Two Profound Properties of the CMB

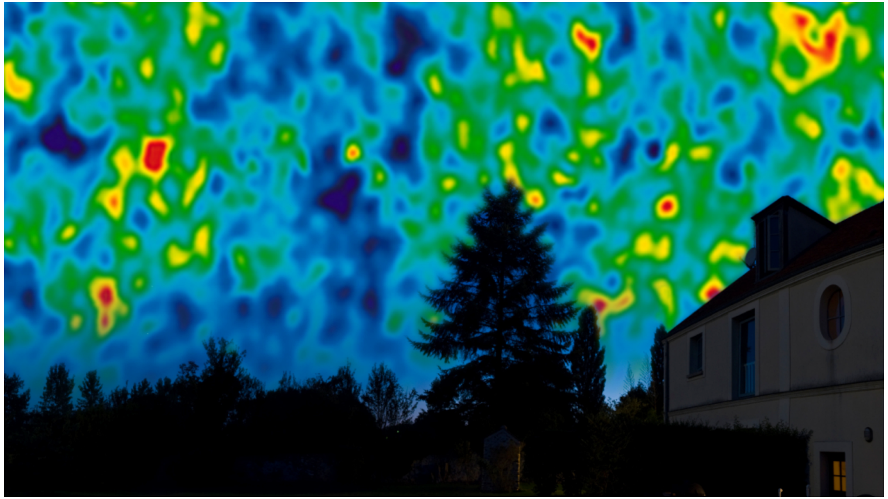
Let's return to the CMB, and try to unravel its profound implications for our ultimate origin

Two Profound Properties of the CMB

- While the CMB provides **strong evidence** for a **hot, dense beginning** (afterglow of the BB) it raises two **deep mysteries**, which provide **profound clues** to our **ultimate origin**:
    - Why is the temperature of the CMB **almost perfectly uniform**?
    - Why is it **not** perfectly uniform? What is the origin of the **tiny temperature fluctuations**?

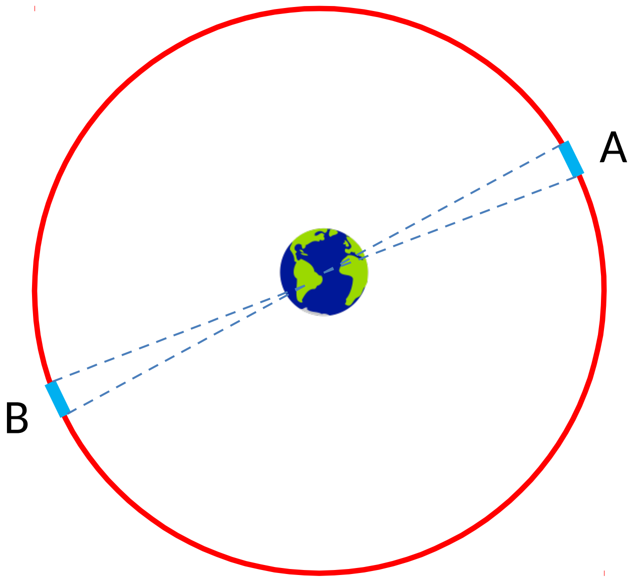
Average temperature $= 2.7260 \pm 0.0013$ K

Temperature **fluctuations** ≈ 1 part in $100{,}000$



Two Profound Properties of the CMB

- Why is the temperature of the CMB **almost perfectly uniform**?
    - By exactly the **same rough argument** we gave before, the angular size of the "blobs" (regions that have the same temperature) should be about **1° on the sky**.



Shown are two blobs of gas, A & B, seen in opposite directions on the sky (light coming from long ago, far away). In the 380,000 years since the BB, the gas in each blob (**separately**) would have had time to **thermalize** (come to the same temp), say: T_A & T_B.

In principle, however, T_A & T_B could be **very different** temperatures. But in fact, they differ by only **1 part in 100,000**. We need to explain this! This is called the **horizon problem**.

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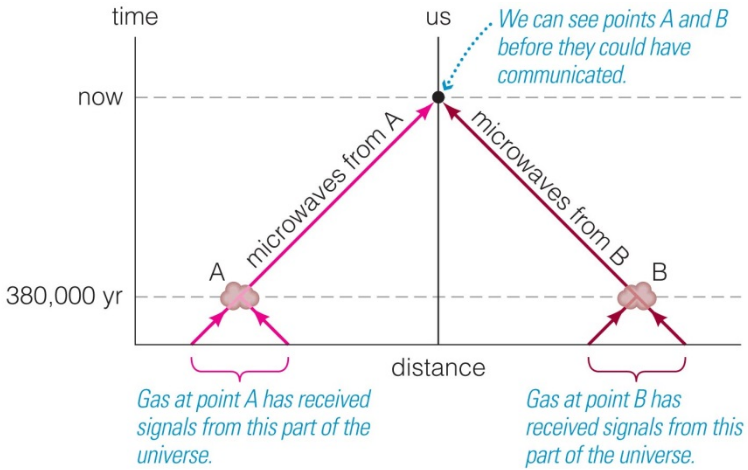

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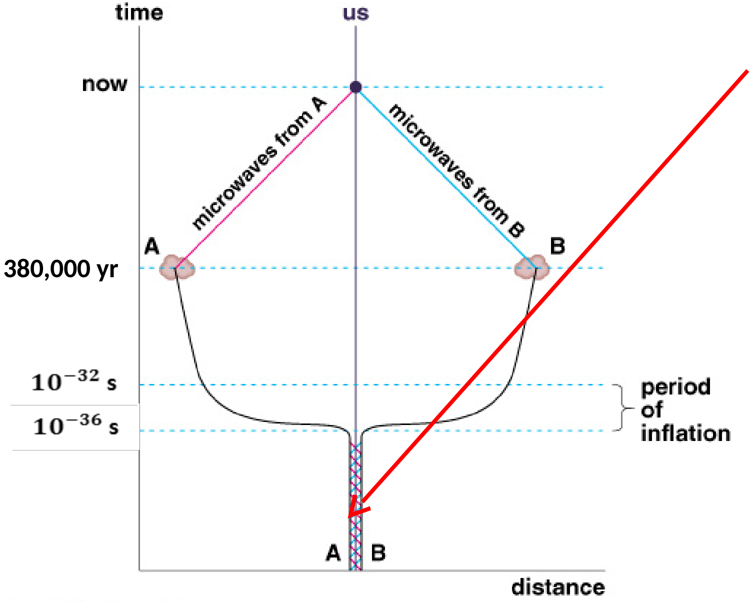
Two Profound Properties of the CMB

- Why is the temperature of the CMB **almost perfectly uniform**?
  - Current widely adopted hypothesis: **Cosmic Inflation** (Alan Guth, 1980)



In the early universe ($t < 10^{-36}$ seconds), the space in the current observable universe was **very tiny**, **much smaller** than the nucleus of an atom.

Although 10^{-36} seconds is a **very small time**, this region was **so tiny** that any "stuff" in it, that would eventually give rise to all the matter and radiation in the observable universe today, had **plenty of time to thermalize**. It was in **perfect thermal equilibrium**.

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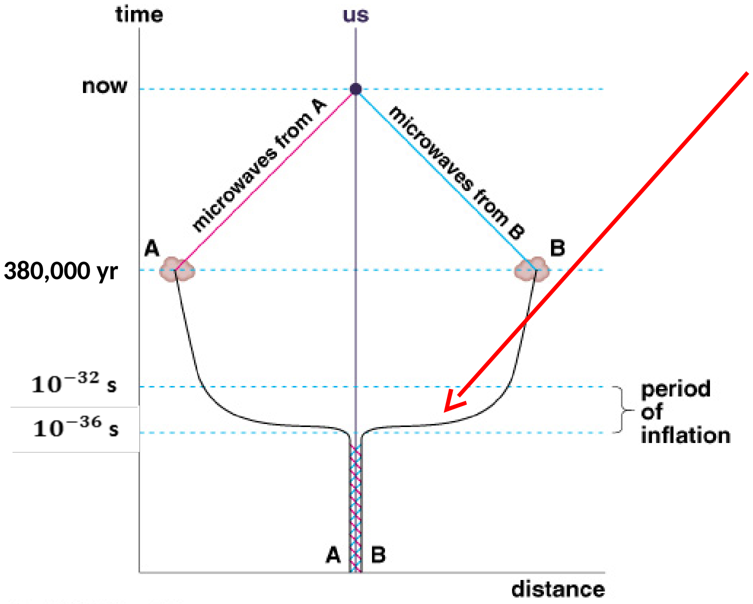

Then came a very short period of **extremely** rapid accelerated expansion, called **inflation**.

In roughly seconds, space expanded in size by an **enormous factor** (e.g., to pick a number), to something, say, the size of a marble.

How? E.g., just simple Einstein/Friedmann: , where is value of the cosmological "constant" during this inflationary period.

