THE BIG BANG: THE ORIGIN AND EVOLUTION OF THE UNIVERSE

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Plan

- Day 1:
  - Structure and scale of the Universe
  - Observed expansion and its interpretation

- Day 2:
  - Creation of the chemical elements (BBNS)
  - The Cosmic Background Radiation (CMB)

- **Day 3:**
  - **The very early Universe – inflation**
  - **The first stars**
  - **The first galaxies**

Background

- Redshift:
- At redshift z, the Universe was 1/(1+z) its current size
- Examples:
  - At z=2, the Universe was 1/3 its current size
  - At z=6, the Universe was 1/7 its current size
  - At z=1100, the Universe was ~1/1100 its current size

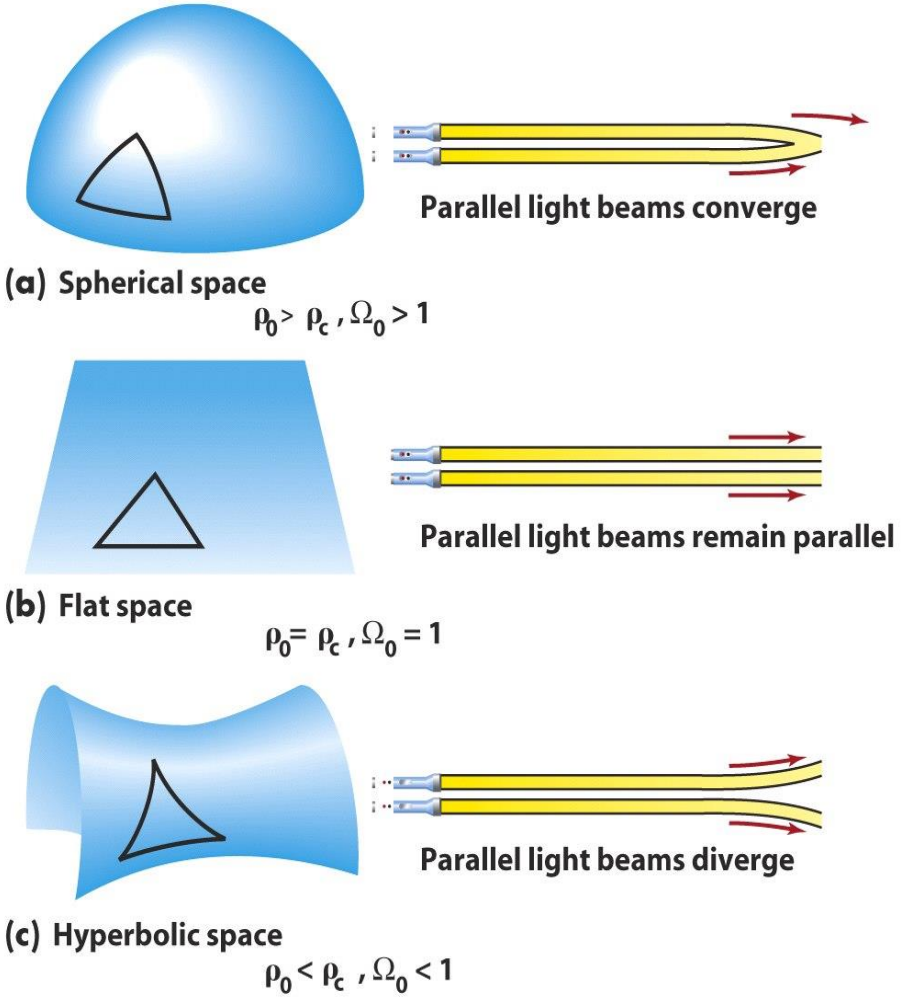
The Big Bang Revisited

Inflation

- Is all well with the Big Bang?
  - Universe expands
  - Light elements
  - Background radiation
- No!
  - Flatness problem
  - Horizon problem
  - Monopole problem
- Nothing fundamentally wrong – but we need to `tweak' the picture

