Final Chapter:

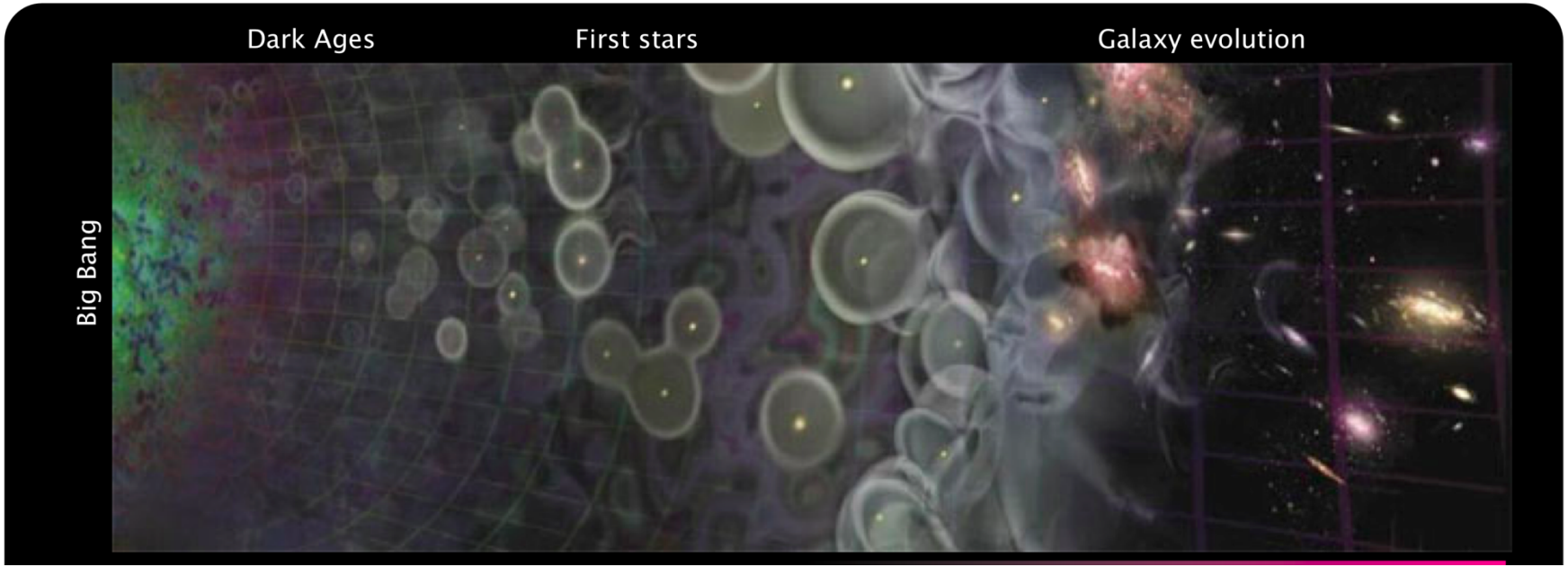
What is the ultimate origin of the **free energy** used by **life** today?

Can we trace this free energy through **ever lower entropy** sources back to the **Big Bang**?

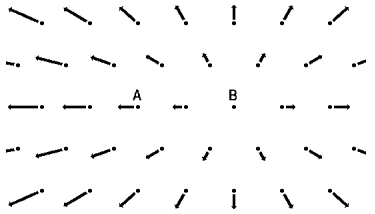
Why did the Big Bang result in an early universe in such a relatively **low entropy** state?

Evolution of the Universe in Broad Brushstrokes:

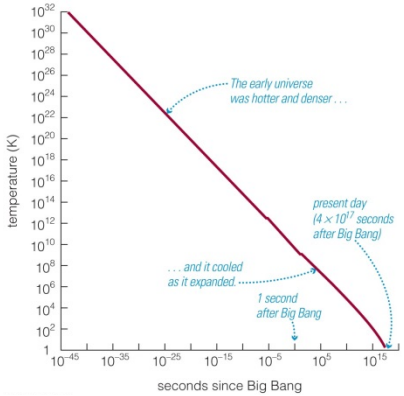
- The matter in the early universe was **hot and dense**, and filled all of space **almost perfectly uniformly**. There was **no structure**.

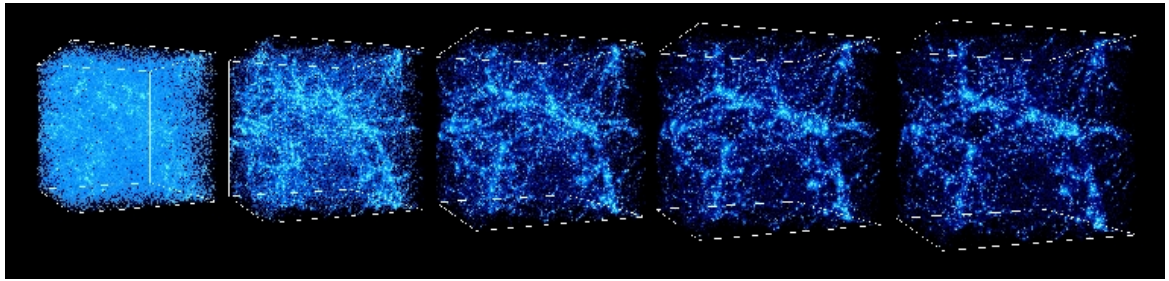


Evolution of the Universe in Broad Brushstrokes:



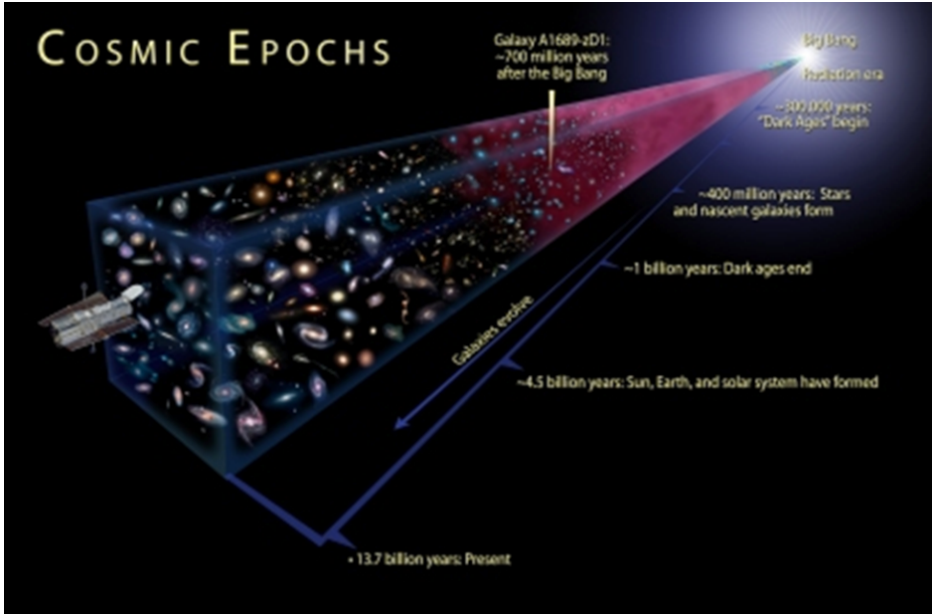
- As space expanded, the matter **cooled and condensed**, e.g.:
  - quark-gluon plasma cooled and condensed into protons & neutrons
  - protons & neutrons cooled and condensed into light nuclei (nucleosynthesis)
  - light nuclei & electrons cooled and condensed in neutral H & He atoms (⎵ CMB)
  - neutral H & He gas cooled and condensed gravitationally into the first stars
  - stars gravitationally clumped into galaxies, clusters of galaxies, etc.





Evolution of the Universe in Broad Brushstrokes:

- **Like snowflakes** condensing out of a cooling cloud of water vapour, each represents a spontaneous **creation of structure, or order**.



Problem:

- The early universe seems to have been in a state of **thermodynamic equilibrium** (a gas of particles with uniform temperature & density), and thus **maximum entropy** (thermodynamic equilibrium is, by definition, the state of maximum entropy).
    - The present universe is certainly **not** in thermodynamic equilibrium: there are all kinds of local gradients (temperature, density, chemical, etc.) and flows. How did it get **out of equilibrium**, which is a *necessary prerequisite* for **life to exist**?
    - Isn't **starting** in a state of **maximum** entropy a **blatant violation** of the Second Law of thermodynamics? Surely, the early universe must have been in a state of **minimum** (or at least *relatively* low) entropy, so that the entropy could increase as it **evolved** (in the process of producing stars, planets, life, etc.).

Role of Gravity:

- Gravity plays key roles in solving these problems:
    - **Expansion of space** caused the universe to come out of equilibrium; it increased the "ceiling" of maximum entropy, allowing room for entropy to increase.
    - **Gravitational clumping** generates gradients and structure, and is a *catalyst* that facilitates entropy-increasing processes essential for life, e.g., fusion in stars.
    - **Black holes** (apparently) contain almost all of the entropy in the universe today.
- We will discuss these in turn, and ultimately trace the **free energy** required for life back to the early universe…

Role of Gravity—Expansion of Space:

- **Equilibrium** means everything is **static** (temperature, density, etc.). But if space is **expanding**, density & temperature are **changing** (decreasing) ▭ what does this mean for equilibrium?

- Imagine a gas in a cylinder with a piston:

  - If we pull the piston out ***slowly*** compared to the time it takes the gas atoms to "adjust" ("quasi-statically": through a sequence of slowly-changing equilibrium states), the gas remains in *instantaneous* **equilibrium**. Entropy remains **constant**; process is **reversible**.

  - This was happening in the **very early universe**. The expansion (after inflation) was slow ***compared*** to the time it took for the elementary particles to "adjust" to new *instantaneous* equilibrium states. For example, the process: quark-gluon plasma ▭ protons & neutrons is **constant entropy** and **reversible** — just reverse the expansion!

Role of Gravity—Expansion of Space:

- **Equilibrium** means everything is **static** (temperature, density, etc.). But if space is **expanding**, density & temperature are **changing** (decreasing) ⇨ what does this mean for equilibrium?

- Imagine a gas in a cylinder with a piston:

  - But if we pull it out ***quickly***, the gas will get **out of equilibrium**—no time to "adjust." There will be **gradients** that **dissipate**. Entropy **increases**; process is **irreversible**.

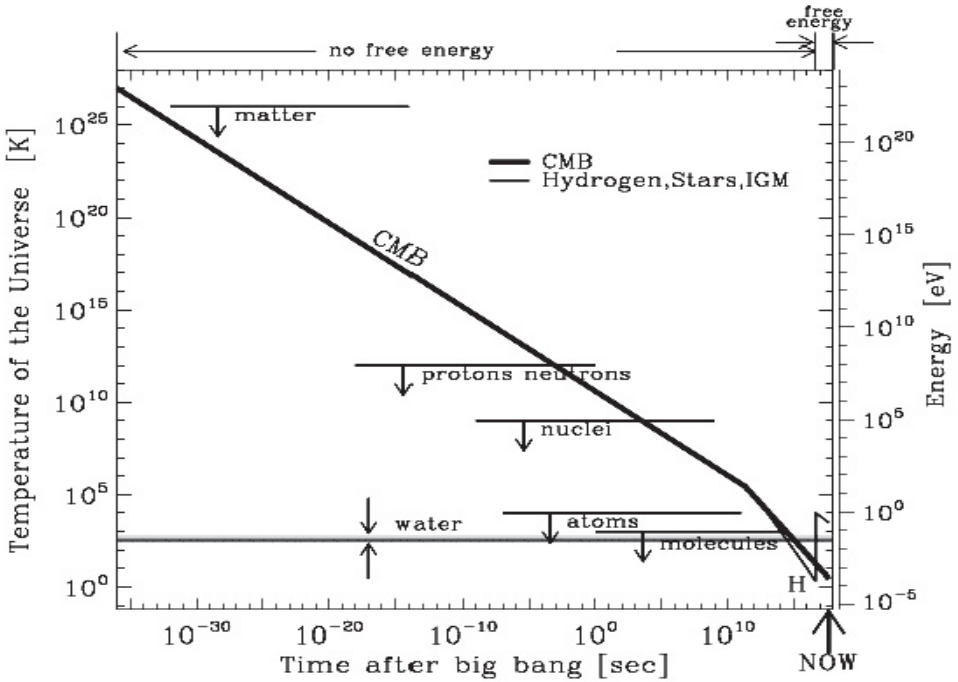
  - This was happening **later** in the early universe, during **nucleosynthesis**: if the universe **stayed** the same size and temperature during nucleosynthesis, then *all of the hydrogen would have had time to fuse into iron*. But the expansion was **too fast** for this (fusion too slow), and it only got *part way through* this fusion (to 25% He, leaving 75% H) before the temperature and density dropped too low to continue.