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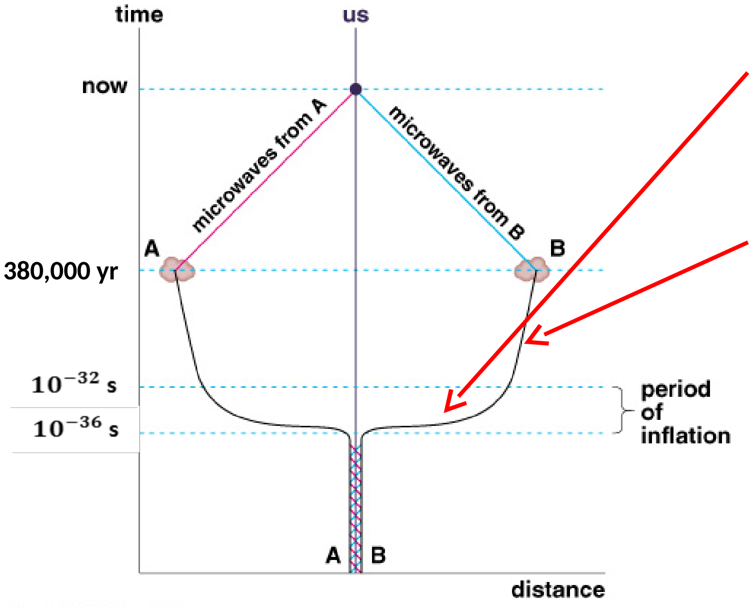

would have been **huge**, corresponding to an **extremely high** vacuum energy density.

Then inflation (somehow) “turned off”, and the universe continued to expand normally, with the present-day, very much smaller, cosmological constant.

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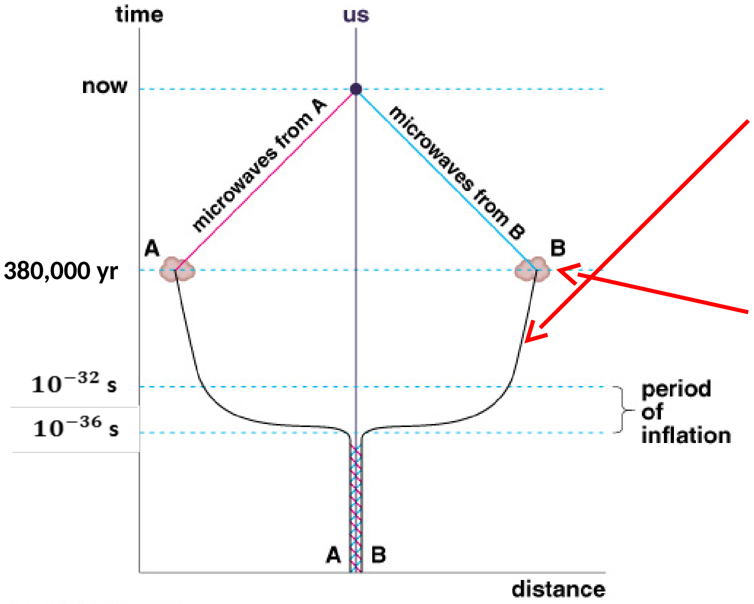

So what? All of the "stuff" in the normally-expanding "marble of space" would have been in <u>perfect thermal equilibrium</u>.

When the marble had expanded to the size of the observable universe at 380,000 years (1100 times smaller than it is today), all of the hot gas in it would have been in **perfect thermal equilibrium**: $T_A = T_B$.

The CMB would have been **<u>perfectly uniform</u>**.

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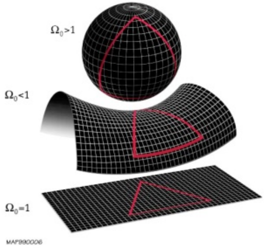

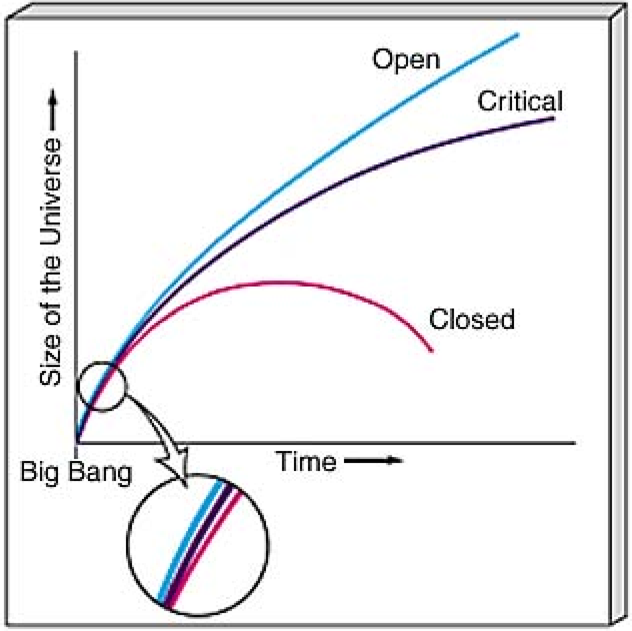

Aside: Inflation also solves the **flatness problem**:

CMB observations tell us that space (on the cosmic scale) is **almost perfectly flat** (critical density ≈ 1)

Problem: A universe that starts off close to, but not exactly on, the critical curve soon deviates greatly from it, so if the universe is **close to critical now**, it must have been **extremely close to critical** in the past.

This is a **severe** "fine-tuning" problem!

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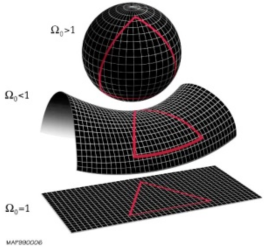

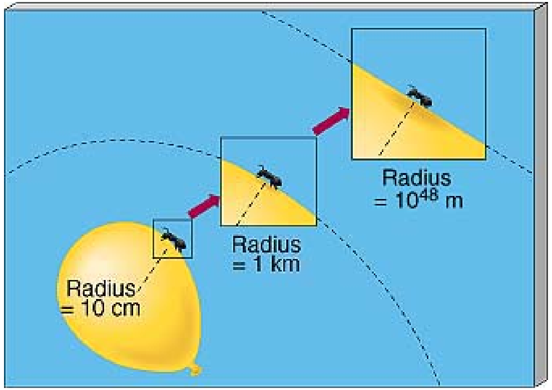

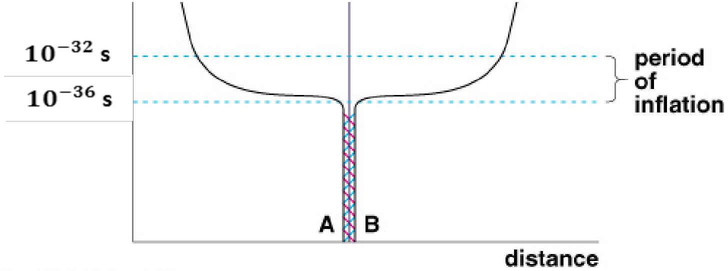

Aside: Inflation also solves the **flatness problem**:

Before inflation started, space could have had **any random curvature**.

But inflation allows the entire observable universe to come from a **extremely tiny patch** of that space, which is **extremely** flat.

…flat enough that even after cosmic time, space is still almost perfectly flat. Problem solved!

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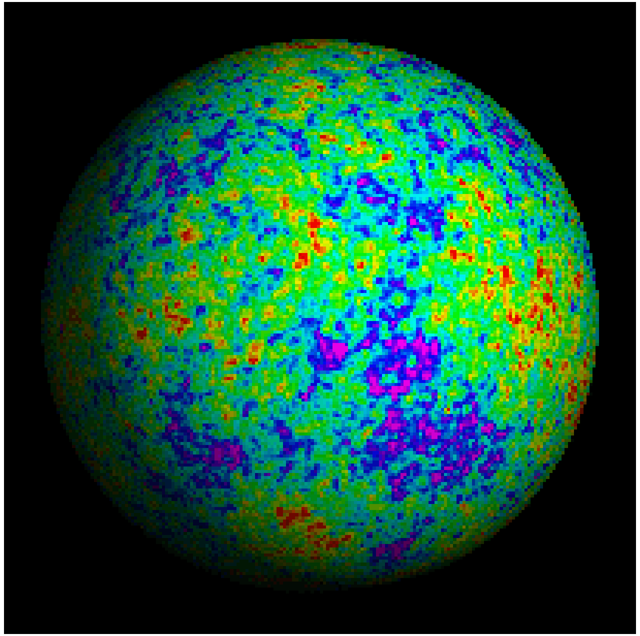

Back to the CMB:

We discussed how inflation would have made the CMB **perfectly uniform**. Virtually **zero** fluctuations in temperature. All of the hot gas at time 380,000 years would have been in **perfect thermal equilibrium**.

Problem: **Perfectly** uniform is not what we see. We see only **almost** perfectly uniform. Fluctuations of 1 part in 100,000.

