ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 25 • Inflation and Multiverses

12/02/2021

Logistics

- Homeworks
  - Homework #4 solutions are on Canvas
  - Homework #5 due tonight!
  - Homework #6 assigned today,
    due **next Thursday 12/9**
- Review & study guide next Thursday

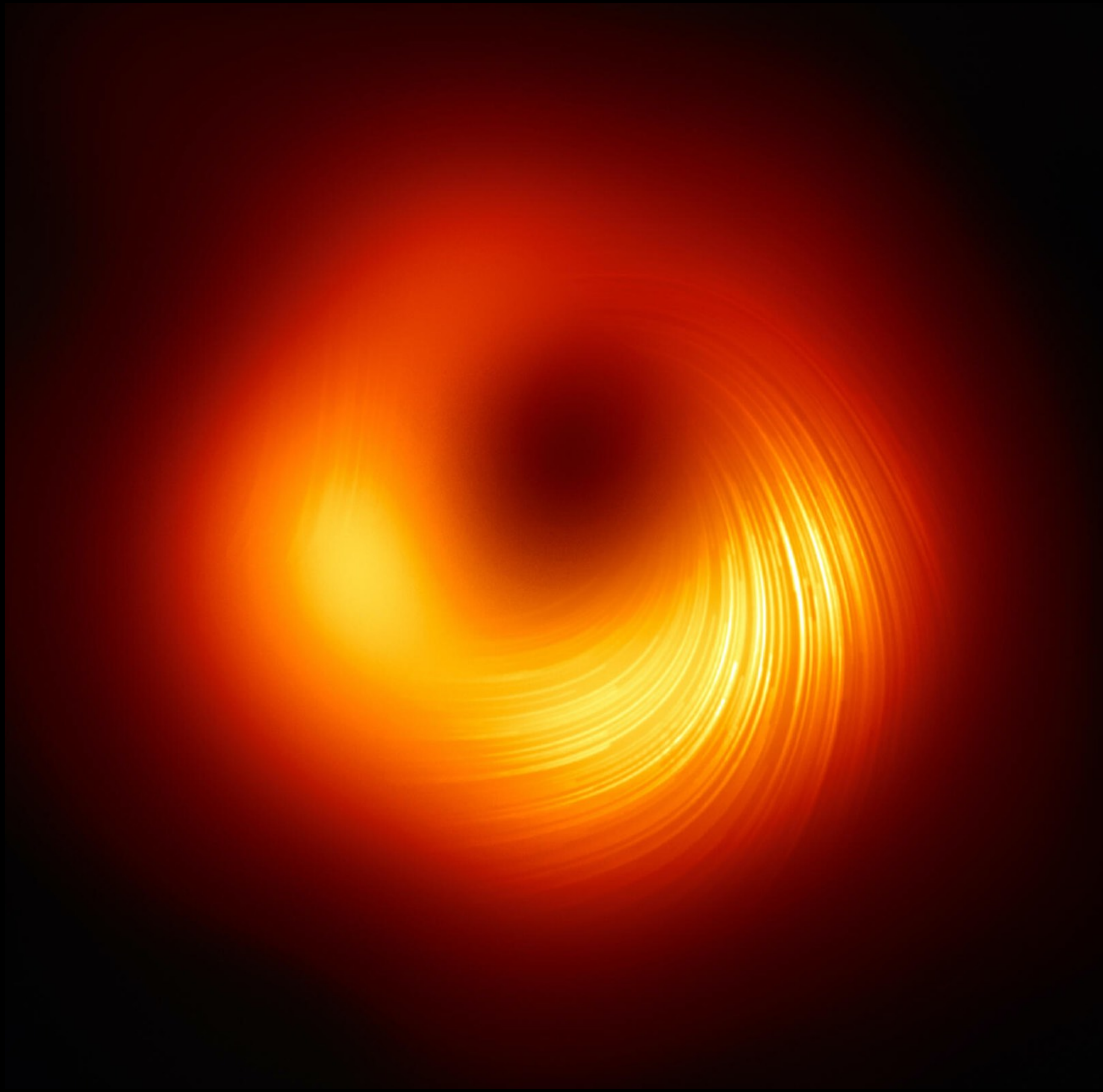
Logistics

- Course evaluations are now open
  - From 12/01 to 12/14
  - https://www.courseevalum.umd.edu

More on the Event Horizon Telescope

EHT Image with polarization

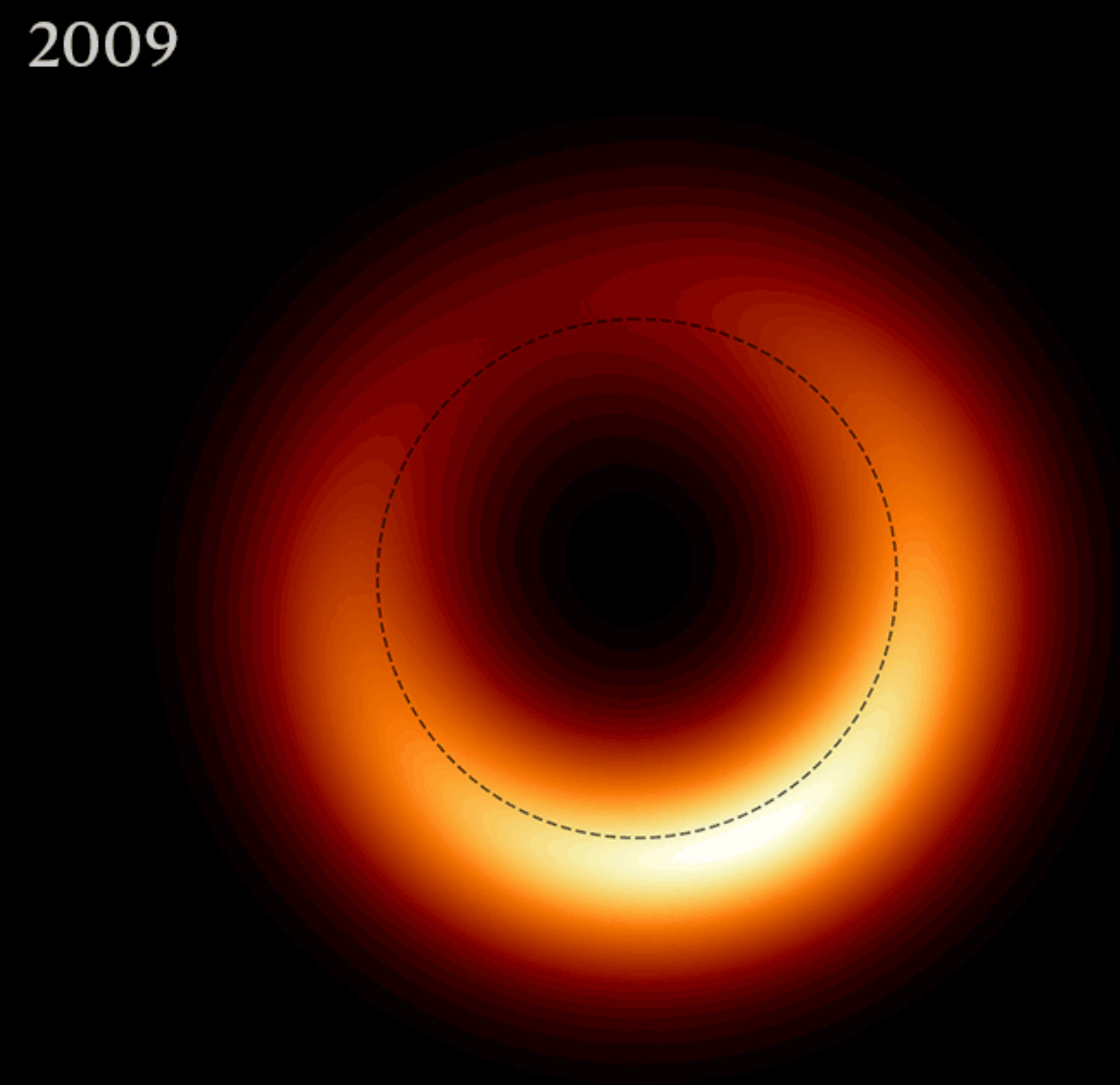
- Image in **polarized light**
- Tells us about **magnetic fields** near the black hole