Role of Gravity—Expansion of Space:

- This had **profound consequences**:
    - It left the H & He gas **out of equilibrium**. By the Second Law, it would "love" to move toward equilibrium by fusing into iron, thereby generating "tons" of energy that would disperse as KE of particles and light, hugely increasing the entropy of the universe. But it couldn't. *Expansion made the conditions no longer right for fusion*.
    - The expansion of space increased the "ceiling" of maximum entropy. The universe left the H & He with a **huge potential** to generate energy and entropy, i.e., a huge amount of free energy. **This is the source of all of the free energy (of ordinary matter, at least) in the universe**. (We can trace this back one more step to "baryogenesis", when all the baryons annihilated with the antibaryons, flooding the universe with light, except there was a slight, mysterious, imbalance that left a few baryons after the annihilation…)

Role of Gravity—Expansion of Space:

- This had **profound consequences**:



There was **no free energy** in the universe until the universe was driven out of thermodynamic equilibrium by the expansion of space.

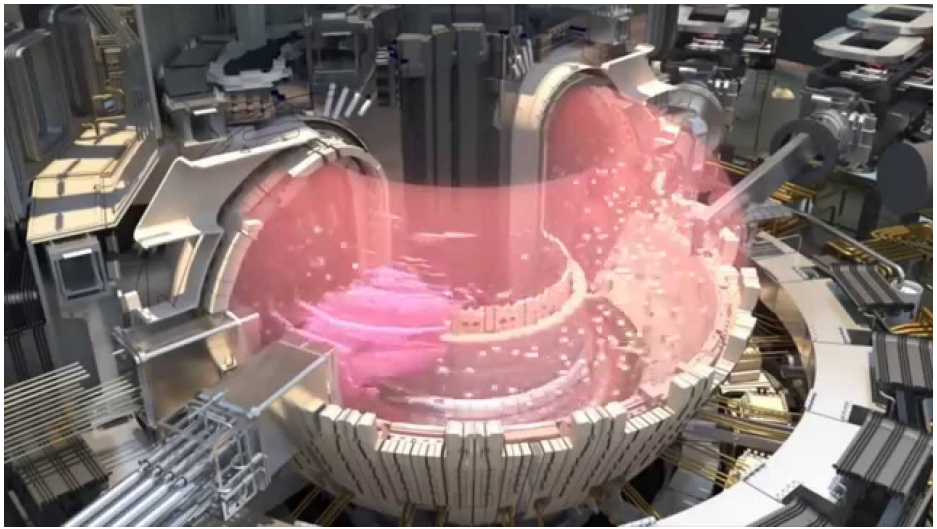
Figure from Lineweaver: Cosmobiology: Our Place in the Universe

Role of Gravity—Expansion of Space:

- This had **profound consequences**:
  - So H & He are the **oldest** and **most abundant** fossil fuels in the universe!
  - **Gravitational collapse** creates the right conditions in **stars** to release this energy via **fusion** (more shortly…). **This powers all phototrophic life** (and a whole lot more!).
  - If we could create the right conditions here on Earth in "**artificial stars**" (e.g., using magnetic fields instead of gravitational fields, or "inertial confinement"), it could **end the world's energy problem** forever, in one fell swoop (and related environmental & climate problems), and possibly propel the human race to a whole new level of "civilization" (interstellar space travel?).
  - Physicists are hard at work on this, see, e.g., ITER, NIF, etc.

Role of Gravity—Expansion of Space:

- This had **profound consequences**:
    - **ITER:** International Thermonuclear Experimental Reactor