Two Profound Properties of the CMB

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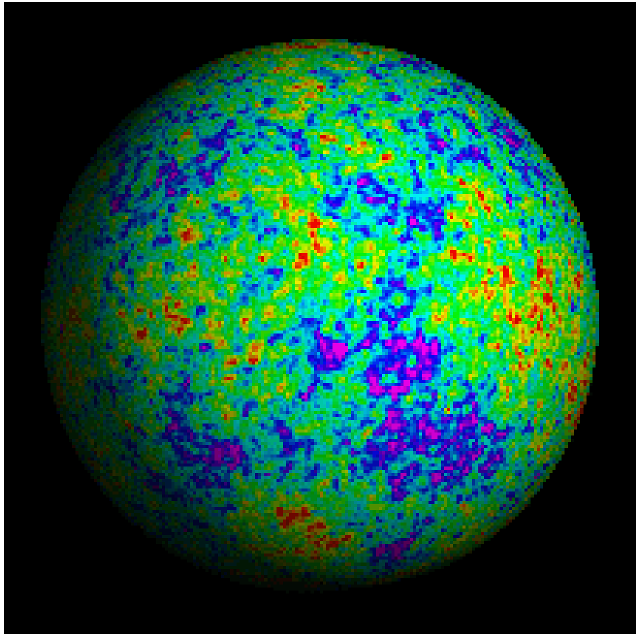

This leads to the **second** profound property of the CMB: Why is it **not** perfectly uniform? What is the origin of the **tiny temperature fluctuations**?

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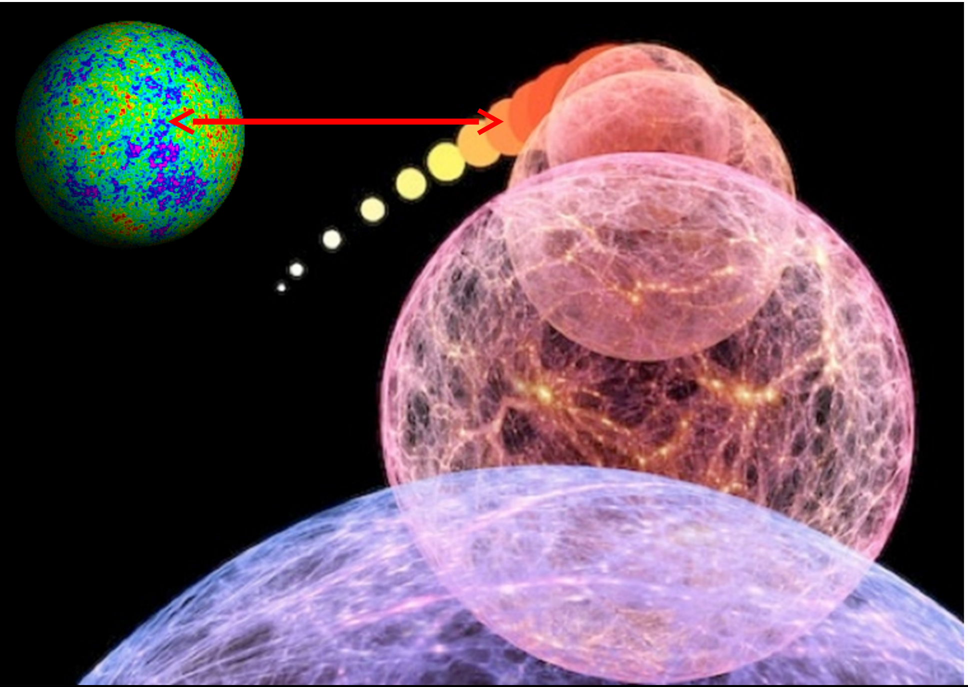

Why do we care? It is precisely these **tiny** temperature (and density) fluctuations in the hot gas in the universe at time 380,000 years that were the **"seeds" of gravitational clumping** that gave rise to all of the structure in the present universe: stars, galaxies, clusters of galaxies…**and us**.

Without these fluctuations, all of the matter (ordinary and dark) would have just expanded uniformly as space expanded. NO STRUCTURE would have formed **no life**.

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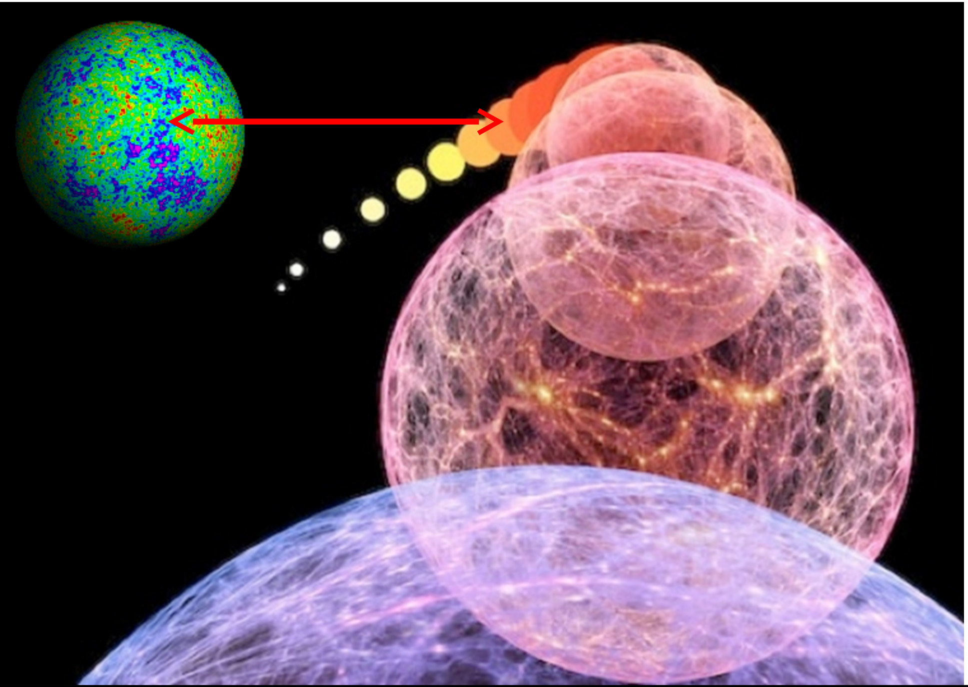

So explaining the origin of these tiny (1 part in a 100,000) fluctuations is also answering the question "**Where do we come from**", at a very deep and profound level…

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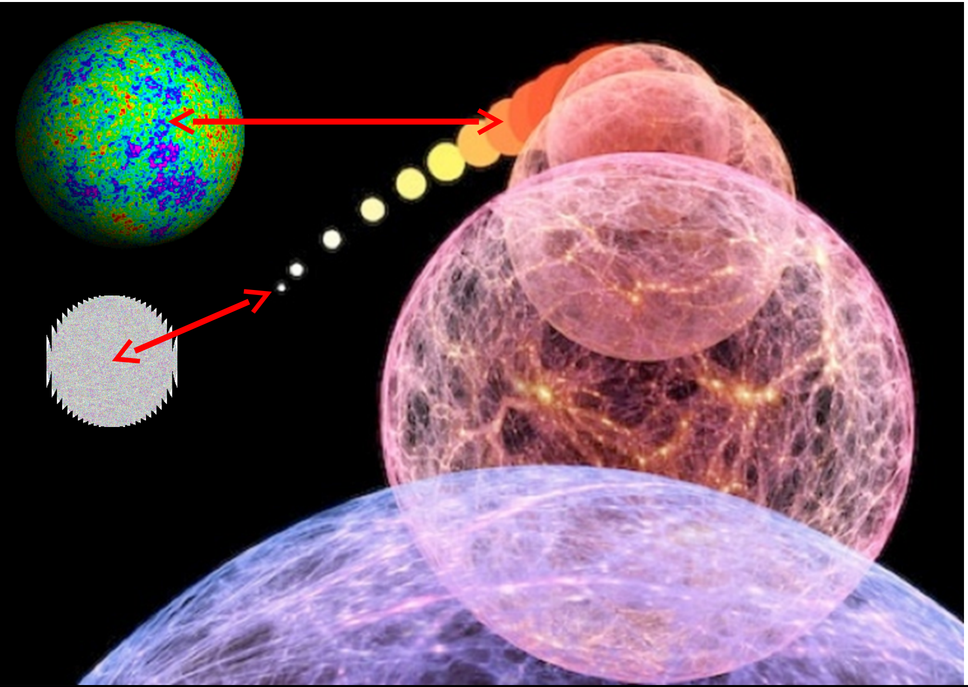

Basic Idea:

Before inflation, the bit of space that would eventually expand into our observable universe was **very tiny**, say 10^{-43} m across.

On this tiny scale, the vacuum would have been filled with **quantum fluctuations**: incessant spontaneous creation and annihilation of virtual particle-antiparticle pairs.