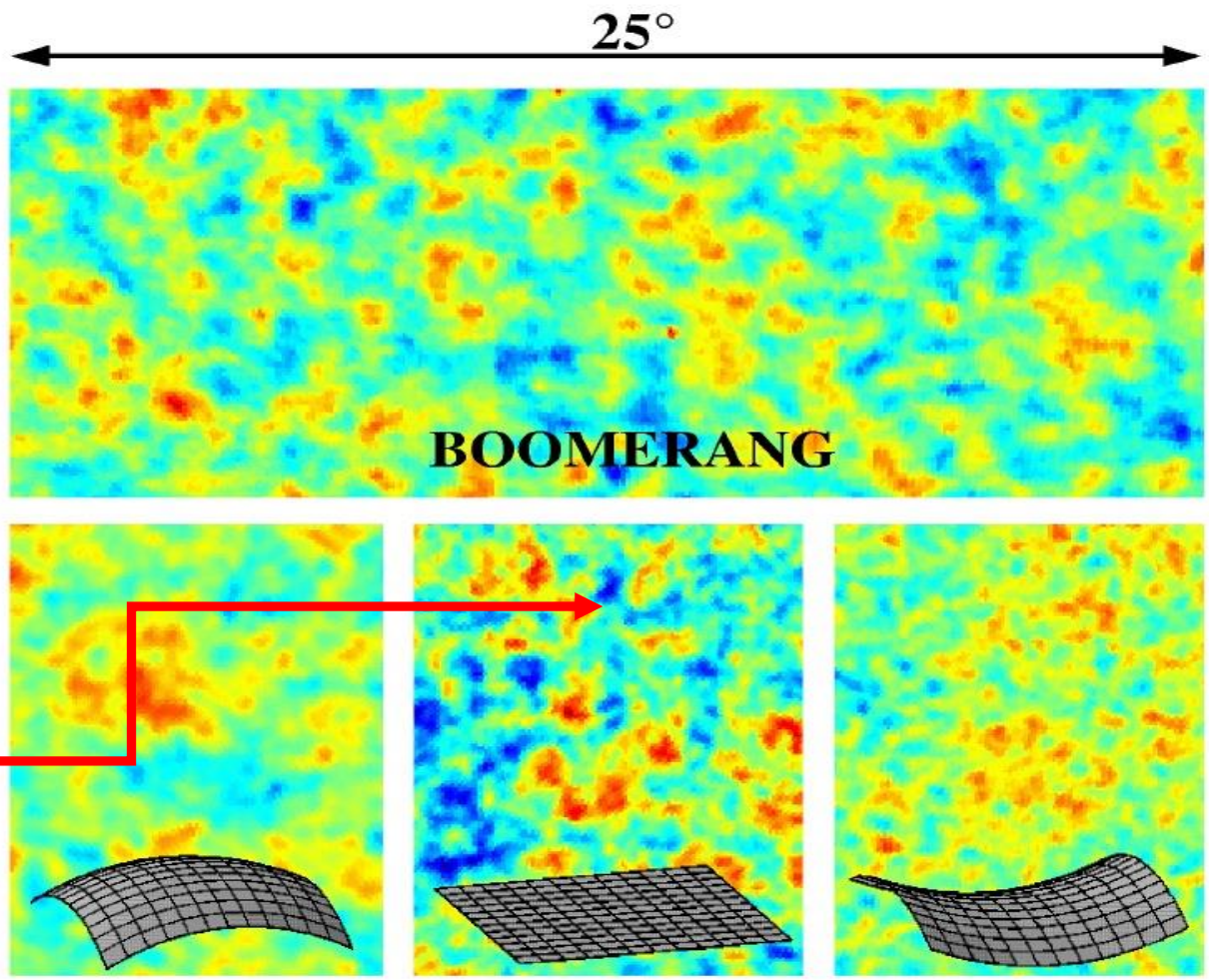
Measuring The Geometry of Space

- We can't triangulate the distant Universe
- Can we look at distant objects of known size?
- Yes – the pattern in the CMB
- We know the size because we know <u>when</u> the structure is seen



Which model best matches (statistically) the BOOMERANG data?

A. Positive curvature?
B. Flat?
C. Negative curvature?

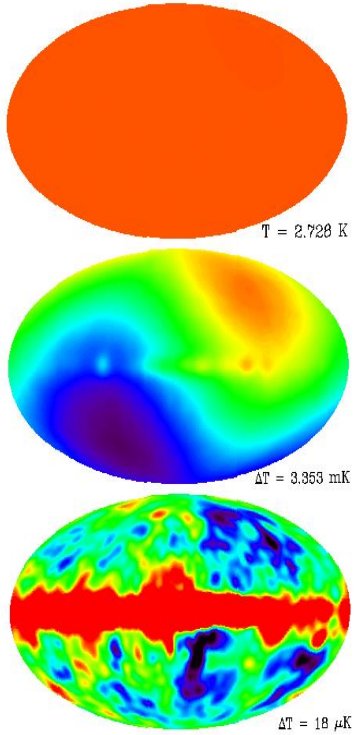


What density of matter causes this? Critical.

Flatness Problem

- The average density of matter is so close to critical now, it must have been within 50 significant figures of critical at the Big Bang – why would it have been so “fine tuned”?
- Perhaps it is “critical”
- This is called the flatness problem, because an alternative perspective is to say why is space so flat?