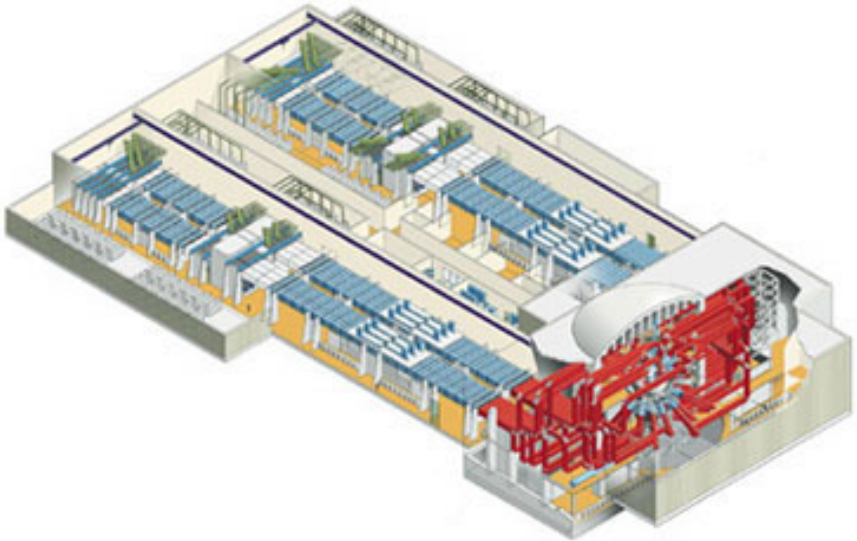


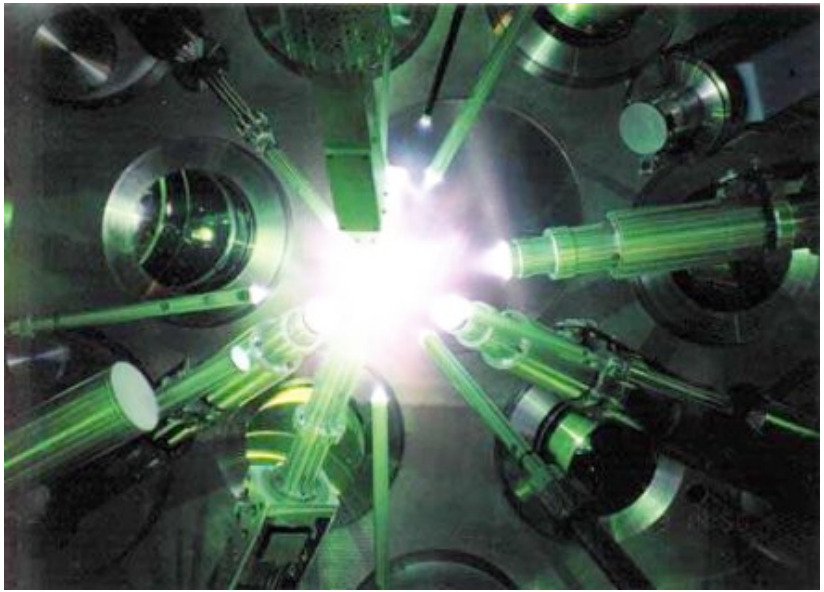
One of the largest science and engineering projects in human history…

There's a difference between **fusion** and **fission**…

Role of Gravity—Expansion of Space:

- This had **profound consequences**:
    - **NIF:** National Ignition Facility, Lawrence Livermore National Laboratory



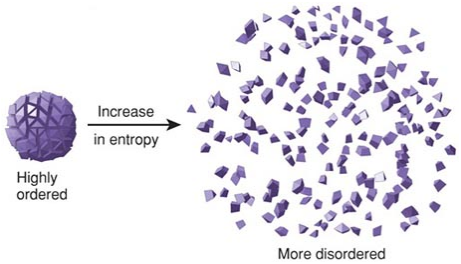


Role of Gravity—Expansion of Space:

- **Summary:**
  - **Expansion of space:**
    - **Initially:** Universe moves through a **sequence of instantaneous equilibrium states**. Universe in a state of **maximum, constant entropy; no free energy.**
    - **Nucleosynthesis:** Fusion **too slow** compared to expansion **to maintain equilibrium**. Universe pulled **out of equilibrium.** Expansion increases the "ceiling" of maximum entropy, allowing room for entropy to increase.
  - Expanding space is what **stopped hydrogen fusing to iron**, and allowed the universe to have **lots of free energy** that maintains life and other **low entropy structures**.
  - **Einstein's** theory of space, time, and gravity is a deep insight into the **ultimate nature of reality**. The ability for space to **expand**—be **dynamical** is crucial for the existence of life.

Role of Gravity—Gravitational Clumping:

- **Gravitational clumping** lowers entropy (locally), creating more ordered structures



- **Rough argument:**
  - Imagine a **cloud of gas particles** floating in space.
  - As the cloud **gravitationally collapses**, the particles **occupy less volume** ␣ **fewer** possible ways to arrange their positions (smaller number of microstates) ␣ **entropy decreases. More ordered**.
  - **But wait:** As the cloud collapses, gravitational PE ␣ KE. There is **more KE** to distribute amongst the particles ␣ **more** ways to do so (larger number of microstates) ␣ **entropy increases. Less ordered.**
  - Competing effects…**which wins**? Decreasing volume ␣ net **local lowering** of entropy

Role of Gravity—Gravitational Clumping:

- **Gravitational clumping** lowers entropy (locally), creating more ordered structures

Next 5 slides is a more detailed, mathematical argument, for those who are interested—won't be on test!

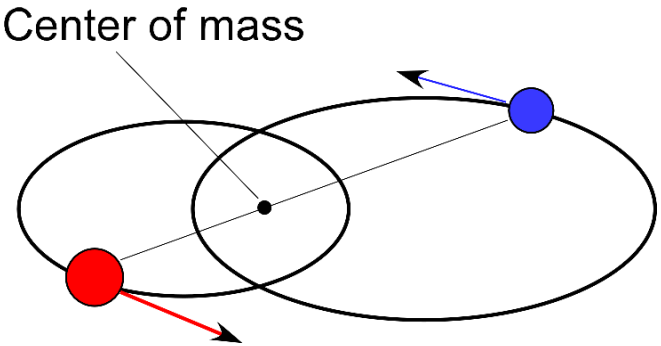
(For more details, see this article by John Baez: Can Gravity Decrease Entropy?)

Why Gravitational Clumping **Decreases** the *Local* Entropy

- But every **local** decrease in entropy requires a **compensating increase** in entropy **elsewhere**, so that the **total entropy** of the universe **increases** (or at least stays the same).

- *Where is this compensating increase in entropy happening?*

- In order for a gas cloud to collapse, it must **lose energy**. Why? Consider the two gravitationally bound particles in the diagram, orbiting about their common center of mass. When they are far apart, they are moving slowly (small KE, large PE). When they are close together, they are moving quickly (large KE, small PE). Even though KE and PE are **changing**, the **total** energy, E = KE + PE, is **constant** (total energy is **conserved**). *Unless the system loses energy, it cannot gravitationally collapse*.

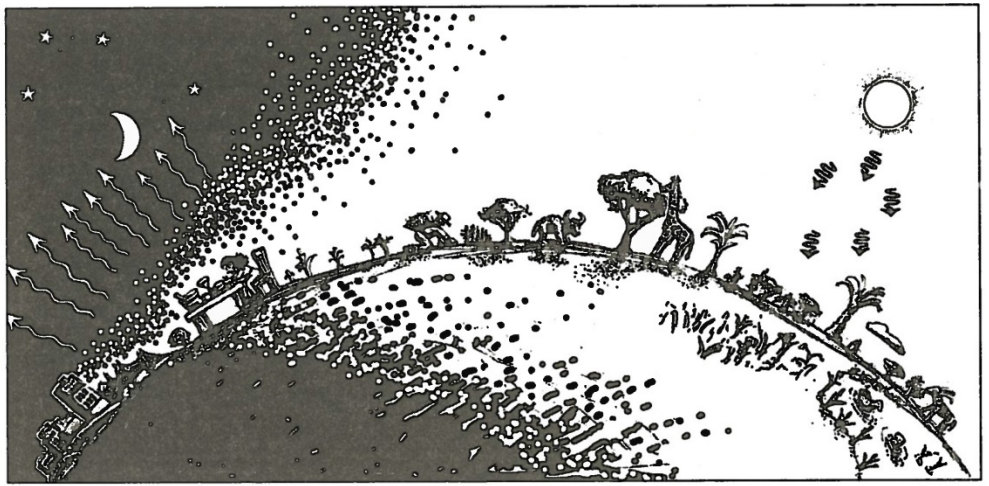


Why Gravitational Clumping **Decreases** the *Local* Entropy

- How does a gravitationally collapsing cloud of gas **lose energy**?

