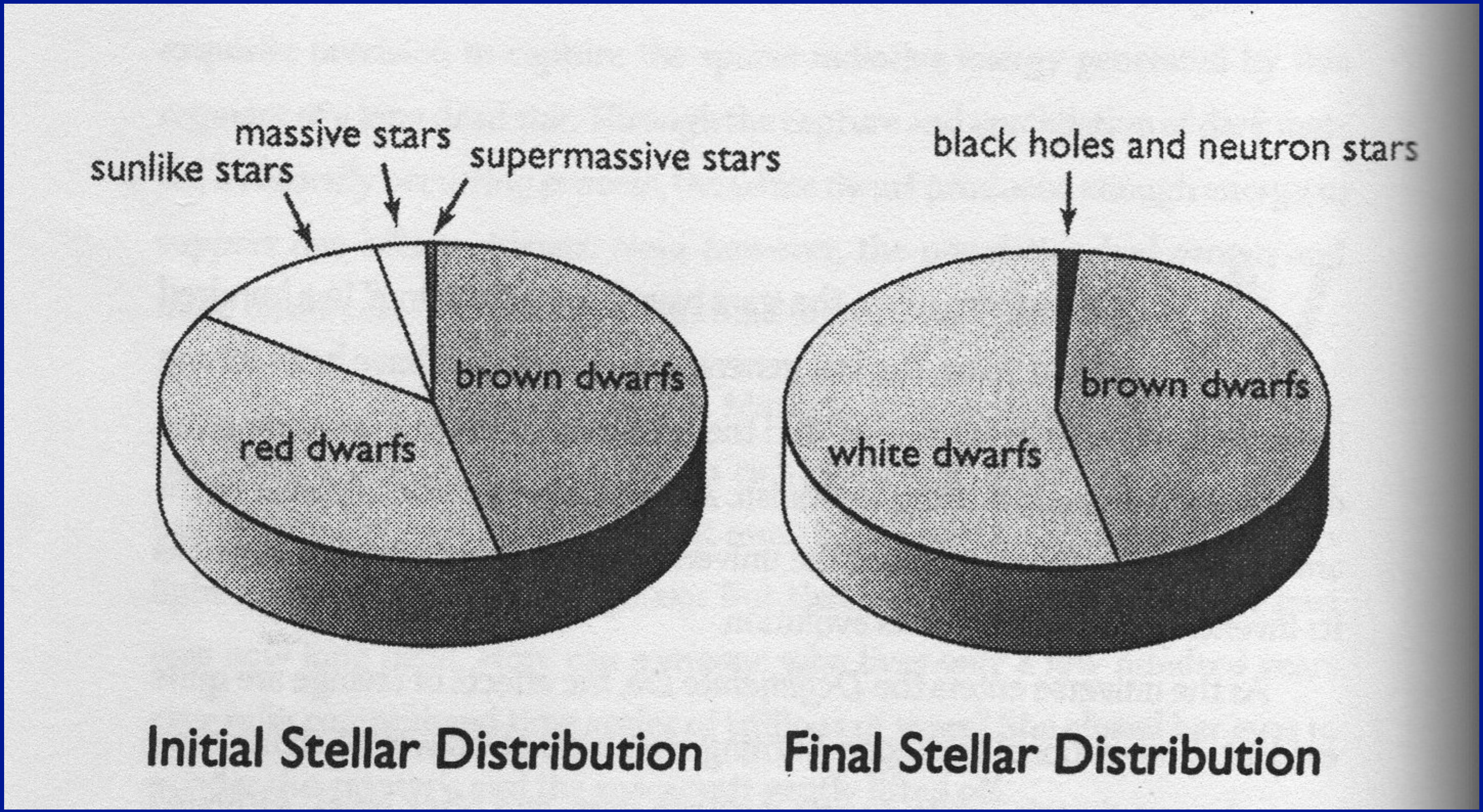
Brown Dwarfs

Mass < 0.08 M_sun

Brown dwarf collisions can create occasional warm spots in an increasingly cool universe