Horizon Problem



- Once we subtract
  - the 'dipole' anisotropy
  - the contribution from our Galaxy
- the CMB is uniform to 1 part in 100,000 – that's **too uniform!**
- Uniformity implies 'communication' (contact) – the opportunity to come into equilibrium

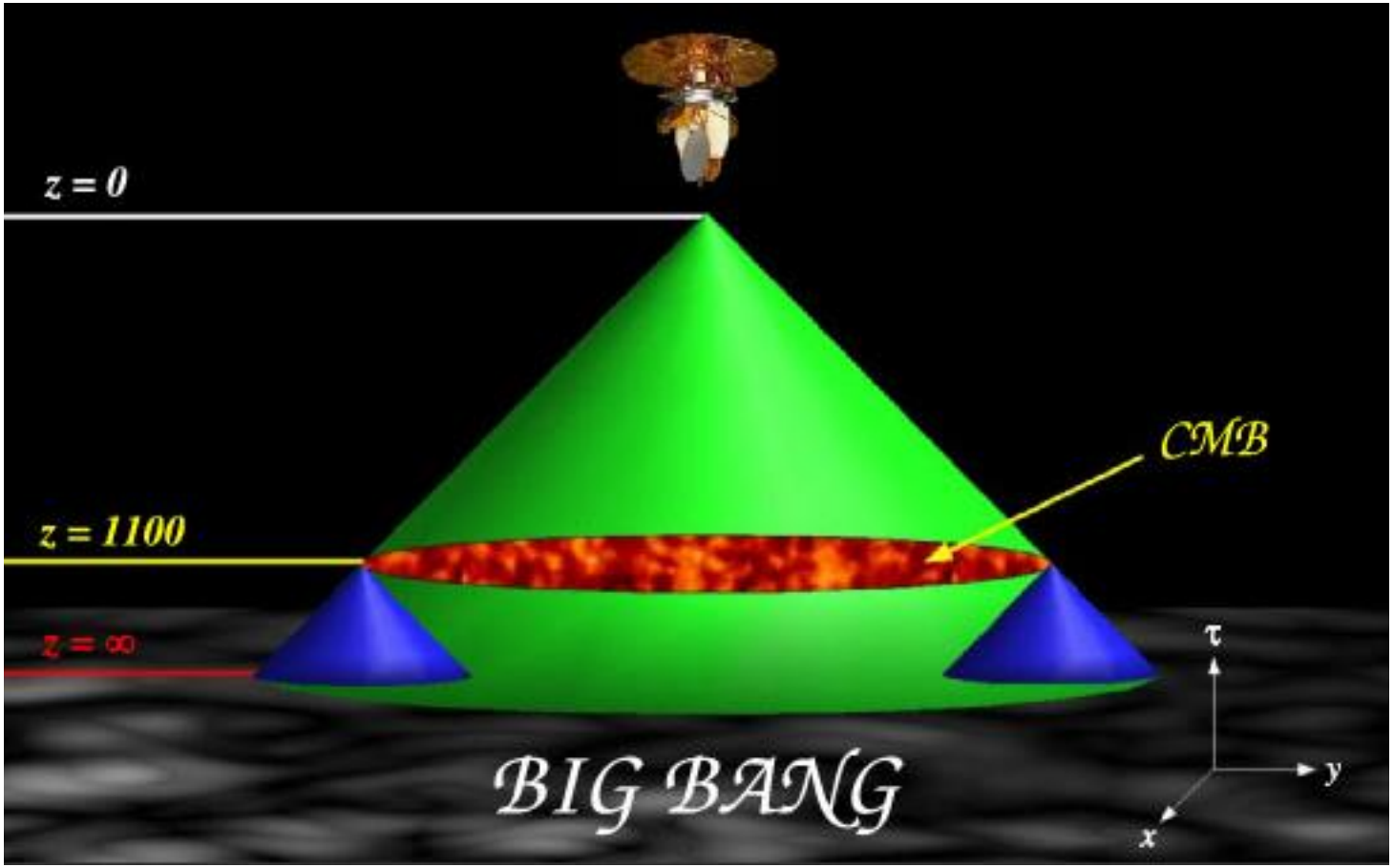
Horizon Problem

- Bring in a sealed flask of water from Lake Michigan, the Indian Ocean, the Arctic Ocean, open and quickly compare; the same temperature? It would be extraordinary
- A day later? They have come into equilibrium
  - There has been time for heat to be exchanged