- Gravitational PE ⎵ KE ⎵ Thermal Energy (via collisions) ⎵ Thermal Radiation. The cloud heats up and glows, radiating thermal photons (plus gravitons) into the surrounding space.

- Like thermal photons radiated from Earth into space, allowing creation of all the low entropy (ordered) structures on the Earth (hurricanes, life, etc.), the thermal photons radiated by the cloud **increase** the entropy of the surrounding universe **more** than the entropy of the cloud decreased during gravitational collapse: **Net entropy <u>increase</u>, and <u>irreversible</u>!**



Why Gravitational Clumping **Decreases** the *Local* Entropy

- **Note:** *The way gravity binds particles together is peculiar*:
  - As the cloud gravitationally **collapses**, it **loses energy** by radiating thermal energy
  - Nevertheless, the core of the cloud still heats up (**gets hotter**) as it collapses
  - **The less energy it has, the hotter it gets**! This is **typical** of gravitational systems (e.g., black holes are like this—more later…), and the **opposite** of other systems (e.g., a regular box of gas particles gets **colder** when it loses energy).
  - This is yet another example of how gravity is profoundly different from the other "forces" in nature, and plays a key role in life.

Role of Gravity—Gravitational Clumping:

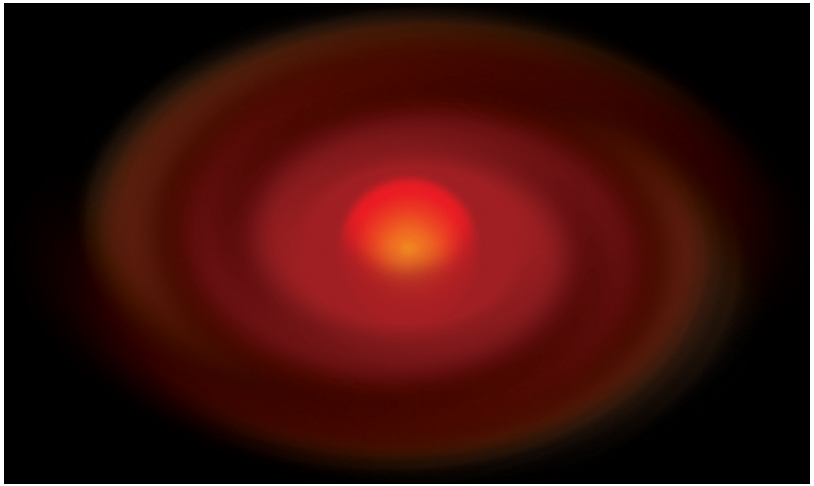
- **Gravitational clumping** lowers entropy (locally), creating more ordered structures

So what?

Role of Gravity—Gravitational Clumping:

- **Gravitational clumping** lowers entropy (locally), creating more ordered structures
    - Gravity clumps (first dark then) ordinary matter to form a star:

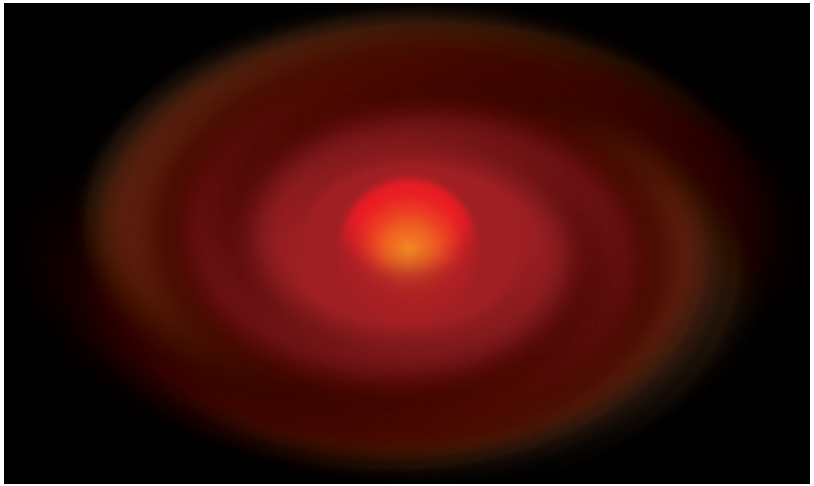
✓ Even though the clump is losing energy, it is heating up. It **heats up** enough to **spark thermonuclear fusion**, i.e., it recreates the early universe conditions of high temperature and density that allows the H & He gas to *continue on* with their fusion, thus **liberating free energy,** and **increasing the entropy** of the universe in the process



Role of Gravity—Gravitational Clumping:

- **Gravitational clumping** lowers entropy (locally), creating more ordered structures
    - Gravity clumps (first dark then) ordinary matter to form a star:

✓ Gravity thus acts as a **catalyst** to allow thermodynamically favourable nuclear reactions to occur **reasonably fast** (without it, fusion reactions would be so rare as to be virtually non-existent), exactly like a box of hydrogen and oxygen gas: the reaction $2H_2 + O_2 \not\rightarrow 2H_2O$ is thermodynamically favourable, but needs a spark to get it going. In this sense, gravity is the "**spark of life**" (like natural proton gradients…)



Role of Gravity—Gravitational Clumping:

- **Gravitational clumping** lowers entropy (locally), creating more ordered structures
    - Gravity clumps (first dark then) ordinary matter to form a star:

✓ This answers our earlier question of **why the Sun is a hot spot** (in an otherwise cold sky), i.e., a relatively **low entropy** (ordered) source of **free energy**.

