

# Astro 5 – Life: Why Our Universe is Suitable for Life

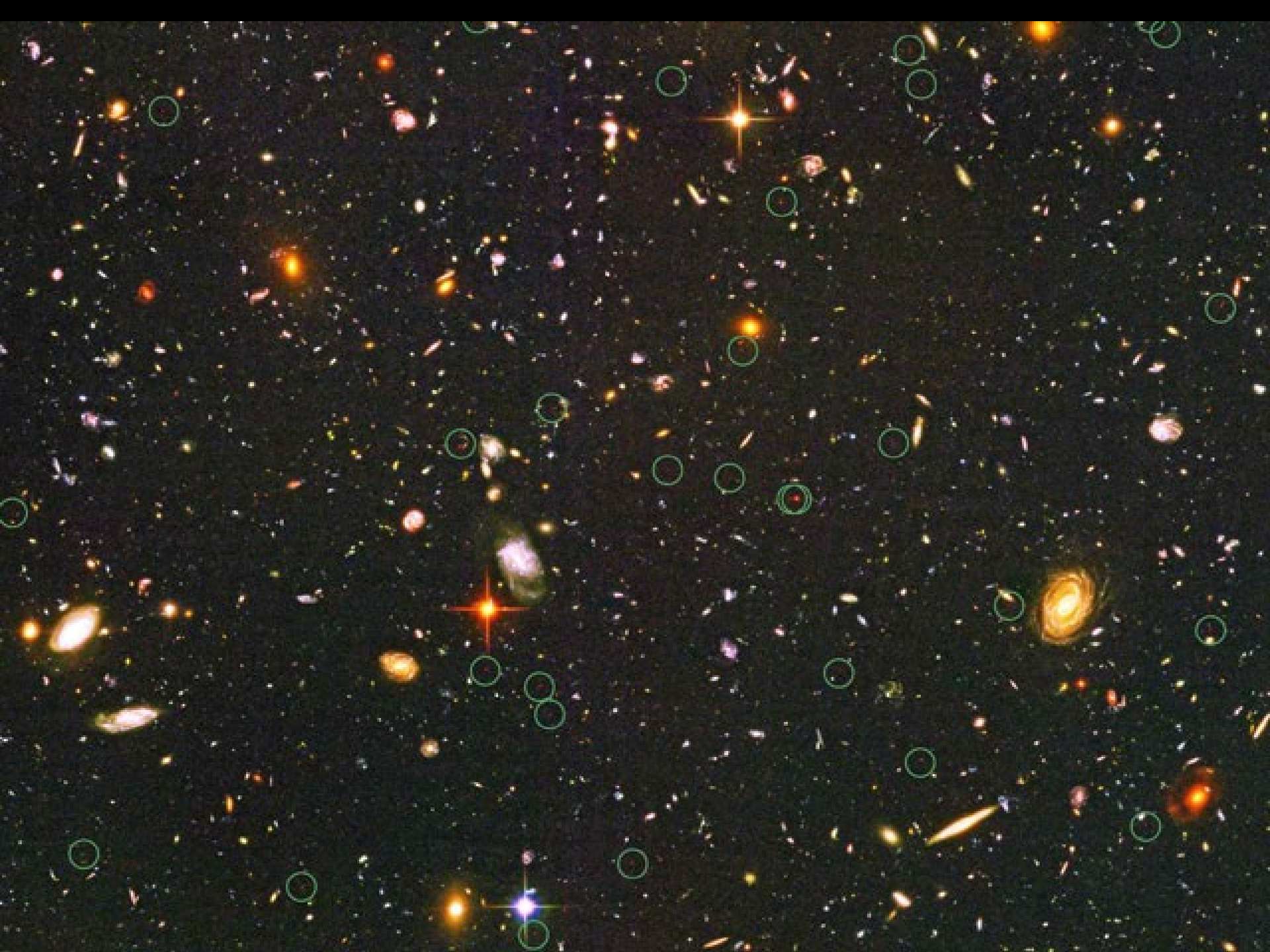
Dr. Richard Nolthenius

- Expanding Universe – consistent w/ a Big Bang?
- Olber's Paradox
- Large Scale Structure and relation to Dark Matter
- Evidence for the Big Bang
- The Cosmic Microwave Background
- The abundances of the elements
- Problems with the old Standard Big Bang – Symmetry breaking and Inflation
- Matter/Energy Density and the future of the Universe
- Introduction to Inflation.
- Eternal inflation could solve the mysteries of the Standard Model, our Universe and the existence of Life (see Chap 24)

# Evidence that the Universe had a Beginning

Notice - Looking **out in space** is looking **back in time** (because of the finite speed of light)

- So, Big Telescopes = Big Time Machines!
- We can SEE what the younger Universe looked like, by just looking far out into space with big telescopes!
- How to look far out in space? Look at a galaxy, measure its spectrum lines and therefore redshift to get how fast it's moving away from us  $V$ , then...
- Hubble Law:  $V=HD$ . Large redshift = large distance = large look-back time
- So, What do distant galaxies look like...?



# Distant Galaxies DO Look *Different*

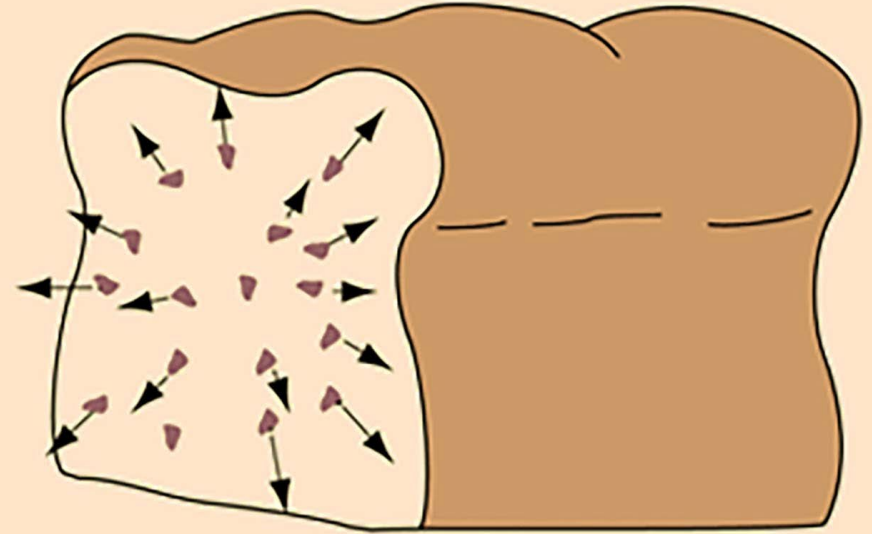
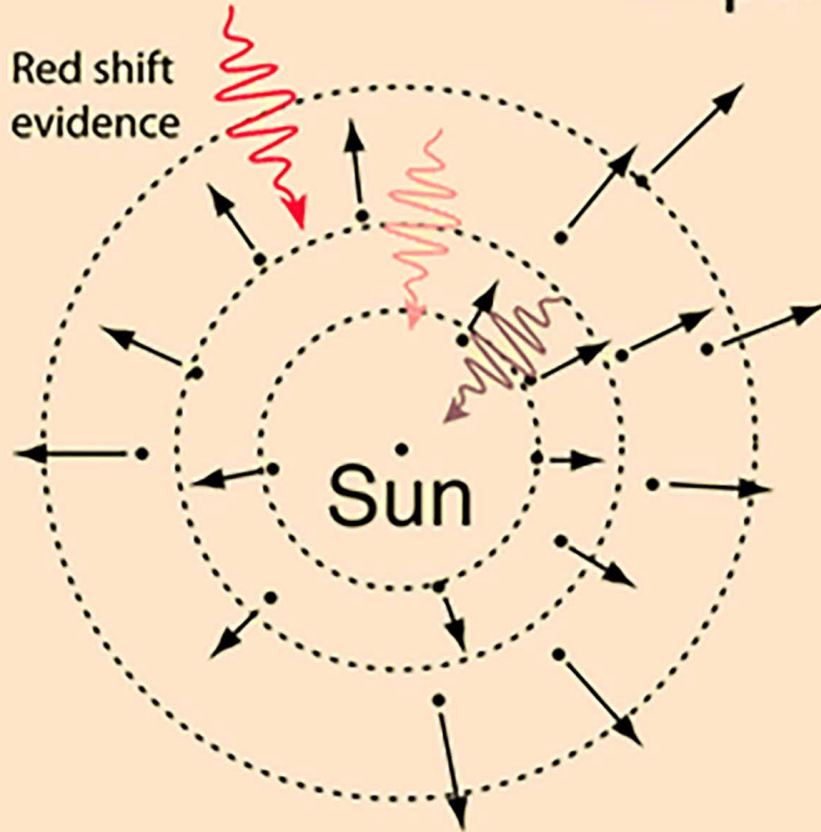
- Active galaxies are more common far away and so in the distant past
- Quasars especially are all very distant. None in the local universe...i.e. none in Today's universe.
- Irregular Galaxies are more common far away and therefore in the distant past.
- Therefore, the universe IS evolving! We do **not** live in a static, “Steady State” universe

# The Expanding Universe: Hubble's Law

- $V=HD$ ; It's a "Raisin cake" expansion; velocity of a galaxy away from us is proportional to its distance, just like raisins with more yeast between them will move away from each other faster
- This kind of expansion is ***consistent*** with a Big Bang origin, which is a necessary first step.
- Does it prove there was a Big Bang? No...
- Can we find stronger evidence? Let's use a little logic as we go backwards in time...

# A Universe of Galaxies as Raisins in a BAKING cake (gotta be in the oven!)

Expanding universe



Every raisin in a rising loaf of raisin bread will see every other raisin expanding away from it.

$$H = 71 \text{ km/s/Mpc}$$

# Going Back in Time...

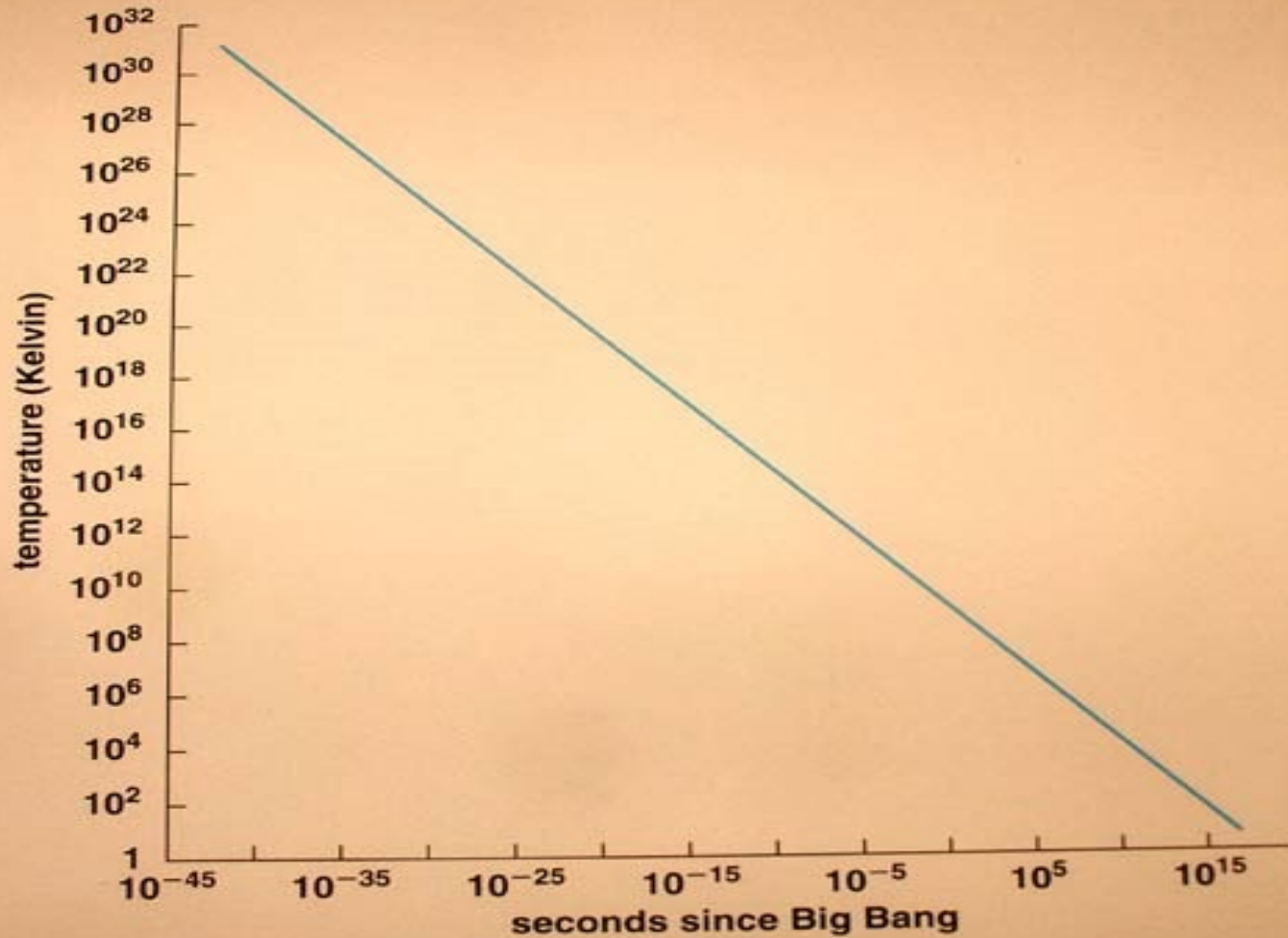
- Density goes up and up
- Far enough back, it's all raw material: gas
- Go back far enough,  $T=3,000\text{K}$  = ionization temperature for hydrogen. This happens only  $\sim 300,000$  years after the supposed Big Bang
- But ionized gas is opaque: So, we should see through closer, more recent, and therefore cooler transparent gas until our line-of-sight hits gas so young and so hot that it's ionized and opaque.
- Thus: A Prediction –
- We should see very distant 3,000 K gas radiating at us from all directions = **The Cosmic Microwave Background Radiation. The CMB!**

# **Photons were first able to travel freely, with little chance of further absorptions, beginning 300,000 years after Big Bang**

- Universe was opaque until  $\sim 300,000$  years after Big Bang, when it cooled to about 3,000K
- Then cool enough for protons and electrons to combine to form hydrogen and this neutral gas was  $\sim$ transparent; only able to absorb certain narrow discrete wavelengths, most pass through it unabsorbed.. (just like air around you behaves the same)
- The Universe has been transparent ever since.



# The Temperature of the Universe (The Cosmic Background Radiation) over its history



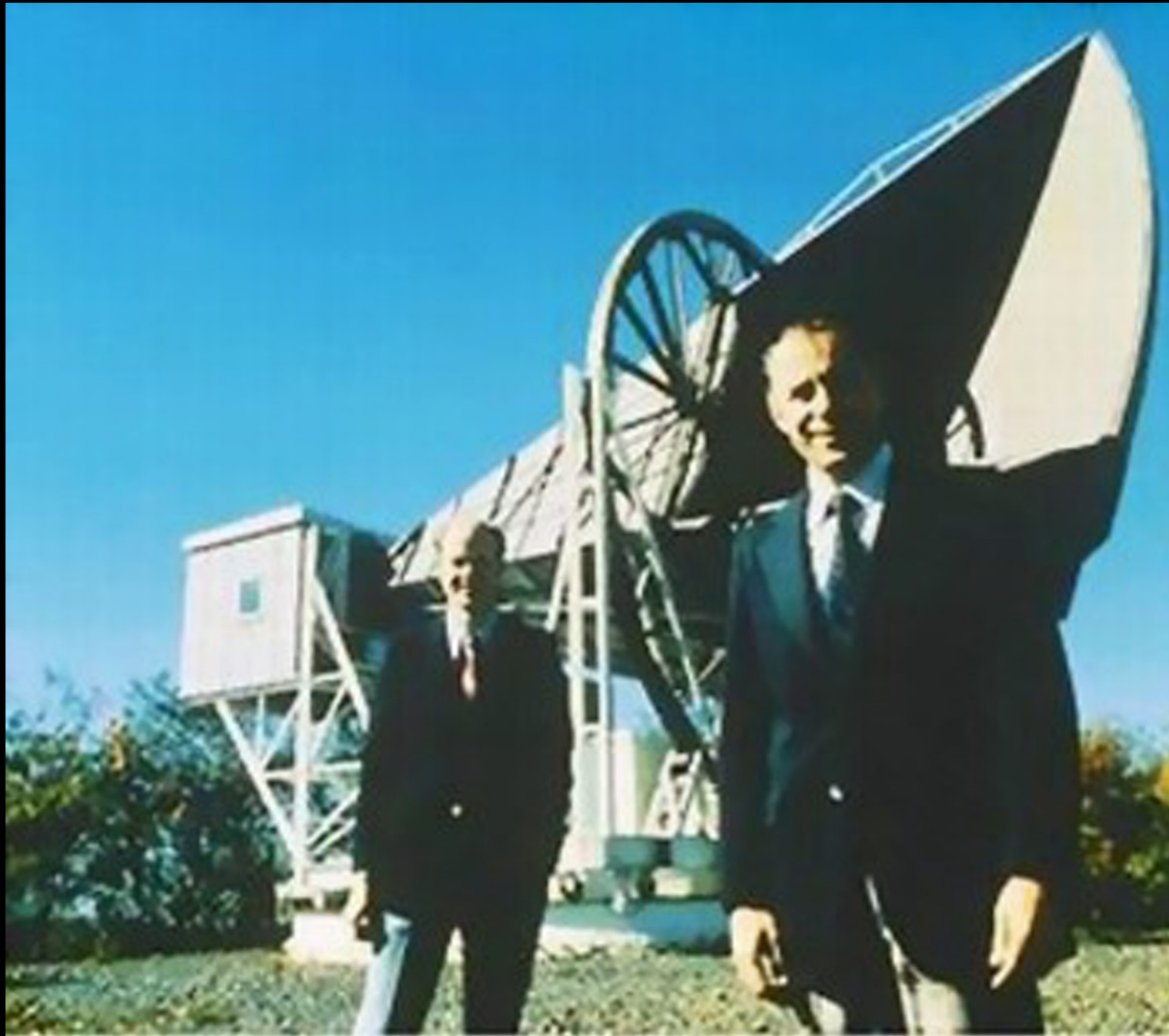
# What should this Opaque “Surface” look like?

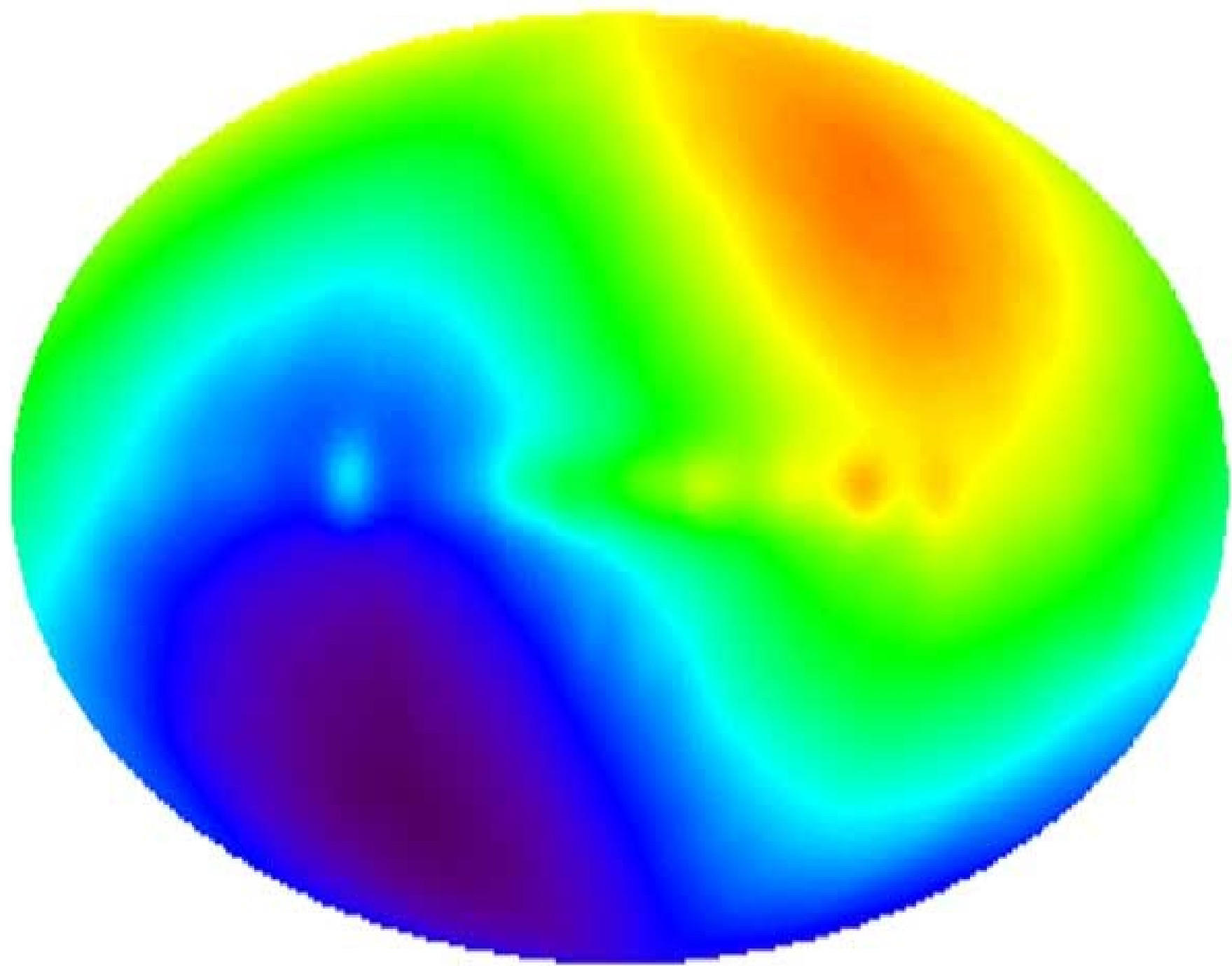
- Note that since it's coming from material vastly far away, the Hubble Law says it's moving away from us almost at the speed of light. Working out the numbers – 99.9% of the speed of light!
- So, it'll be Doppler-shifted by a factor of  $\sim 1300$ , so it will not look like 3,000K thermal light, it will look like 2.7K thermal light
- This is not visible light, nor even infrared light, but *microwave* radiation
- Princeton physicists realized this in the late '40's and searched for it with new microwave detector technology in the 1960's