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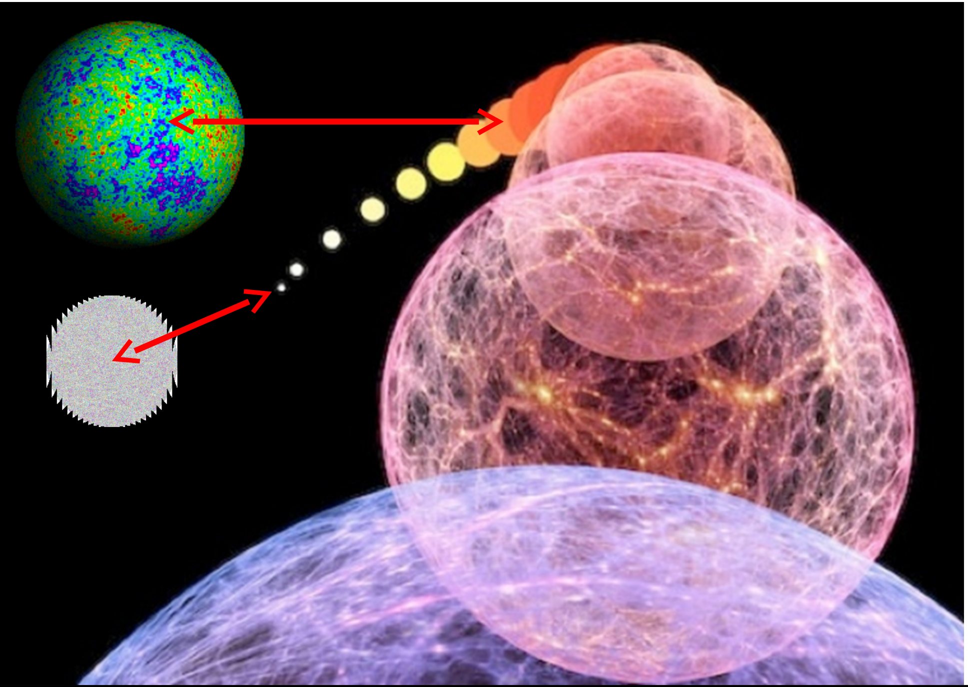

Basic Idea:

Normally, quantum fluctuations are **submicroscopic**. But inflation theory predicts that the **extremely rapid expansion** of space from some 10^{-43} m across to about the size of a marble would have similarly expanded these **submicroscopic** quantum fluctuations to **macroscopic** size, much like expanding space stretches the wavelength of a photon.

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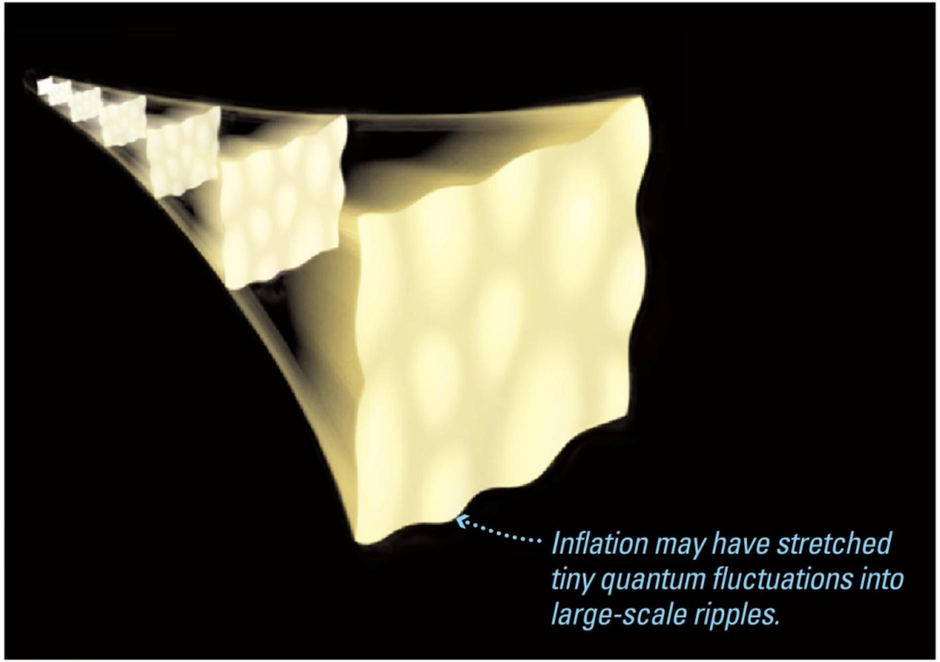

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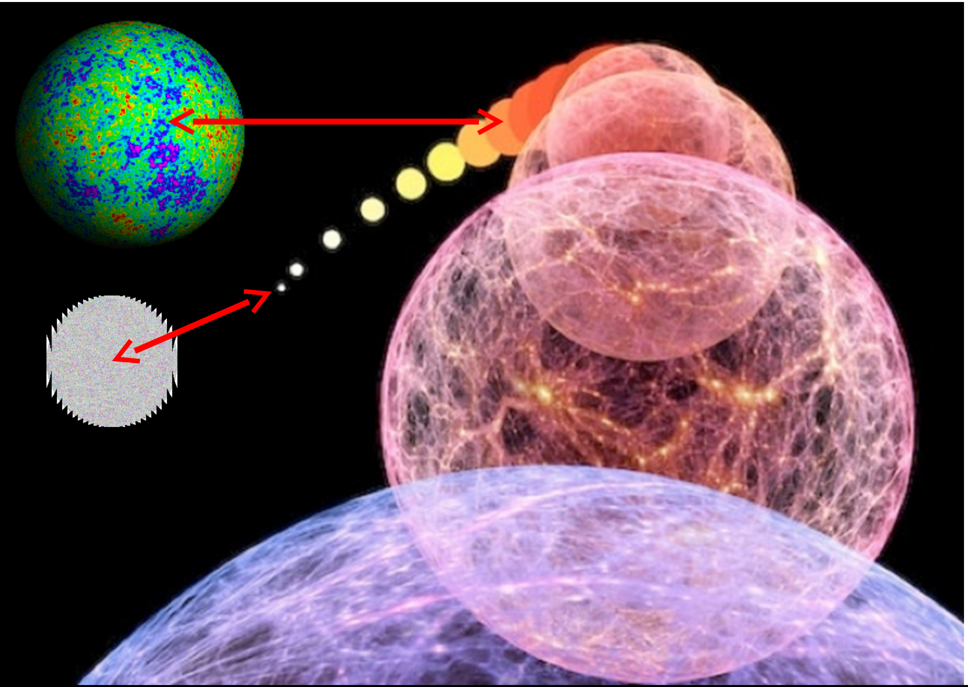

Basic Idea:

By the end of inflation, the **expanded quantum fluctuations** would have left an **imprint** on the **density and temperature fluctuations** in the stuff in the **marble-sized** observable universe.

Over the next 380,000 years, these density and temperature fluctuations **continued to expand** in size, until they became the **cosmic sized fluctuations** we observe in the CMB.

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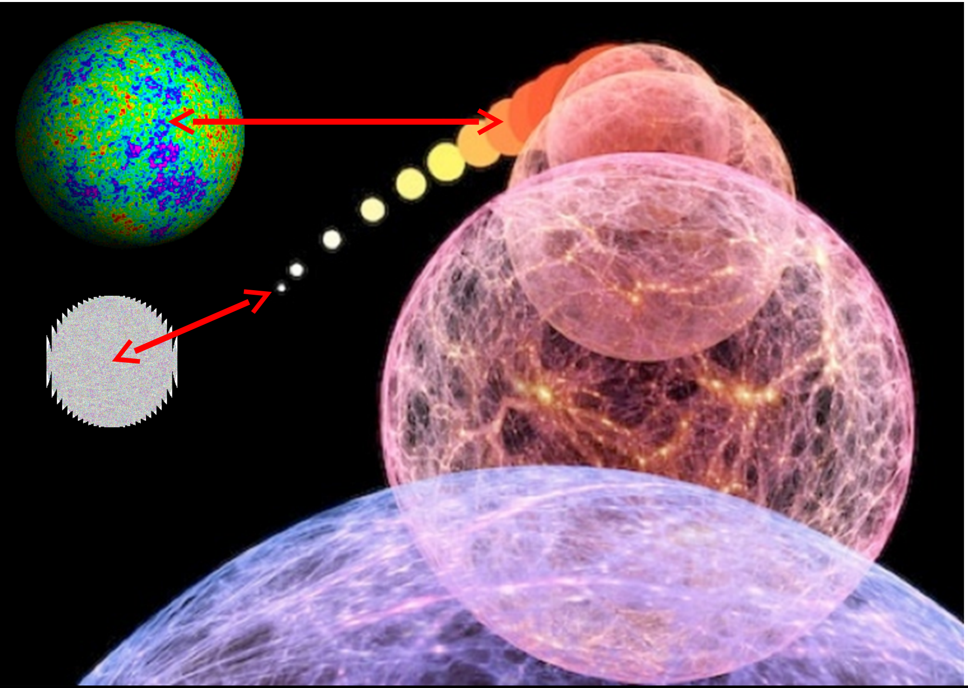

Basic Idea:

These then became the **“seeds” of gravitational clumping** that gave rise to all of the structure in the present universe: stars, galaxies, clusters of galaxies…**and us**.