EHT Collaboration

EHT Image with polarization

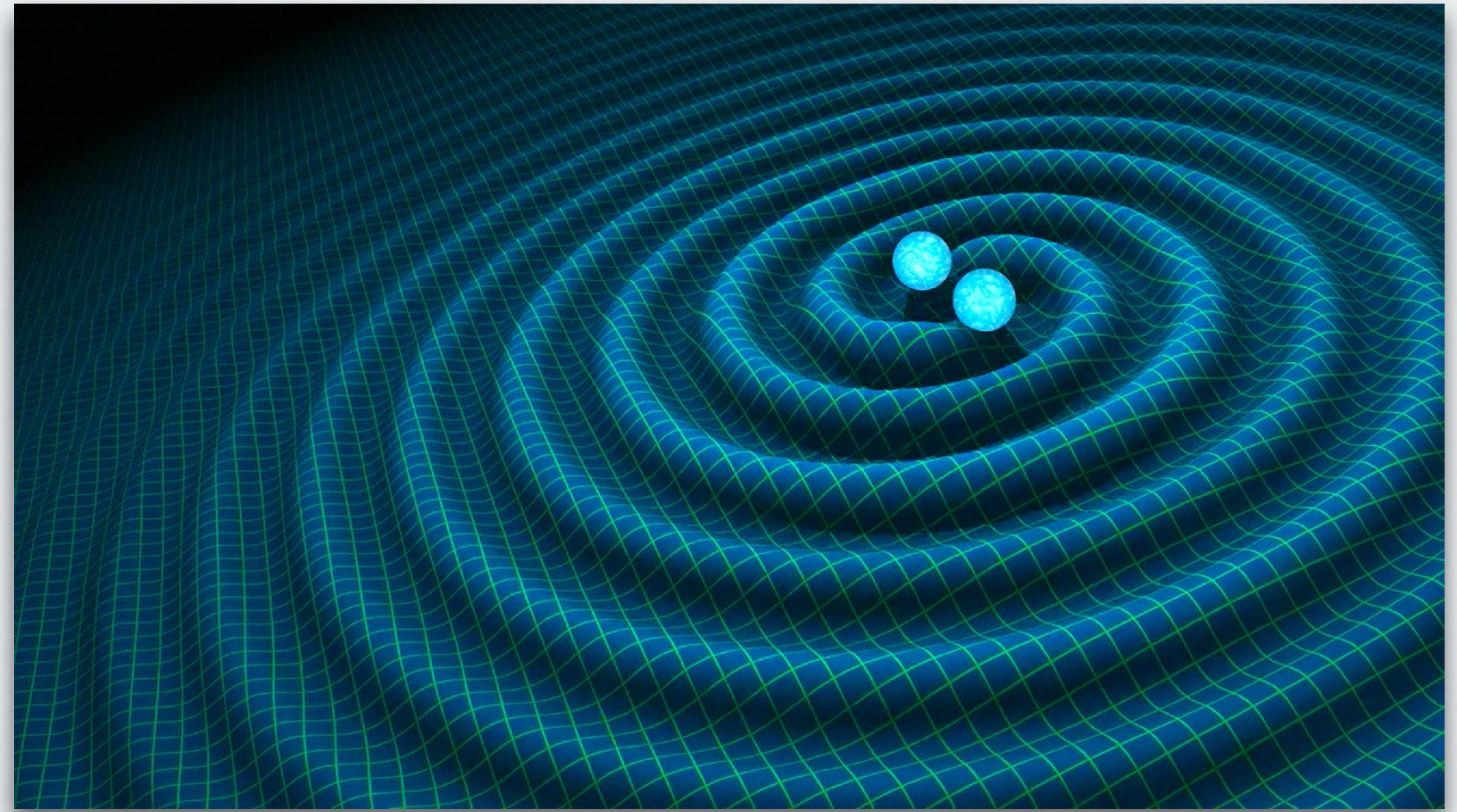
- Datasets taken prior to the 2017 set that create the famous image are of lesser quality, but sufficient to reconstruct images
- The black hole shadow stays the same, but the **bright spot moves** around. There are two possible explanations:
  - The accretion disk "wobbles" and the direction where it is coming towards us changes
  - Patches in the accretion disk become brighter and dimmer, which would possibly offset the "Doppler boosting" effect



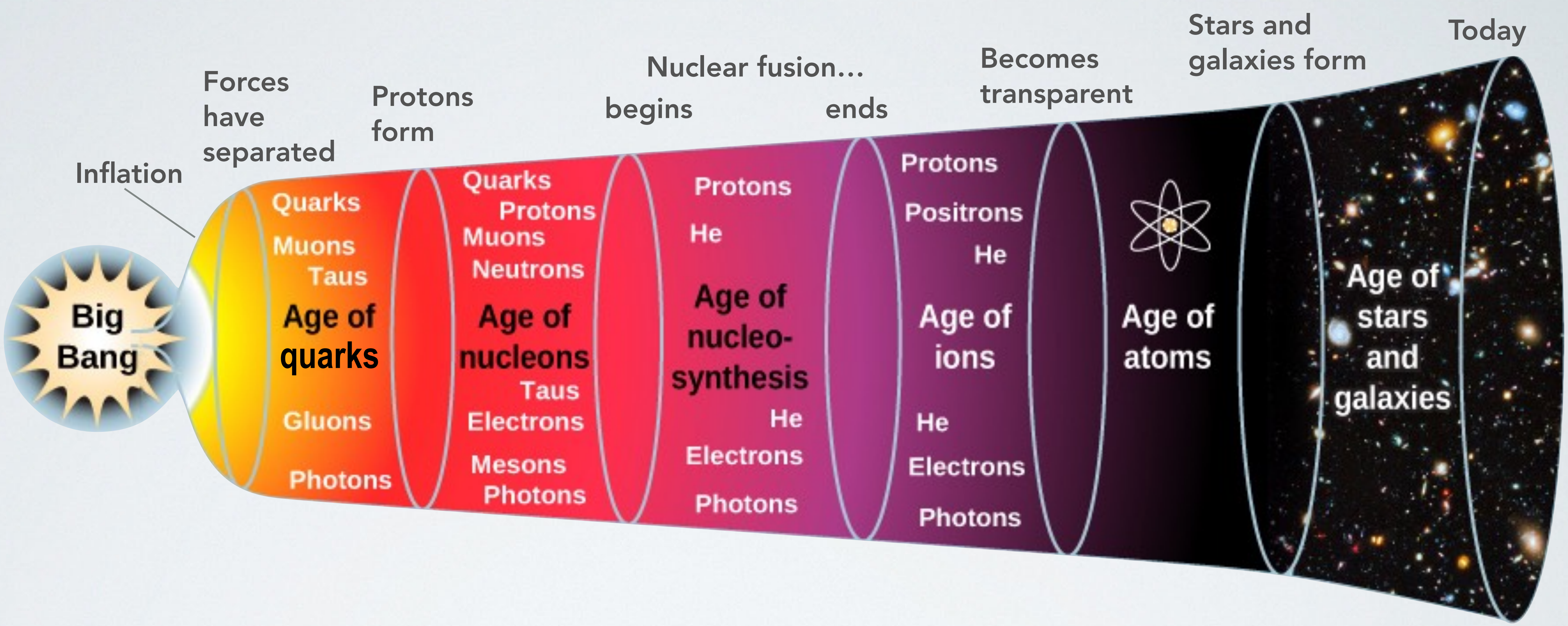
EHT Collaboration

Are gravitational waves redshifted?

- **Yes,** gravitational waves experience redshift
- However, it is difficult to measure the redshift of a gravitational wave because its form gives us $M(1+z)$, where M is the total mass of the merging system and z the redshift.



History of the Universe



Time	0	10^{-12} s	10^{-6} s	15 s	30 min	380,000 yr	$\approx$ 100 Myr?	13.8 Gyr
Temperature (K)	∞	10^{15}	10^{13}	5×10^9	3×10^8	3000		2.725

Today

- The fine-tuning of flatness
- Inflation
- The horizon problem
- The relic problem
- Multiverses

Part 1: The fine-tuning of flatness

Fine-tuning problems

- Imagine you turn on the TV and see a lottery show that you didn't know about
- They draw six numbers, and the result if 5-6-7-8-9-10
- What's your first thought?
  - No way, that's impossible!
  - I haven't understood how this particular lottery works
- On second thought…
  - What if I told you that same lottery has been done thousands of times, and this is the **first time** a number like this has come up?
  - Why is 5-6-7-8-9-10 **special**? Is it special in every number system?
  - How big can the numbers be? 1-10? 1-100? How likely is our draw **statistically**?
  - Is this a rerun of an older episode that they are showing **because** it yielded a strange result?
- This is a very silly example of a **fine-tuning problem**: if our "theory" is that this is a random draw and it gives a very special number on the first (and only) draw, then we lose confidence in our theory


Six in a row: winning numbers in South African lottery are: 5, 6, 7, 8, 9 and 10

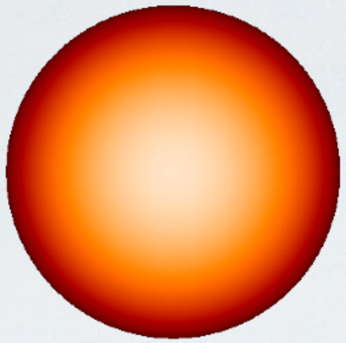
Surprising winning combination sparks accusations of fraud as 20 people win share of jackpot

Guardian 12/02/2020

Recap: Curvature and the fate of the Universe

Case 1: Closed Universe

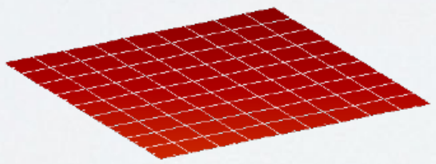
$$\Omega_{m+\Lambda} > 1 \implies \Omega_k < 0$$
$$\implies k > 0$$



Collapses eventually (big crunch)

Case 2: Flat Universe

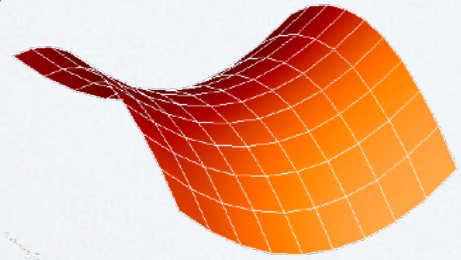
$$\Omega_{m+\Lambda} = 1 \implies \Omega_k = 0$$
$$\implies k = 0$$