The Degenerate Era: 10^{15} - 10^{39} y

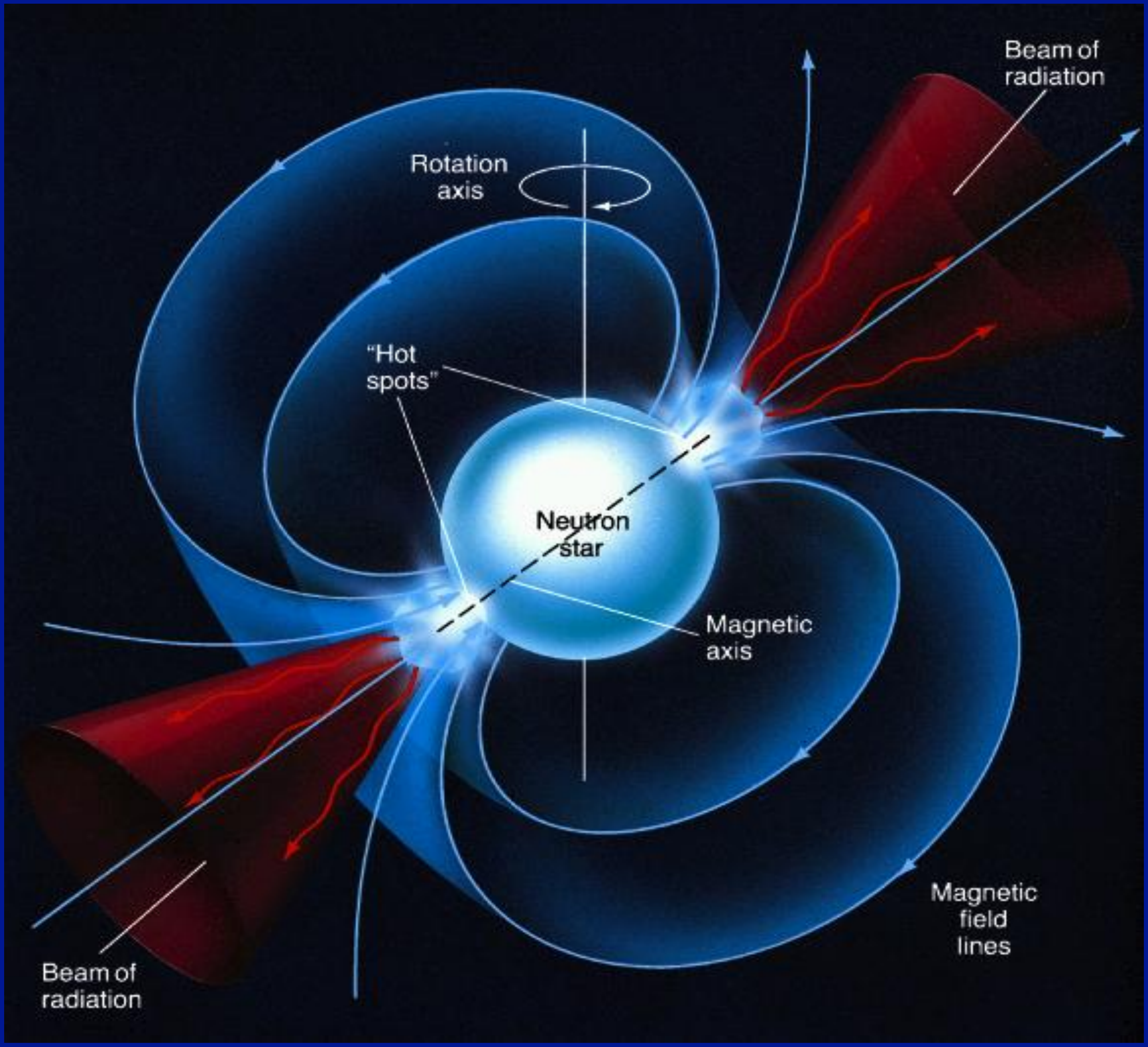


The Degenerate Era: 10^{15} - 10^{39} y

Neutron stars:

Cold and no longer pulsating

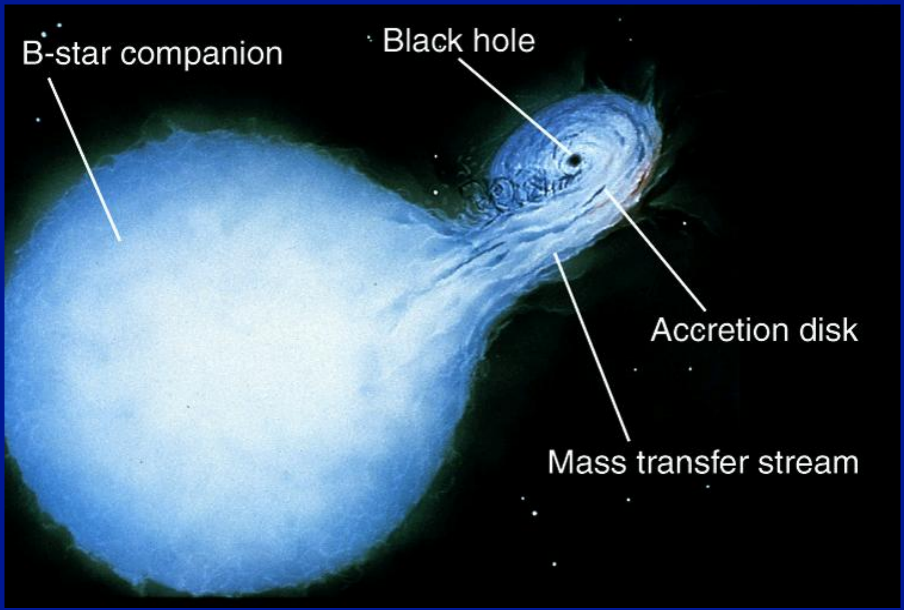
Mass ~ 1.5 M_sun



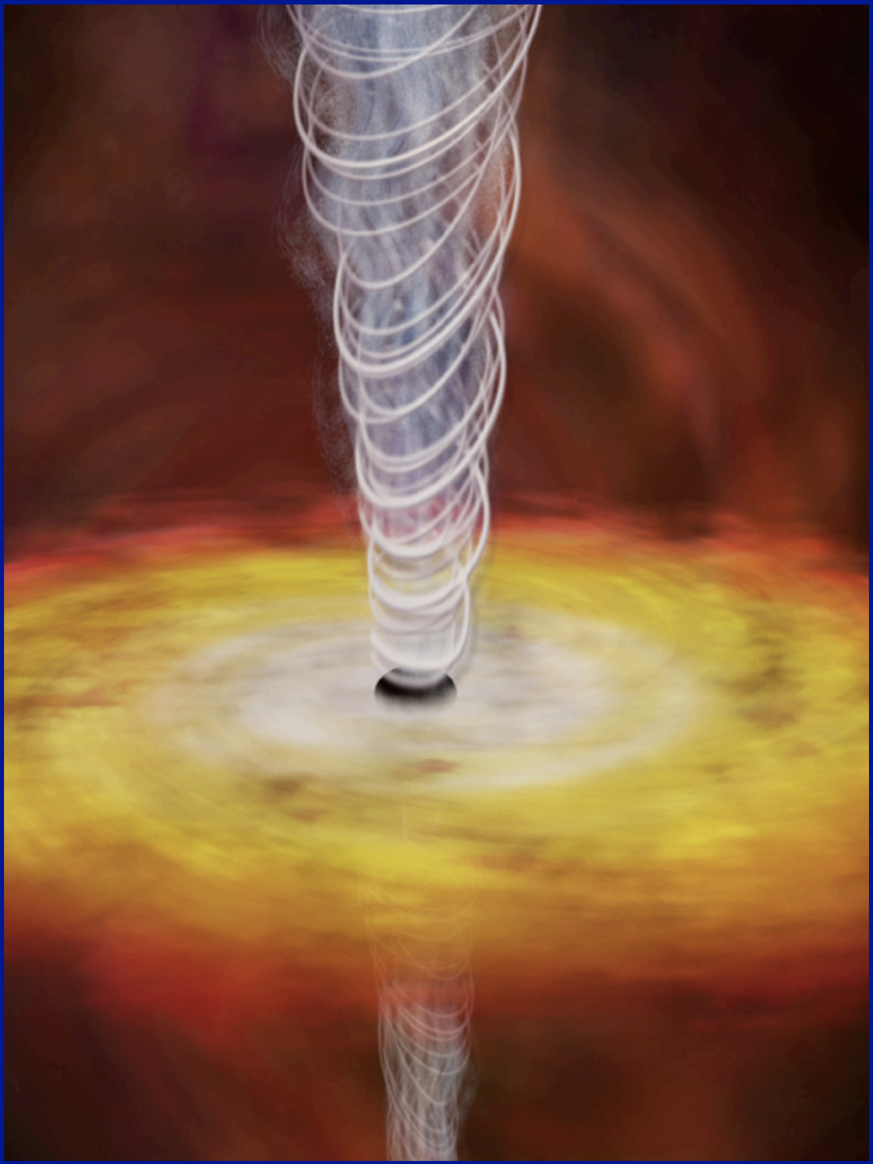
The Degenerate Era: 10^{15} - 10^{39} y

Black holes

Stellar mass black holes



Supermassive black holes