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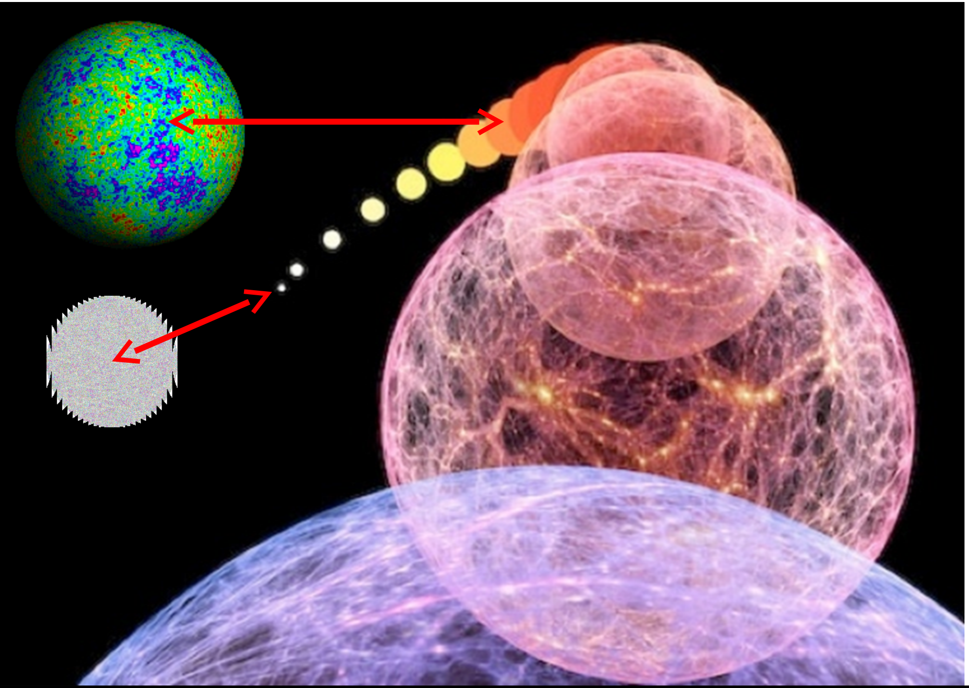

Basic Idea:

…and these seeds were of **just the right amplitude**: if the fluctuations were even just **half** the amplitude, they would have been too weak for galaxies and clusters to form.

…and these seeds were of **just the right type: same** amplitude across **different** sizes. E.g., bigger amplitude at smaller sizes ▭ lots of black holes; at larger sizes ▭ huge aggregates of matter pulling everything in

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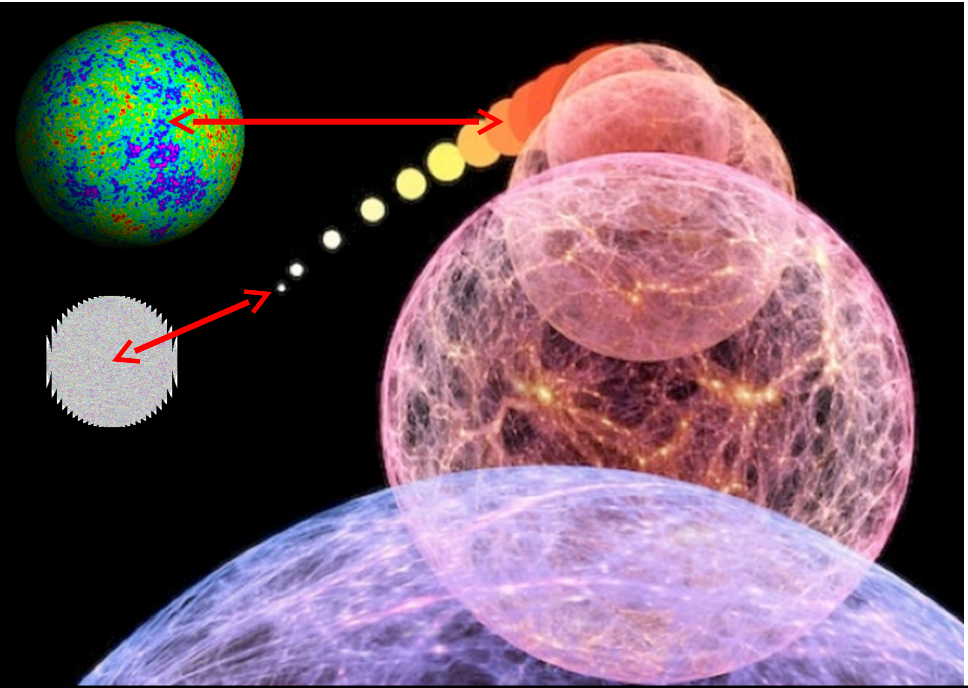


Basic Idea:

Notwithstanding many deep questions that remain, in broad brush strokes, **inflation + quantum** can actually **explain** all this!

Right or not, we are actually coming up with **plausible "origins stories"**, like RNA World, but now all the way back at 10^{-32} seconds after the Big Bang!

Two Profound Properties of the CMB

So what?

Two Profound Properties of the CMB

Old story: We are stardust…

New story: We are quantum fluctuations…

All of the structure in the universe today originated in **quantum fluctuations** that existed a tiny fraction of a second after the Big Bang in a region of space much smaller than an atomic nucleus.

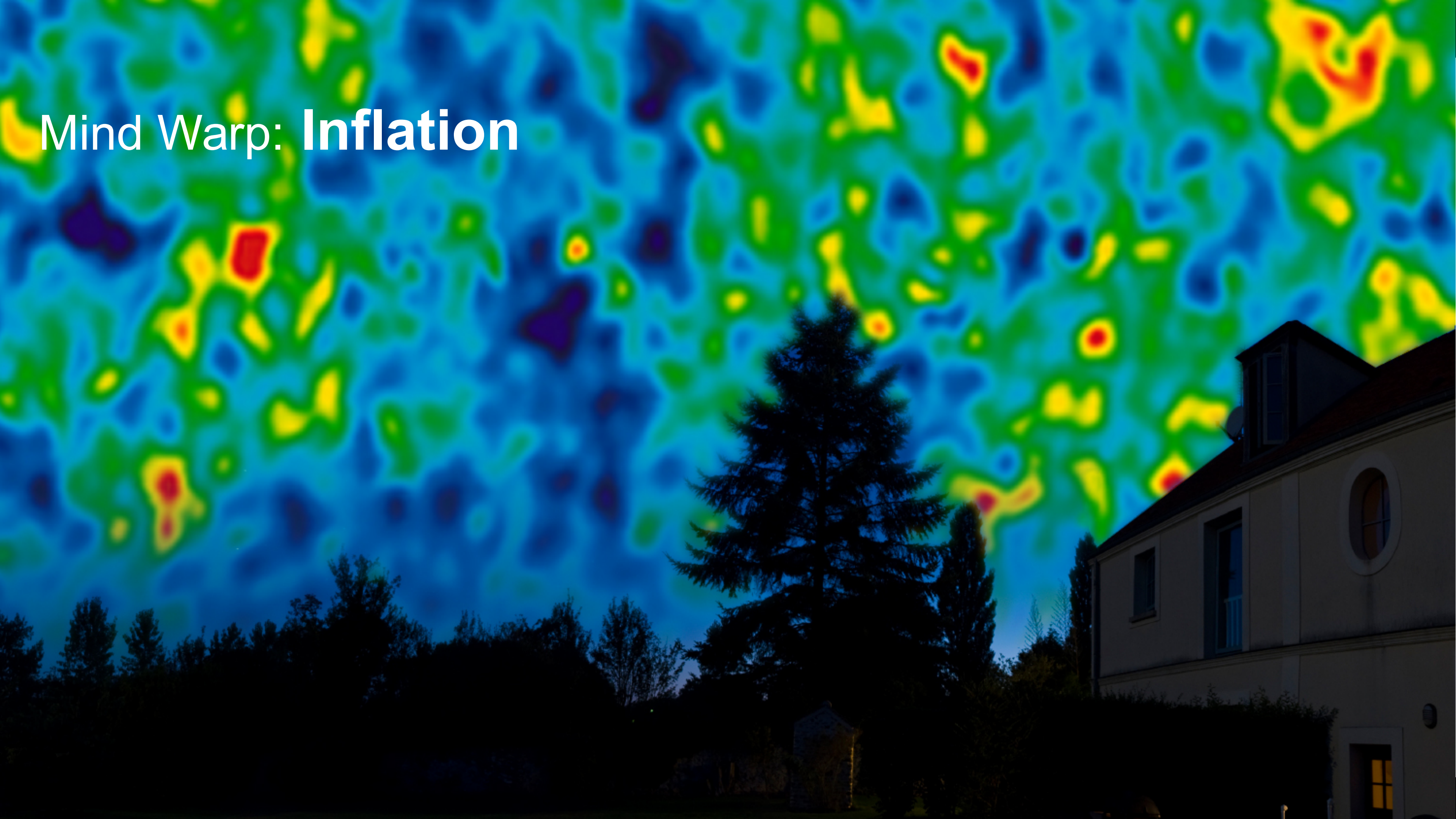
During **inflation**, these **microscopic** quantum fluctuations were almost instantly expanded to **macroscopic** size, which we can now see **imprinted on the Cosmic Microwave Background**.

If these 1:100,000 density fluctuations weren't there (or were even just a bit smaller, say less than half the size), the matter (dark and ordinary) would have **diluted *before gravitationally clumping***: no stars, no galaxies, **no life**.