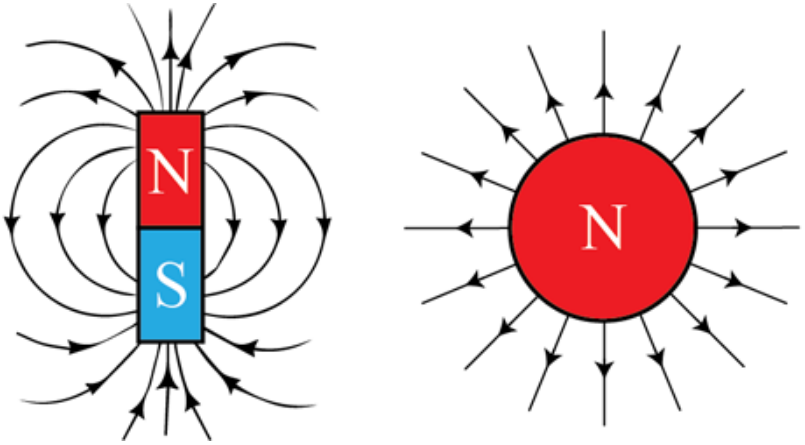
Horizon Problem

- There has not been time in the history of the Universe for two 'sides' of the Universe to come into equilibrium



Monopole Problem

- In today's Universe, magnetic monopoles can't exist: you can't split the N & S poles of a magnet



- But exotic physics in the early Universe is quite likely to have led to monopoles – so where are they?

Inflation

- No, not this inflation....



- This inflation.....

Inflation I



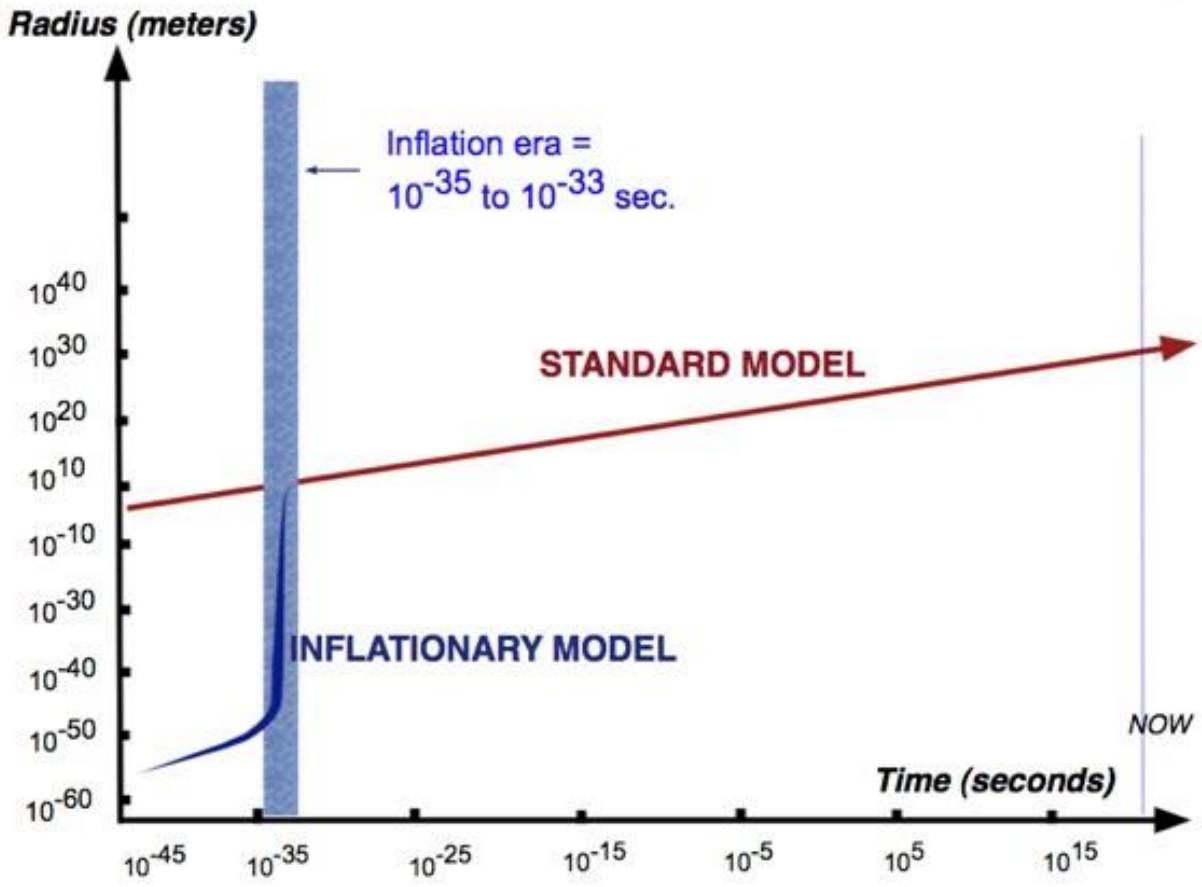
- The solution: **inflation**
- Proposed by Alan Guth (1980)
- Followed by '**new inflation**' due to Linde and Albrecht & Steinhardt (1982)



- Historically, it is related to the concept behind Einstein's *cosmological constant*, Λ

Inflation II: The Concept

- Size of Universe increases rapidly – by 10^{50} in 10^{-35} seconds



The Three Obvious Questions

- Doesn't that mean the Universe expanded vastly faster than light speed?
  - Yes! Motion through space is limited to this speed; but motion of space itself is unlimited; today, distant galaxies recede faster than light
- Why would the Universe do that?
- How does it resolve the flatness, horizon and monopole problems?