# The Cosmic Microwave Background Radiation

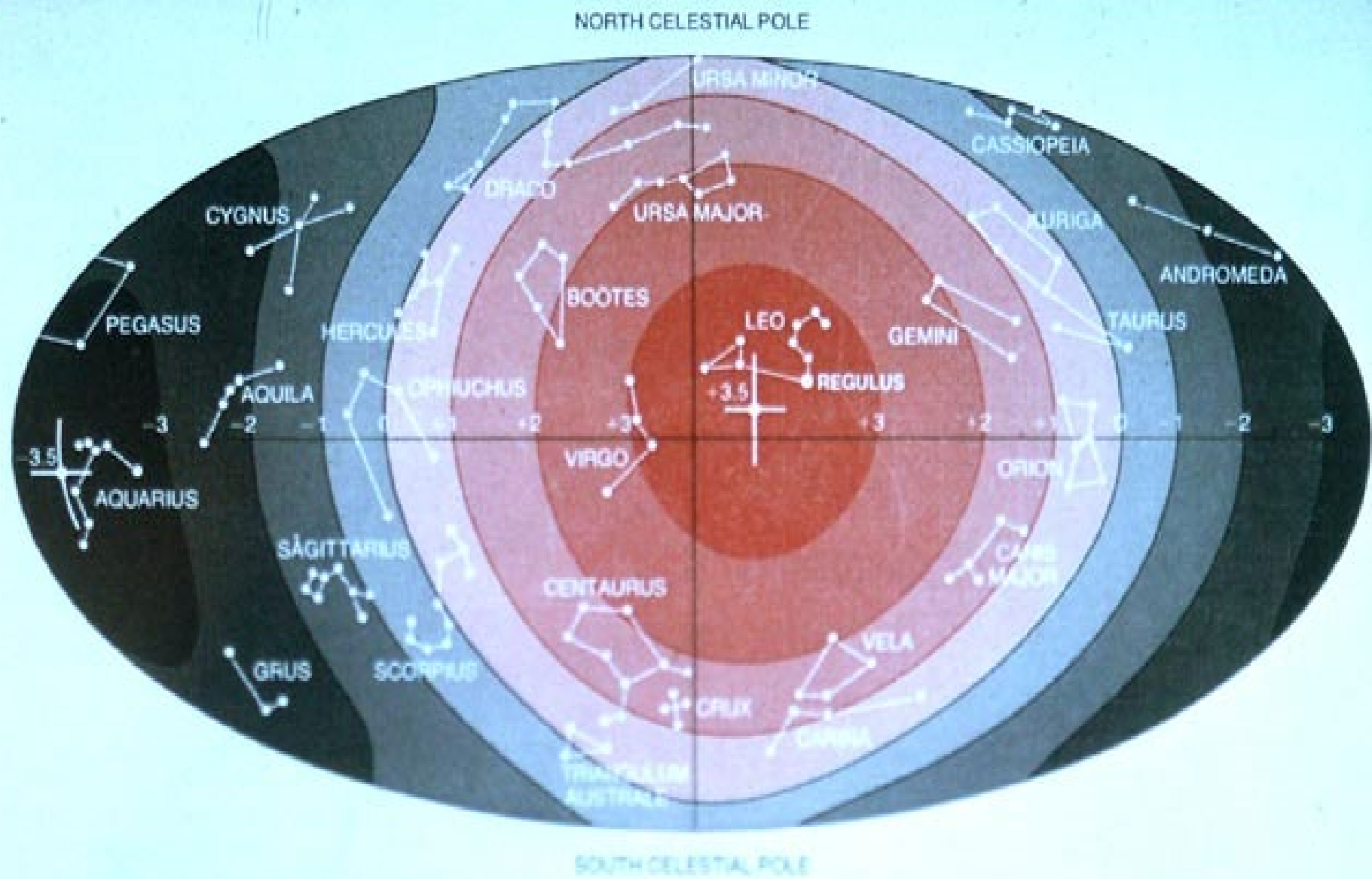
- But they were scooped by a couple of Bell Labs engineers calibrating a big microwave antenna for the first intercontinental satellite telephone service
- Discovered in 1965, we're being bathed by thermal microwaves from every direction
- Here's the first map of this radiation, constructed from data from the [COBE mission](#)...

**Penzias and Wilson, trying to calibrate the first intercontinental phone call system for AT&T, Discovered instead the Big Bang Glow – the CMB**





- Note the bumps along the “equator” – these are foreground microwaves from interstellar clouds in the Milky Way Galaxy.
- In order to properly measure the properties of the **Cosmic Microwave Background (CMB) Radiation**, these foreground contaminants must be removed. It’s a very tricky job, and it took a number of years of work to do it well.
- Here’s an all-sky map, projected differently, and showing constellations, of the resulting hotter and colder directions for the CMB (next slide)



**ANISOTROPY OF THE BACKGROUND RADIATION**, as deduced from the U-2 survey, is plotted on the celestial sphere in contours of one millidegree K. The "hottest" spot, indicating the direction of the earth's maximum relative motion toward the background radiation, lies in the constellation Leo at right ascension 11 hours

( $\pm 5$  hour) and latitude six degrees ( $\pm 10$  degrees). The "coldest" spot, the direction in which the radiation is most "reddened" by the earth's relative motion away from the incoming photons, lies 180 degrees away in Aquarius. If the temperature difference between hottest and coldest points is plotted against distance, the result is a cosine curve.



# Let's Pause Here and Digest...

- Centered on every place in the universe, including us, is an imaginary sphere called its “**observable universe**”: that sphere includes all places from which light has had a chance to get to us since the Big Bang.
- If the Universe is 13.7 Billion years old, as the evidence says, then our Observable Universe is 13.7 billion light years in radius. That “edge” is called the “horizon”.
- It's an edge in TIME, not an edge in SPACE!
- It is NOT the ENTIRE Universe. Our ENTIRE Universe is almost certainly VASTLY larger, or even infinite in size.



# Here's a Little "Thought Experiment"

- Imagine the entire universe were filled with firecrackers. And at a single moment in cosmic time, every firecracker went off.
- What would you hear?
- --- one GiNormous ear-splitting "BANG"?
- --- or, a continous ROAR that would never end?

# You'd Hear a Continuous Roar...

- ...that would never end. As more and more distant sources of the instantaneous ignitions finally arrived at your ears.

# But Wait! (you say...)

- That means that the stuff out beyond the horizon must be moving away from us **FASTER** than the speed of light!
- In a way – yes. But space itself does not have such speed limits. Only matter within space.
- **Space is expanding, carrying the galaxies with it.** These galaxies beyond the horizon are unobservable, not just due to limited technology, but even in principle, so it's not meaningful to talk about their “velocity relative to us” since ultimately velocity is a measured concept requiring the ability to measure distance to the object.
- If you delve into it, you'll be impressed with how deeply Relativity shows how important the *observer* is!

# The Discovery of the CMB Showed...

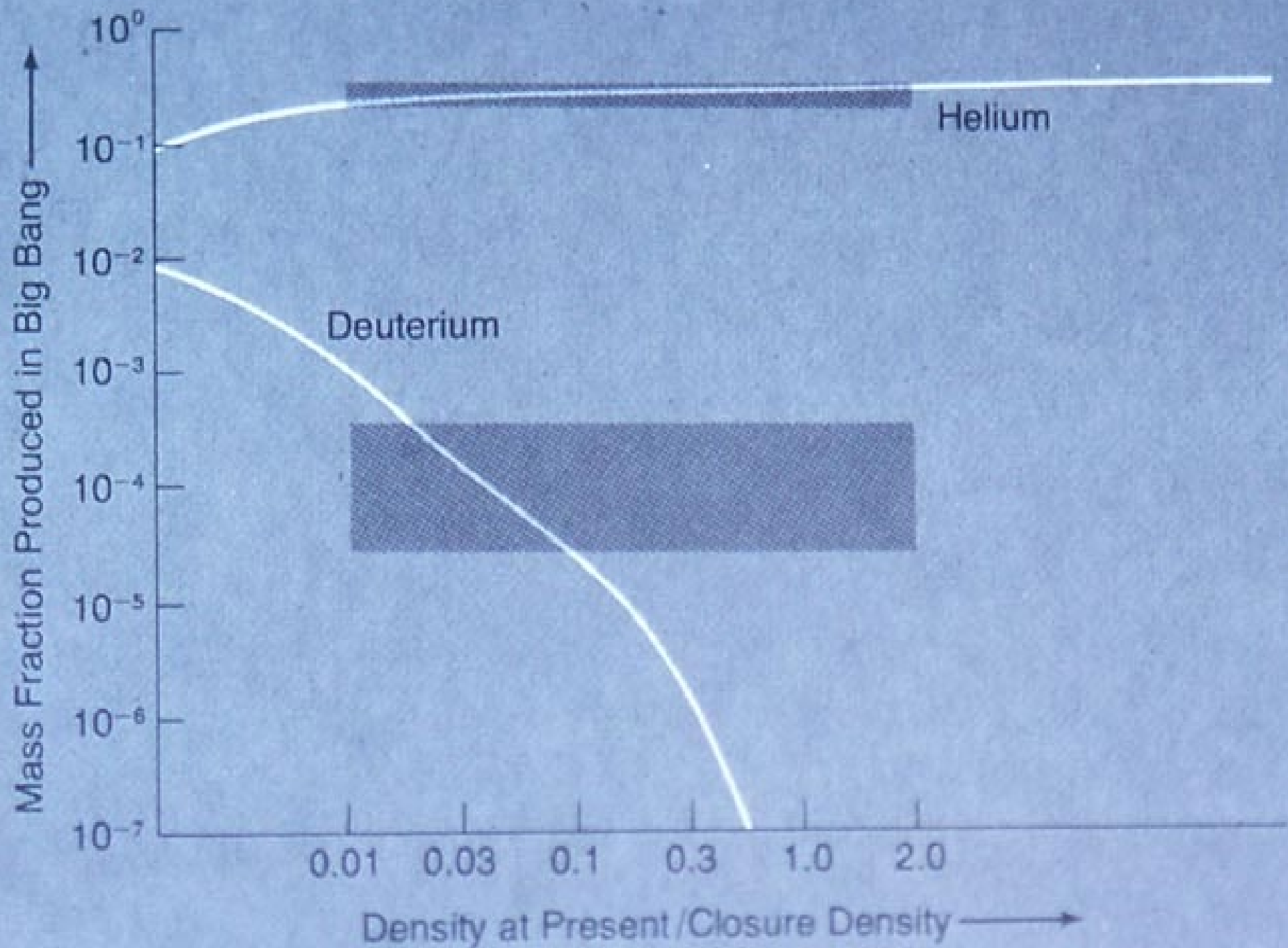
- The Big Bang origin and evolution of the universe can be traced back 99.9% of way to that first moment, with strong observational evidence.
- Can we find evidence going back even closer to the Big Bang itself?
- Since the universe is opaque, we can't directly see past the CMB. But everything around us was part of the Big Bang, and it all carries clues...

# 1~3 minutes after Big Bang...

- Temperature is ~few million degrees K
- Hot enough for nuclear fusion
- Some of H cooked into Helium but...
- By the time there was enough Helium around, the density was already too low for Helium fusion
- So – ***prediction***: pure hydrogen and helium in earliest stars (and only 1 part per 10 billion of Lithium 7 and Beryllium 9).
- ***Test***: Abundances of the elements from the oldest stars

# The Oldest stars we can find and Study...

- Are in the globular star clusters of our own Galaxy
- 12-13 Billion years old, measured by the main sequence turnoff point on their HR diagrams, as we talked about in the “stars” chapters
- These are made up of **pop II stars** – almost pure hydrogen and helium, in exactly the proportions predicted – ***Test successful!***
- But wait! We can say more... the amount of “heavy hydrogen” (deuterium) is very sensitive to the amount of ordinary matter...



# **This shows that only 4% of the Matter and Energy of the Universe is made of Ordinary Matter**

- This is yet one more piece of evidence showing the existence of Dark Matter, since the true density of all matter must be about 30% if the whole observational/theoretical picture is to fit together.

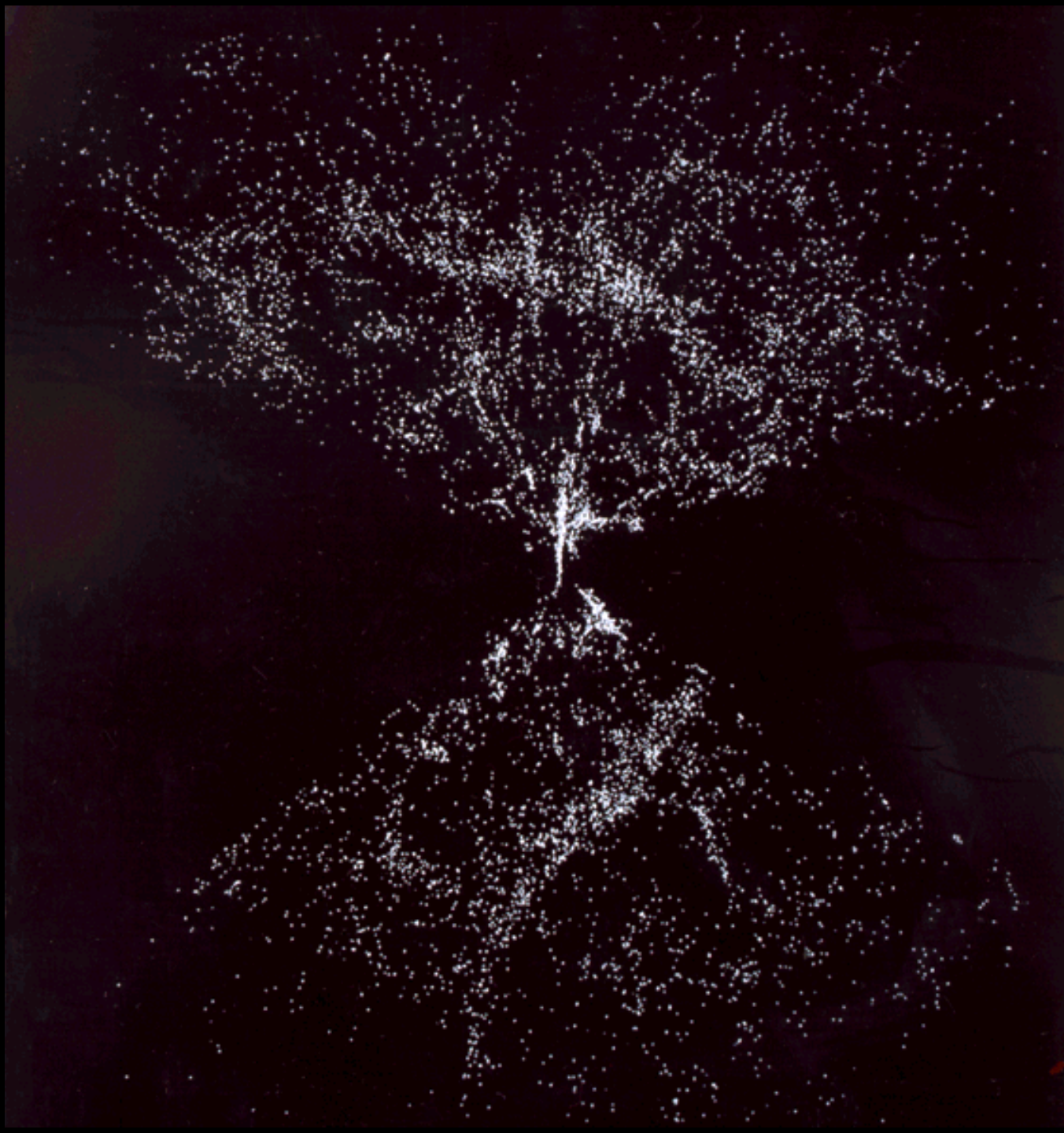


# How Did Structure Emerge from this Uniform “Primordial Soup”?

- Current universe is lumpy. *Very lumpy!* Dense galaxies surrounded by lots of fairly empty space, and even within galaxies, dense stars surrounded by lots of empty space.
- Gravity appears to be why
- Overdense regions will get more overdense with time, as material falls into the initial density fluctuations.
- Need some kind of initial density fluctuations in order for gravity to do the rest...
- Where did the initial density fluctuations come from? Ah! THAT's the big question... We think we know, but let's save that for later...
- There are more clues buried in...

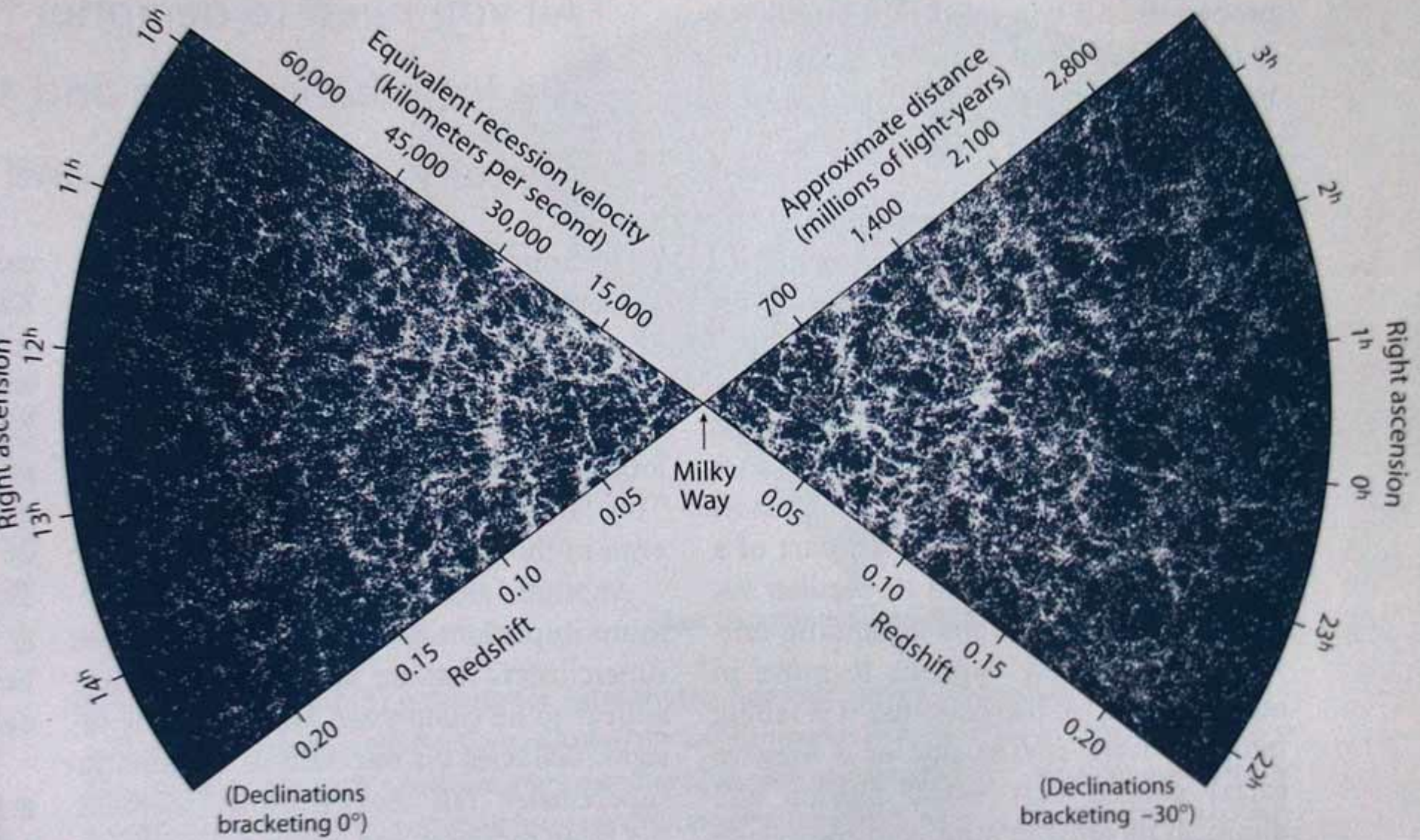
# ...The Shape of the Universe's Large Scale Structure

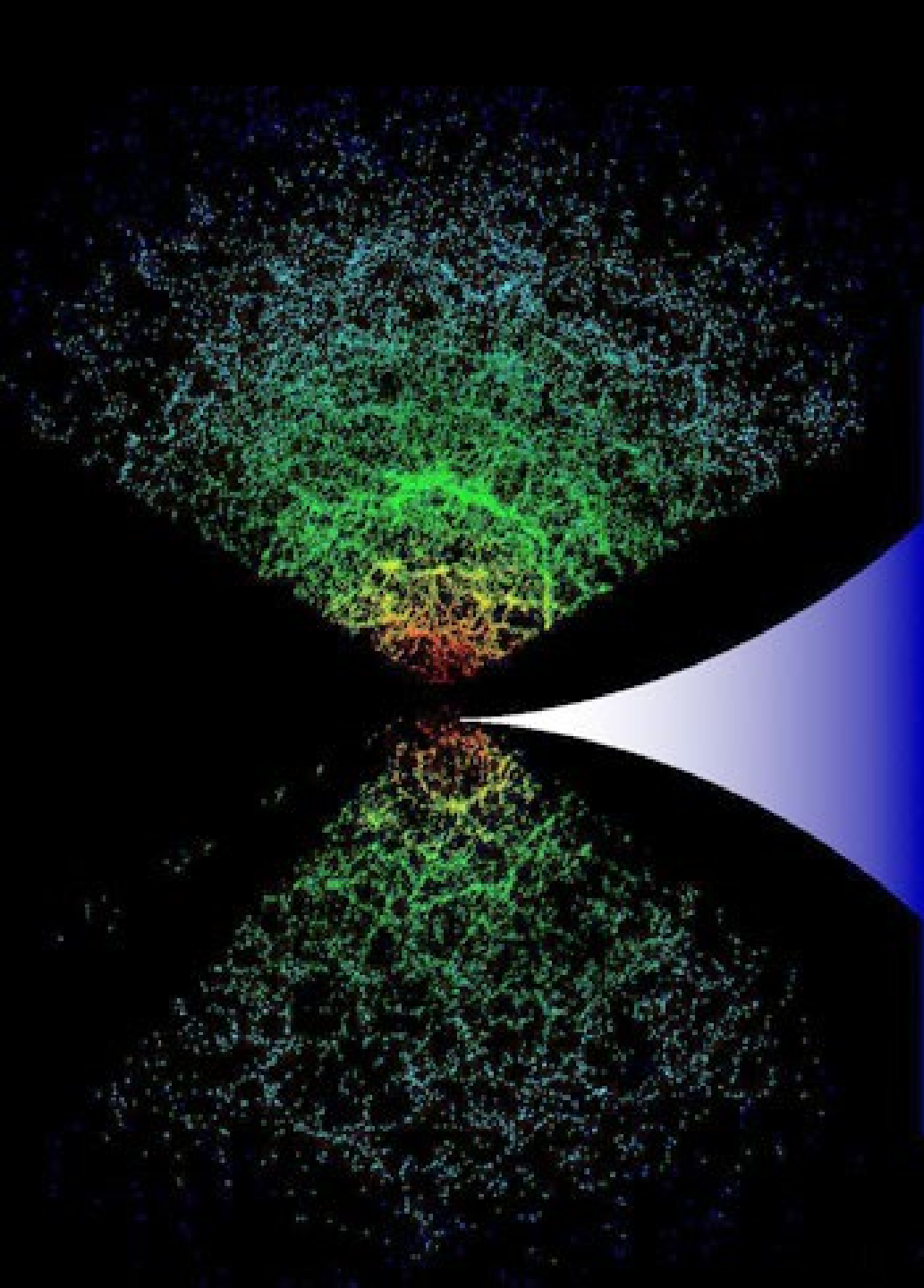
- **Topology** = the geometric form of the matter concentrations
- Lots of possibilities it could've been... “meat ball”, “Swiss Cheese”, “filamentary”, ...
- Let's take a look...