The **quantum nature of the universe [and Einstein's gravity]** is **paramount to our existence**.

Our quantum origins are **written in the sky**!

Mind Warp: **Inflation**



Let’s go even deeper…

Origins

- One of the deepest questions of all is: **Why is there something rather than nothing?**

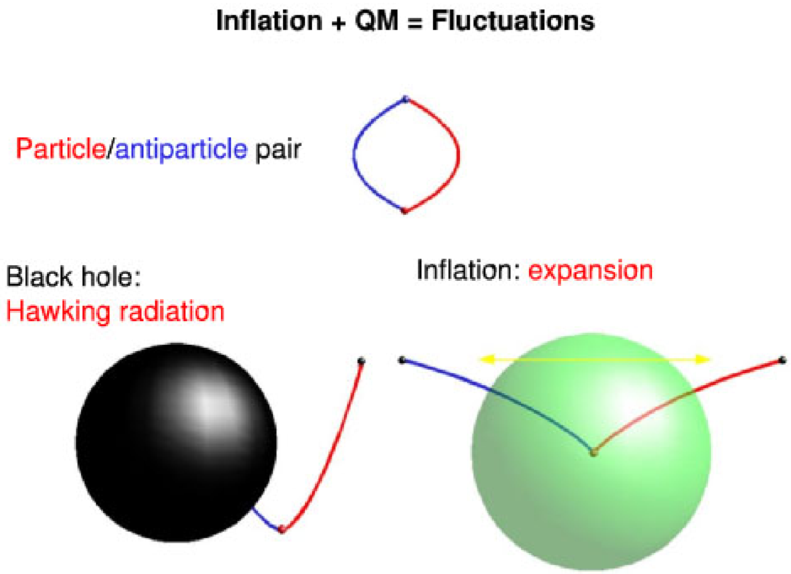
- Of course, **no one knows**, but here are two intriguing ideas to contemplate:

    - QUANTUM: **Spontaneous creation and annihilation**.

    - GRAVITY: **Space itself is dynamical, and gravitational energy is negative**

- Let's try to put these together…

- One of the deepest questions of all is: **Why is there something rather than nothing?**



Spontaneous creation & annihilation:

Normally, **virtual** particles spontaneously appear and disappear too fast to become **real** particles.

But near a **black hole** (Einstein gravity), one can fall into the BH so that the other cannot "find" it to annihilate with, and so becomes a **real** particle.

Similarly, during **inflation** (also Einstein gravity), the pair is quickly separated and cannot "find" each other to annihilate with, so **both** become **real** particles.

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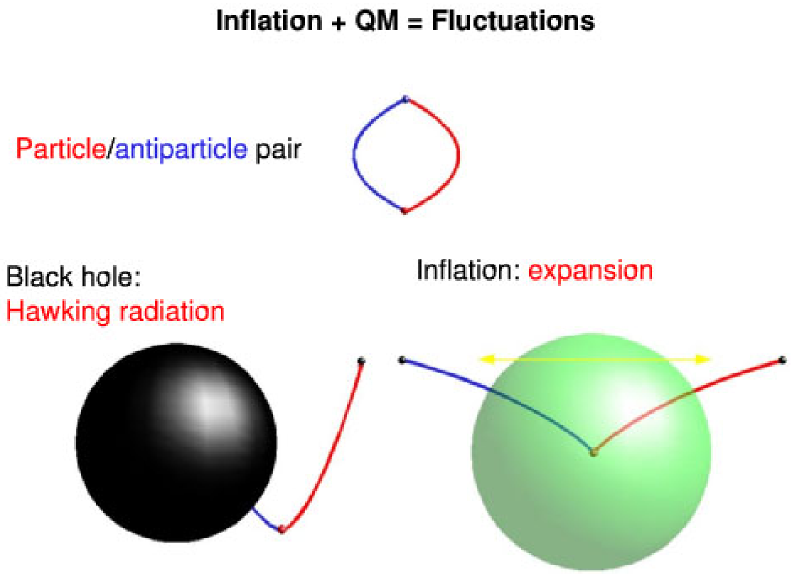

It *appears* as if we are "**getting something from nothing**"

But **not really**:

In the **BH case**, the BH loses the same amount of energy as the created real particle has.

In the **inflation case**, we need some kind of energy to drive inflation; ***where does that come from***?

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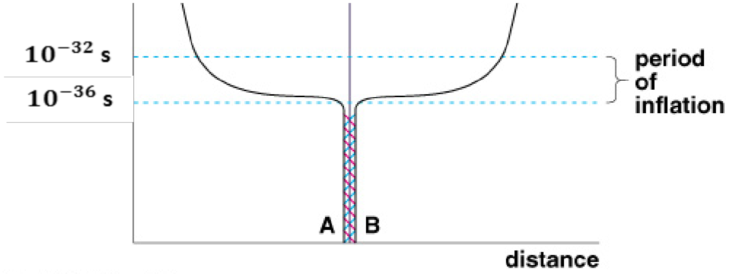

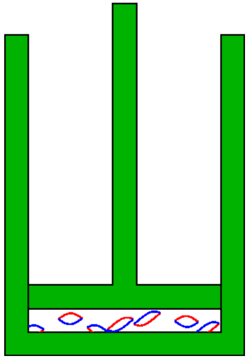

Recall: Inflation requires a very large cosmological constant, or equivalently, a **very high vacuum energy density** (energy per unit volume). [Technically: "inflaton field" potential energy density.]

But the volume of the space when inflation begins, that will eventually become the observable universe, is **exceedingly tiny** (<< atomic nucleus).

(Large energy per unit volume) x (Exceedingly tiny volume) can be a **relatively small** amount of total energy, e.g., the energy equivalent of a 1 g mass.

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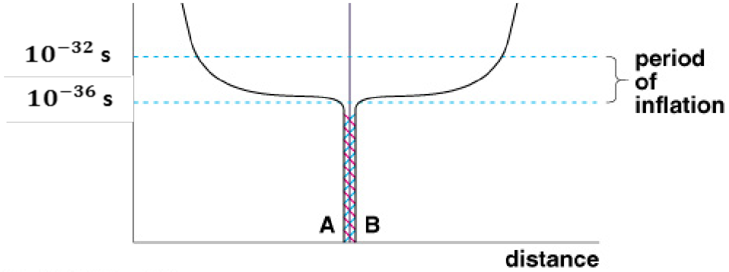

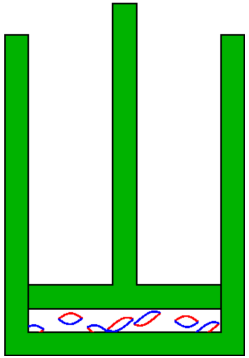

Recall: During inflation, the **negative pressure** of this vacuum energy *drives* the accelerated expansion of space ("pulls up on the piston"), just through the "magical" math of Einstein's theory.

Every cubic meter of **space** created, creates **more vacuum energy**. When inflation stops, **all this vacuum energy** (technically: inflaton field potential energy) **decays into particles (matter & antimatter)** and fills the universe with Standard Model particles (photons, electrons, quarks, etc.)!

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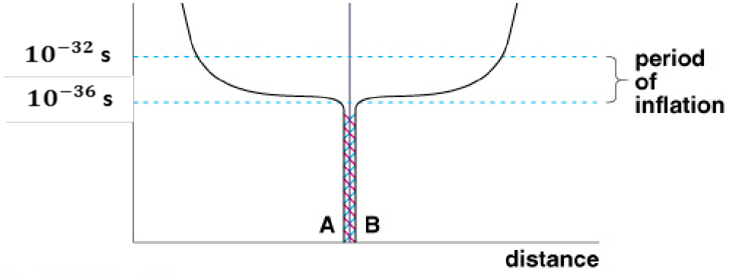

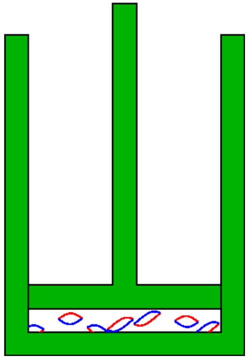

So: *Are* we getting something from nothing?!
Maybe, but maybe not:

The vacuum energy **creates spacetime curvature** (even if space is flat, its dynamical expansion means space*time* is curved), i.e., a **gravitational field**.

Bringing in the idea that this gravitational field might have "**negative energy**", it **<u>may</u>** be that this **growing negative** gravitational energy (as the expansion continues) balances the **growing positive** vacuum energy contained in the ever larger space. (**Speculation!**)

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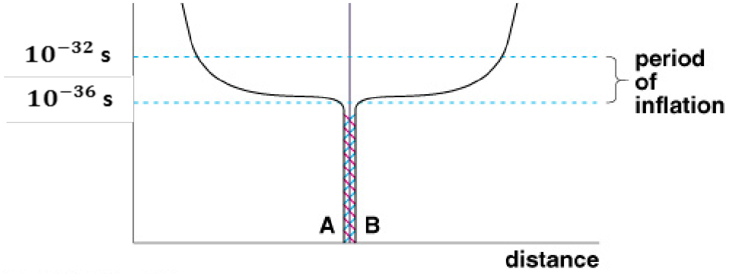

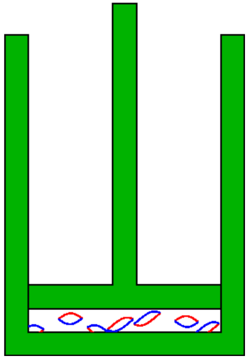

If so, the **total** energy—matter plus gravitational—**remains constant** (conserved) and very small (e.g., 1 g worth), and could even be **exactly zero.**

Thus, we may not be getting **something** from nothing, but **nothing** from nothing.