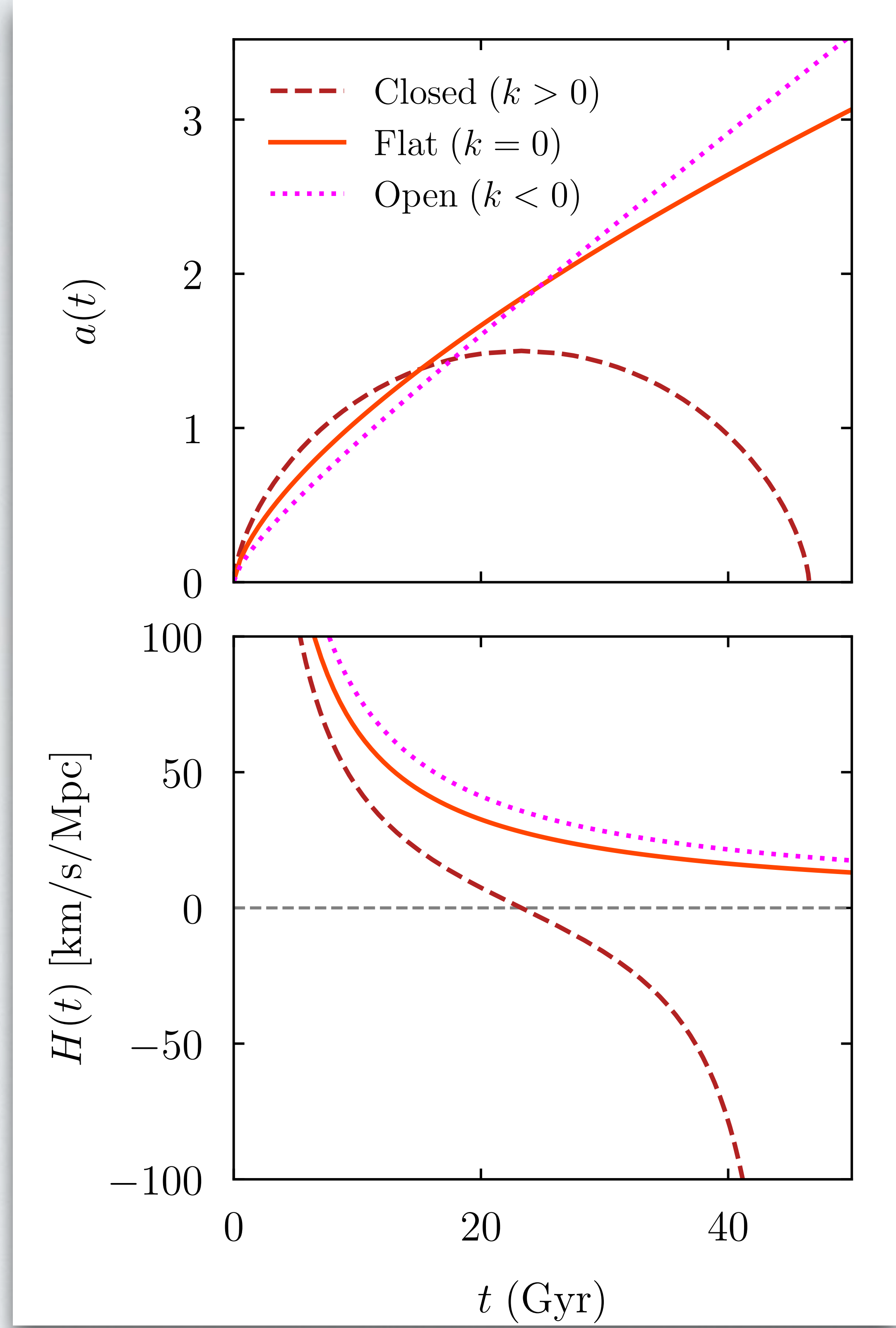
Slowly grinds to a halt

Case 3: Open Universe

$$\Omega_{m+\Lambda} < 1 \implies \Omega_k > 0$$
$$\implies k < 0$$



Expands forever



The flatness problem

Friedmann Equation

$$H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda}{3}$$

$$\Omega_{\rm m} \equiv \frac{\rho}{\rho_{\rm c}}$$

Means that components must some to one:

$$\Omega_{\rm tot} \equiv \Omega_{\rm m} + \Omega_\Lambda + \Omega_{\rm k} = 1$$

$$\Omega_\Lambda \equiv \frac{\Lambda}{3H^2}$$

$$\rho_{\rm c}(t) = \frac{3H^2(t)}{8\pi G}$$

$$\Omega_{\rm k} \equiv -\frac{kc^2}{a^2H^2}$$

From cosmological data, e.g., Planck:

$$|\Omega_{\rm k,0}| < 0.01$$

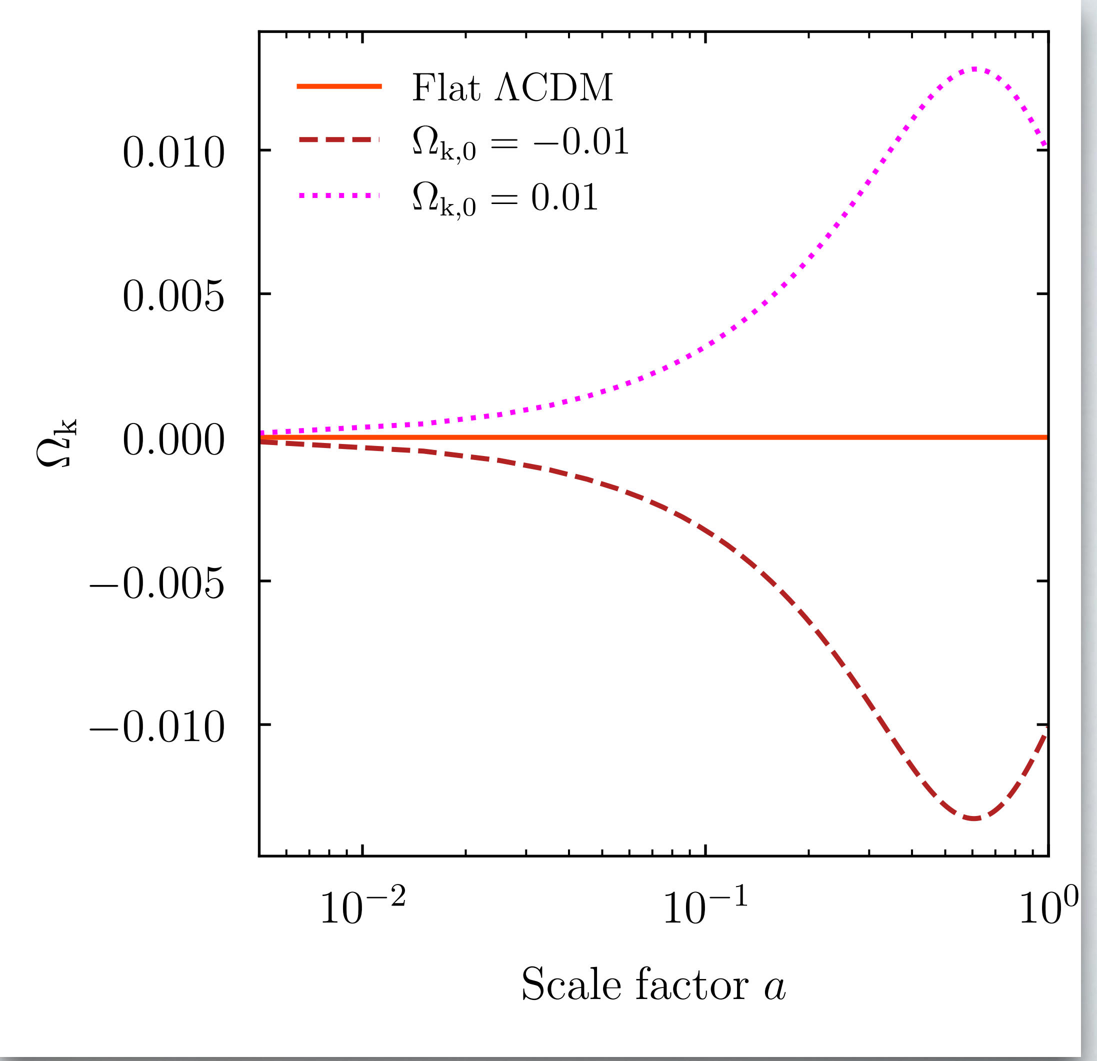
Question: doesn't it seem random that the Universe is flat, i.e., that $\Omega_{\rm m,0} + \Omega_{\Lambda,0} \approx 1$ so that $\Omega_{\rm k,0} \approx 0$?

The flatness problem

- The curvature term evolves as $\Omega_k \propto 1/a(t)^2 H(t)^2$
- This scales with time between $\Omega_k \propto t$ and $\Omega_k \propto t^{2/3}$
  - If the Universe is slightly open in the beginning, that accelerates the expansion compared to flat, leading to lower density / even more open-ness
  - If the Universe is slightly closed in the beginning, that slows down the expansion compared to flat, leading to higher density / even more closed-ness
- If the Universe is close to $\Omega_k = 0$ today, it must have been even much closer in the early Universe
- At end of the Planck epoch (10^{-43} s), $|\Omega_k| < 10^{-60}$!
- This is a "**fine-tuning**" problem: why would $\Omega_m + \Omega_\Lambda$ take on a value so close to one?
- Why do we care?
  - If $\Omega_m + \Omega_\Lambda$ had been much above 1, would have recollapsed very early **before making galaxies**
  - If $\Omega_m + \Omega_\Lambda$ had been much below 1, would have expanded so rapidly that **structures would not have formed**

$$\Omega_{tot} \equiv \Omega_m + \Omega_\Lambda + \Omega_k = 1$$

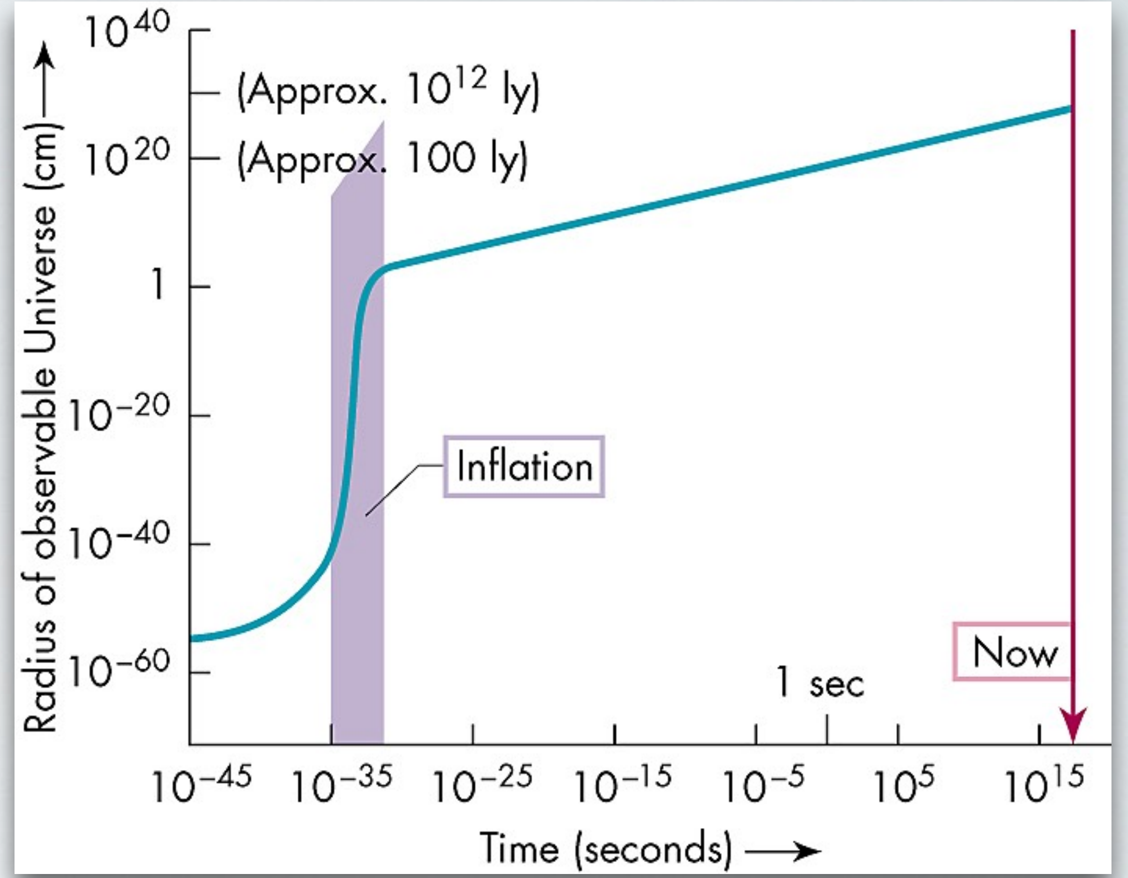
$$\Omega_k(t) = -\frac{kc^2}{a(t)^2 H(t)^2}$$