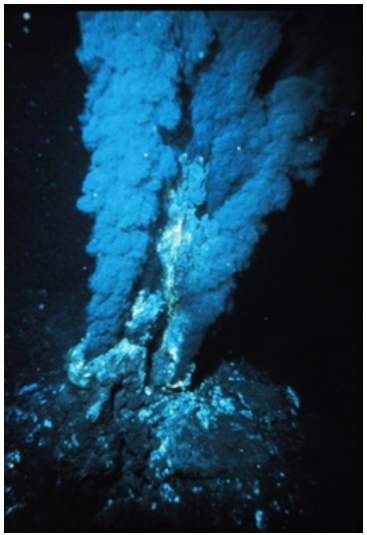
Role of Gravity—Gravitational Clumping:

- **Gravitational clumping** lowers entropy (locally), creating more ordered structures
    - Gravity clumps (first dark then) ordinary matter to form a star:
    - ✓ Or course, stars are also the source of **heavier elements**, like oxygen, without which we would have no H_2O, and so no life (at least as we know it).

Role of Gravity—Gravitational Clumping:

- **Gravitational clumping** lowers entropy (locally), creating more ordered structures
    - Gravity clumps (first dark then) ordinary matter to form a star:

✓ More generally, the energy that **heterotrophs** (like us) extract from **organic** compounds, or that **chemotrophs** extract from **inorganic** compounds, is essentially just electrons sinking deeper into electrostatic potential wells…**chemical disequilibrium**…

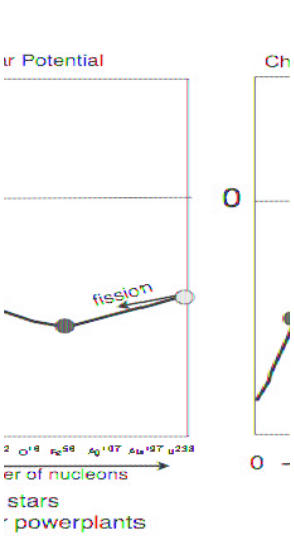


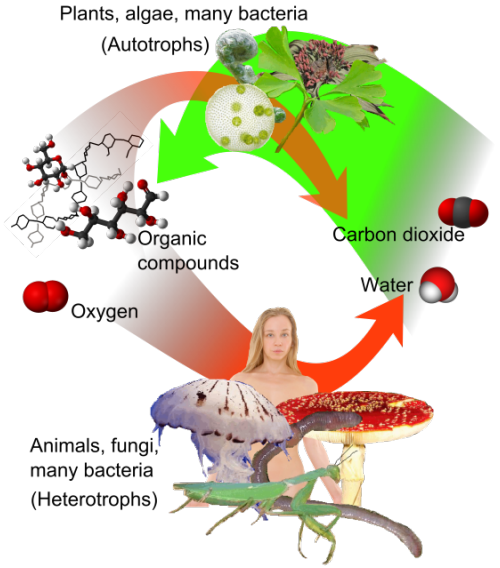
Role of Gravity—Gravitational Clumping:

- **Gravitational clumping** lowers entropy (locally), creating more ordered structures
  - Gravity clumps (first dark then) ordinary matter to form a star:

✓ …in every **redox reaction**, an electron starts out at a higher potential in the electron donor (e.g. sugar), and ends up at a lower potential in the electron acceptor (e.g. oxygen). **Stars give us *all* the elements**.

✓ And **phototrophs** use the **free energy in starlight** to raise the electrons back up to the top of the potential wells, so the **cycle can repeat**.





Role of Gravity—Gravitational Clumping:

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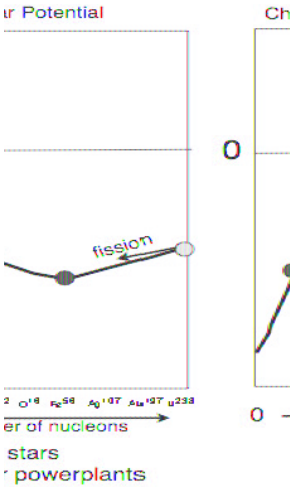
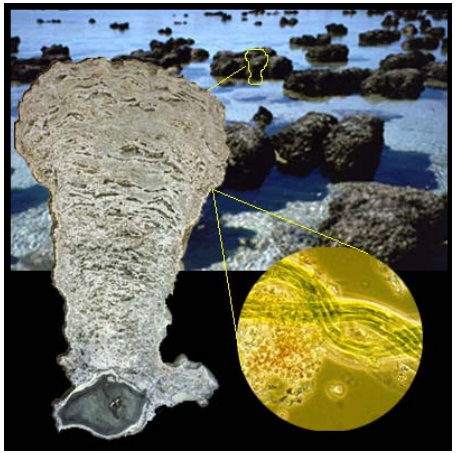


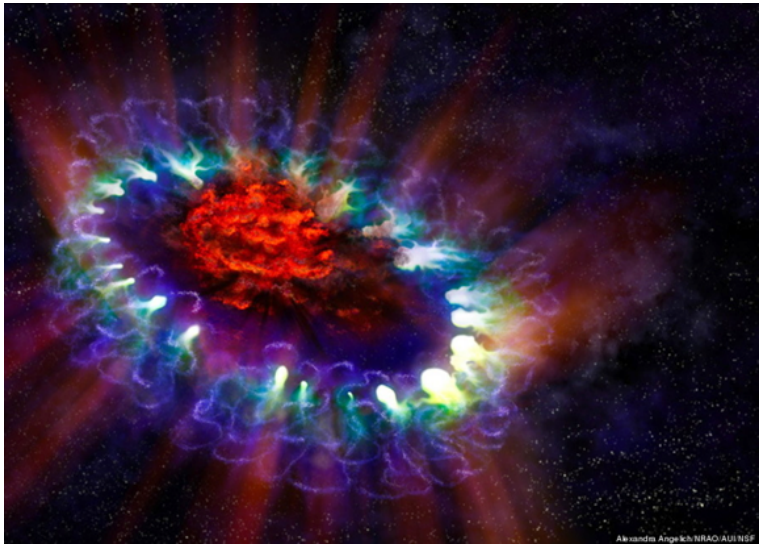


Role of Gravity—Gravitational Clumping:

- **Gravitational clumping** lowers entropy (locally), creating more ordered structures
    - Gravity clumps (first dark then) ordinary matter to form a star:

✓ If the star is large enough, it will explode as a supernova, creating **all of the elements heavier than iron**, e.g., uranium.