Flatness Problem – Solved!

- Recast the question:
  - Why is the density of the Universe so close to “critical”?
  - Recall: critical density ⇔ flat space
  - Why is space so close to being flat?
- We are seeing a tiny fraction of the whole
  - Earth appears flat seen close up



Horizon Problem – Solved!

- Parts of the Universe in causal contact – having reached equilibrium – at 10^{-35}s, are “ripped apart” by inflation
- The regions that *appear* unconnected today, *were* connected just after the Big Bang



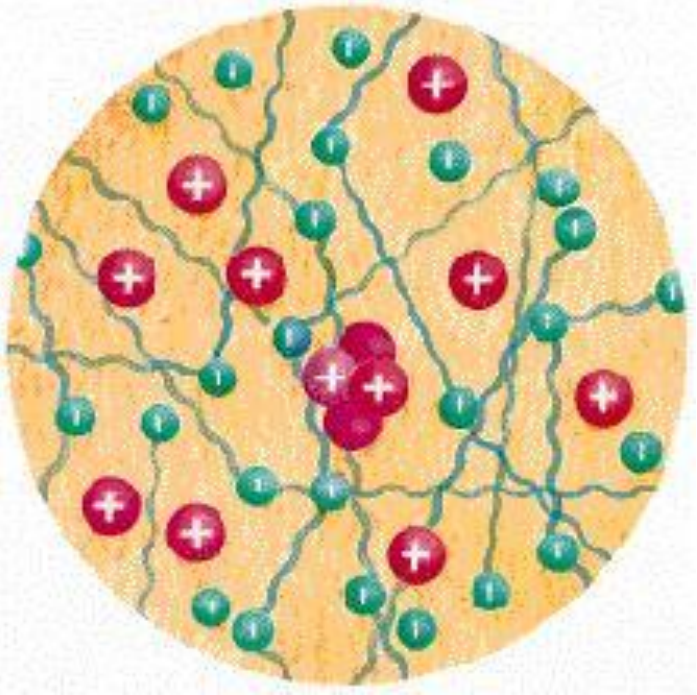
Monopole Problem – Solved!

- The expansion associated with inflation has diluted the density of primordial magnetic monopoles to the extent that there may be few or none within the visible Universe

Why Is There **Any** Structure?

Formation of Structure

- How do we go from this:



- to this?

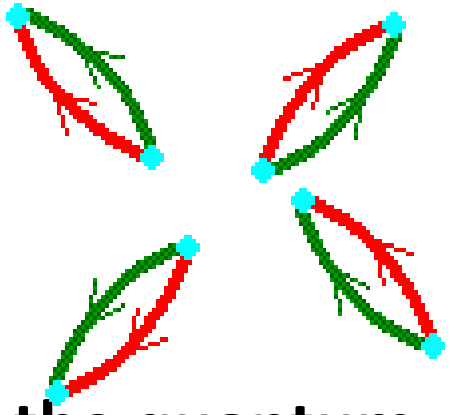


The Quantum World

- We can understand the origin of structure through the ideas of quantum fluctuations and inflation

Quantum Fluctuations

- Space is a sea of virtual particles popping into and out of existence
- Pairs can appear for a short time determined by the Heisenberg Uncertainty Principle