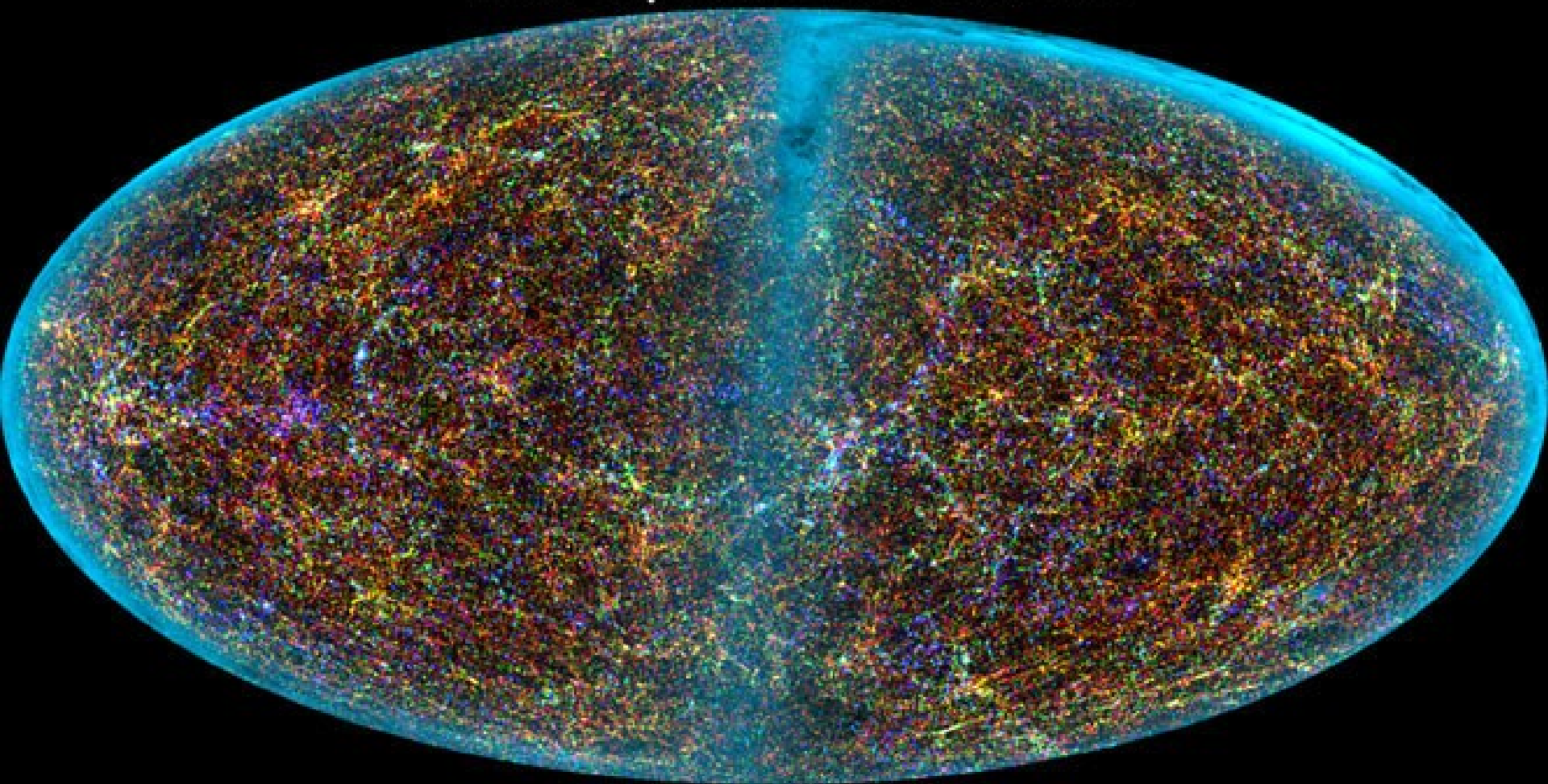


# Galaxies: knots inside Dark Matter filaments

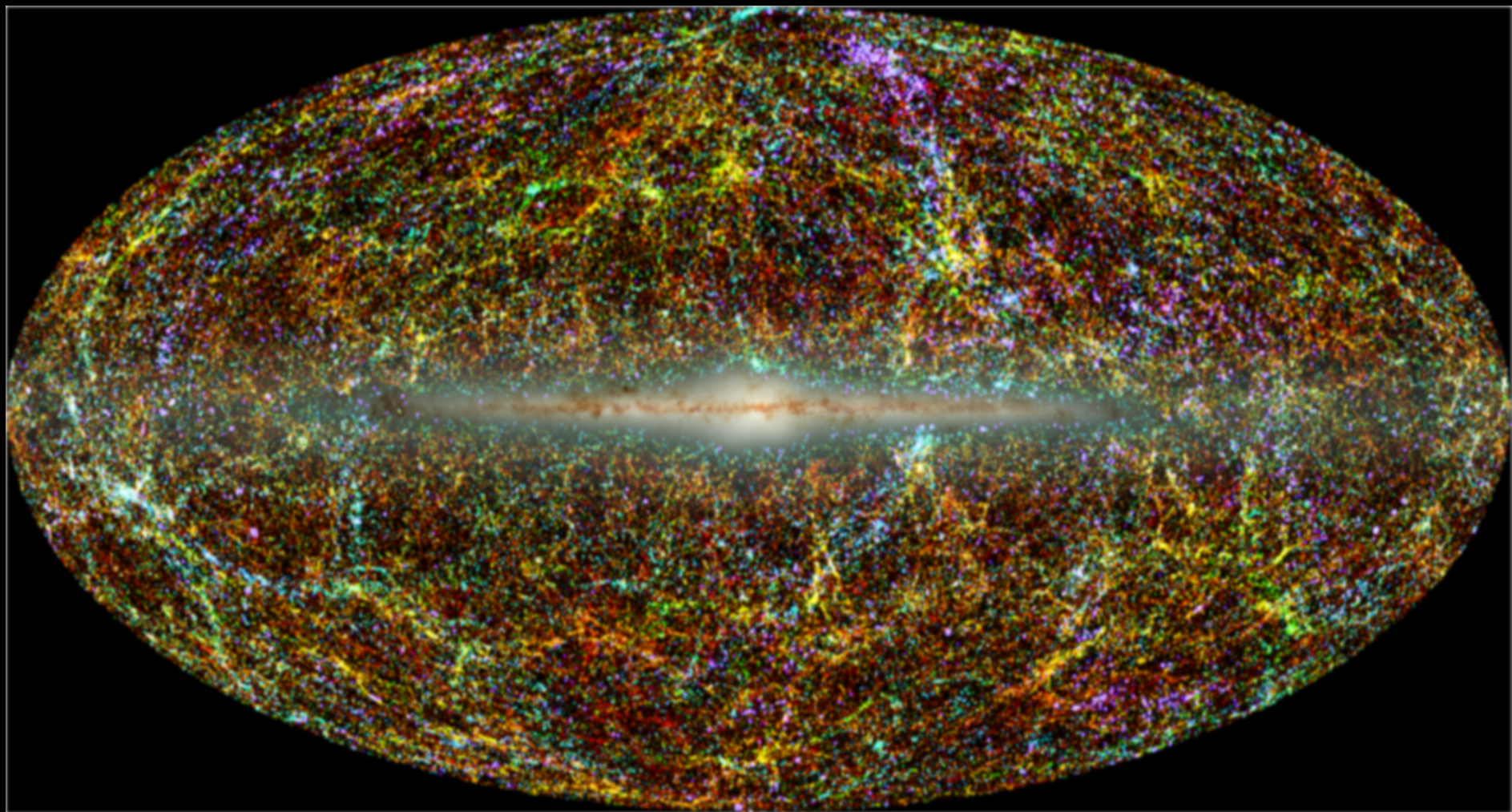




*SuperGalactic View of the  
Near-Infrared Local Universe*







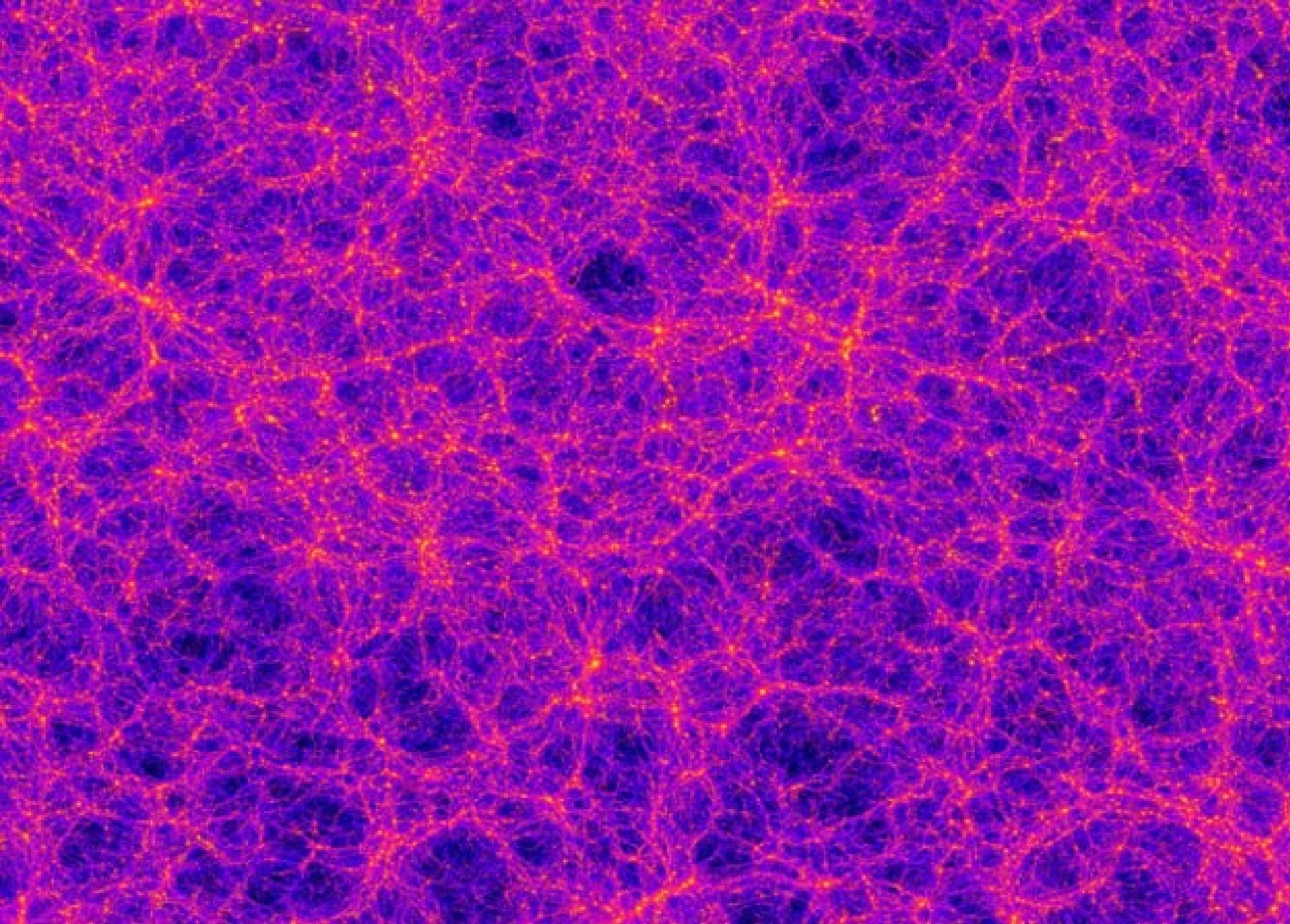
# The Structure and Motions of the Local Universe

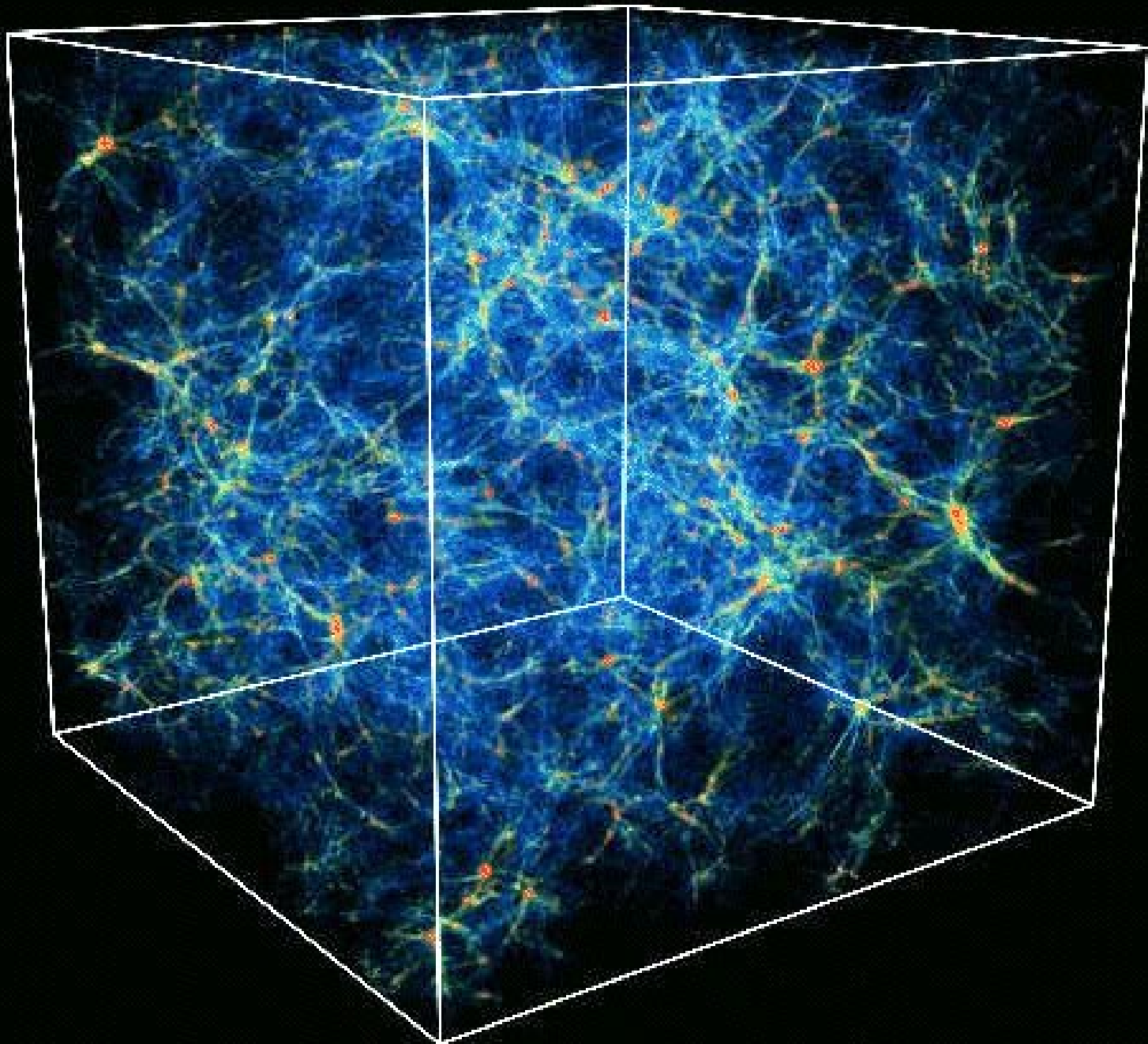
- There is a new, very beautiful 17 min narrated animation showing the positions and motions and sheets, filaments, groups and clusters of thousands of galaxies in the relatively nearby Universe.
- See on this [link page](#) the link near the beginning labelled “video” to see it.