Part 2: Inflation

Inflation

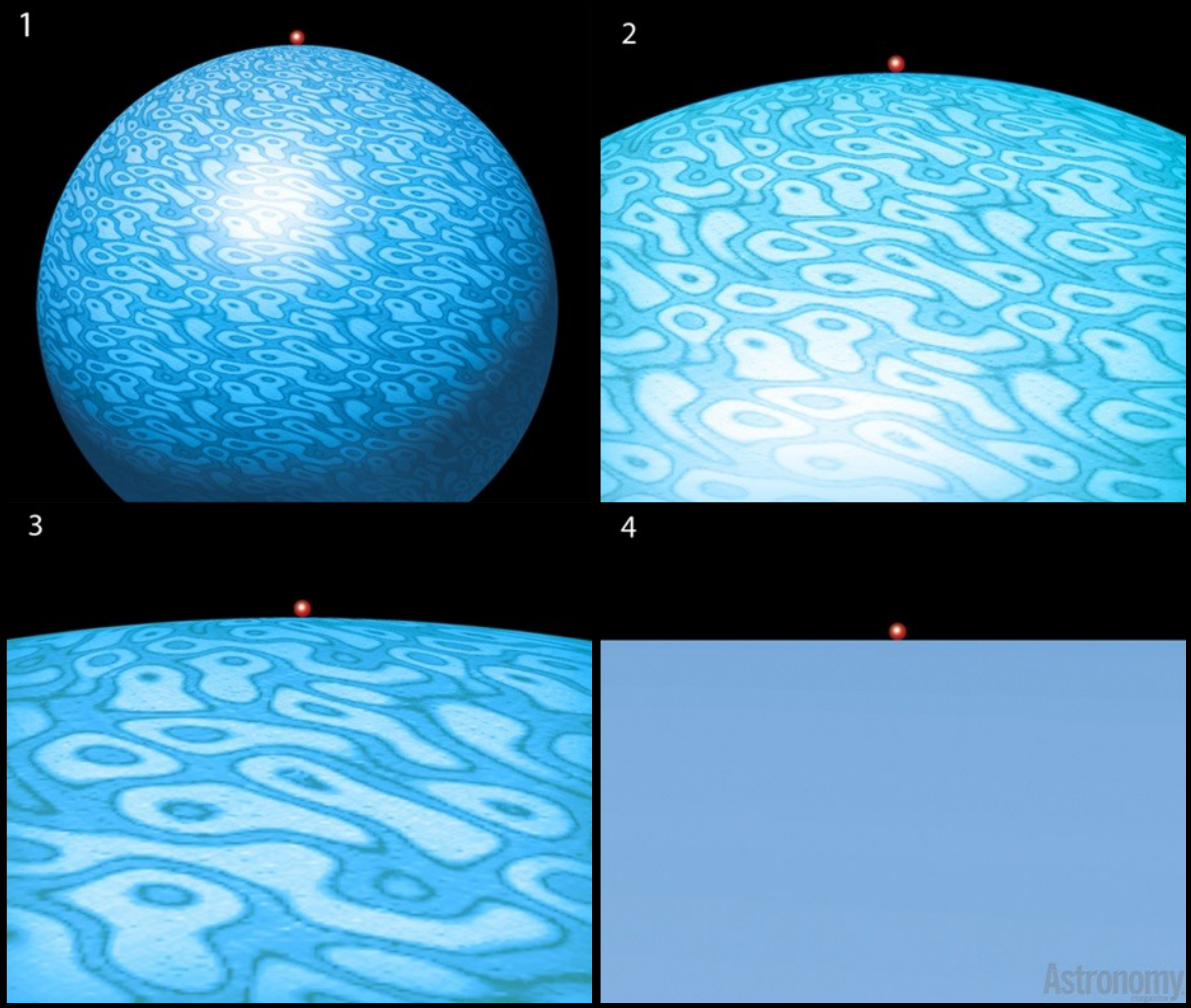
- Theory of cosmic inflation was first proposed by Alan Guth in 1982
- Inflation is a **very rapid expansion** of Universe at $t = 10^{-37}$-10^{-32} s after the Big Bang
- Universe expanded by a **factor of 10^{40} - 10^{100}** during this time!
- Looks a lot like **exponential expansion** due to dark energy, $a(t) \propto e^{Ht}$, just faster
- Super-light-speed expansion does not violate relativity because spacetime itself expands (same argument as for later Hubble expansion)



McGraw-Hill

The flatness problem

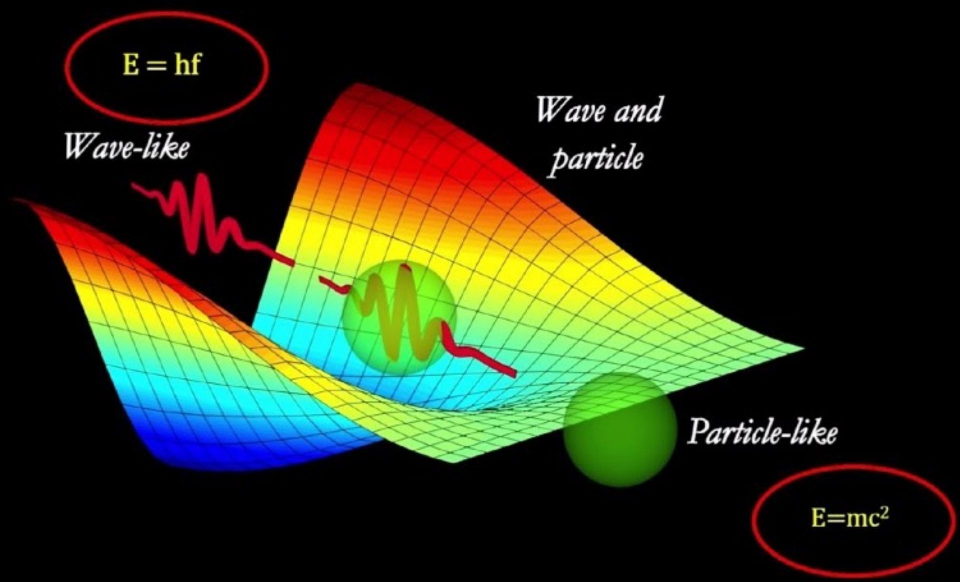
- Take any reasonably curved surface and expand it by a very large factor: it will look flat
- Inflation naturally **predicts a flat Universe**…
- …if the initial value of Ω_k was within some relatively generous range
- But what causes inflation?

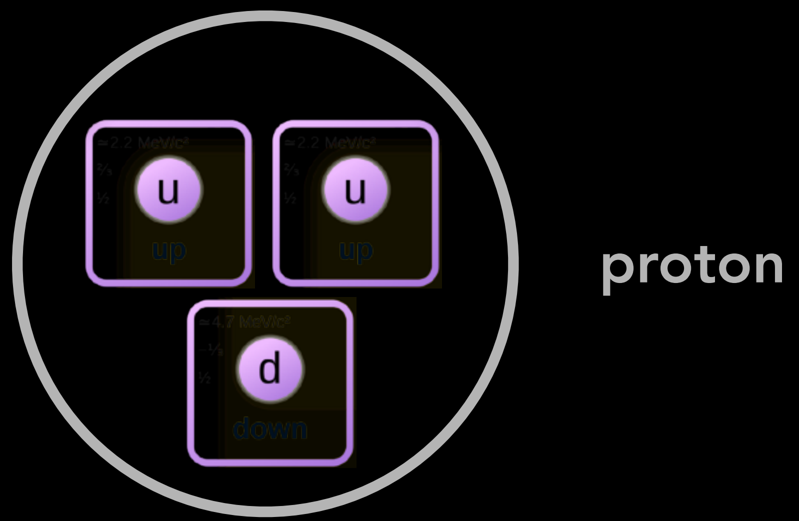


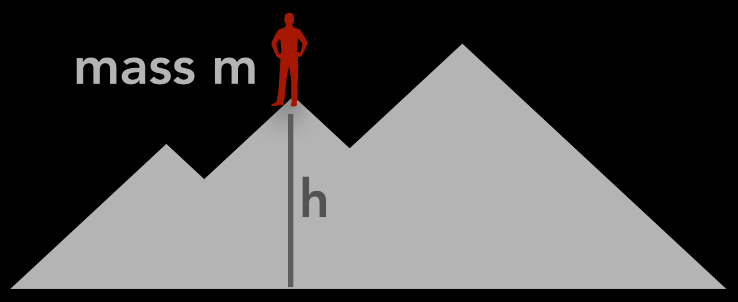
Astronomy Magazine

Quantum field theory

- Quantum Field Theory (QFT) is the foundation of modern particle physics
- A "**field**" has a value **everywhere in space** (e.g., the temperature in a room is a field)
- For example, the basic entity of electromagnetism is the electromagnetic field
  - Energy in the fields is "quantized", i.e., comes in small, particular portions
  - Photons are excitations (ripples) in the field
  - They behave both as a **wave** (think interference) and as a **particle** (think momentum)
- All other particles are the same way!
  - Quark Fields (excitations = quarks)
  - Gluon Fields (excitations = gluons) etc.
- A field can have a **potential energy** associated with it
  - For example, the height above sea level is a field defined on Earth's surface; it has an associated gravitational potential: if you're higher, you have more potential energy