Galaxy evolution: dynamic relaxation during the Degenerate Era

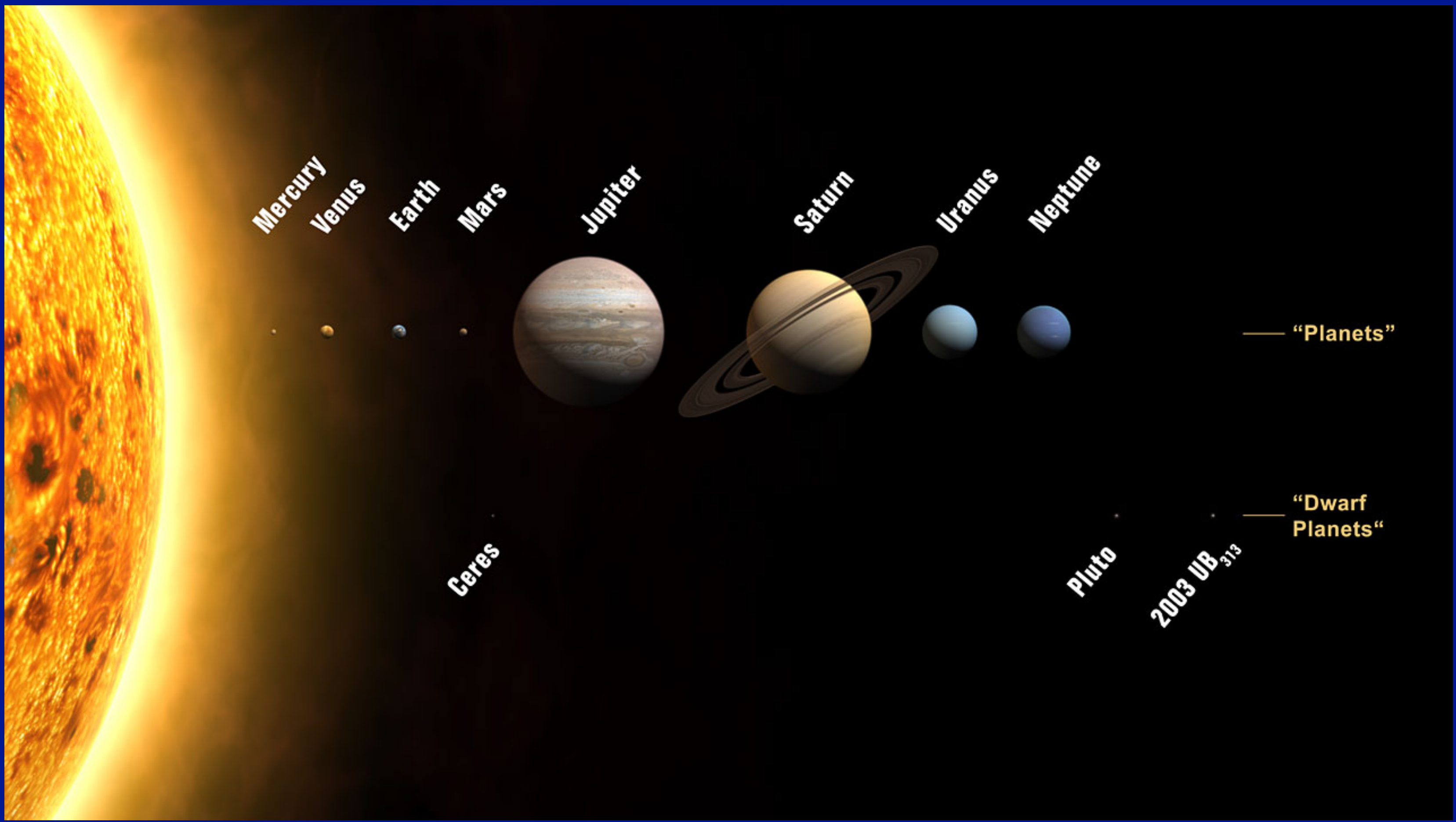
Galaxies continue to merge to form large meta-galaxies (entire local group merges into a single galaxy); spirals merge --> ellipticals