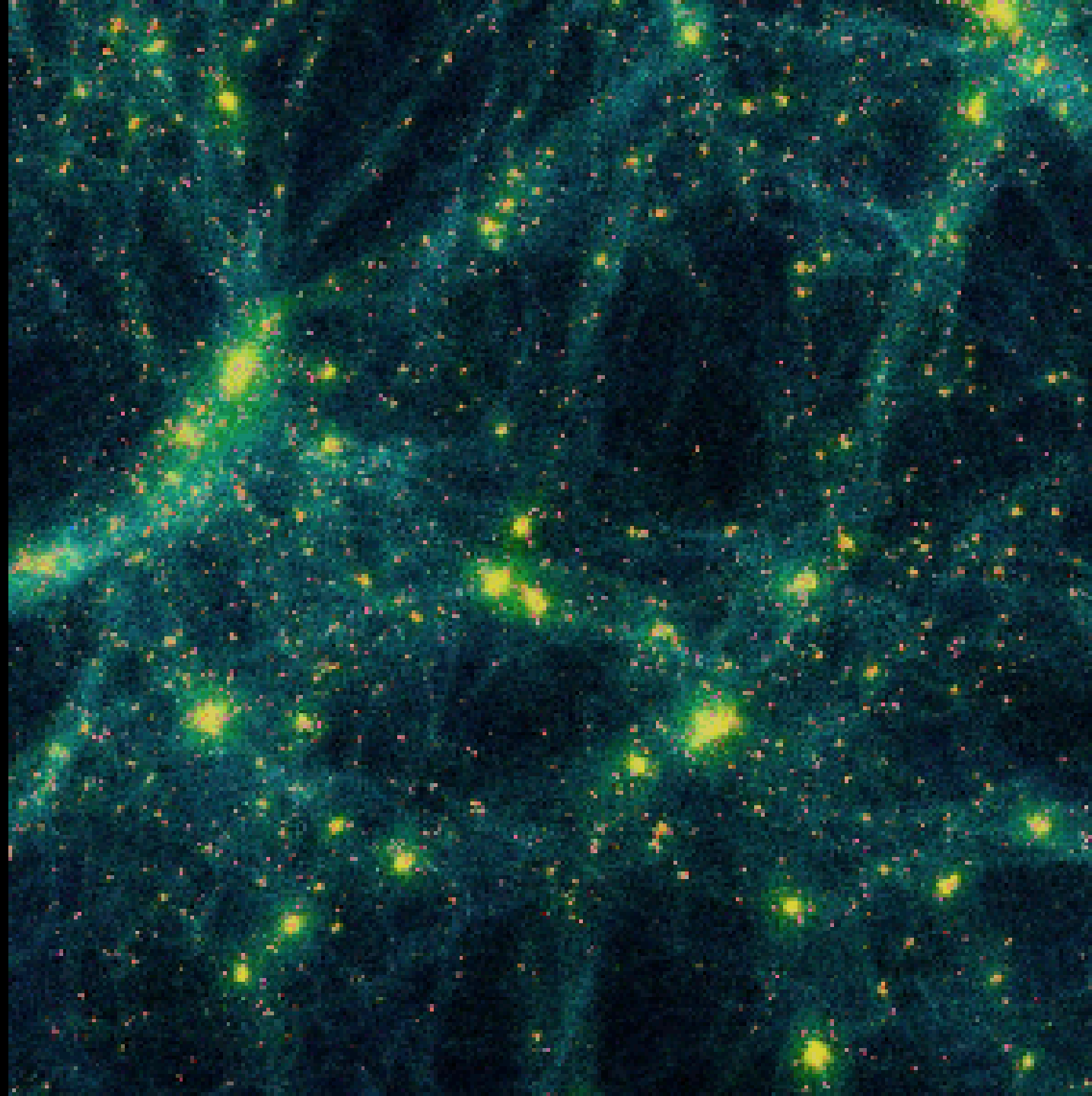


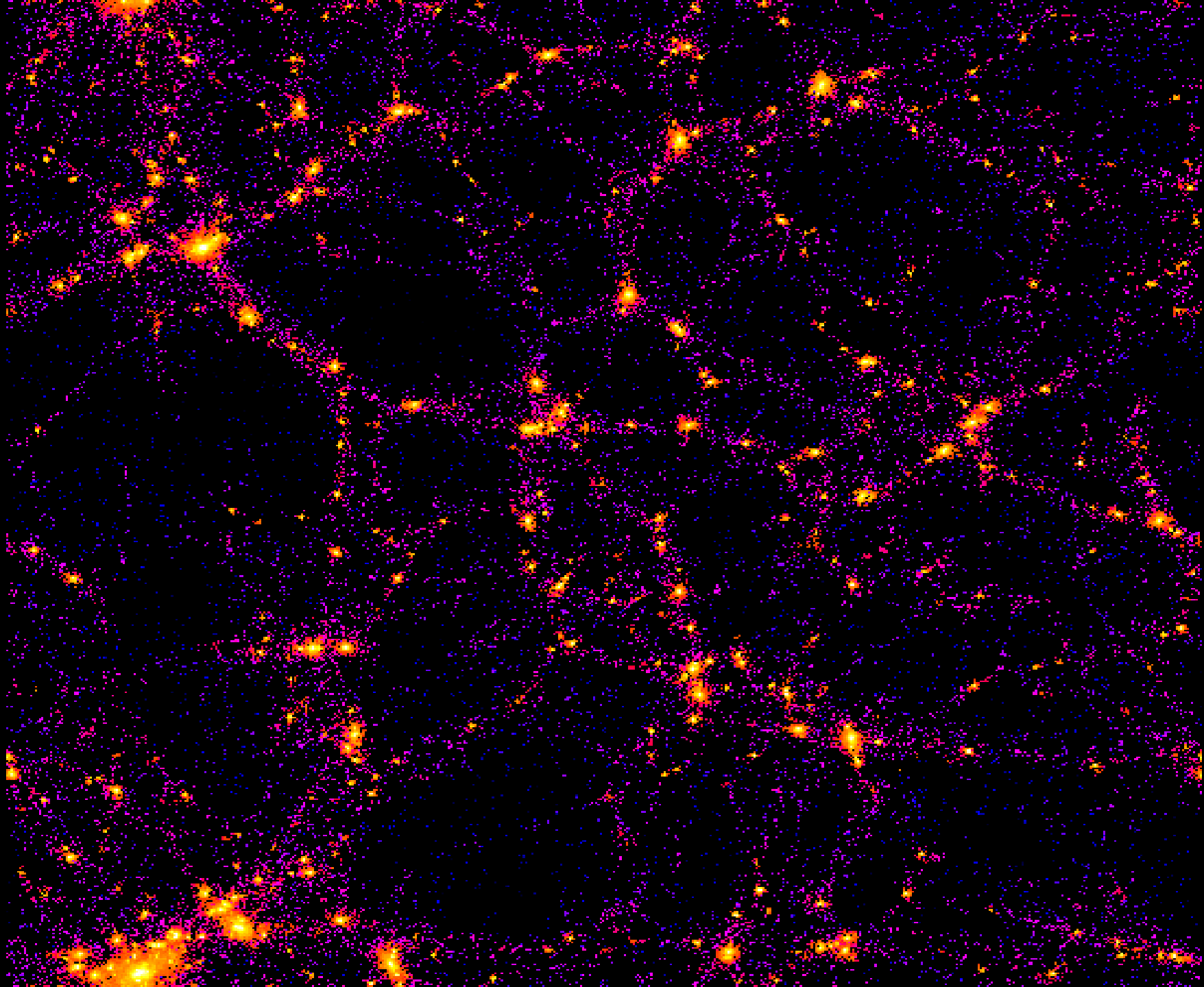
# Numerical Simulations of the Evolution of the Universe

- How does this reality compare to cosmological models. Have we captured the essential physics?
- Cram a cosmological model, its initial conditions, a bunch of physics... all into a supercomputer, and evolve the universe forward to the present day and see if it looks like the real thing...
- Volker Springel had one of the best codes in the business.
- **But UCSC's astrophysics group led by cosmologically impressive superstar Joel Primack, is the new leader! here!**









# So - Gravity Made Large Scale Structure

- **The large scale structure is filamentary!**
- All of this confirms – gravity was the prime mover.
- Overdensities collapsed under gravity; first along one direction (making sheets), then along another (making filaments), and eventually everything drains into clumps (galaxy clusters), but the universe isn't old enough for this process to be very far along yet (remember; the structure in a Cold Dark Matter universe forms on small scales first, and big scales only later on).
- This process proceeds at different rates depending on how overdense the area is, so we expect to see a mixture of filaments, sheets, and clusters in the real universe – **exactly what we do, in fact, see!**

# Next Question – How Old is the Universe?

- By measuring the expansion rate of today, we can ‘run the movie backward’ and see when everything was in one place...
- The expansion rate is measured by the Hubble parameter:  $H$ .  $H$  is now measured accurately (in the nearby universe) to be  $70 \pm 3$  km/sec of additional recession velocity for every megaparsec of additional distance.

# How do we Determine H?

- **Cepheids** = pulsating variable stars, obey a relation between their luminosity (not directly observable) and their pulsation (and brightness) period (easy to observe). The Cepheid relation is calibrated from Milky Way Cepheids who now have good distances from parallax.
- Cepheid distances can only be done for galaxies out to about 20 Megaparsecs; then they get too hard to see within the billions of other stars in galaxies; but that's many hundreds of galaxies. However, internal motion within galaxy clusters make it hard to tease out the general expansion when confined to this fairly nearby distance



# But Cepheids give us good distances to hundreds of Galaxies nearby

- And many of these have had Type Ia supernovae go off in them over the past few decades when we've had good instrumentation follow those explosions
- That allows a solid calibration of Type Ia SNe, and they are brilliant and visible to the ends of the universe, far beyond where small motions within clusters add too much noise to velocity measures.
- They allow a good determination of  $H = 72 \text{ km/sec/Mpc}$
- But there is many steps and required relations to make this work. Is there independent confirmation?

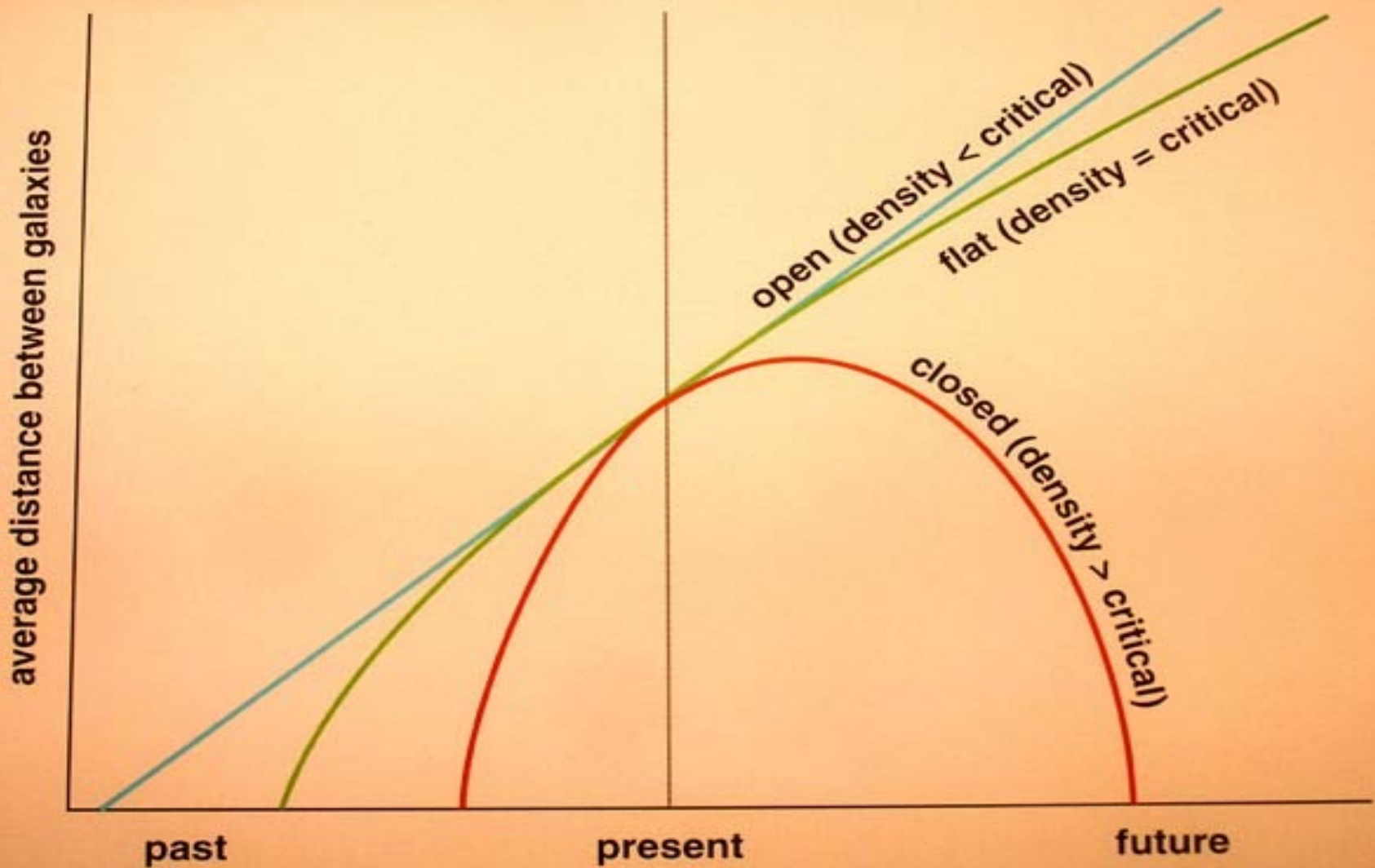
**Yes; an elegant (if rare) opportunity is  
to use gravitationally lensed quasars  
behind nearby galaxies**



# Quasars vary; Measure the time delay between the different images

- The different images travel different curved paths to get to us.
- We know the speed of light extremely accurately.
- We can see what relative paths the light must have followed to get to us, from the image.
- There is only one distance to that galaxy which allows the time delays to be what we observe, thus fixing the distance.
- Then, measuring recession velocity lets us find  $H = V/D$  for that galaxy, and repeat for the other lensing galaxies.
- The result?  $H=71.9 \pm 2.6$  km/sec/Mpc. Excellent agreement with the Supernovae method

# Scale of Universe vs. Cosmic Time. Open/ closed/ critical density versions: Tells us Age of Universe



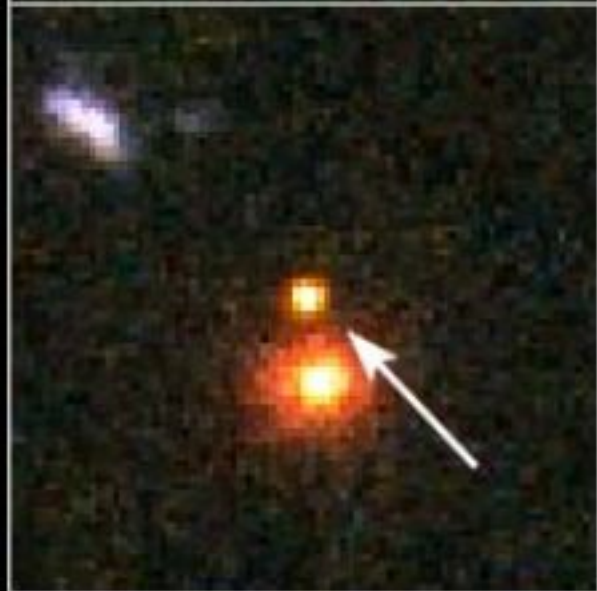
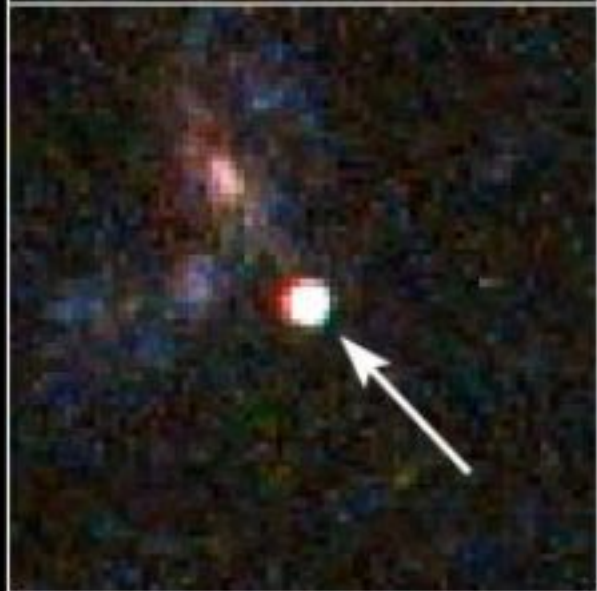
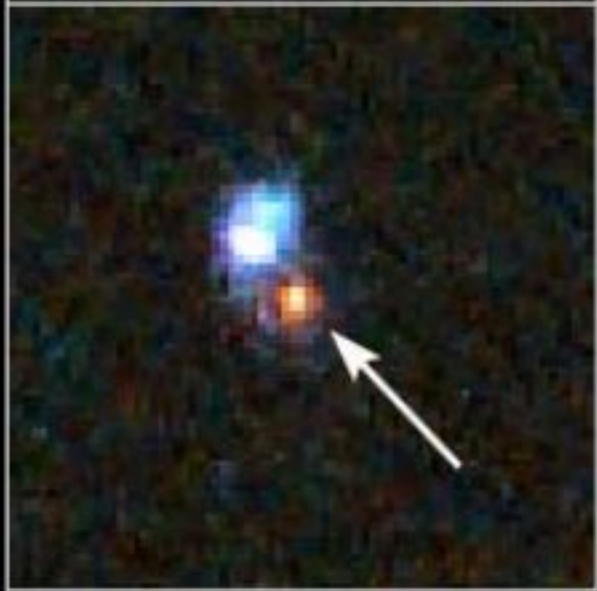
# So, by the time we're up to the early 1990's the "Standard Big Bang Model" has emerged

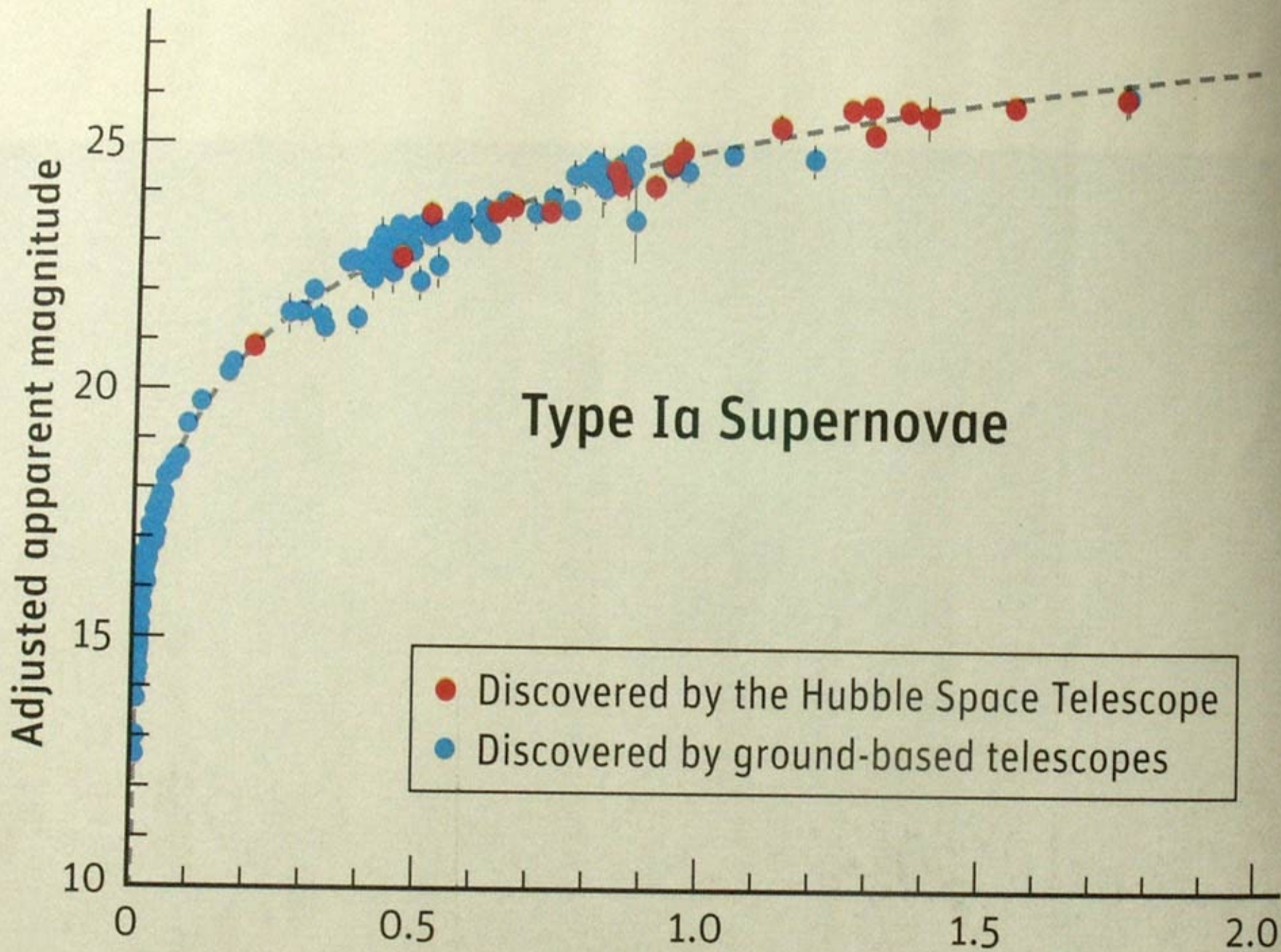
- The "Standard Big Bang Model": A universe at "critical density", with 95% in the form of Dark Matter and 5% in ordinary matter.
- But, there were major problems with this...

# Problems with the “Standard Big Bang” Model...

- **Problem #1** - Age of the universe as measured by Hubble Law disagrees with the age of oldest globular clusters. If  $H=70$  km/sec/Mpc in a critical density universe, implies the universe is only 9.3 Billion years old. But stellar structure astronomers calculate that globular clusters are older; some up to 13 billion years old. Obviously a discrepancy!
- So, measure Hubble Parameter  $H$  not just locally but over most of the observable universe and maybe that'll clarify things.
- Best distance indicator is Type Ia supernovae. These are the “carbon bomb” supernovae which are triggered when a 1.4 solar mass white dwarf has matter dumped on it by a close companion going Red Giant. These are all the same! They're all 1.4 solar mass white dwarfs made mostly of carbon! They have the same light curves, so if we calibrate them carefully using nearby SN Ia's in galaxies with other distance indicators, then we can use SN Ia's at any distance. Since they're brilliant, we can see them all the way to the edge of the observable universe – which is perfect for doing cosmological evolution studies.
- SN Ia's ; distance accuracy as good as 5% if done carefully









# New Generation of BIG Telescopes were completed in the '90's, showed by 1998...

- A few dozen of the best observed of these type Ia supernovae, all the way out most of the way to the edge of the observable universe.
- Comparing their distance and their velocity away from us, we saw – amazingly enough – that the universe is actually NOT slowing its expansion.
- Instead, it is **ACCELERATING!**

# Acceleration requires some kind of Energy Density (that's the simplest explanation anyway).

- Einstein and his Cosmological Constant... He inserted a constant term into his differential equations of general relativity, to make the universe stand still (this was before Hubble discovered the expansion).
- The physical interpretation of this “cosmological constant” is an inherent property of space to expand, such that if you double the space, you double also the “expansion-ness”; *i.e.* it does not dilute away as does matter *within* space does.
- So, as the universe expands and gravity's grip weakens with increasing distances, it comes more and more to be dominated by the unchanging expansion force of space itself.
- Is this the way of it, in the real world? Maybe! Data so far show that  $H$  varies with distance in a way which is consistent with a Cosmological Constant which behaves just as described.
- It's the simplest mathematical form, agrees with Relativity, and solves some problems once you get used to the initial strangeness of the idea.