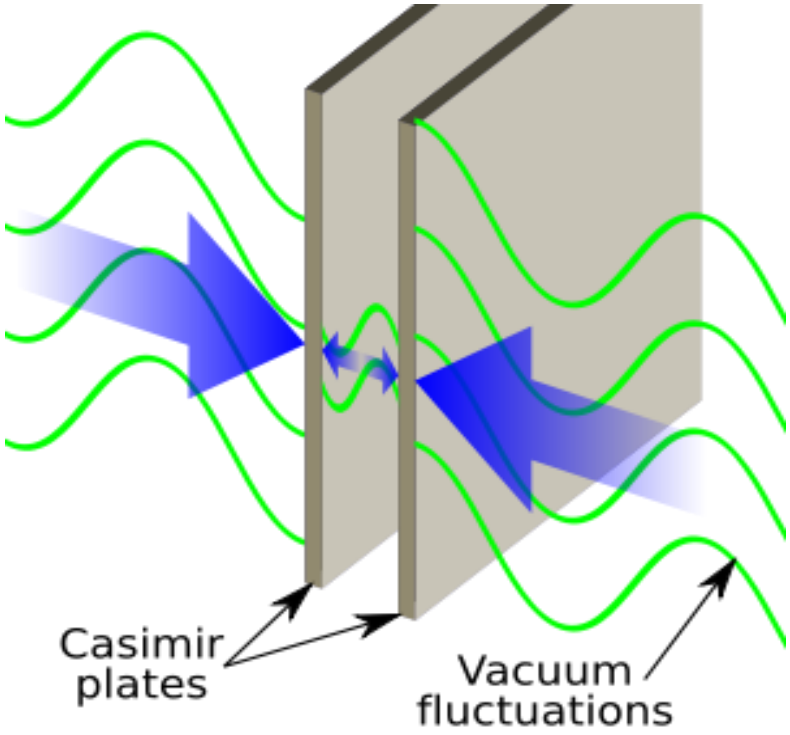


- **Random fluctuations are inevitable in the quantum world**

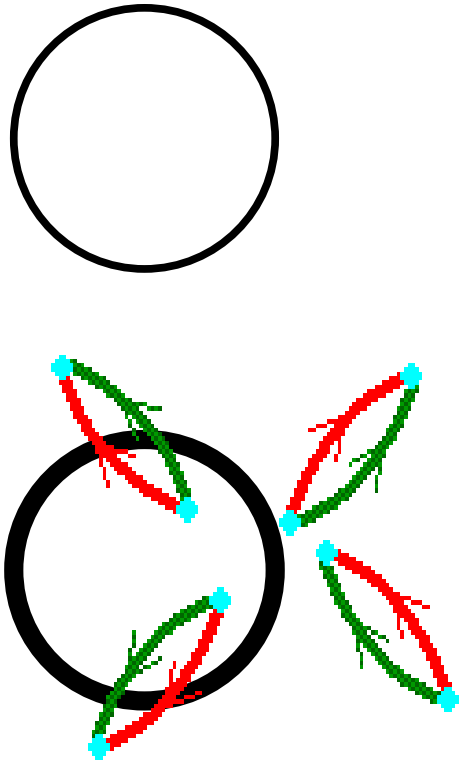
  (cf. random variations in density associated with Brownian motion)

Evidence For Virtual Particles

- Casimir Effect



- Lamb Shift



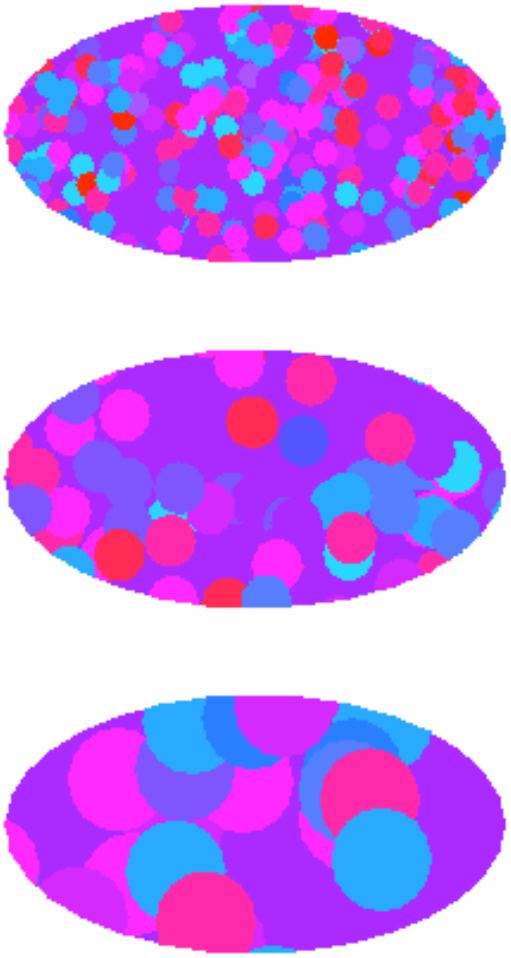
An Analogy



- Jackson Pollock quickly paints a work – the canvas expands until the paint dries, at which time the canvas stops expanding
- He starts over, with a new canvas using slower drying paint, and again, and again….
- If you superposed all his attempts, what would the result look like?