✓ We use radioactive elements like uranium as **fossil fuels** (fission); they also helped to keep the interior of the Earth warm and thus **geologically "alive,"** which is important for the **existence of life**.

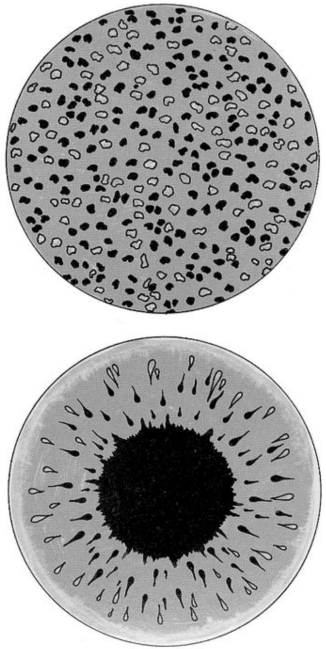


Role of Gravity—Gravitational Clumping:

- **Gravitational clumping** lowers entropy (locally), creating more ordered structures
    - Gravity also clumps matter in accretion disks to form **planets**

✓ Gravitational PE ⎵ KE ⎵ thermal energy, which provided the **primordial heat** of the Earth, making Earth **geologically alive** (**thermal disequilibrium**)

✓ The same gravitational clumping also makes planets **ordered structures** via **differentiation**: layers of heavier elements sinking to the bottom, and lighter elements rising to the top, etc…

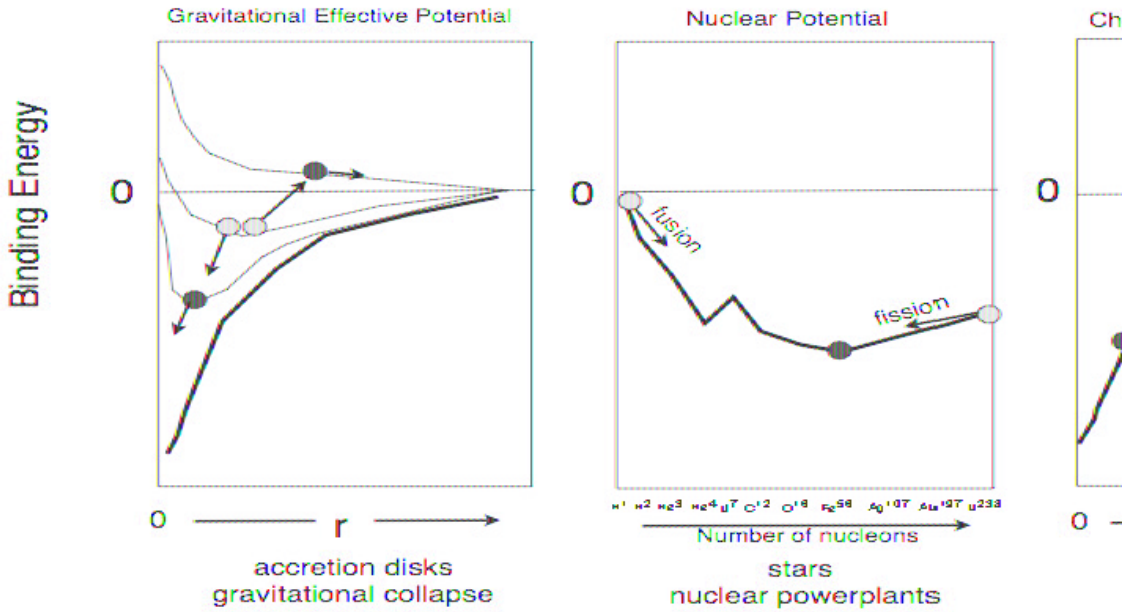


Role of Gravity—Gravitational Clumping:

- **Summary:**
    - **Gravitational clumping** generates gradients and structure, and is a *catalyst* that facilitates entropy-increasing processes essential for life, e.g., fusion in stars.
    - **Also:** Even though matter started in a **relatively high entropy** state, the (uniform) gravitational field was in a **very low entropy** state. Clumping **decreases** the entropy of matter (as structures form), at the expense of **increasing** the entropy of gravity.
    - There are many senses in which gravity—that still most mysterious of nature's "forces"—is essential to life in the universe…see next page for a diagram.

Role of Gravity—Gravitational Clumping:

- **Summary:**



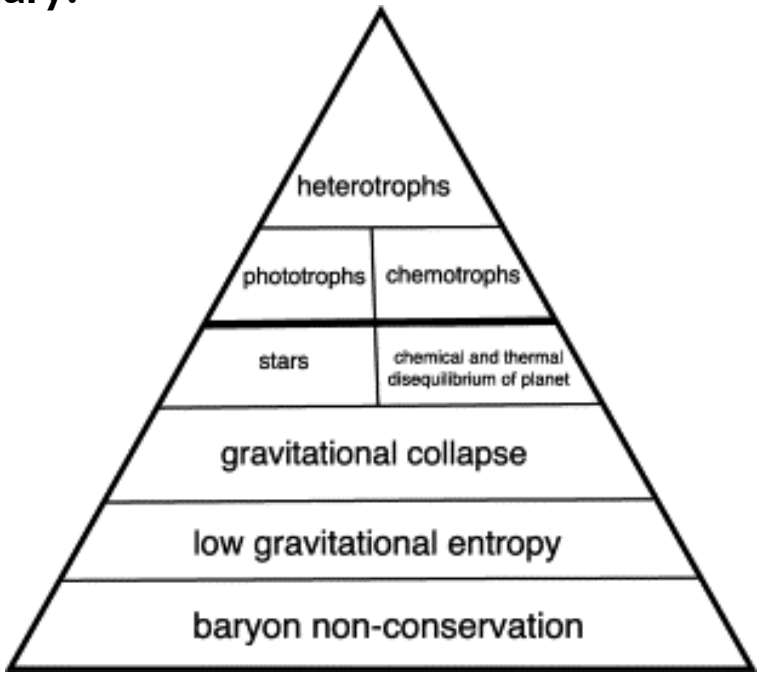
The three sources of free energy for life: **gravitational**, **nuclear**, and **chemical**.

But they are **not independent**: e.g., gravitational collapse enables fusion in the Sun, which in turn powers the chemistry of life on Earth.