# Could this “Dark Energy” (DE) be more complicated?

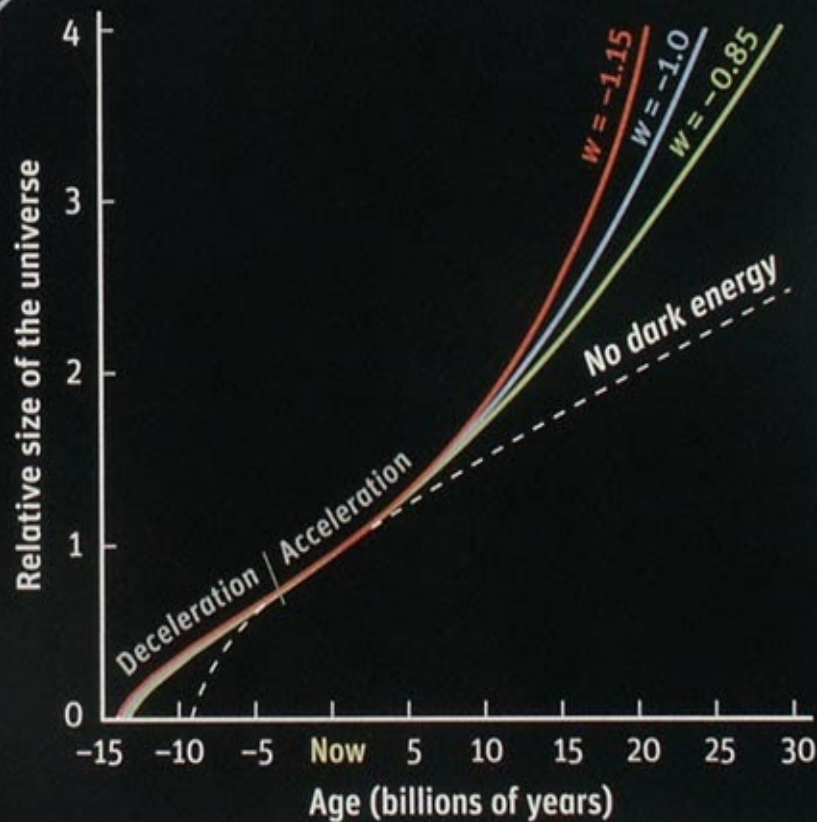
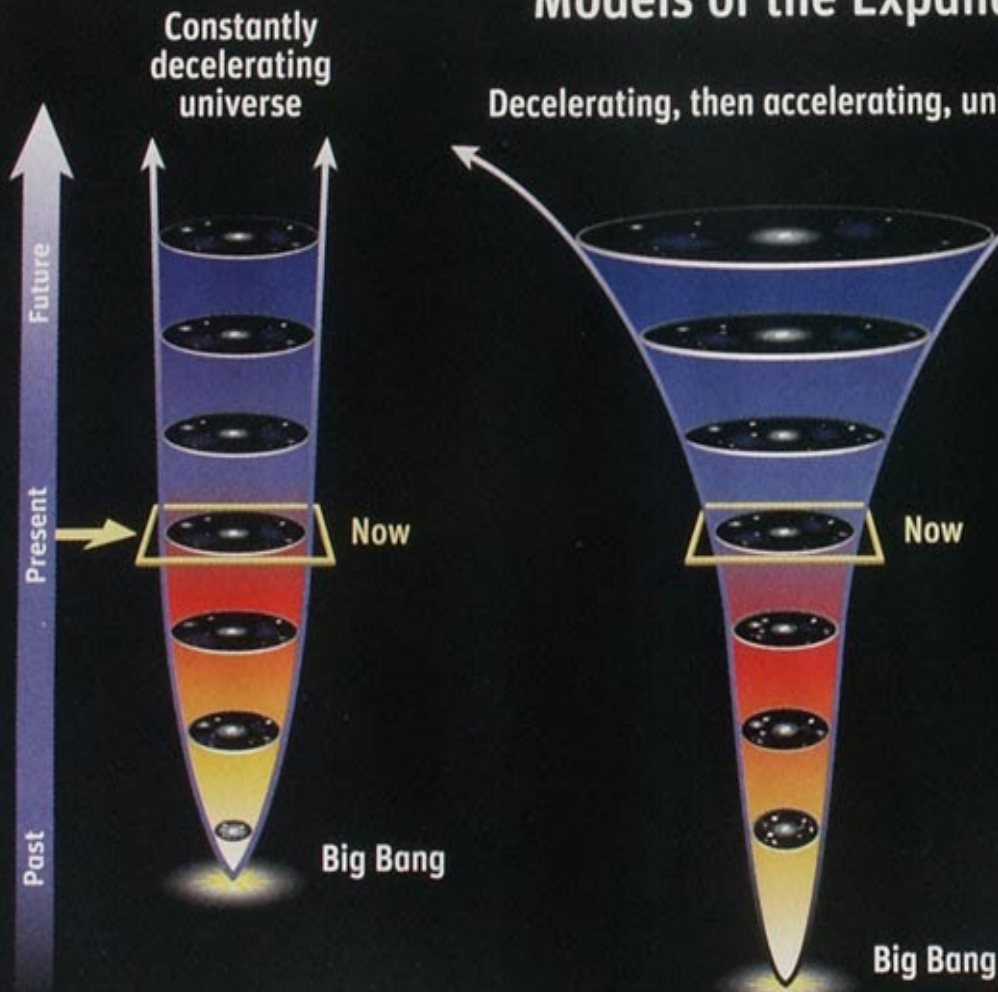
- For example, DE could be lumpy - more in some places, less in others
- It could evolve with time
- It could involve particles which decay with a certain half-life
- But – no, as the data slowly improve, the simplest model – an energy density which is constant in time and uniform in density everywhere, fits the data best.
- This is the same form as Einstein’s Cosmological Constant

# So, not only is there Dark Matter, now there's "Dark Energy" too!

- A complication, you're no doubt saying. But let's look on the bright side...



# Models of the Expanding Universe



# Dark Energy Resolves the Age Discrepancy

- Using the measured acceleration and assuming the simplest form - a “cosmological constant” - you get an age of the universe of 13.72 Billion Years
- Perfect agreement with Globular Cluster ages 😊. Now everyone - particle physicists, cosmologists, stellar structures types... -
- **they're all... happy!**



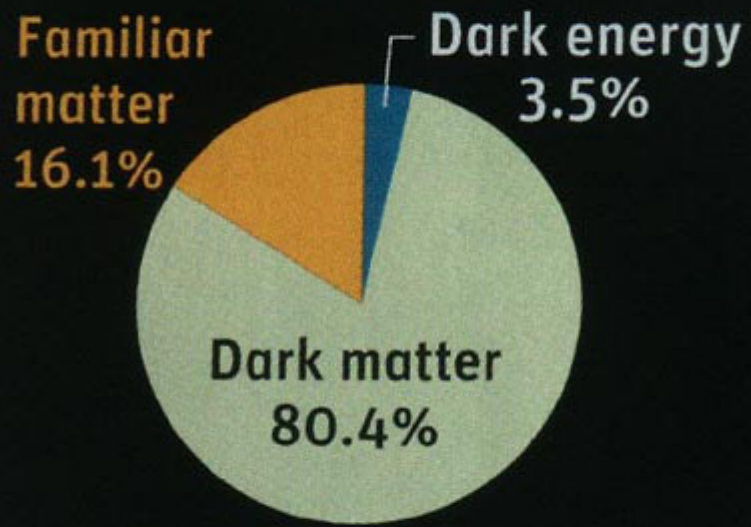
Dark Energy – It is your Destiny,  
Luke!



- Note that the “Cosmological Constant” has a bizarre property – it doesn’t “thin out” as space expands. It stays at the same density.
- But matter IS thinning out as the universe expands, and this is why **DARK ENERGY comes more and more to dominate the universe as time passes.** Hence - *acceleration*

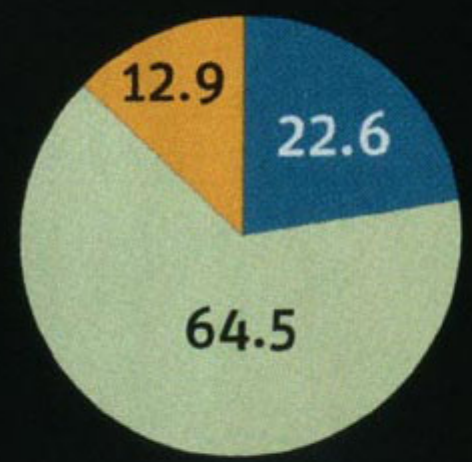


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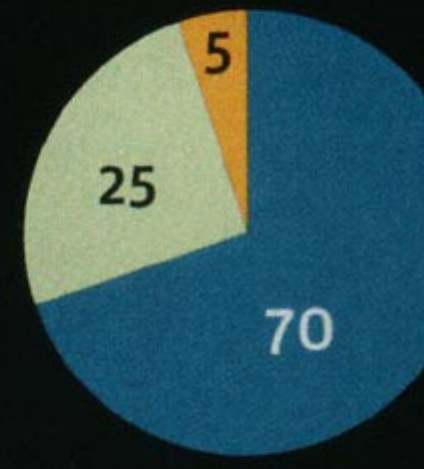
-11.5 billion years

Size =  $\frac{1}{2}$



-7.5 billion years

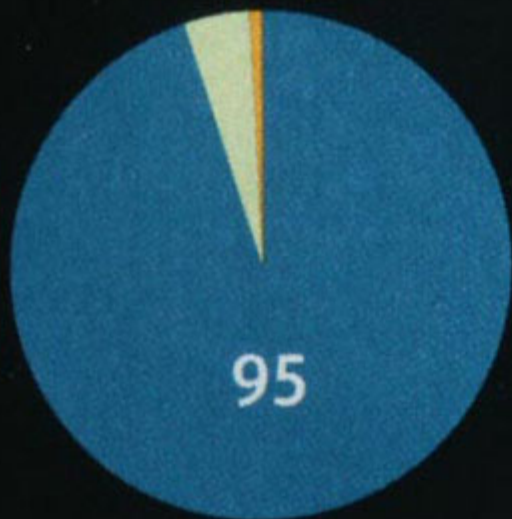
Size = 1



Now

Size = 2

4.2 0.8



+11.5 billion years

Size = 4

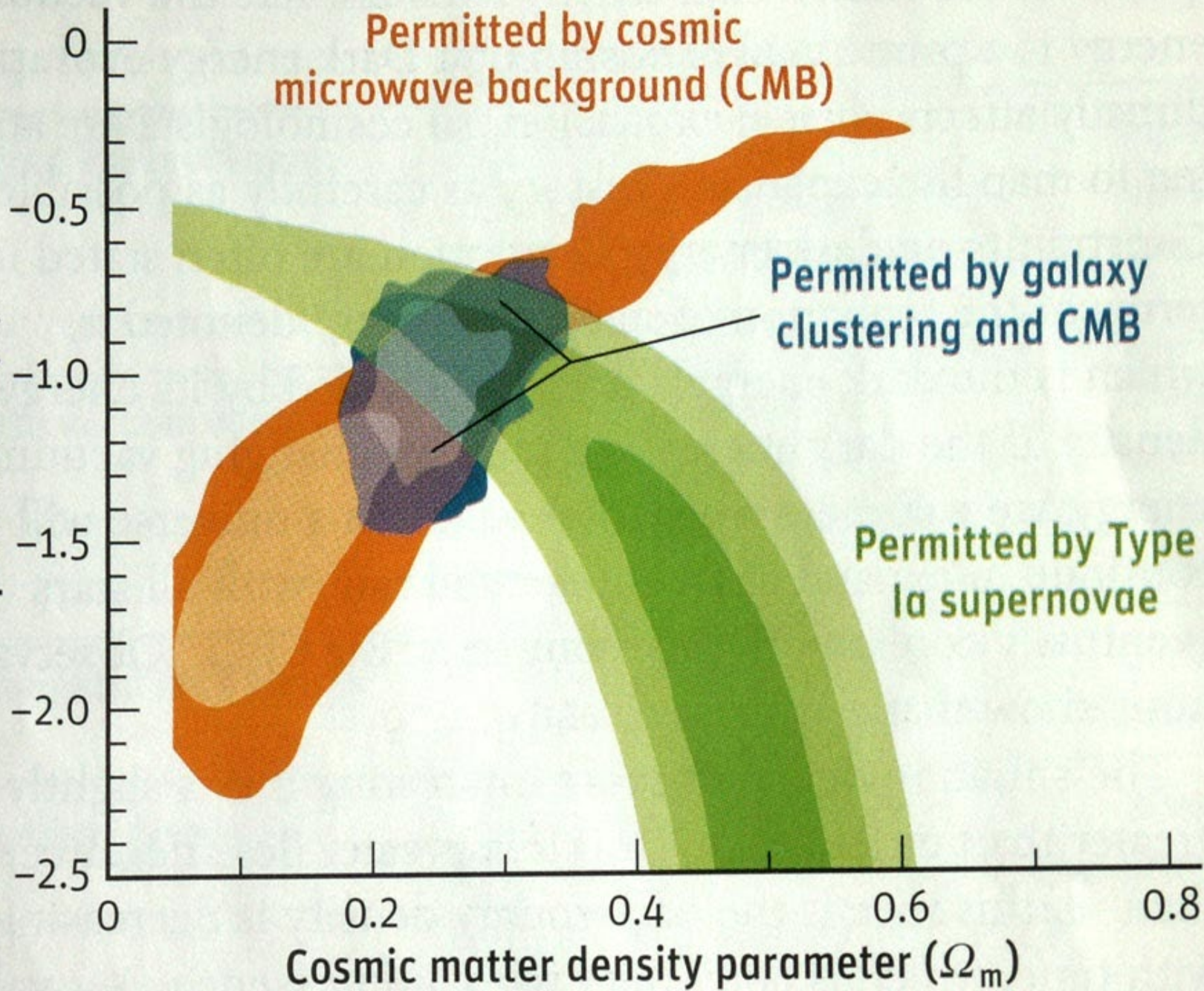
0.6 0.1



+24.5 billion years

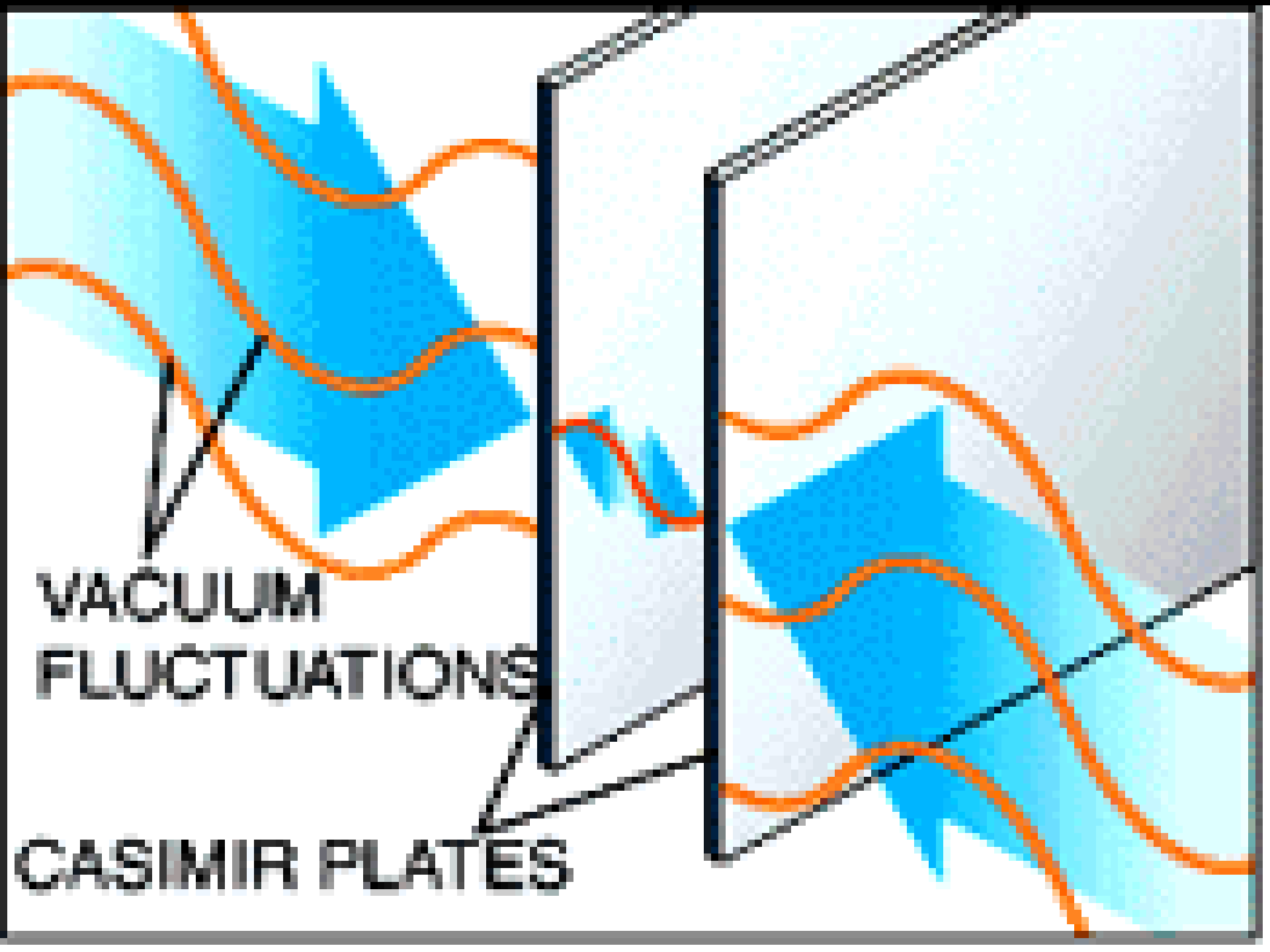


Dark energy equation-of-state parameter ( $w$ )



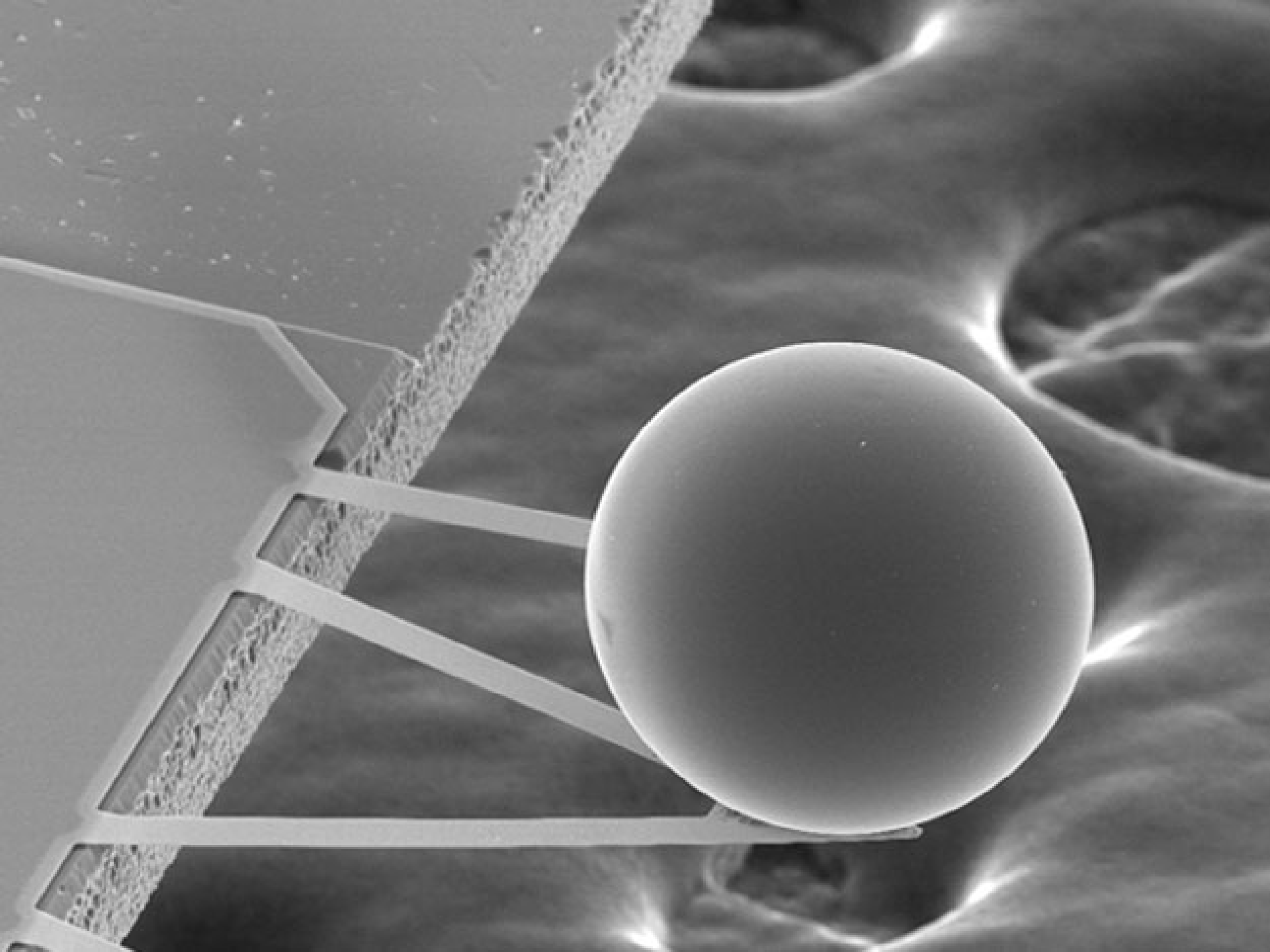
# Is there Direct Evidence of an Energy Density Possessed by Space Itself?

- Yes – the Casimir Effect
- Predicted by the Dutch physicist Hendrick Casimir in 1948. According to quantum theory, the vacuum contains virtual particles which are in a continuous state of fluctuation (see physics FAQ article on virtual particles). Casimir realised that between two plates, only those virtual photons whose wavelengths fit a whole number of times into the gap can be counted when calculating the vacuum energy, the rest destructively interfere.
- Thus, the energy density between the plates decreases as the plates are moved closer, which implies that there is a small force drawing them together. It is tiny – first measured in 1996 for the EM field.
- Is this the Dark Energy? Not clear - other fields besides the electromagnetic field can contribute to the Casimir Effect, including perhaps the Dark Energy field, whatever it may be.
- Interesting: the Casimir Effect would be cancelled out for EM if Supersymmetry for the EM field were true. Therefore, if supersymmetry is obeyed by Nature, it is a “broken symmetry”. Since Supersymmetry particles have been a favored candidate for the Cold Dark Matter, this is interesting.