If the total energy in the universe is exactly zero, the universe is just an interesting way of writing "0", e.g., 0 = 2 + (–2) !

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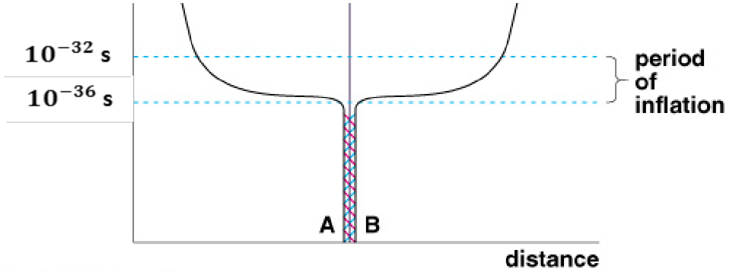

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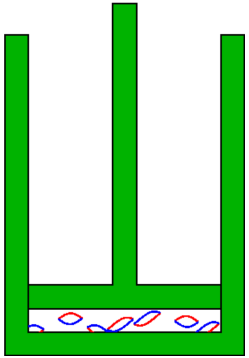
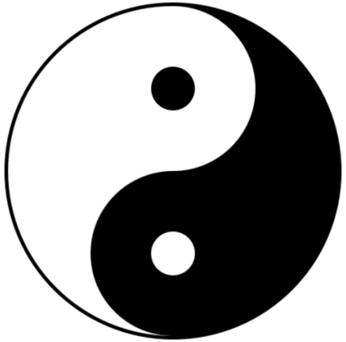


Like **Yin and Yang**:
Complementary opposites (positive and negative energy) "give rise to each other as they interrelate to one another…"
—Wikipedia



Origins

- One of the deepest questions of all is: **Why is there something rather than nothing?**

Either way **(nothing from nothing** or **something from nothing),** it's a **remarkable story…**

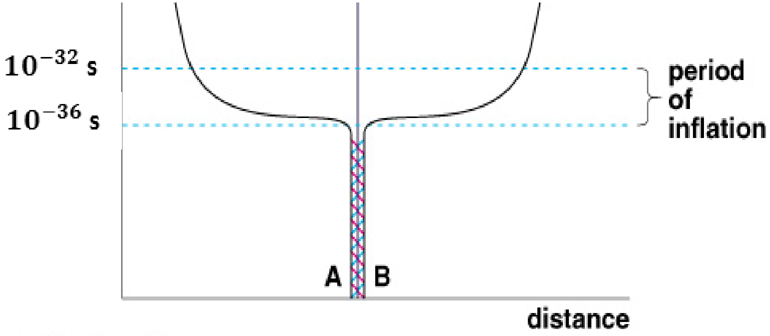
Quote from Alan Guth, inventor of the cosmic inflation idea:
"This borrowing of energy from the gravitational field gives the inflationary paradigm an entirely different perspective from the classical Big Bang theory, in which all the particles in the Universe (or at least their precursors) were assumed to be in place from the start. Inflation provides a mechanism by which the entire Universe can develop from just a few ounces of primordial matter. Inflation is radically at odds with the old dictum of Democritus and Lucretius, "Nothing can be created from nothing" If inflation is right, everything can be created from nothing, or at least from very little. If inflation is right, the Universe can properly be called **the ultimate free lunch**."

Popular science article: Why is there something rather than nothing (BBC)

So what?

Origins

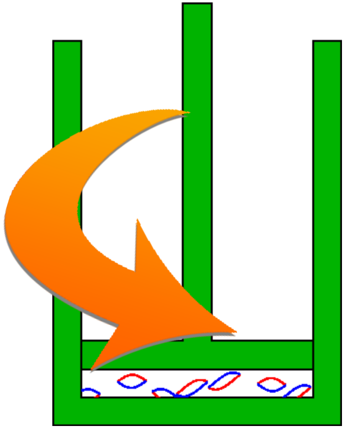
- Before inflation began, space may have had “stuff” in it: Standard Model particles, exotic particles, etc. Then something happened that **triggered** inflation: perhaps the energy released when the strong and electroweak forces “**froze out**” of the GUT force, like energy released when water freezes?

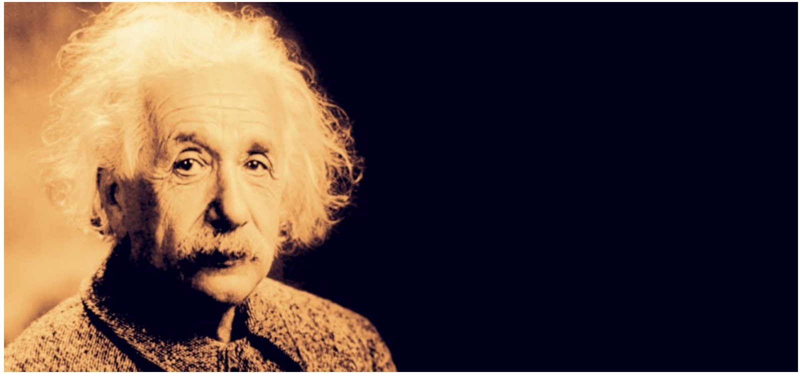


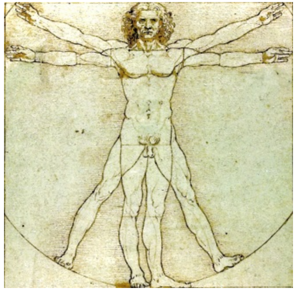
- But the expansion of space during inflation was **so extreme** that any pre-existing “stuff” would have been **diluted to virtually zero density**. Space would have been **almost perfectly empty** of everything **except the uniform “inflaton vacuum energy”**. The amount of this energy, in the tiny region of space that would become our observable universe, was **small before inflation began**, but grew large as space became large (“**ultimate free lunch**”).

- As mentioned earlier, at the end of inflation, during what's called "reheating", this "inflaton vacuum energy" then **decayed into the Standard Model particles** (photons, electrons, quarks, etc.) that fill the universe today, and that **eventually became us**.

- If inflation is right, we exist as a direct result of the weird effect that **persistent** quantum vacuum energy (pressure = – energy density) has on expanding space, according to Einstein's ideas about spacetime and gravity.







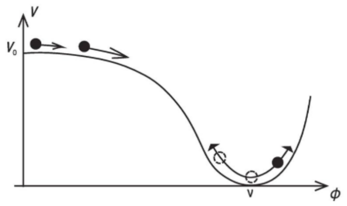
- Did inflation really happen?
  - It explains the surprising **homogeneity** of the observable universe: the matter, at any given time in cosmic history, is, on average, almost perfectly uniformly distributed (**density** and **temperature**). Relatedly, it accounts for the observed **flatness** and **absence of magnetic monopoles**.
  - It also explains the origin of the **large-scale structure** of the universe: microscopic quantum fluctuations, magnified to cosmic size, became the **seeds** for the gravitational collapse into the structures we see today. It predicts the peak CMB fluctuations of **one degree** on the sky (due to flatness), and is consistent with its amplitude (**1:100,000**).
  - Technically detailed prediction: CMB is a “nearly-scale-invariant Gaussian random field”. The “nearly” part predicts a “spectral index” between 0.92 and 0.98. CMB measurements show 0.963 ± 0.012. This is considered an important confirmation.

Origins

- While there is some evidence supporting inflation (and none against it), and it is a **widely pursued** hypothesis, with many variants (e.g., eternal inflation), it is also **widely criticized**:

  - The "**inflaton field**" that drove inflation does not correspond to any know physical field (no concrete connection with particle physics; **yet**, at least. Inflaton = Higgs?...)

  - The theory has **ad hoc elements**, that can be adjusted to fit a wide range of data...