Quantum Fluctuations + Inflation

- The Universe was a sea of quantum fluctuations at the start of inflation
- Inflation stretches these – no "sloshing" because inflation is so fast the fluctuations are effectively frozen into the flow
- Each successive generation of fluctuations is inflated less
- After inflation, the Universe expands, encompassing a hierarchy of structure



Quantum Fluctuations + Inflation

- **The seeds of today's structure start as the random variations inherent in the quantum world!**

The Nature Of Matter

- It has been found that most of the matter in the Universe is 'dark’
- Various lines of evidence (including BBNS) show that the baryons in the Universe can't contribute more than 4-5%
- So most dark matter must be non-baryonic
- **It's something that does not interact with ordinary matter or radiation, except through gravity**

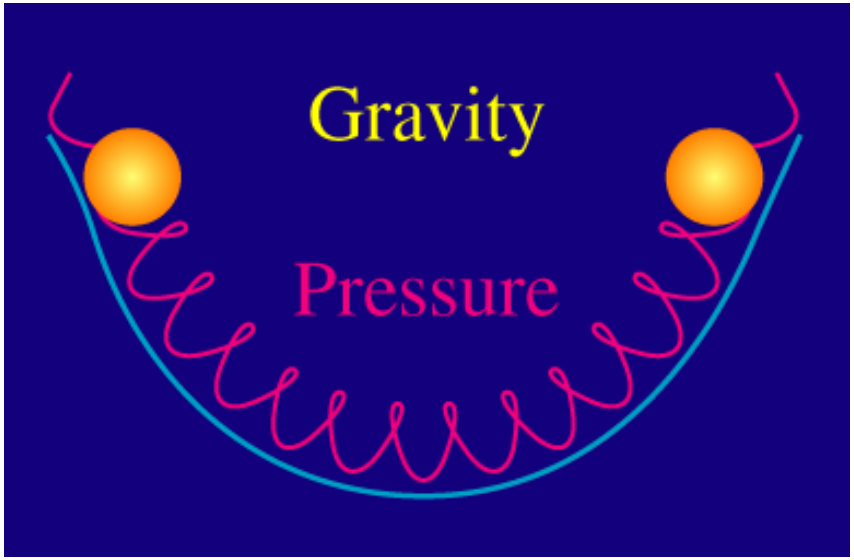
Structure Starts To Form

- What dominates the mass in the Universe?
- Dark matter particles

- But dark matter particles don't interact with radiation, so they start to grow – overdense regions are pulled together by their mutual gravity – **from soon after Big Bang**

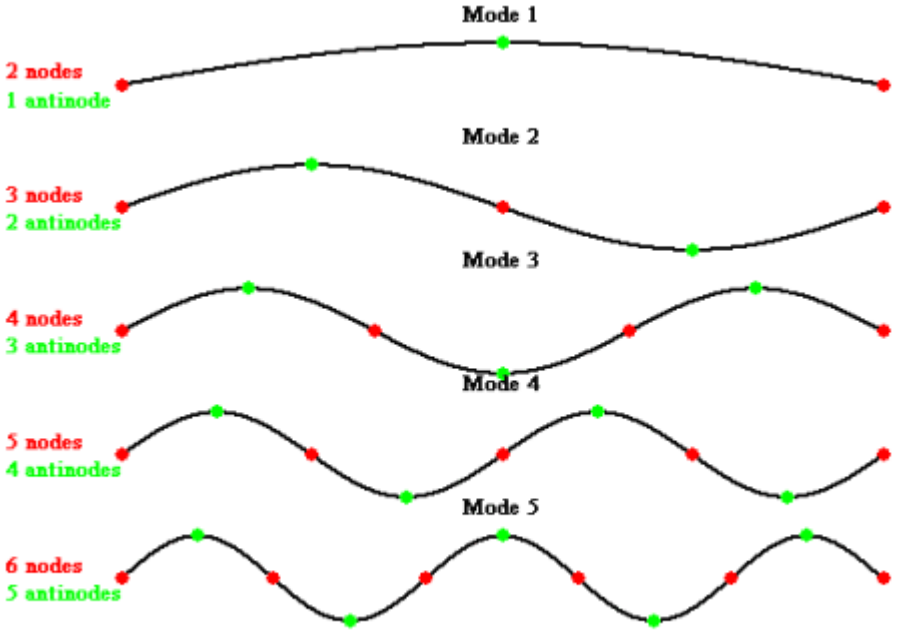
Bouncing Baryons

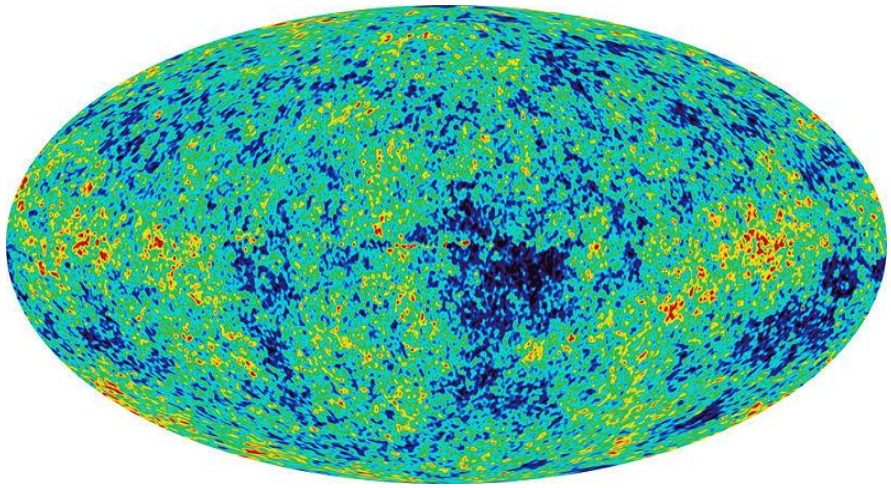
- Why doesn't the density of *baryons* grow from that time?
- Baryons and photons are strongly coupled (via electrons)
- If a clump of baryons/electrons tries to fall into an overdense region, pressure of the photons resists