VACUUM  
FLUCTUATIONS

CASIMIR PLATES



# Standard Big Bang Problem #2

- **The Horizon Problem...**
- Opposite sides of the sky are out of causal contact, have *ALWAYS* been out of causal contact – yet they are essentially identical (temperature, structure...)
- They **MUST** have once been in causal contact!
- Solution to problems?...

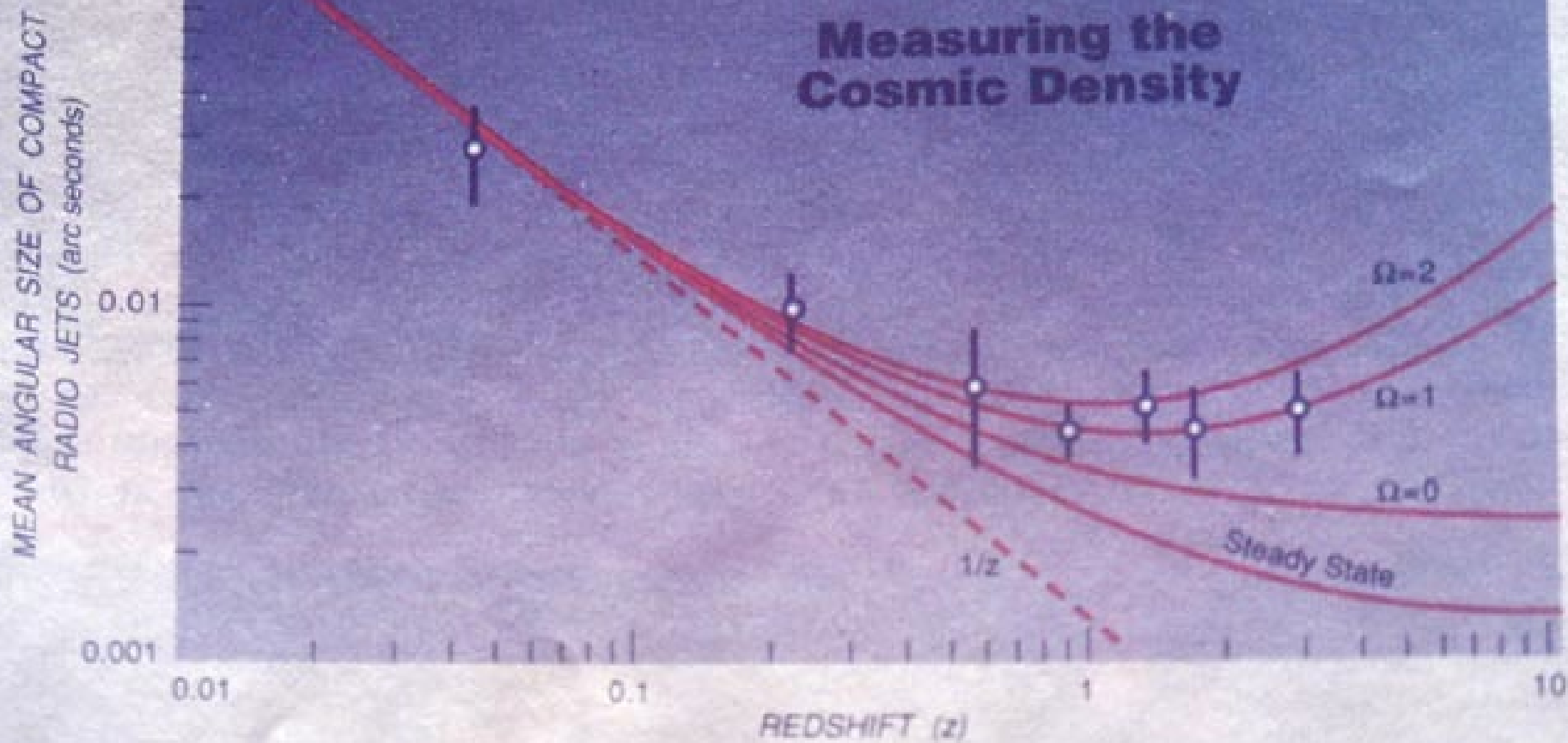
# The Inflation Paradigm

- Symmetry and symmetry breaking
- Water analogy
- Energy of the vacuum
- Inflationary epoch: first  $\sim 10^{-30}$  second
- Symmetry breaking went into expansion of scale of the universe, by  $\sim 10^{60}$
- Sounds VERY bizarre and unbelievable but...



# If Inflation Really Happened...

- Predicts the density of the Universe = the critical density, and total energy = 0 (remember, gravitational potential energy gets counted with a negative sign so zero total energy isn't as ridiculous as it sounds)
- Density fluctuations due to the quantum uncertainty principle get blown up to *galaxy-sized* fluctuations by Inflation and this. Quantum theory gives an exact shape to the spectrum of these density fluctuations.
- Small temperature fluctuations in the Cosmic Microwave Background are due to small density fluctuations in the ordinary matter and in the underlying dark matter
- Therefore, Inflation makes a specific prediction for the spectrum of the temperature fluctuations we should see in the **Cosmic Microwave Background**
- And what do we see?... First, let's look at a measurement of the total matter+energy density:

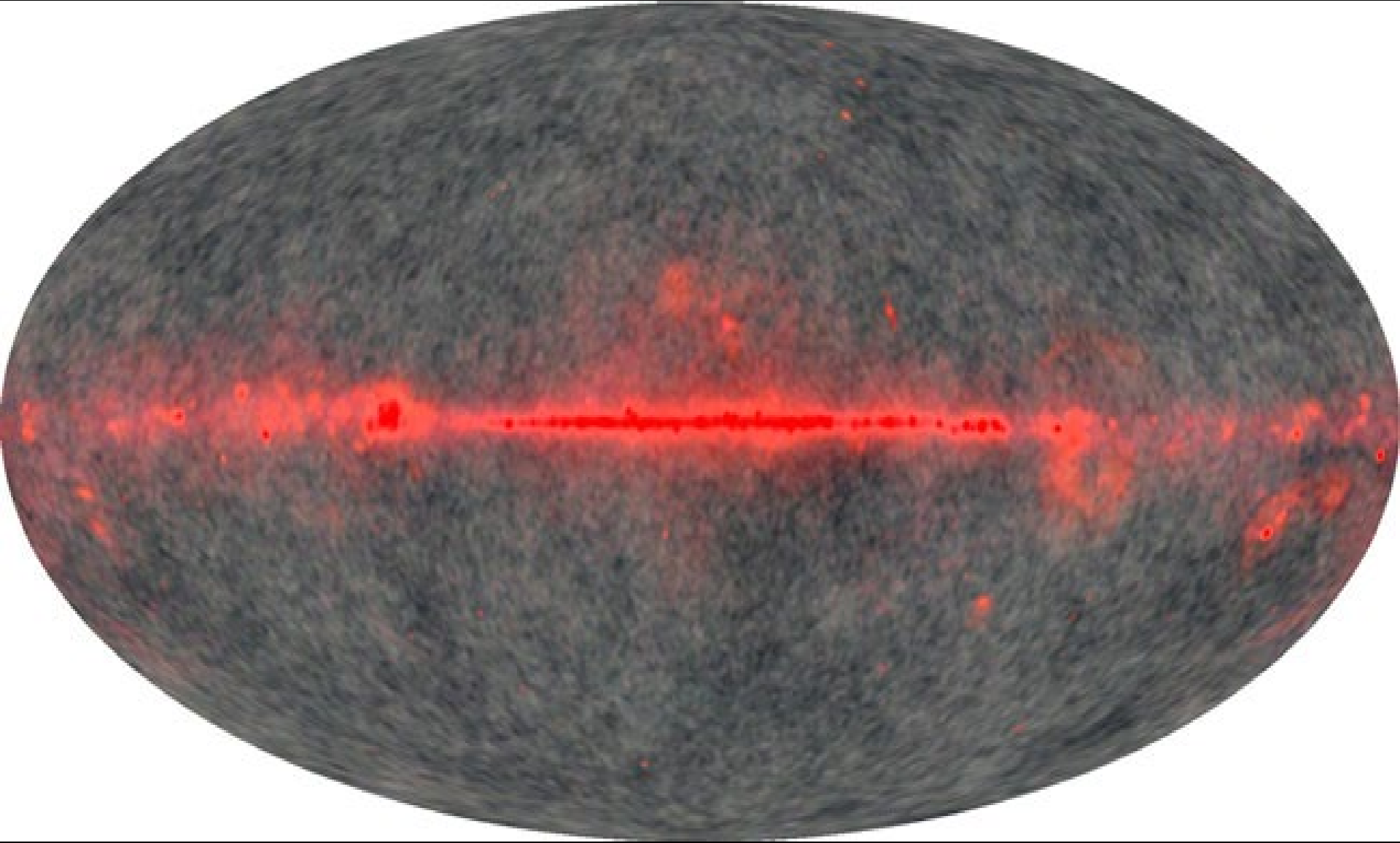


The total density of the universe,  $\Omega$ , can be found if objects of well-known sizes are observed at great distances (high redshifts,  $z$ ). In nonexpanding space such as we're familiar with in everyday life, a measuring stick seen twice as far away appears half as long (dashed line). But in an expanding universe, a measuring stick seen from an early time does not obey such a simple rule. If the expansion is being decelerated by gravity, the rate of deceleration can be measured and the density of the cosmos found. By assuming that compact radio jets are a good standard measuring stick, Kenneth Kellermann (National Radio Astronomy Observatory) found that the cosmic density is just about at the critical value needed to close the universe,  $\Omega = 1$ . The dots are his data with error bars showing their ranges of uncertainty. Courtesy Kellermann.

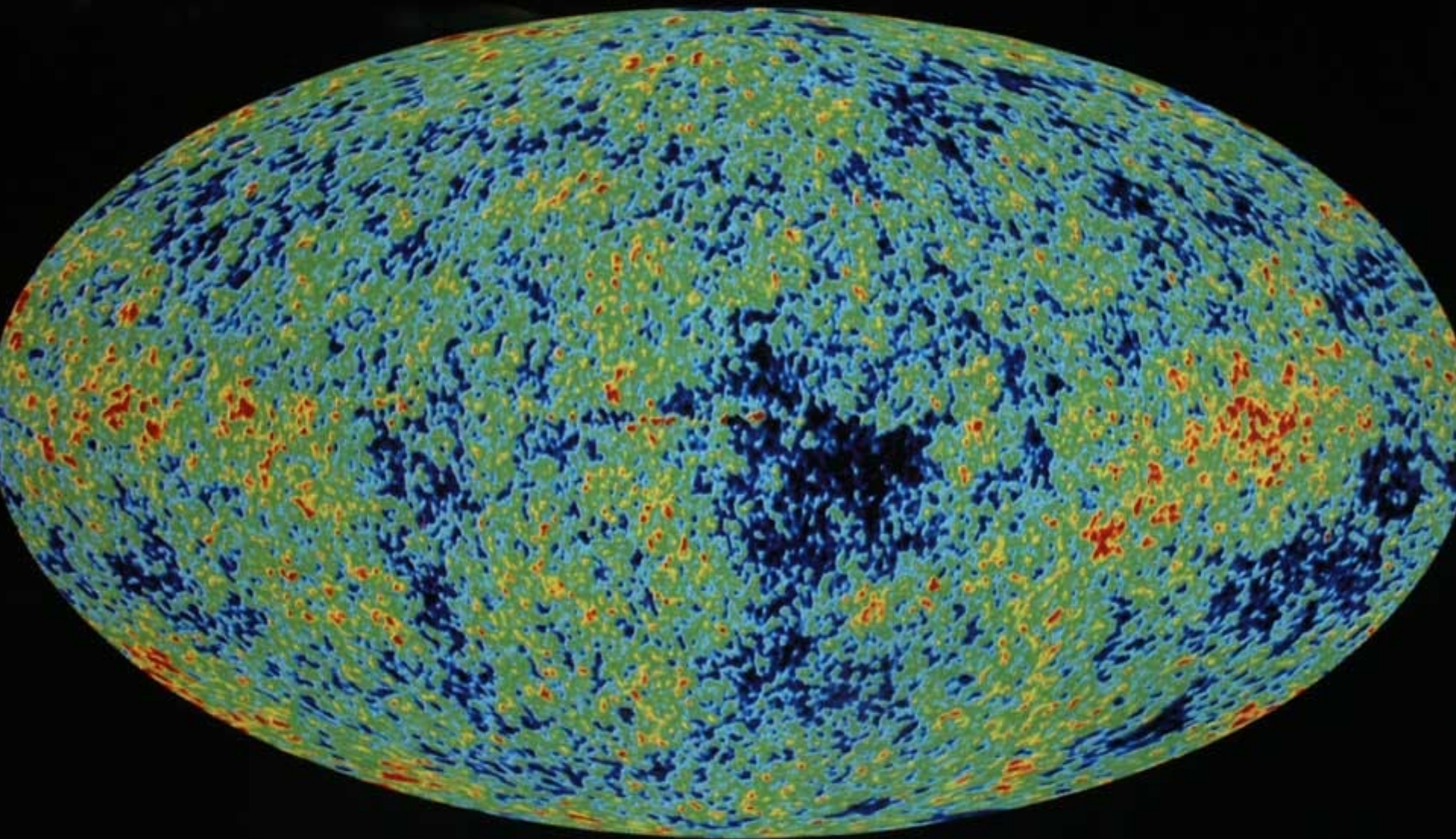
# So: it looks like the Universe is at our theoretically favored Critical Density. Now, what about those Temperature Fluctuations?

- Here are all-sky maps of the Cosmic Background Radiation. Note the many small, medium, and large sized regions of (very slightly) varying temperature
- These data are from the Wilkinson Microwave Anisotropy Probe (**WMAP**) satellite mission, recently completed.

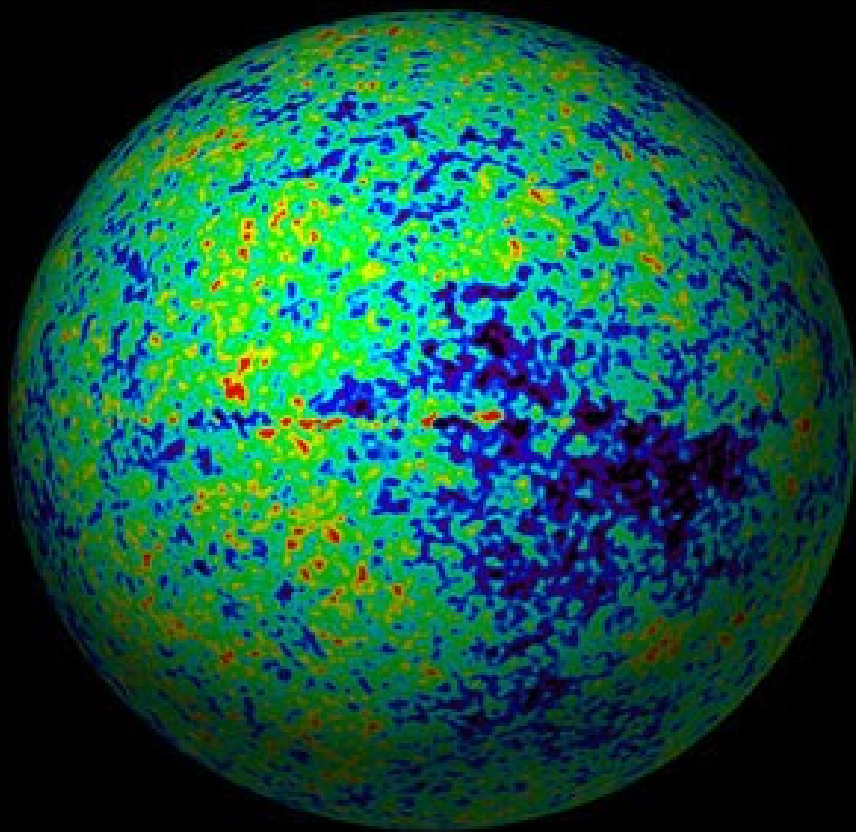
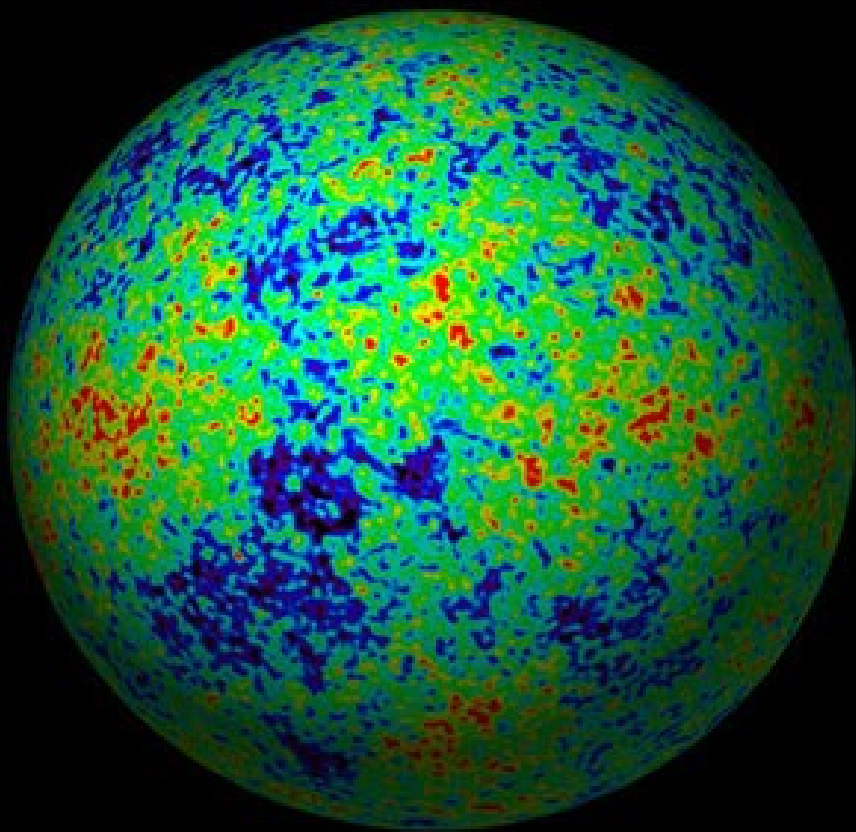
**WMAP's CMB fine scale structure (gray), with  
Milky Way foreground contamination (red)**



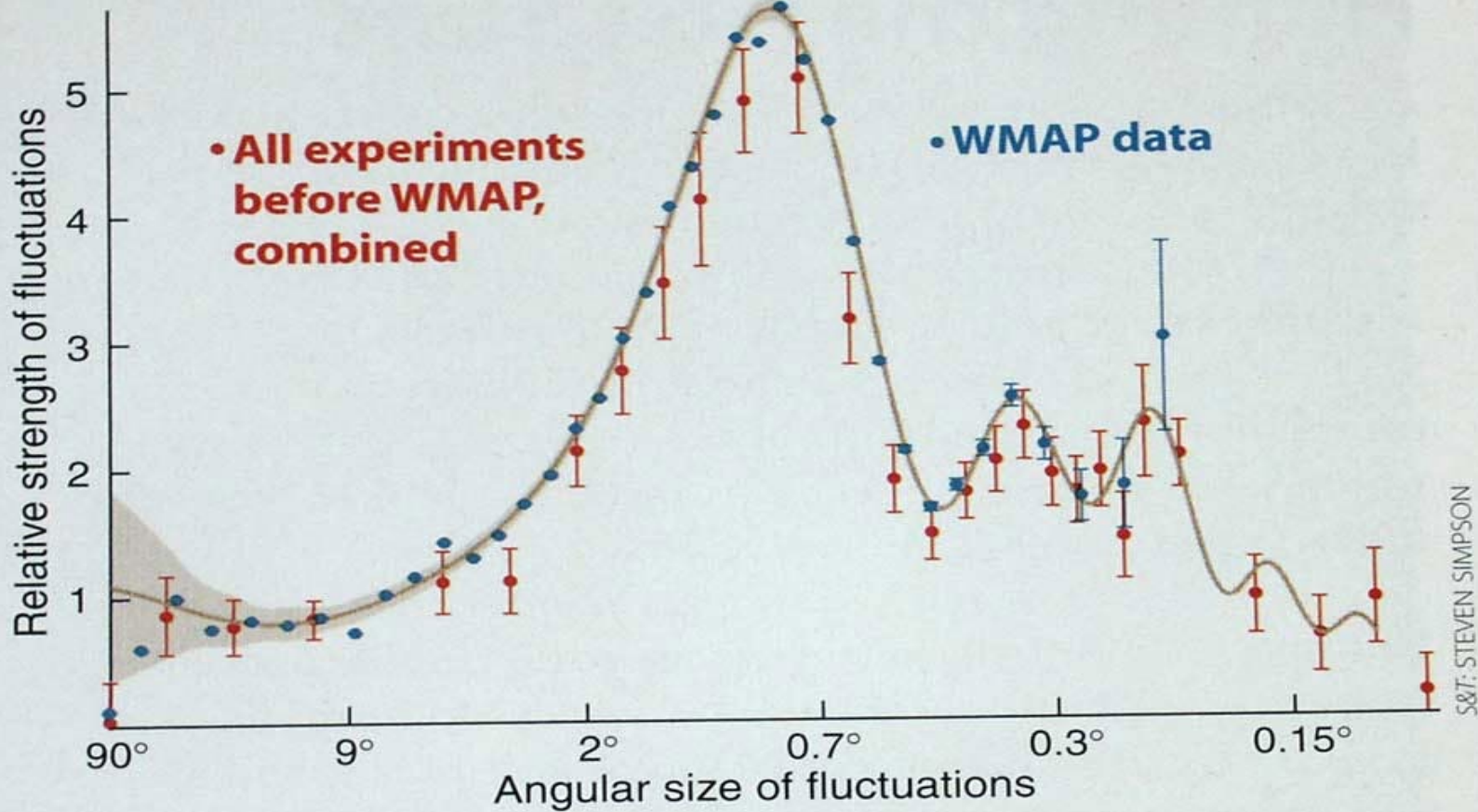




**Here's another  
version, let the sky  
look like a sphere and  
let's see it front and  
back....**





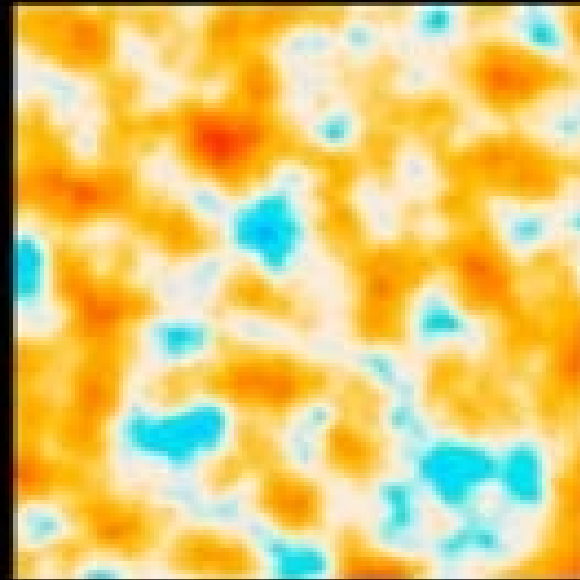


S&T: STEVEN SIMPSON

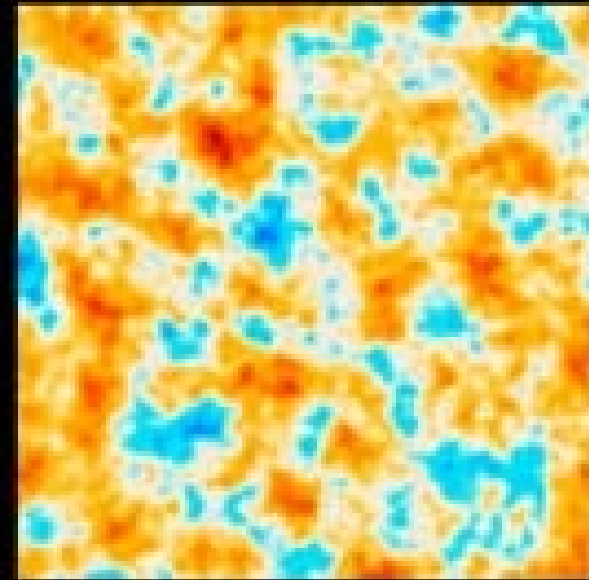
The most revealing display of the ripple data is a “power spectrum” showing how strong the ripples are at each size (dots with error bars). The observed power spectrum can be compared to the predictions made by different theoretical models of the universe; the solid line is the model that best fits the WMAP data (the tan areas reflect uncertainty in the model’s predictions). By tweaking basic cosmic parameters, the model can be fine-tuned to match the data.