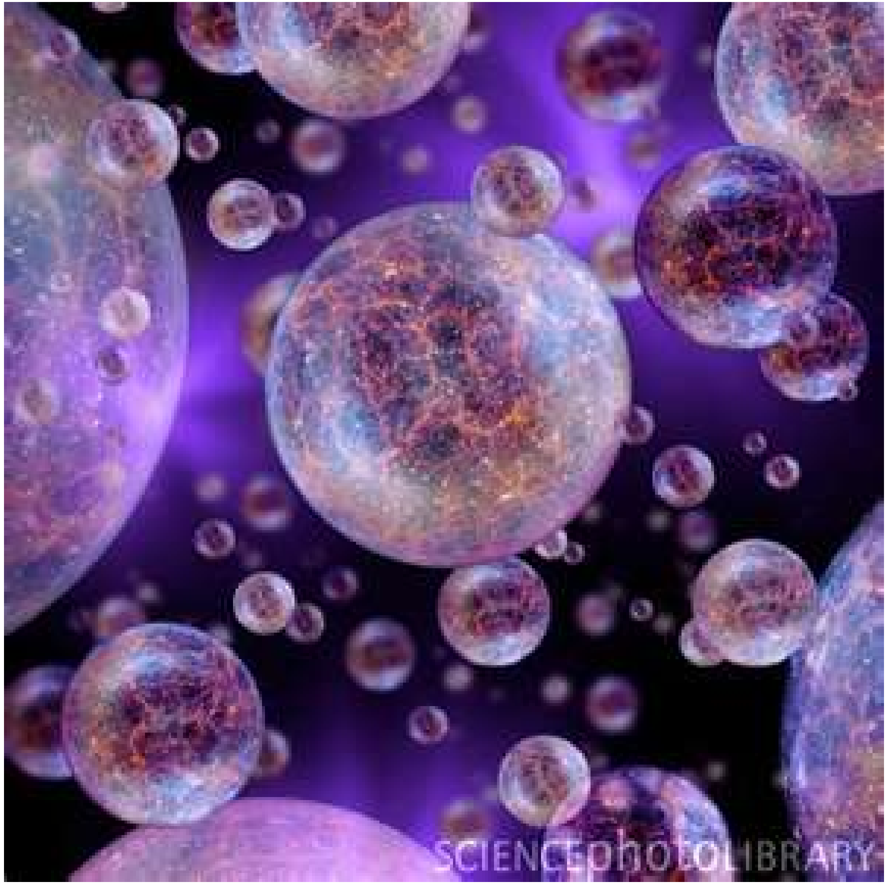


  - The **initial conditions** for inflation itself may be just as "**fine tuned**" as the initial conditions (very flat universe) inflation tries to explain (e.g., exceptionally low entropy)...

- While inflation (1980+) has provided one plausible "origins" model (like "RNA World" in origin of life), it is still fraught with mysteries, and is almost certainly not the final word!

Origins

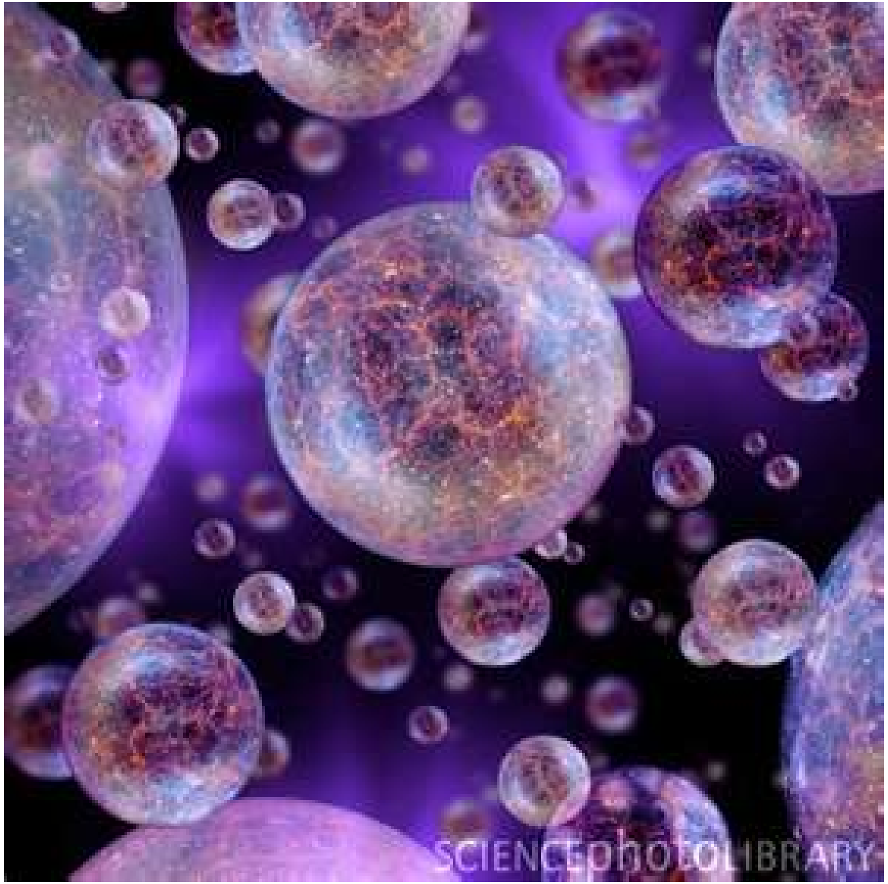
- There are **other origins hypotheses** being pursued (research these on your own):
  - Within **classical gravity**, e.g., Roger Penrose's **Conformal Cyclic Cosmology**, popularized in his book *Cycles of Time: An Extraordinary New View of the Universe*; focus on **entropy** (video interview with Roger Penrose)…but also strongly criticized, e.g., by Sean Carroll.
  - Within **quantum gravity**, e.g., **Loop Quantum Gravity** can "soften" the classical Big Bang singularity and push back to a universe that existed *before* the Big Bang (video interview with Abhay Ashtekar), i.e., a general resurgence of the "**Big Bounce**" idea.
  - Within **Superstring Theory**, inspired by extra dimensions, D-branes, etc., e.g., the **cyclic model** of Turok & Steinhardt. Video presentation by Paul Steinhardt (includes **general critique of eternal inflation, multiverse**, etc. & **tests** through cosmic gravitational waves)
- Early universe cosmology is a **very active** area of physics. There is great interest in understanding **where we come from**, and **where we're going**!



Eternal Inflation & Multiverse

Imagine that space is **infinite** and **eternal**. Assuming inflation can occur at all, it may occur at **different rates** in **different places**, and **shut off** after different amounts of time.

All of space could be **eternally inflating**, and ***randomly*** shutting off in "pockets" → bubble universes. These universes may have very different, ***randomly*** determined properties (physical constants **including** Λ, number of dimensions, etc.). **Some may support life**, but most probably not.



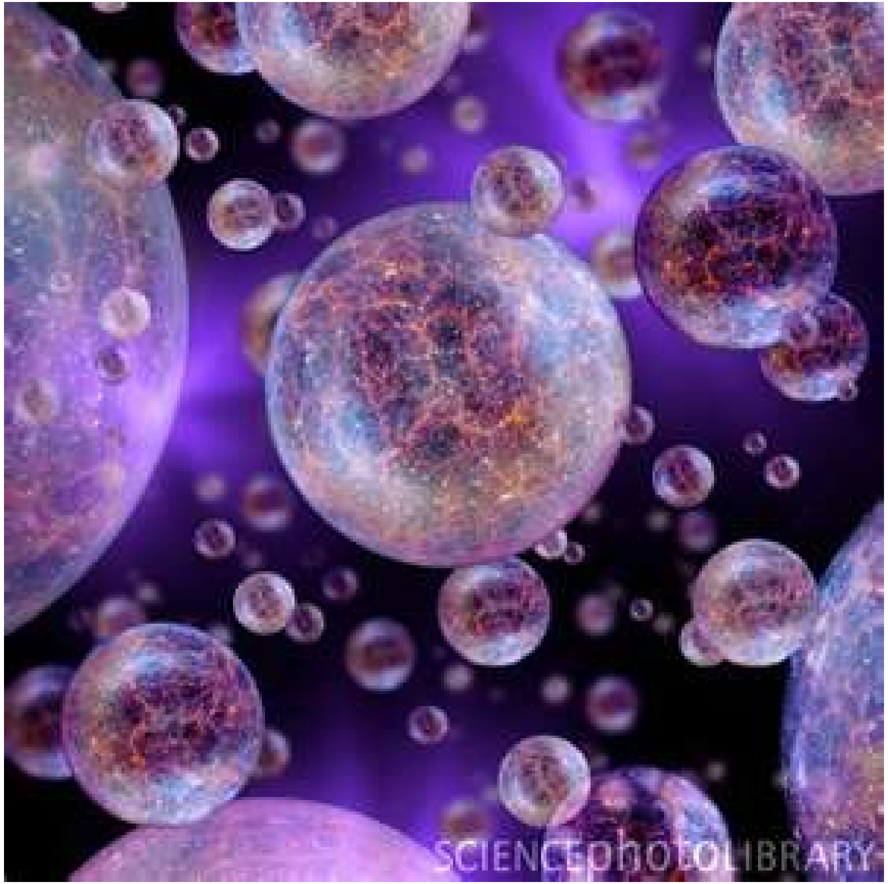
Eternal Inflation & Multiverse

Are we just **one bubble** in such a multiverse?

Is this the “explanation” for the cosmological constant problem (and other “**fine tuning**” problems)?

Do we just happen to live in a bubble where Λ is small (and the other physical constants are “just right”) for **existence of complex life**?

Do we really have to resort to such “**anthropic reasoning**”? Is this the **end of science**?



Or do we just need to work harder…maybe a **theory of everything** will explain more?

A Brief History of the Universe…