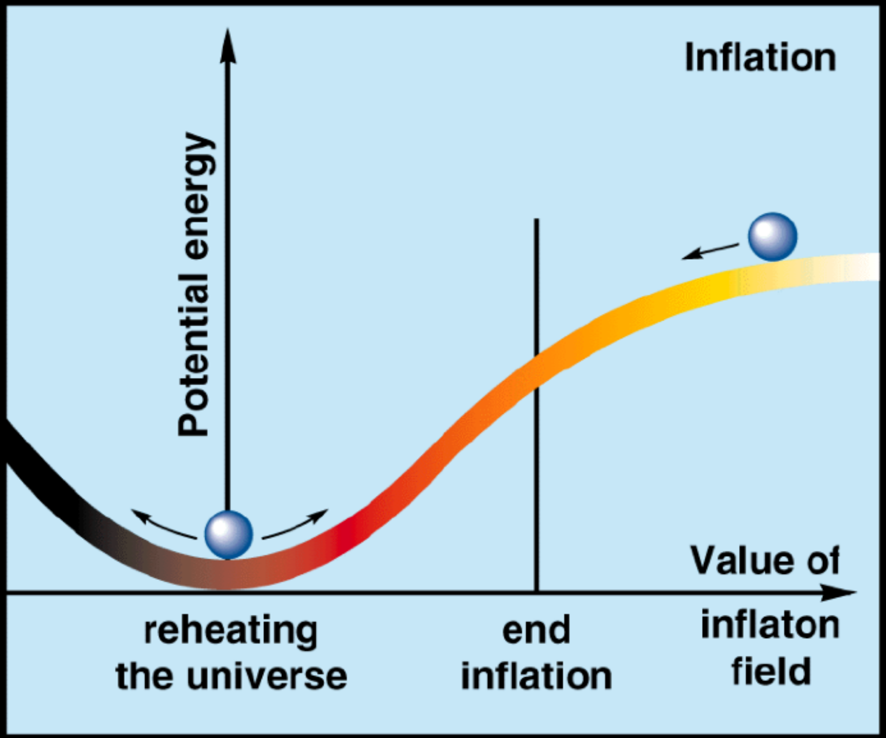




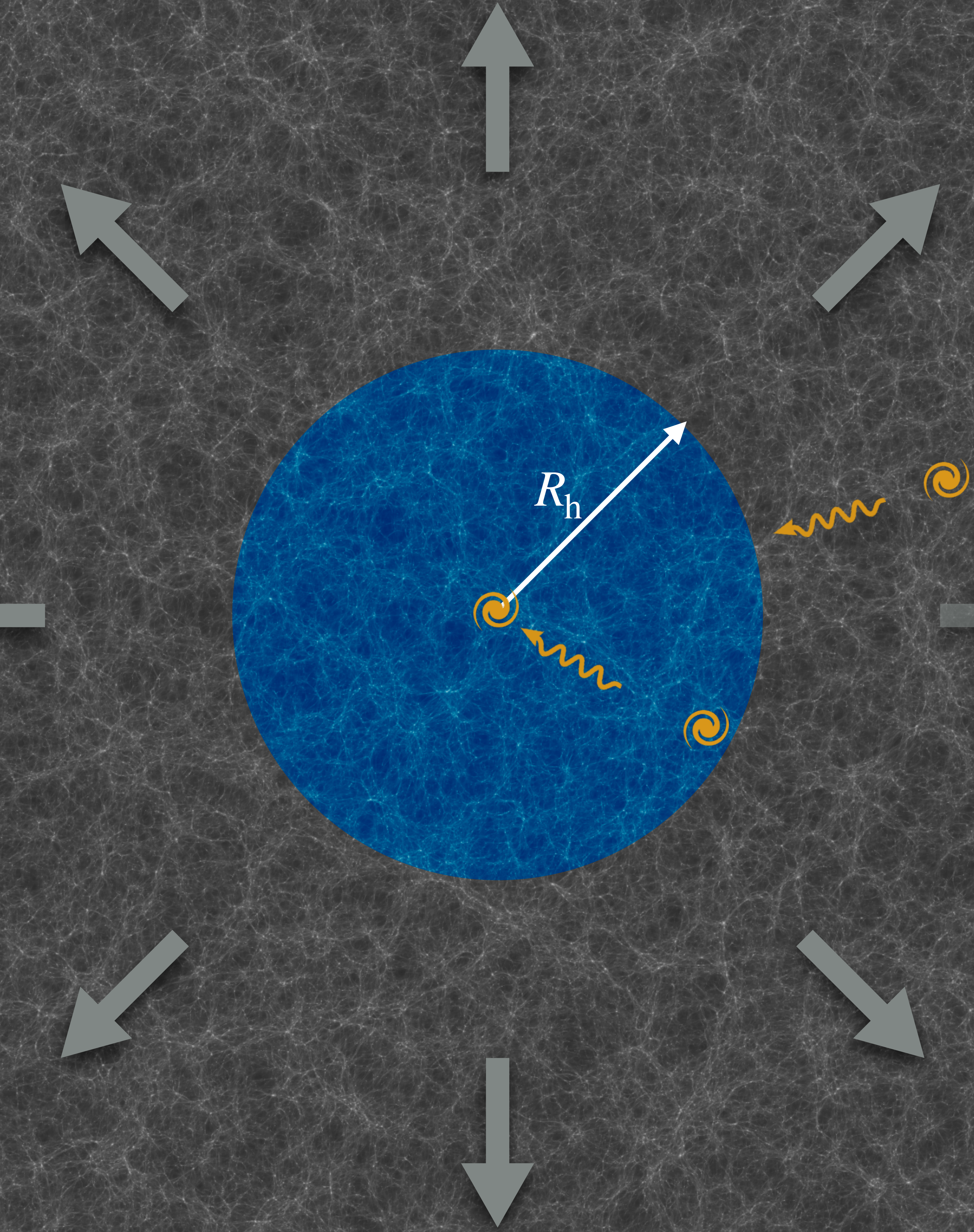
potential energy $= m \times g \times h$

Inflation field

- The idea: in the early universe, there was some an exotic particle (called "**inflaton**") and a corresponding **quantum field**
- This field was initially stuck in a **high-energy state** (analogous to a marble resting on top of an upside-down bowl, or a pencil balanced vertically on its point)
- This created an enormous **"false vacuum" energy** that drove the inflation of the Universe (similar to dark energy that is making the Universe expand now)
- **During inflation**, the inflaton field **slowly moves down** to lower potential
- **Inflation ends** when the field eventually settles into lower-energy "true vacuum" state
- During inflation, temperature and density plummet; the universe becomes cold and empty
- After inflation ends, vacuum energy is converted into ordinary particles and radiation, which reheat the universe
- Subsequent evolution of early Universe is just as we discussed
- This is **speculation**! We have no direct evidence for the inflaton or its field