Massive remnants sink to the center of the galaxy
Less massive remnants get ejected from the galaxy (all the brown dwarfs are gone by 10^{20} y).

What happens to Solar systems like ours?

Inner planets are fried during end of stelliferous era
Planets are gradually stripped away during stellar encounters in the degenerate era

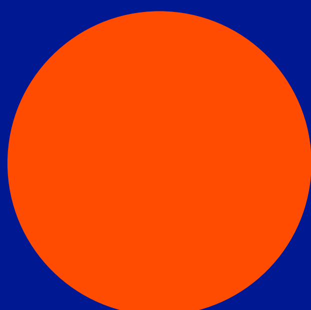
10^{17} 10^{15} 10^{12} y



Dark Matter?

Annihlation of WIMPs (Weakly Interacting Massive Particles)?

- In the halo of the galaxy
- In the cores of white dwarfs (power ~ 10^{15} Watts, 10^{-9} L_sun)



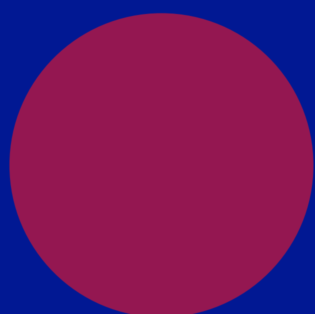
Surface temperature ~60 K

Steady energy source for ~10^{20} y

Proton Decay?

Predicted lifetime of protons (and neutrons) is 10^{37} y

- In white dwarfs (power ~ 400 Watts, 10^{-22} L_sun)



Surface temperature ~0.06 K

Composition changes to frozen H

Star expands

Slow decay over ~10^{39} y

Eventual disintegration into photons

Neutron stars, planets, dust, all face the same fate.

4. The Black Hole Era: 10^{40} - 10^{100} y

Black holes inherit the Universe

- mostly in the form of stellar mass black holes

Some electrons, positrons, neutrinos and other particles remain

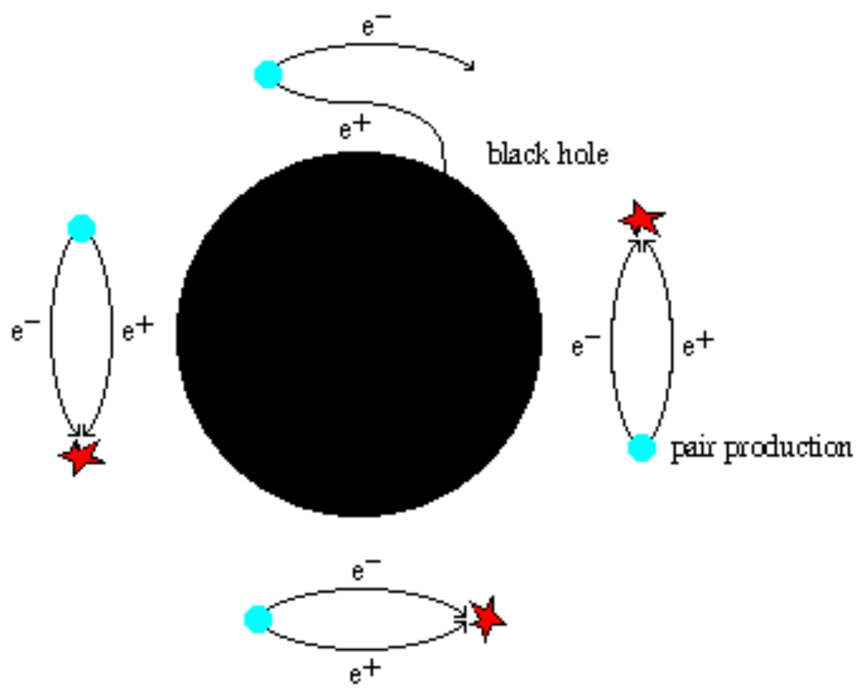
Planets, Stars and Galaxies are all long gone