Figure from Lineweaver: Cosmobiology: Our Place in the Universe

Role of Gravity—Gravitational Clumping:

- **Summary:**

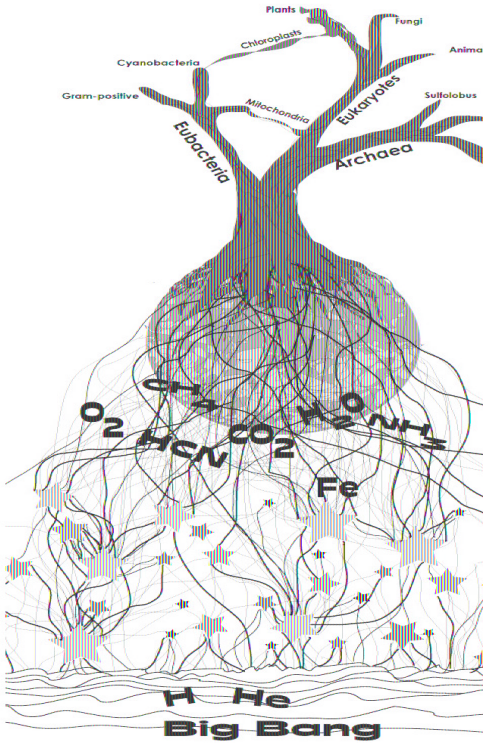


Tracing the free energy (that heterotrophs like us need to live) all the way back to the mysterious baryon non-conservation (**slight imbalance of matter and antimatter**) in the very early universe.

Figure from Lineweaver: Life, gravity and the second law of thermodynamics.

Role of Gravity—Gravitational Clumping:

- **Summary:**



The tree of life has *roots* all the way back to the Big Bang. We really are *deeply rooted* in the cosmos!

Figure from Lineweaver: Cosmobiology: Our Place in the Universe

Role of Gravity—Black Holes:

- **Black holes** contain most of the entropy in the universe today.

$$S_{BH} = \frac{kA}{4\ell_{\mathrm{P}}^2}$$

  - **Black holes** are a most extreme consequence of Einstein's theory of space, time, and gravity.
  - According to Bekenstein & Hawking, SMBHs have **very large entropy**.
  - Although they represent only a **tiny fraction of the total energy** in the observable universe, they (*seem to*) represent the **vast majority of its entropy**. **WHY?**

objects	entropy	energy
10^{22} stars	10^{79}	$\Omega_{\mathrm{stars}} \sim 10^{-3}$
relic neutrinos	10^{88}	$\Omega_{\nu} \sim 10^{-5}$
stellar heated dust	10^{86}	$\Omega_{\mathrm{dust}} \sim 10^{-3}$
CMB photons	10^{88}	$\Omega_{\mathrm{CMB}} \sim 10^{-5}$
relic gravitons	10^{86}	$\Omega_{\mathrm{grav}} \sim 10^{-6}$
stellar BHs	10^{97}	$\Omega_{\mathrm{SBH}} \sim 10^{-5}$
single supermassive BH	10^{91}	$10^{7} M_{\odot}$
$10^{11} \times 10^{7} M_{\odot}$ SMBH	10^{102}	$\Omega_{\mathrm{SMBH}} \sim 10^{-5}$
holographic upper bound	10^{123}	$\Omega = 1$

Role of Gravity—Black Holes:

- **Black holes** contain most of the entropy in the universe today.

$$S_{BH} = \frac{kA}{4\ell_{\mathrm{P}}^2}$$

  - **Recall:** When a cloud of gas **gravitationally collapses** to form a star, it **heats up**, and its entropy **decreases**.
  - However, when this star **gravitationally collapses** to form a black hole, the BH is **much colder**, and its entropy is some *30 orders of magnitude* **larger**, than that of the star from whence it came.
  - This is still **mysterious**!

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stellar BHs	10^{97}	$\Omega_{\mathrm{SBH}} \sim 10^{-5}$
single supermassive BH	10^{91}	$10^{7} M_{\odot}$
$10^{11} \times 10^{7} M_{\odot}$ SMBH	10^{102}	$\Omega_{\mathrm{SMBH}} \sim 10^{-5}$
holographic upper bound	10^{123}	$\Omega = 1$

Role of Gravity—Black Holes:

- **Black holes** contain most of the entropy in the universe today

$$S_{BH} = \frac{kA}{4\ell_{\rm P}^2}$$

  - In the third and final part of the course—**Everything**, we will discuss where the Bekenstein-Hawking formula for **BH entropy** comes from, and the related **holographic principle** mentioned in the last row of the table.

  - This will take us *very* deep into the "**ultimate nature of reality**"! It will require a bit of **special relativity**, **general relativity**, and **quantum mechanics**, and should be lots of fun!

objects	entropy	energy
10^{22} stars	10^{79}	$\Omega_{\rm stars} \sim 10^{-3}$
relic neutrinos	10^{88}	$\Omega_{\nu} \sim 10^{-5}$
stellar heated dust	10^{86}	$\Omega_{\rm dust} \sim 10^{-3}$
CMB photons	10^{88}	$\Omega_{\rm CMB} \sim 10^{-5}$
relic gravitons	10^{86}	$\Omega_{\rm grav} \sim 10^{-6}$
stellar BHs	10^{97}	$\Omega_{\rm SBH} \sim 10^{-5}$
single supermassive BH	10^{91}	$10^{7} M_{\odot}$
$10^{11} \times 10^{7} M_{\odot}$ SMBH	10^{102}	$\Omega_{\rm SMBH} \sim 10^{-5}$
holographic upper bound	10^{123}	$\Omega = 1$

Summary

- Life is a **physical phenomenon**: subject to the laws of physics.

- It is remarkable how the **nature of life** is echoed in the **nature of the universe**, in particular with regards to the *Second Law of thermodynamics*, and how its roots extend all the way back to the Big Bang.

- The universe basically started out **hot and dense**, and as space **expanded "stuff" cooled**, and **structures condensed out**. Life is one of the most remarkable structures to have condensed out!

- As we probe the "ultimate nature of reality" more deeply in the next part of the course, keep in mind this "human connection," and how the **mysteries of the cosmos** are intimately connected with the **mysteries of life**.