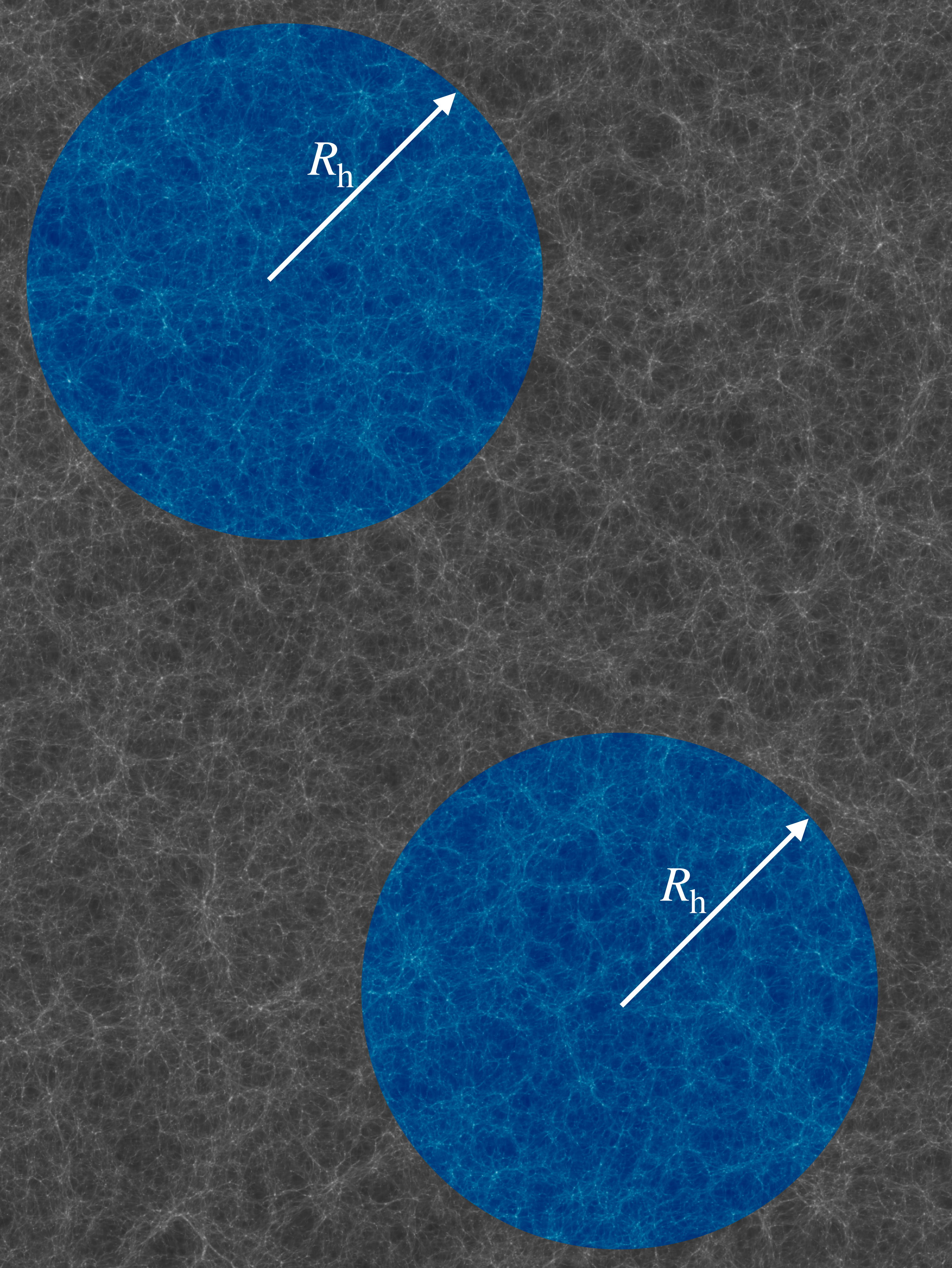
Part 3: The Horizon Problem



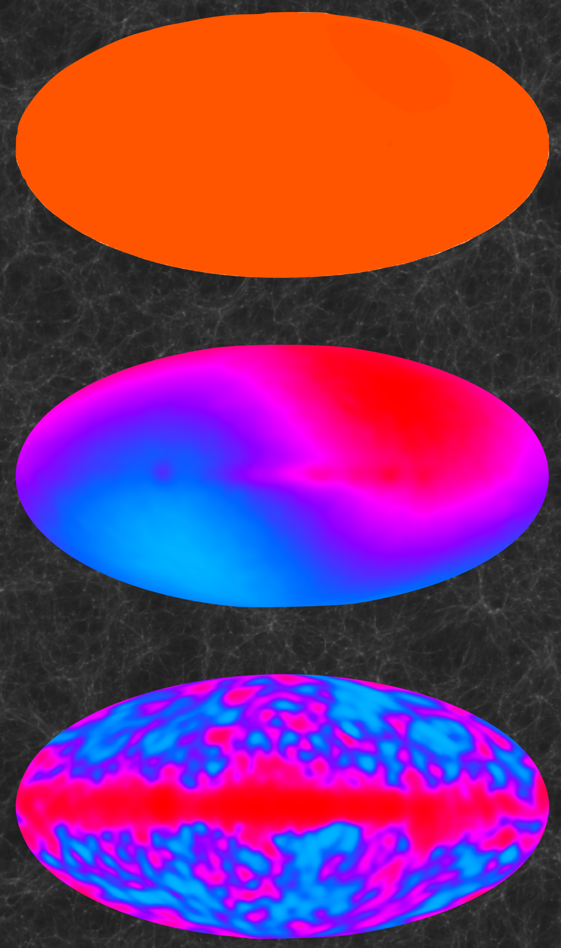
- Horizon is the distance that is **causally connected** (from which we can have received information)
- In a Universe without inflation, $R_h \approx ct$ (the actual horizon is a little different due to the expansion history)
- Structure starts to form around recombination, $t \approx 10^{13}$ s. The horizon at recombination would be

$$R_h \approx ct \approx 10^5 \text{ pc} = 100 \text{ kpc}$$

- How big would this patch be today? It has grown with the scale factor since z = 1100, so 1100 times larger
- But that's only about **100 Mpc**! The distance to the CMB surface of last scattering is about 14 Gpc



- The CMB we see should be composed of many "patches" that had not been in causal contact before recombination
- How can they be so exactly the same? How can the temperature of the **Cosmic Microwave Background** be so homogeneous (1 part in 100,000)?
- This is called the **horizon problem**

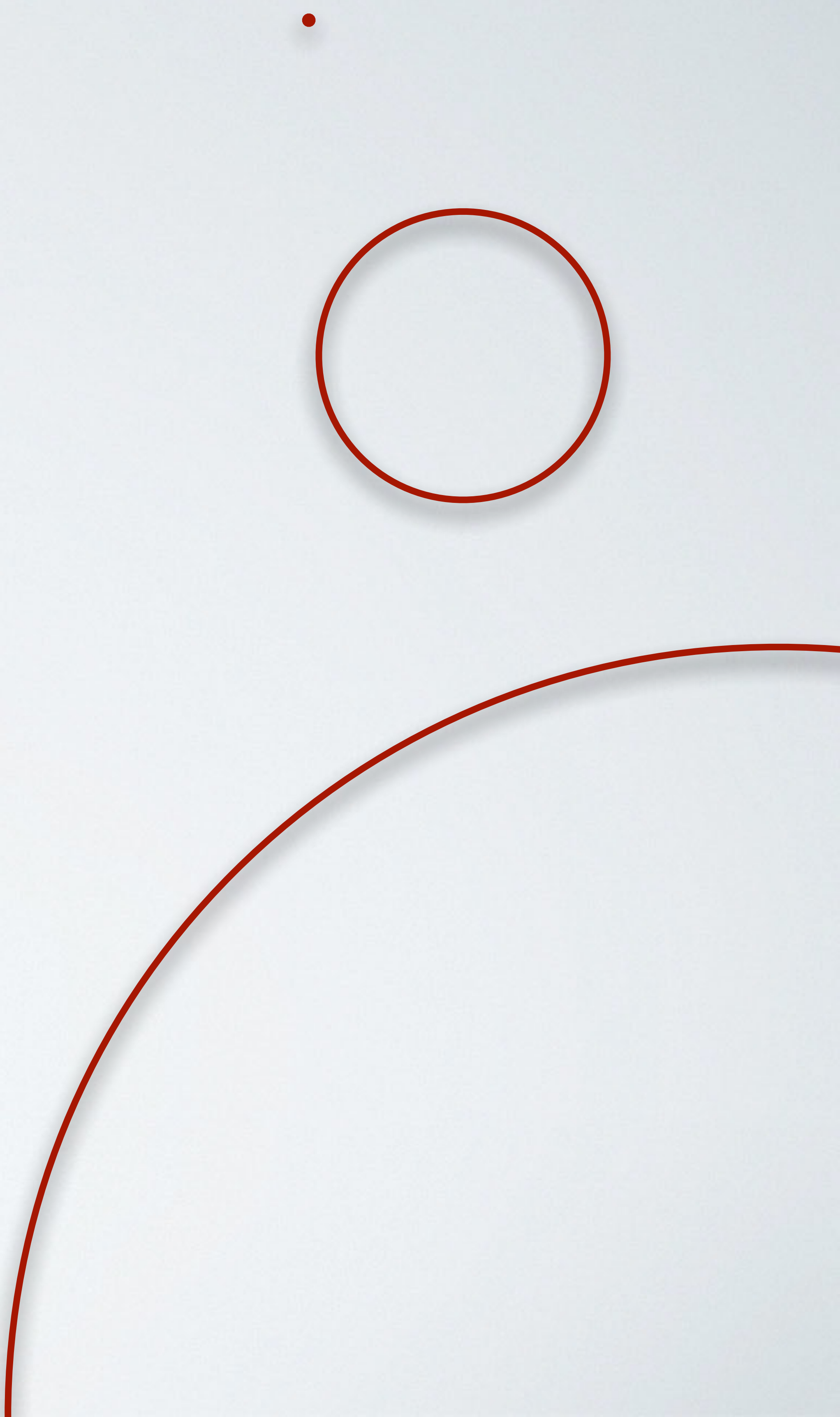


Inflation solves the horizon problem

- Before inflation:

$$R_{\mathrm{h}} \approx ct = c \times 10^{-37}\ \mathrm{s} \approx 10^{-27}\ \mathrm{cm}$$

- Inflation **blows up causally connected regions** by a huge factor to at least 10^{13} cm (but possibly much more)
- Universe expands by 10^{22} by the time of recombination (380,000 years), so causally connected region is then about 10^{35} cm = 10^{7} Gpc or more
- The causally connected region then keeps growing as light travels, and is **much greater than the observable Universe**
- Thus, **inflation solves the horizon problem**

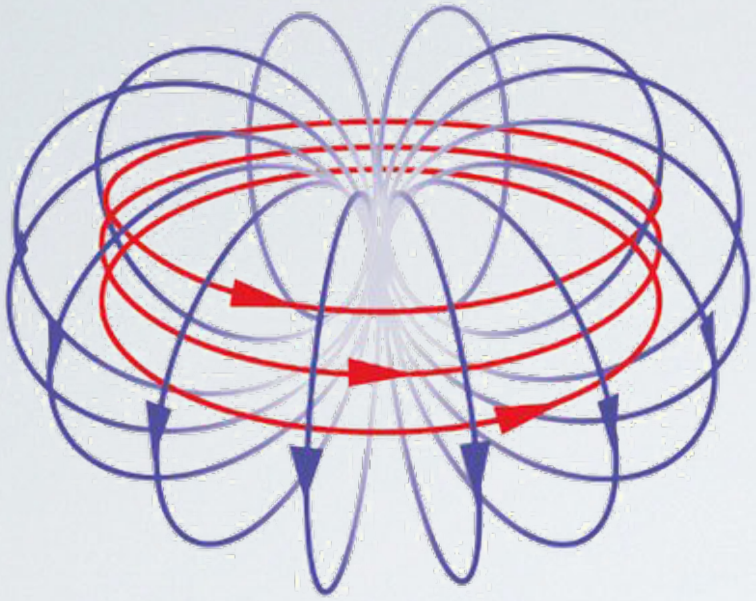


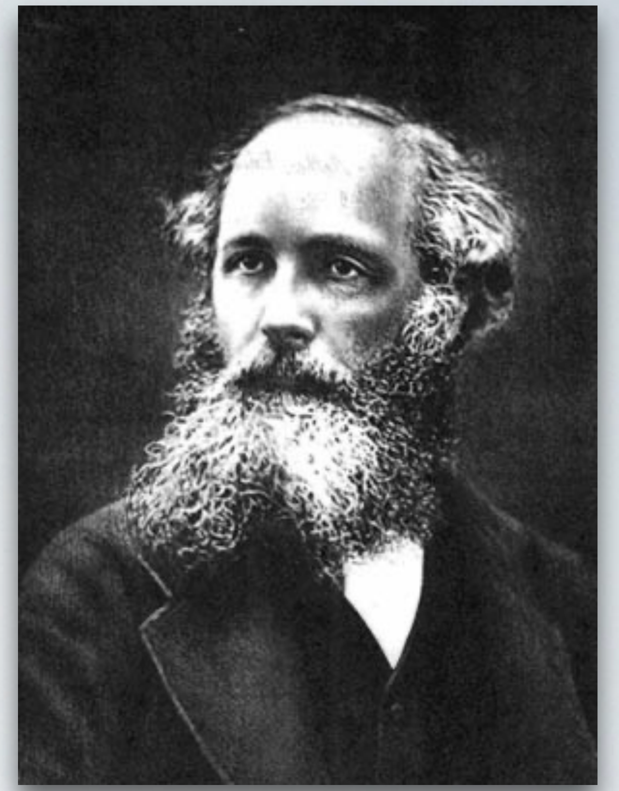
Part 4: The relic problem

The relic problem

- Theories of the early universe, such as Grand Unified Theories (GUTs) that combine all forces, tend to have funny **side products** such as:
  - **Magnetic monopoles**
  - **Topological defects**
- We don’t see these “relics” today. Why?