4. The Black Hole Era: 10^{40} - 10^{100} y

Black holes eventually start to decay by Hawking Radiation

Hawking Radiation

the strong gravitational field around a black hole causes pair production



if a pair is produced outside the event horizon, then one member will fall back into the black hole, but the other member will escape and the black hole loses mass

Hawking radiation continued:

Effective Temperature ~ 1/mass

Universe cools with time, so that after 10^{21} y, the Universe is cooler than a 1 solar mass black hole (10^{-7} K)

After 10^{35} y, even 1 billion solar mass black holes have begun to evaporate.

Final stage of black hole radiation is explosive with 10^{6} kg of mass converted into energy

After 10^{100} y, even the most massive black holes are gone.

Clicker Question:

How will the Earth be destroyed first?

A: Burnt to a crisp by the Sun when it becomes a Red Giant in 5 billion years.

B: Blown to bits by a nearby supernova.

C: Stripped away from the Sun by an encounter with another star in 10^{15} years.

D: Blown to bits by silly humans with atomic bombs.

Clicker Question:

Which of the following particles can live forever (assuming it never encounters its anti-particle)?

A: proton

B: neutron

C: electron

D: He atom

Clicker Question:

Assuming that there were no further interactions with other galaxies, what part of our galaxy would survive for the longest time?

A: our Sun and other stars like it

B: brown dwarf stars

C: white dwarf stars

D: the supermassive black hole at the center

5. The Dark Era: > 10^{101} y

Only some elementary particles and ultra-long-wavelength photons remain inside a vastly expanded Universe.

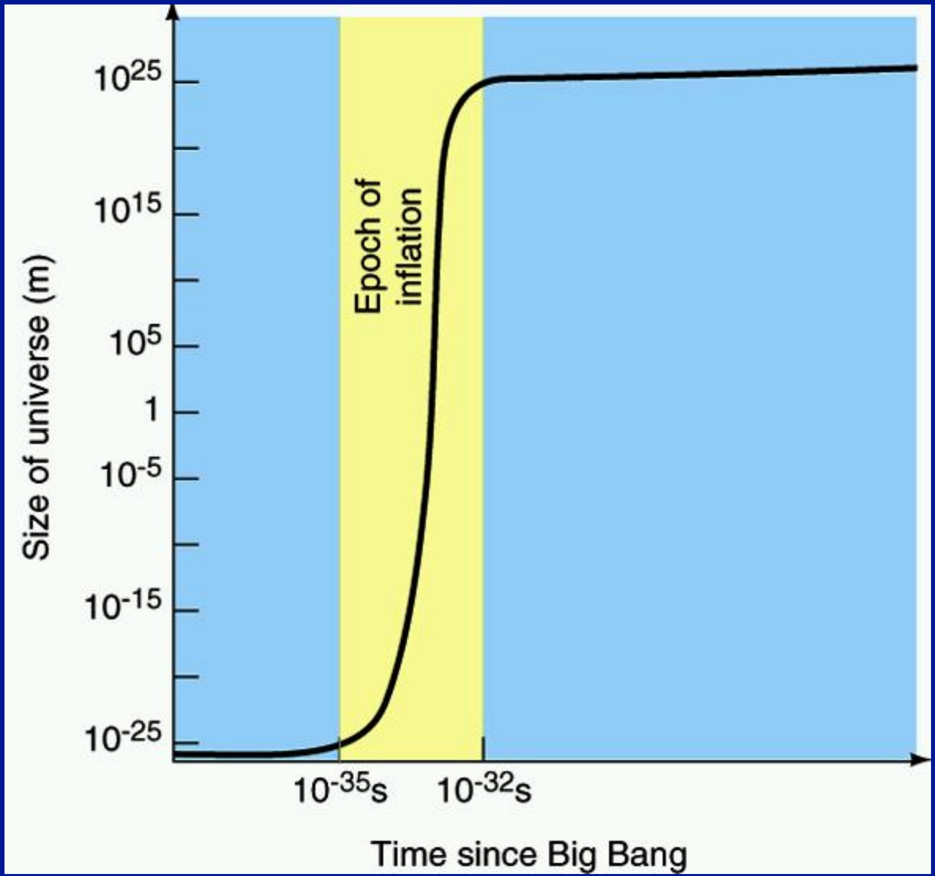
Density is unimaginably low. Our observable Universe now has a size of 10^{78} cubic meters. In the Dark Era there will be one electron every 10^{182} cubic meters.