COBE

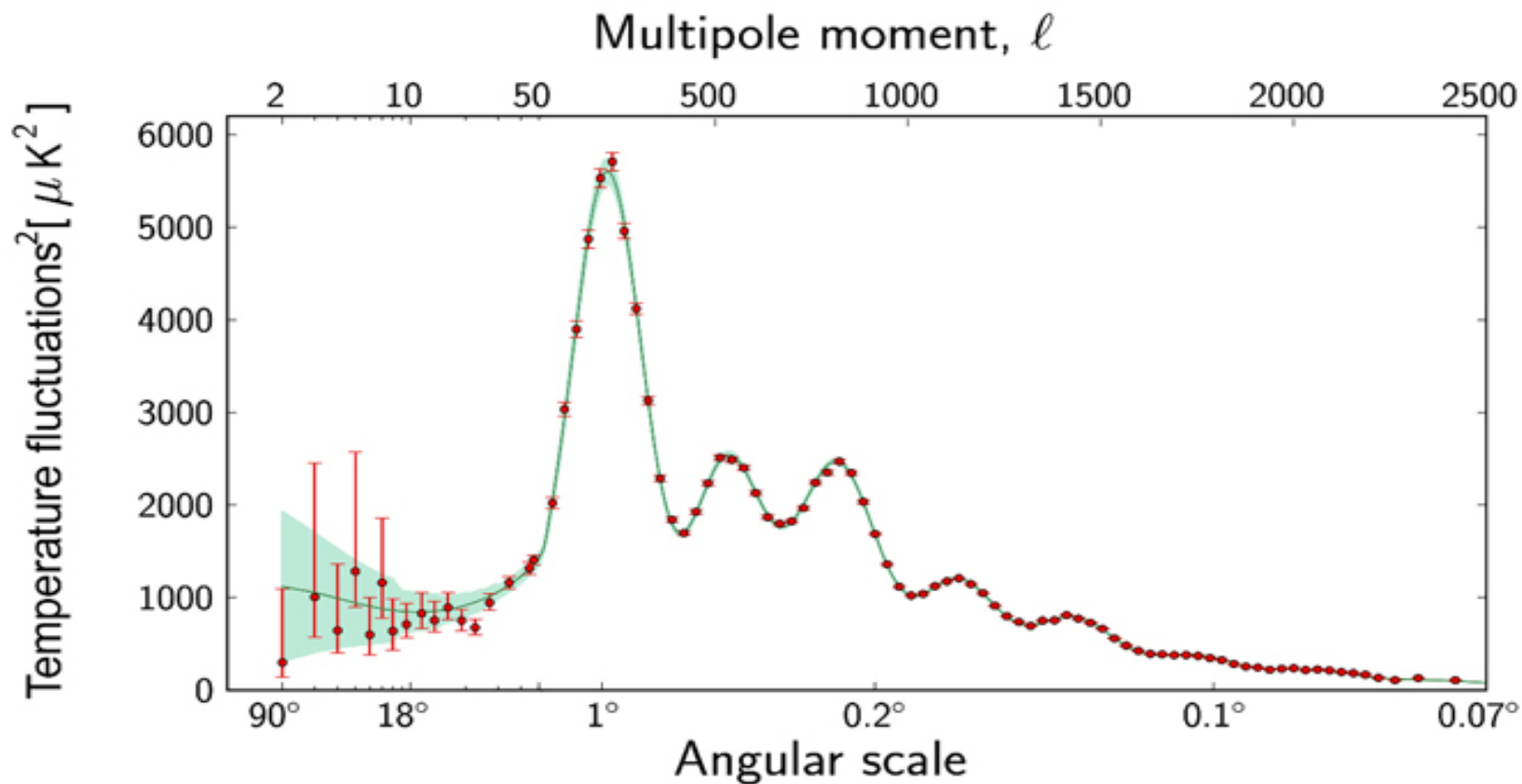


WMAP



Planck

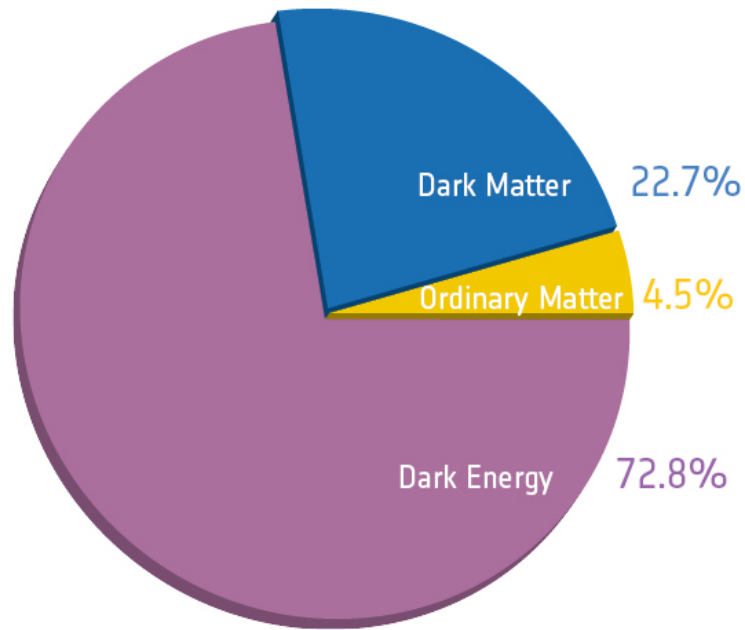
**The Newer Data, from the Planck Mission (red dots),  
Agrees Even MORE Precisely with the Current  
Standard Cosmology of Dark Matter + Dark Energy  
+ Ordinary Matter + Inflation (blue curve)**



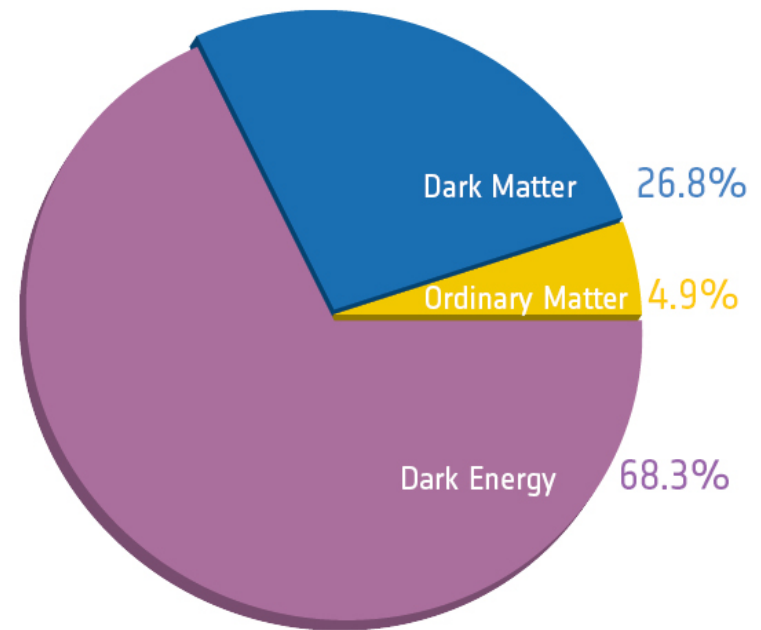
# Inflation's spectrum of density fluctuations, seen in the CMB...

- ... also answers the riddle of where galaxies come from. A perfectly smooth expanding gas won't have any lumps, any gravitationally stronger places which can act as magnets to form the lumpy universe we see today.
- The lumps needed to be there from the very moment of creation – and yes! They were; they were quantum uncertainty fluctuations on the submicroscopic scale, expanded at the moment of Inflationary creation to galaxy-sized non-quantum lumps

# Here's what the universe is made of, after the Planck Mission observing the CMB

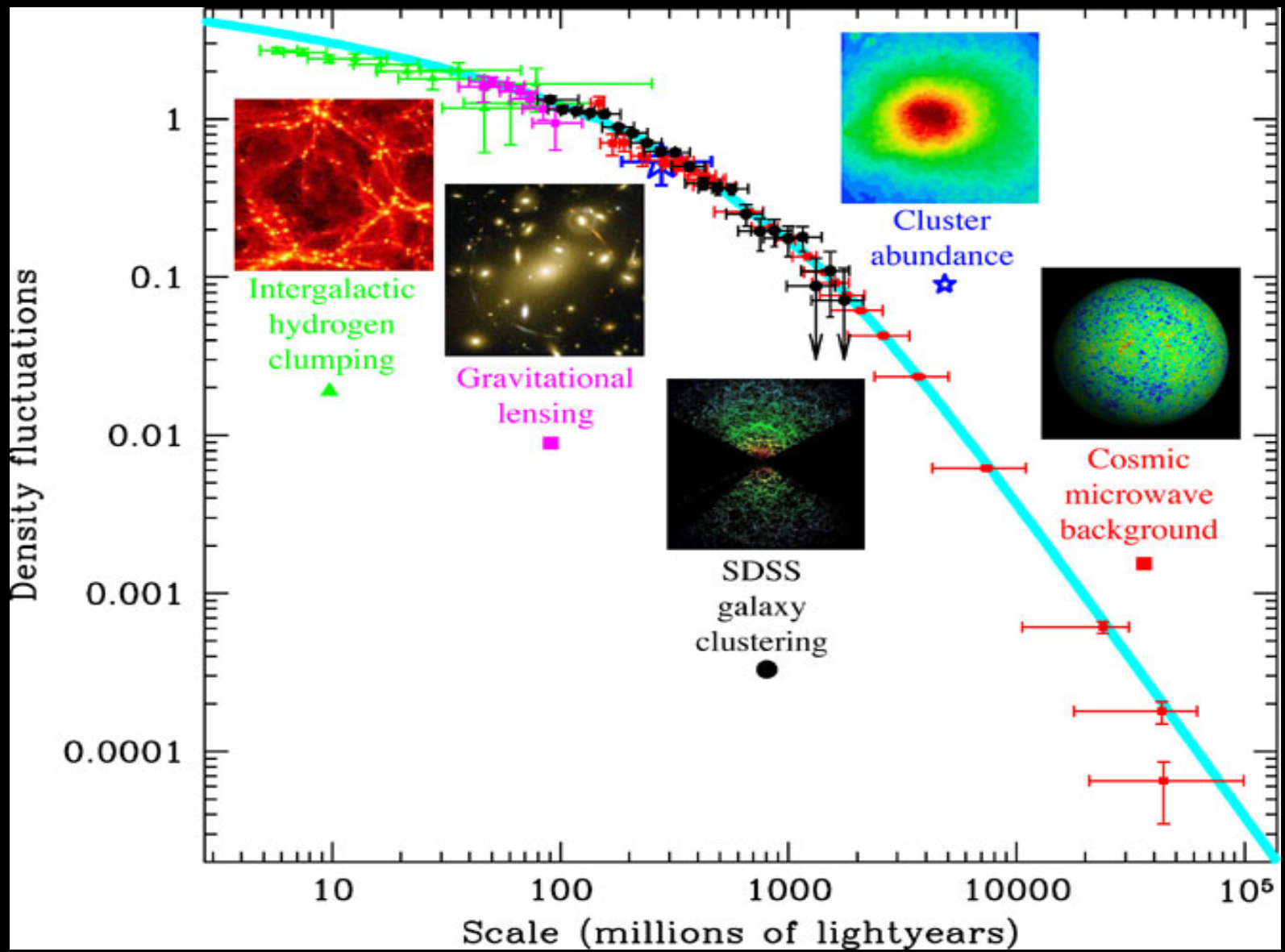


Before Planck



After Planck

The universe is very lumpy on small sizes, but very smooth on the biggest size scales





# Conclusions

- The Universe has exactly ZERO total energy, just **as predicted by Inflation.**
- Spectrum of the strengths of density fluctuations *is* a power law with a slope of  $-1$  in real space, **as predicted by Inflation**
- The acoustic peaks in the WMAP power spectrum follows all the wiggles **predicted by Inflation**
- ...It's looking like Inflation, in it's simplest form, may have really happened!

# The Simplest Inflation Paradigm, agreeing with the evidence, is this...

- An energy field in the larger framework, causes an eternal, continuous, exponential expansion of space.
- But quantum fluctuations within this space can tunnel small places out of this energy expansion - “symmetry breaking” - to a lower field state, and the energy difference between these two states of the “inflaton field” powers the expansion of this new “pocket universe”.
- We live in one of these pocket universes, expanding much slower within a much more rapidly expanding Inflationary Paradigm.

# Each such symmetry break creates a new Universe

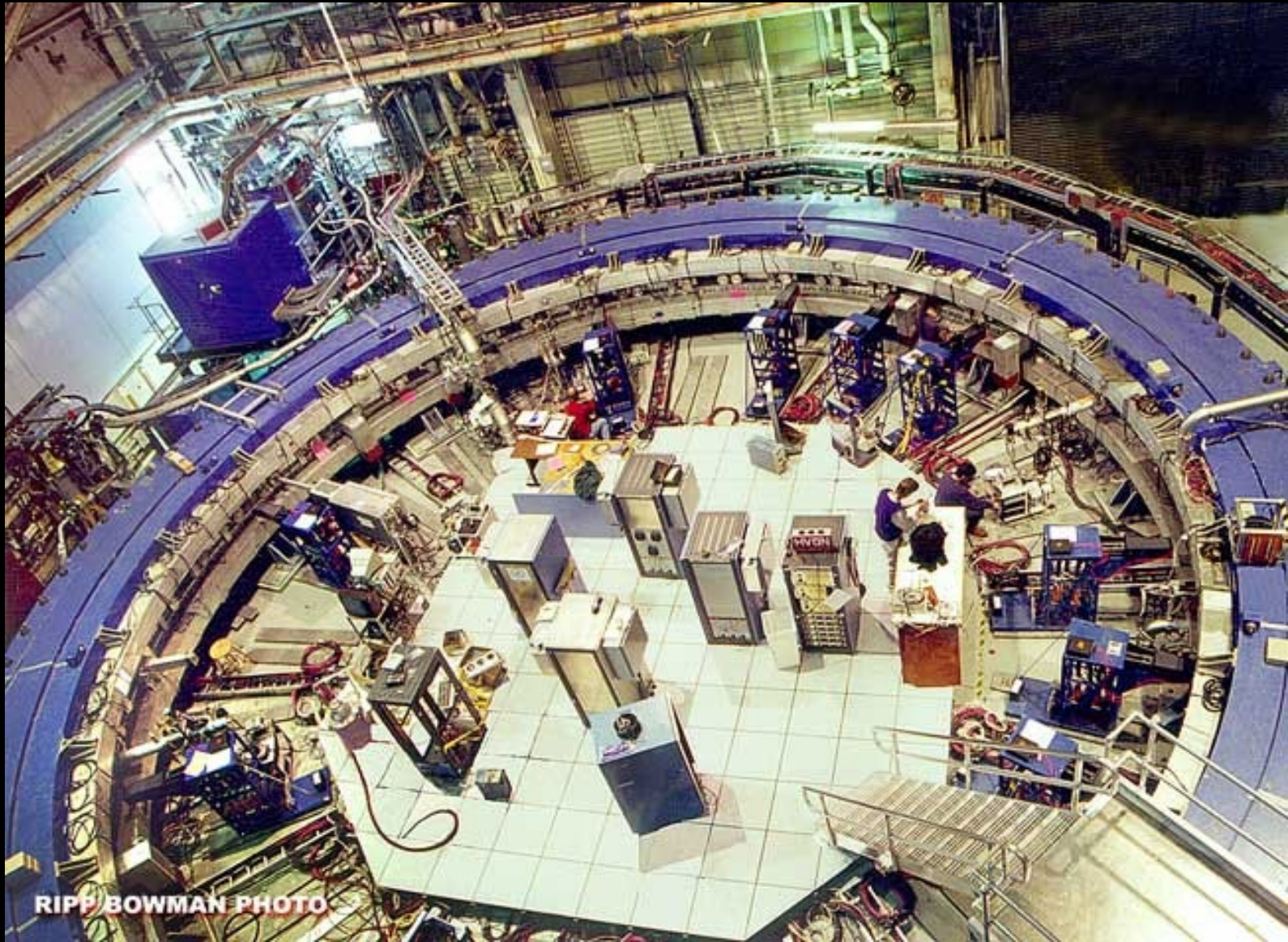
- And all they share in common is Quantum Mechanics.
- The other particulars; the numbers specifying the values in the Standard Model, are random realizations from the quantum “freezing out”.
- Thus, the laws of physics themselves (not including the Quantum Mechanics base) are randomly set at the Inflationary moment of birth for each pocket universe.

# Is there any more “Freezing out” in our Future?

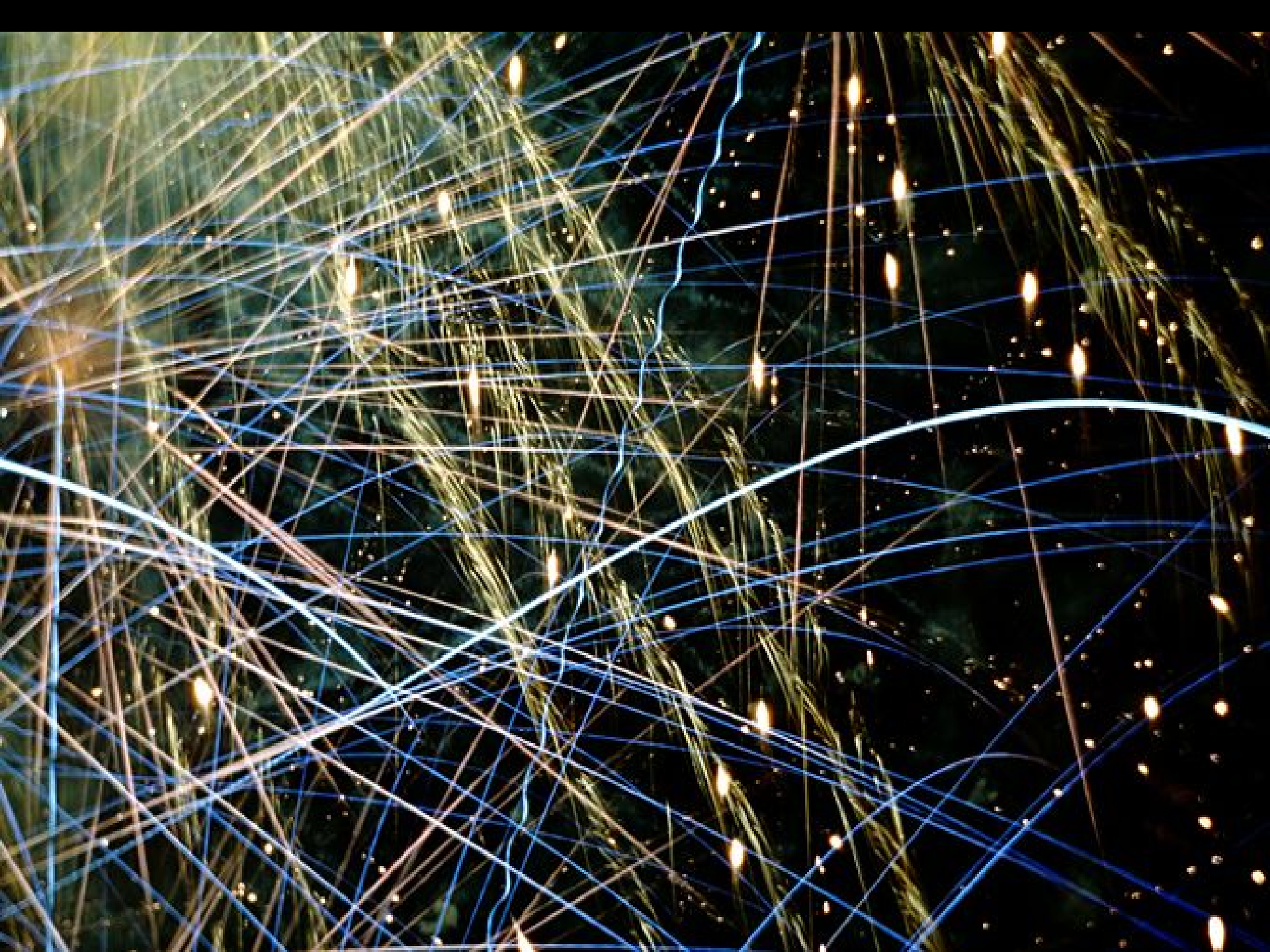
- The long sought Higgs particle, the last piece of **The Standard Model** of particle physics, was discovered in experiments from the Large Hadron Collider in July '12.
- The Higgs gives rise to the property we call “mass”, and the mass of the Higgs – 126 GeV – may mean the Universe is in a “false vacuum” energy state. This particular mass is very close to the critical mass whereby....
- ... in the distant future when the expansion has cooled us sufficiently further, we may spontaneously transition to the true vacuum state – and in the process, destroy everything in our Universe, at the speed of light!
- **Massive Bummer!**
- But this is still a prospect that's **very** speculative – don't lose any sleep over it. And if it happens, you'd never know it anyway.