Magnetic monopoles





$$\nabla \cdot \overrightarrow{E} = \frac{\rho}{\epsilon_0}$$

"electric E-field lines end on charges"

$$\nabla \cdot \overrightarrow{B} = 0$$

"magnetic B-field lines close on themselves"

$$\nabla \times \overrightarrow{E} = -\frac{\partial \overrightarrow{B}}{\partial t}$$

"changes in B cause curling E-fields"

$$\nabla \times \overrightarrow{B} = \mu_0 \overrightarrow{J} + \epsilon_0 \mu_0 \frac{\partial \overrightarrow{E}}{\partial t}$$

"changes in E and currents cause curling B-fields"

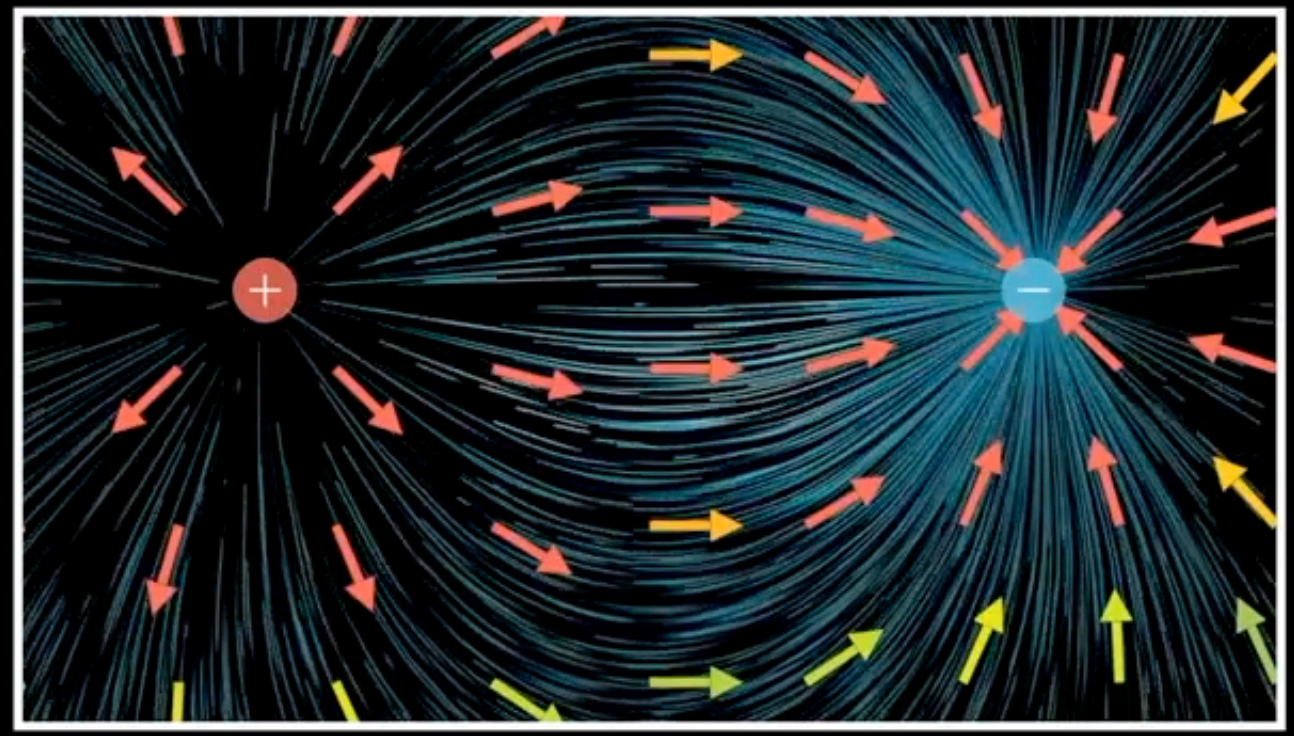
Maxwell's equations

Electric field: $\mathbf{E}$ Magnetic field: $\mathbf{B}$

$$\operatorname{div} \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\operatorname{div} \mathbf{B} = 0$$

$$\operatorname{curl} \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

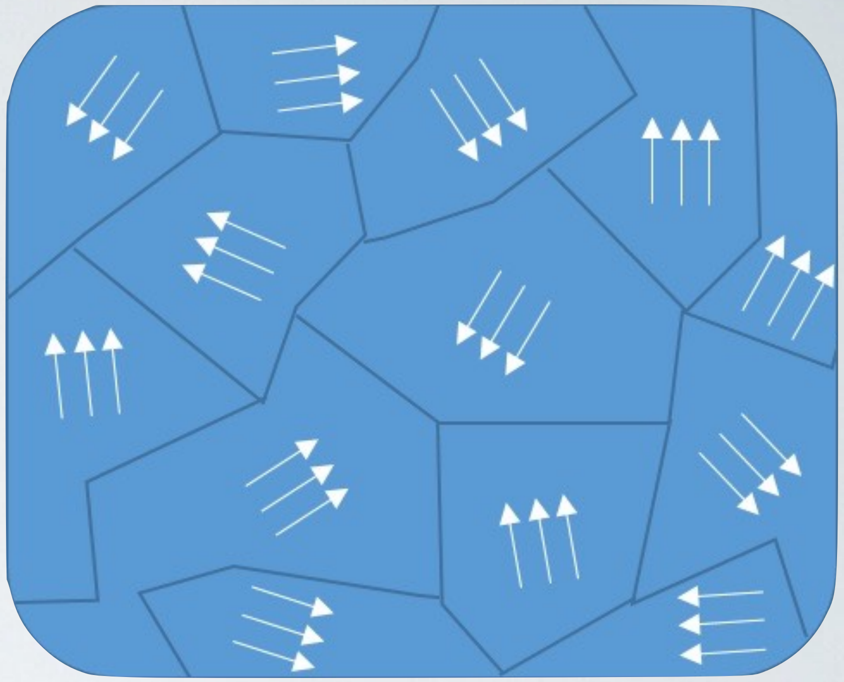


- However, some GUTs suggest that **magnetic monopoles could exist** in principle
- They would be **produced in the very early Universe** when the energy is high enough to produce basically anything
- So where are they?

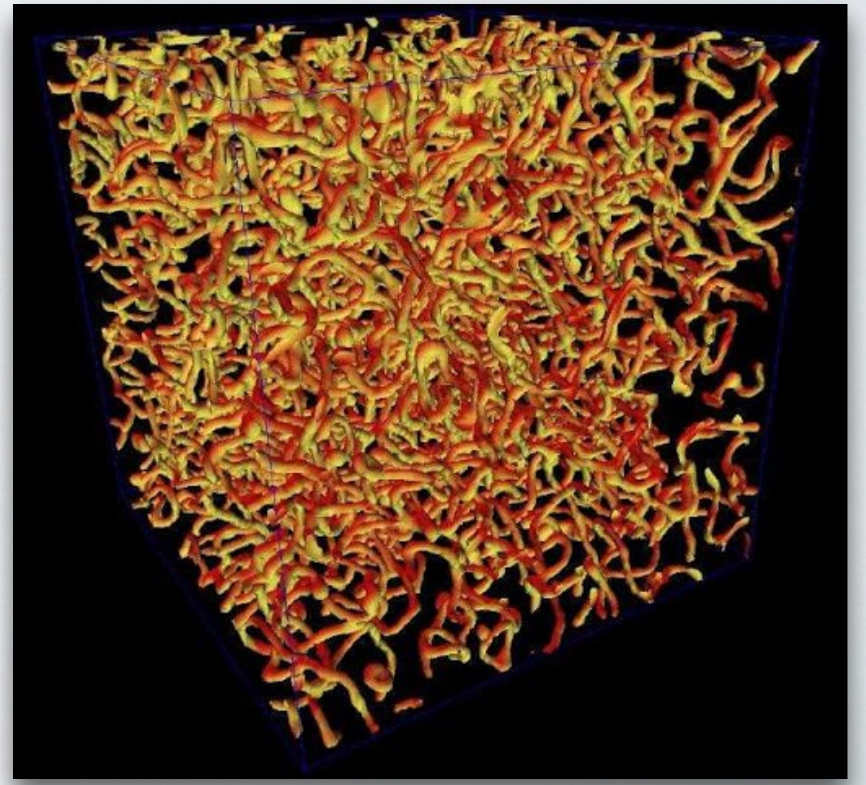
Youtube channel 3Blue1Brown

Topological defects

- Analogy: the freezing of water
  - Starts at certain locations and crystals grow; when crystals merge to form the solid, there are dislocations where the crystals meet
  - The process of freezing is called a "phase transition" (matter changing from one phase to another)
- **Quantum fields** related to particles and forces in the very early universe can undergo **phase transitions**
- They start at particular points in space and grow at light speed; get "**topological defects**" where different regions meet
  - **Domain walls** (2D sheet-like structures)
  - **Cosmic Strings** (1D string-like structures)
- They have observable signatures, e.g., strings would gravitationally lens CMB; but **no defects have been observed**
- **Inflation** would drastically **dilute the density** of such objects from the Planck epoch; probability to see them would now be very small
- Baryons and dark matter are **created after inflation**, so their density is not reduced