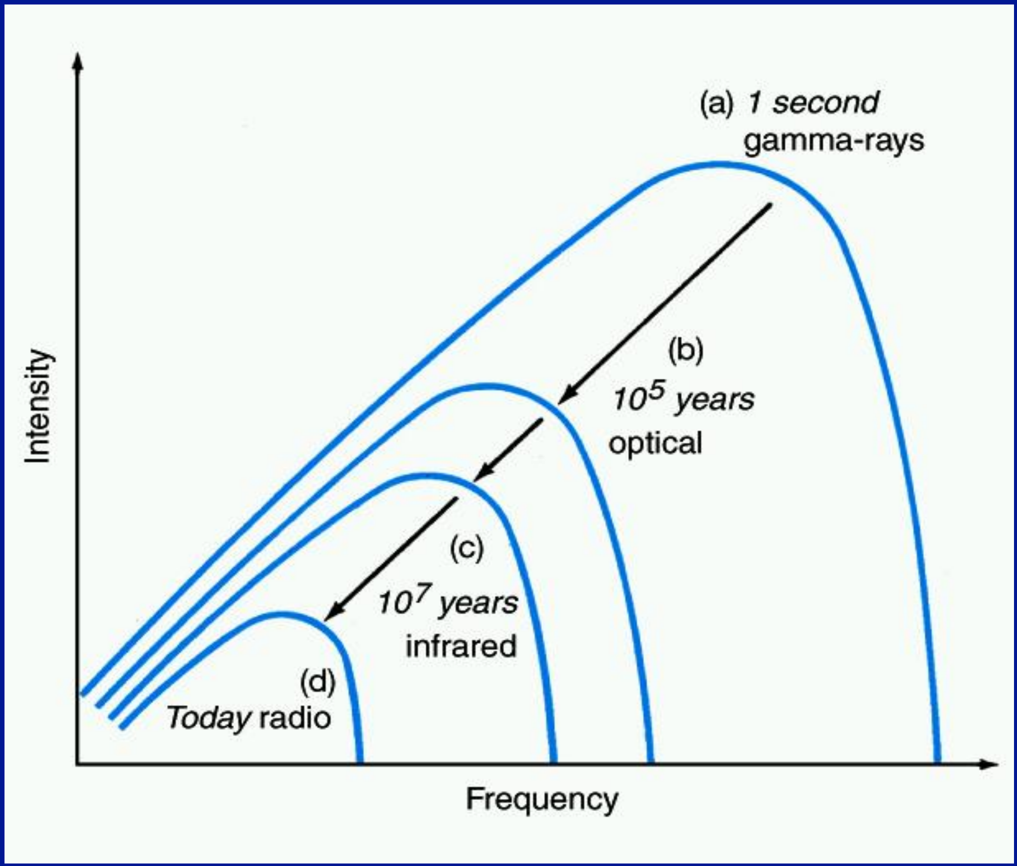
Heat death - nothing happens, no more sources of energy available

Or ….

1. The Primordial Era: 10^{-50} - 10^{5} y

Something triggers the Creation of a child Universe





Child Universe

Living on borrowed energy:

$E_{total} = mc^2 - 1/2\ m\ v_{esc}^2 = 0$

Energy of expansion is about equal to energy in matter

Chaotic Inflation theory predicts multiple universes or “Hubble Volumes”
An Infinite Universe contains an infinite number of Hubble Volumes
There should be an infinite number of Universes similar to ours