# Brookhaven Particle Accelerator



RIPP BOWMAN PHOTO



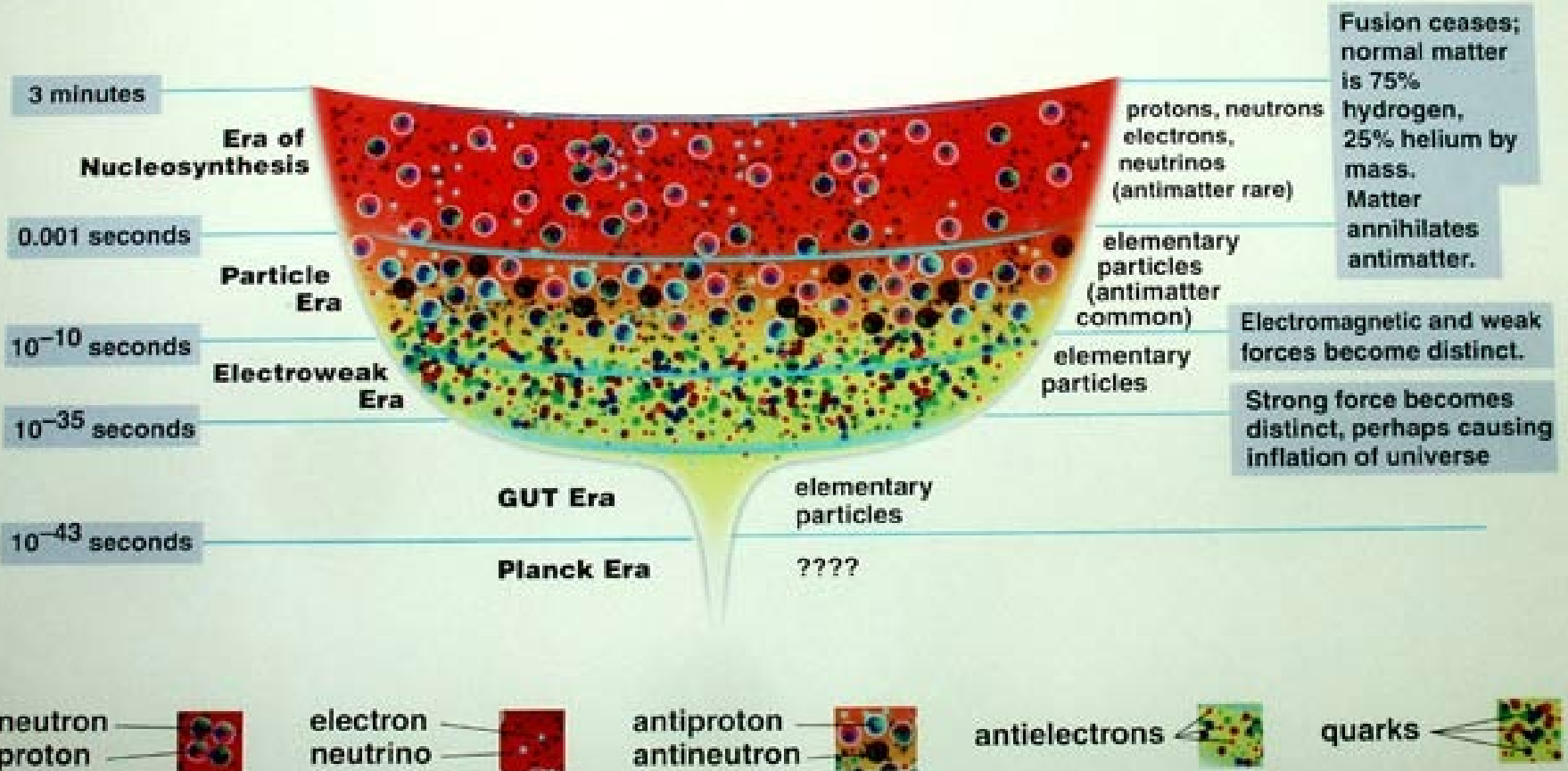


# Cosmic History – First 3 Minutes

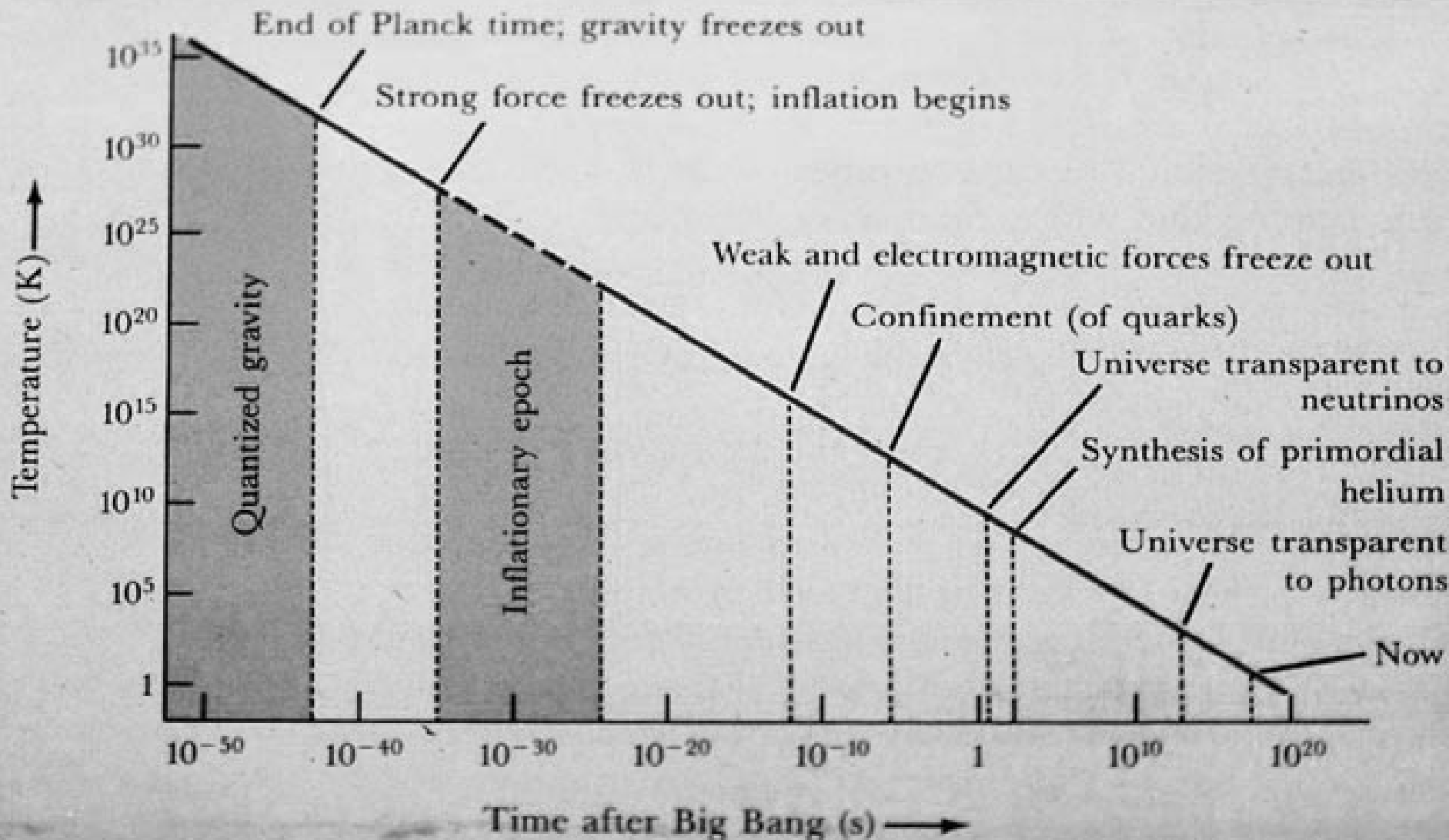
Figure 19.2 Eras of the universe Part 2

Time Since Big Bang

Major Events Since Big Bang



# A history of the universe. The earliest moments more speculative



# Our Universe Allows Life

- Nearly every tinkering with the fundamental constants of Nature wrecks the possibility for life as we know it.
- Example: Change the fine structure constant by 1% and you produce no oxygen. Change it in the other direction by 1%, and you get no carbon. We need both, for life.
- Change the mass of the neutrino, and you change how structure forms, how the weak force operates, and just about everything.

# **Evolving simplicity into complexity requires a special environment**

- Environment must be not too cold (frozen) or hot (high heat destroys all molecules, hence complexity along with it).
- Parts of the Universe must collapse on smaller scales to form planets, stars...
- But yet expand on large scales so that it can be long-lived
- Because.....

# To assemble complexity requires TIME

- **Evolution proceeds by errors in the self-replication of DNA.** But such errors need to be small and “rare”, else death. So intergenerational changes are small and incremental. Successful evolution takes time.
- Therefore, the Laws of Physics must permit stable environments for LONG times.
- Endless ways for things to go wrong. Endless ways the 19 (or 26 Or 32 depending on how you count and view them) different independent(?) parameters which define the **Standard Model of particle physics** (which is very well verified experimentally) can be specified and yet which make for a universe in which complexity cannot evolve at all – no life!
- Example: Our Law of Gravity – an inverse square law - permits stable two-body orbits. Most conceivable gravity laws will not do that, making stable climate impossible.

**Were we just  
very lucky?**

**Not likely...**



**WHAT IF I TOLD YOU**

**THAT THIS IS NO COINCIDENCE**

- Either we were incredibly lucky that the one and only Universe that ever has or will exist, happened to have a rare set of laws of physics which would allow life, or...
- **(1) A God?** - but then, where did HE/SHE/IT come from? If He can be Eternal, why not the Universe?
- Any being as complex as God would need – simple information theory - to be, in fact **NEEDS** to be complex in order to create **EVERYTHING**.
- So, postulating a God leads to circular reasoning and doesn't solve the problem of the origin of complexity from simplicity.
- Instead, physical laws **show** how complexity evolves naturally from simplicity. There are no doubt other sets of laws that could have this property too, but I think we've made a case that such sets of laws are likely very rare among **ALL** imaginable laws
- And...The orthodox religions' versions of God have deep moral and internal logic flaws too numerous to go into here. (see here for some [Online Talks](#) with thoughtful discussions)
- **(2) A Better and More Evidence-based Solution is...**

# Not only does Inflation have solid observational evidence to support it...

- ...It is very difficult to see how any mechanism generating Inflation would NOT also produce a near-infinite number of Universes through ongoing inflationary moments



# A Multitude of Universes! – The MultiVerse

- “Universe” now means a particular instance in this “multi-verse” with its own framework. Space, time, dimensions, and force laws, which tumble out of symmetry-breaking in a random way, subject only to the Quantum Uncertainty Principle and laws of Quantum Mechanics, which we believe is more deeply fundamental than the physical constants and force laws, and is likely common to ALL universes)
- Said another way, we can understand how a multi-verse of universes all obeying the same fundamental laws of quantum mechanics, can yet have a wide variety of physical constants and force interaction laws, and this is the simplest (and most quantitatively explorable) model.
- Could it instead be “deuces wild” on EVERYthing? I suppose that’s hard to disprove, but it’s not necessary, and therefore not so interesting.
- Inflation describes how universes in which Total Energy=0 could be created out of the Vacuum. “Eternal inflation”

# Testing these ideas against reality...not so easy

- String theory versions, and others speculated upon, require such incredibly high energy particle physics experiments that it is hopeless to expect humans will ever be able to design such powerful particle accelerators. They'd require cyclotrons the diameter of the Earth's orbit (!)
- We perhaps can only hope that Nature has done such high energy experiments for us and is leaving, or has left, clues for us to see.

**...If true, the Multi-verse (or “landscape”, its version in String Theory), is a natural solution to the puzzle of our Living Universe**

- How? **Easy!** No need to wonder why we're in such a wonderfully inhabitable universe. We're “self selected” to be in just such a universe.
- Most universes would likely come out of the Cosmic Oven botched – laws of physics may freeze out of the inflationary creation event differently and most are incompatible with the formation of stable environments suitable for the evolution of complexity in any form, thus excluding Life.



**And therefore - there's no living things in those sterile universes to complain about how unlivable their Universe is!**

- We, obviously, could have **ONLY** evolved in a universe in which its randomly set laws happened to allow life to form and evolve –
- **No need to feel lucky or divinely inspired or created. Again, we're “self-selected”.**

# Directly testable or not - It's the most logically compelling and observationally well-motivated idea we have

- Quantum processes within a larger framework create Universes, which, through Inflation, can create and populate their own space, time, laws, all of which may be unique to that particular Universe
- Analog; the laws of fluids are the same everywhere, but yet every snowflake is different. Symmetry-breaking includes randomness.
- We, OF COURSE, find ourselves in one of the rare, wonderfully incredible universes with physics which is friendly to the evolution of life.
- Tons of other Universes are likely to be out there which are totally MESSED UP! In this regard. But, no one lives in them to complain about it!

# Let's look at just one key parameter – the Cosmological Constant $\Lambda$

- This is the parameter that describes the accelerating expansion of the Universe.
- Its value is labelled  $\Lambda$ , the Greek letter lambda, by convention
- The most “natural” expected value is about  $10^{120}$  times BIGGER than the one we actually have, but is a vastly huge number in which no structure, no complexity, let alone life, could possibly develop
- $\Lambda$  must be vastly smaller to be compatible with a universe that can gravitate structure and permit long lived environments for life (given other physics parameters as they actually are)
- A new paper, though, shows surprisingly that it cannot be the other temptingly “natural” value we had originally expected, namely exactly  $\Lambda = 0$  (no accelerating universe)...

## Piran et al. 2015 show...

- ...that a small but non-zero  $\Lambda$  is required, else too many galaxies and stars form too close together and too many nearby fatal Gamma Ray Bursts go off during life's evolution, sterilizing life-giving planets too often.
- The following graph shows our actual universe has a value of  $\Lambda$  which is just about what the probabilities would expect, given all the factors determining a life-suitable Universe such as we live in.

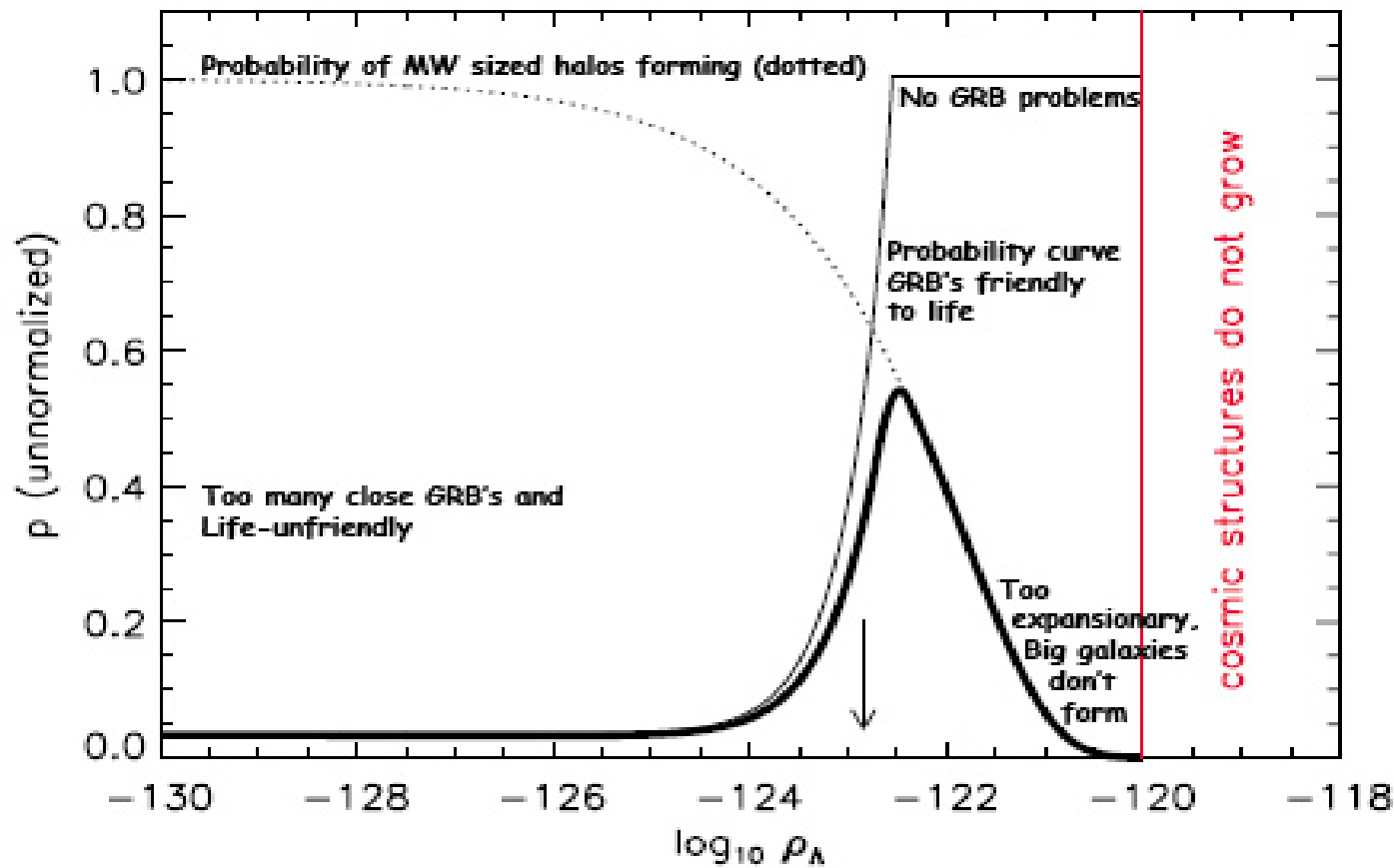


FIG. 2. The probability distribution function for  $\rho_\Lambda$ . The thin solid line is the result of this work ( $I(\Lambda)$  from Eq. 1 and Fig. 1). The dotted line is  $F(\Lambda)$  from [21], for Milky-Way mass halos. The thick solid line is the combined result. The upper bound is the requirement of [1] that large galaxies can form. The arrow shows the value of  $\rho_\Lambda$  for the concordance  $\Lambda$ CDM model.

# Is the Multi-Verse paradigm true?

- We don't know.
- Some versions of this paradigm include expanding universes within a larger space. If, by unlikely chance, these universes overlap and if the laws of physics within these differ, then you'd see the physics of the night sky might not be isotropic – it would show a circular patch with different properties
- Existing data don't show this, but if the changes in the laws are subtle, maybe looking closer could tell?
- Otherwise, we have no tests we have yet thought of.



# The Inflationary Multi-verse paradigm **is** appealing...

- ---1. It is a natural outcome of most cosmologies that produce Inflation; the Inflationary moments are not unique, but happen “all the time”.
- --- 2. The observed properties of large scale structure are perfectly in agreement with the predictions of the simplest models of Inflation, and no other idea we have yet discovered.
- --- 3. The Multi-Verse paradigm answers questions which otherwise don't have apparent solutions.

# Chap 23: Key Points - Cosmology

- CMB shows we had a Big Bang
- Total Energy of Universe=0; balanced between gravity and expansion energy.
- $E=0$  universes can be created by Inflation.  $E$  not zero, we can't see how those could be created.
- Most elegant demonstration that Laws of Physics are the same across space and time is the spectra of Quasars, which so same chemical elements as on Earth today.
- Large scale structure is filamentary, caused by gravity, seeded by density fluctuations in the Dark Matter created by quantum density fluctuations and raised to galaxy scales by the Inflation era.
- Universe is expanding and accelerating- Dark Energy; 68% of the energy of the Universe
- Dark Matter is 27% of the mass/energy of the Universe
- If symmetry breaking of a single force law happened, Inflation might have been the moment the Strong and EM forces split.
- 1 billion CMB photons per particle in our universe, therefore the imbalance in matter/antimatter was only 1 part per billion
- Inflation may create near-infinite universes, continuously, each with their own laws of physics, space, time...