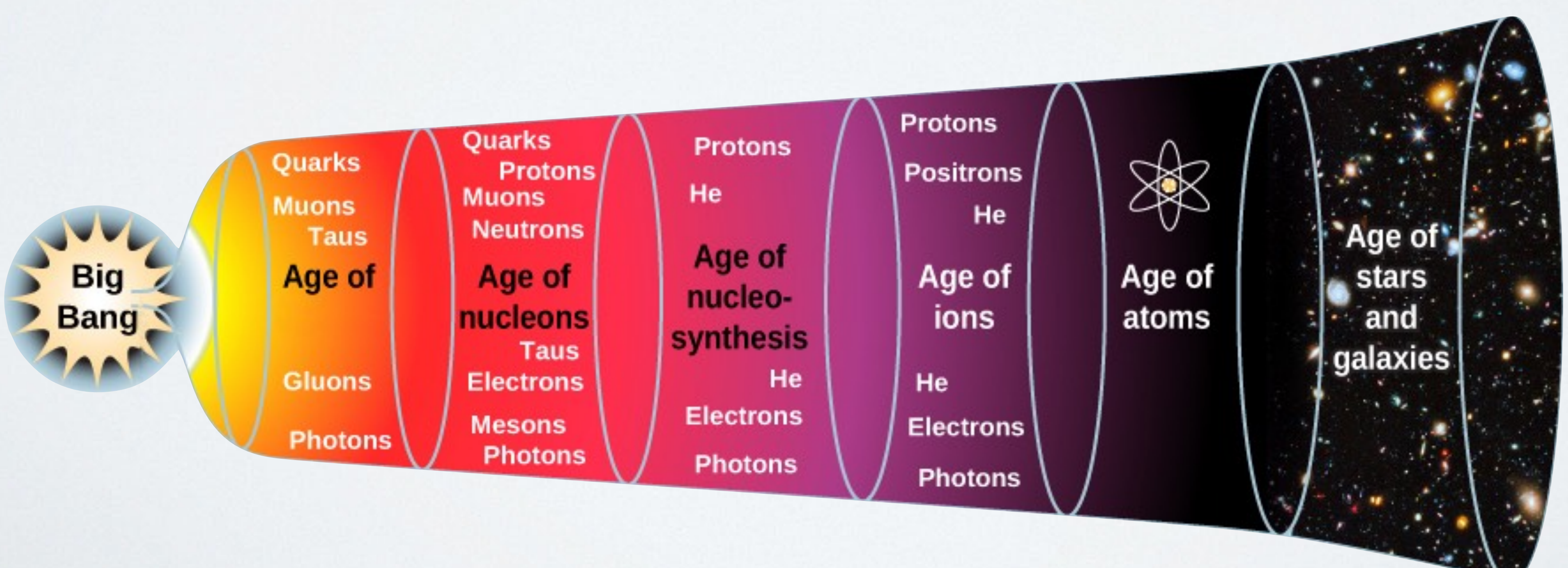


Magnetic domains



The bottom line

- Inflation is purely theoretical
- But it fixes many "ugly" issues in cosmology
  - Space is **flat** because a (possible) initial curvature was inflated away
  - Patches of universe that make up the CMB were **causally connected** before they were separated by inflation
  - We have no seen strange **relics** from the early Universe (such as magnetic monopoles or topological defects) because their density was drastically reduced during inflation
- There are (indirect) signatures that we can look for:
  - Details of the CMB radiation (polarization)
  - Gravitational waves from the early Universe caused by inflation



Participation: Discussion

How would changing the fundamental properties of the Universe change our existence?

We might want to ask ourselves some of these questions:

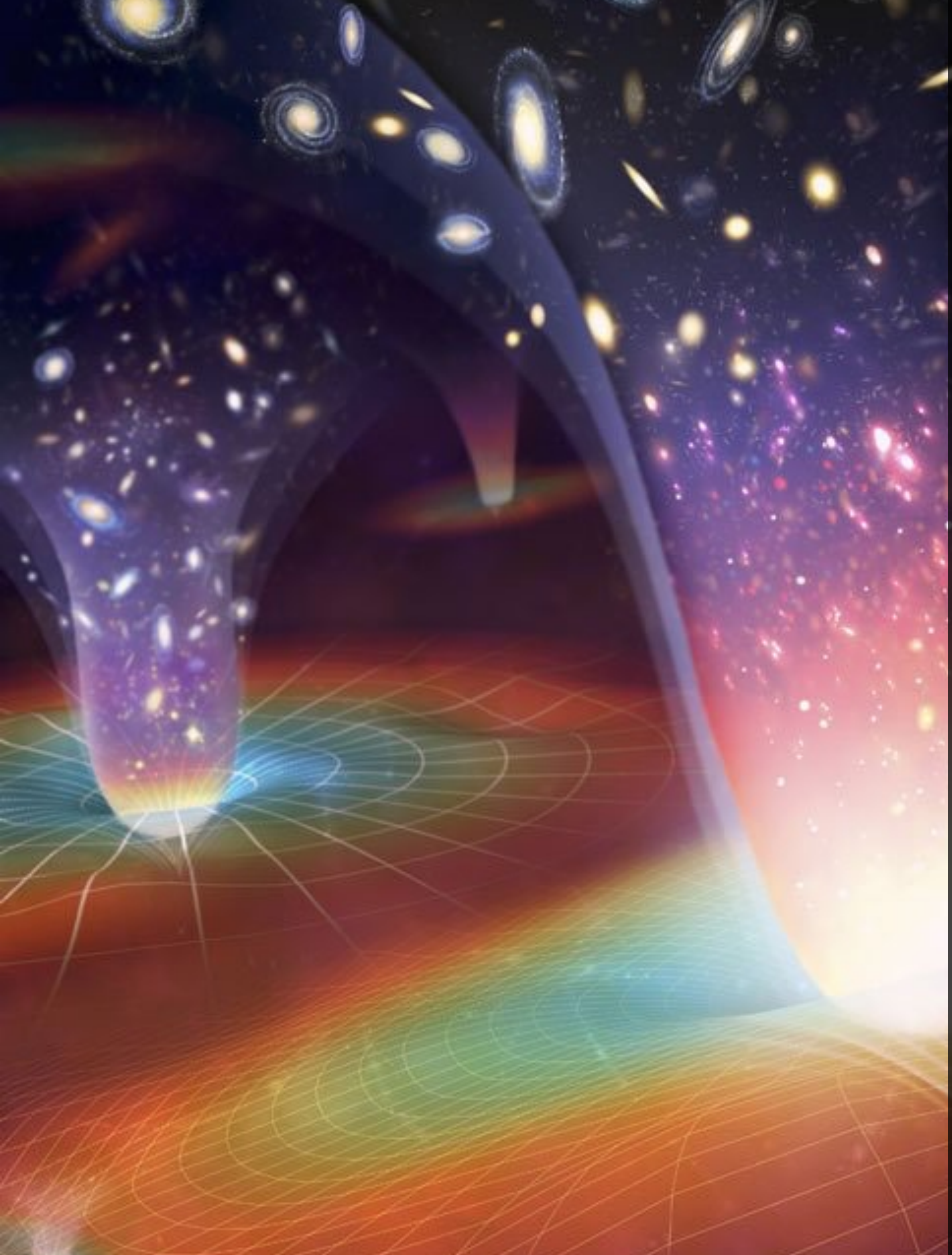
- would there still be any baryonic (normal) matter in the Universe?
- would there still be atoms?
- would the universe still form structure such as galaxies and stars?

There are quite a few "free parameters" or physical laws we can change, e.g.:

- the existence / strength of the fundamental forces
- the masses of the elementary particles
- the strength of the cosmological constant
- the baryon-dark matter ratio

10 minutes

Part 5: Multiverses



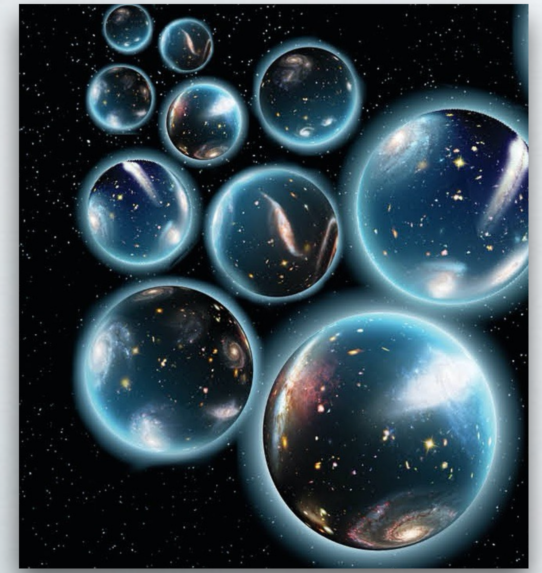
Multiverses

- Basic idea: inflation occurs due to fluctuations in some quantum field in the early universe
- Some regions inflate and some do not; our observable universe is part of one of the “bubbles” that did inflate
- Larger “super-universe” may be continually spawning new bubble universes within it

space-art.co.uk / M. Garlick

Multiverses

- Max Tegmark came up with a taxonomy of four levels of multiverse theories
- **Level 1:** Extension to our universe. There are many Hubble volumes beyond the observable universe, but they follow the same physical laws
- **Level 2:** Multiverses (bubbles) with possibly different physical constants emerge
- **Level 3:** Many-worlds interpretation of quantum mechanics: Every time an event occurs, the universe splits into all possible outcomes (think Schrödinger's cat)
- **Level 4:** "Ultimate Ensemble" of mathematically possibly universes



A way out of fine-tuning problems?

- If there are many bubble universes, they might have different properties
- Would imply a loss of predictability: physical constants would take on whatever values they happen to have in our patch of the multiverse!
- Humankind might only have been able to evolve in a bubble with properties similar to"our universe"
- There may be other interesting bubbles out there, but it is beyond the realm of science to know what they are like (since they are causally disconnected from us)

Image: A. Kamajian

Take-aways

- Standard Big Bang cosmology suffers from the **flatness, horizon, and relic problems**
- All three problems are solved by inflation: a hypothetical **period of exponential expansion** in the very early Universe
- **Multiverses** are a theoretical speculation, but they could explain certain **fine-tuned** properties of our cosmos

Next time…

We'll talk about:

- Fine-tuning and the anthropic principle

Assignments

- Post-lecture quiz (by tomorrow night)
- Homework #5 (due today)
- Homework #6 (due 12/9)