The CMB Fluctuations

- Those waves caught at the maximum of their compression or rarefaction are the patterns seen in the CMB maps – a snapshot – at decoupling when photons stream freely

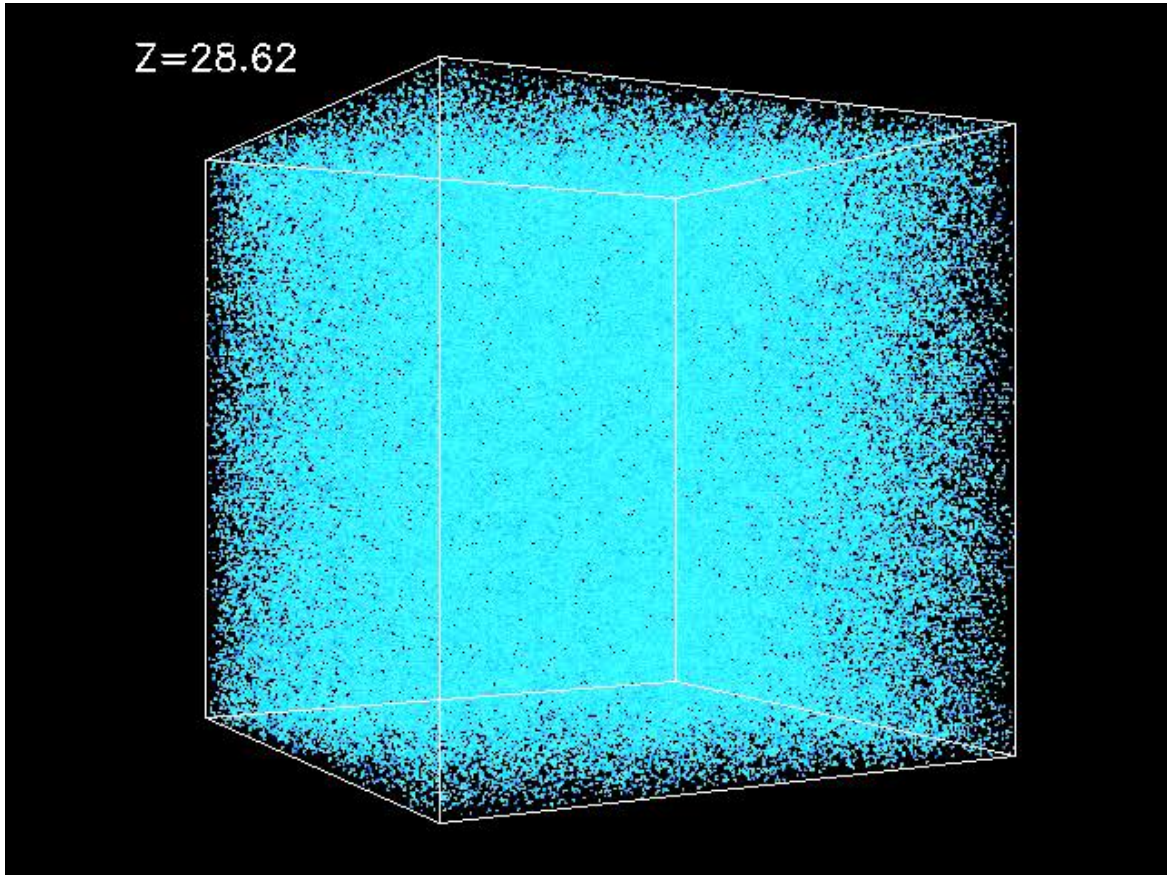




Summary

- So, baryon fluctuations oscillate, rather than grow, until after decoupling when they are still at the 1 in 100,000 level – *too late to explain present structure* – but it does explain the CMB observations
- The dark matter fluctuations have been growing since soon after Big Bang – they are the key seeds of structure – by decoupling they are at the 1 in 1000 level; we would not have structure without dark matter!
- Gravity alone explains the large-scale structure of sheets & filaments!

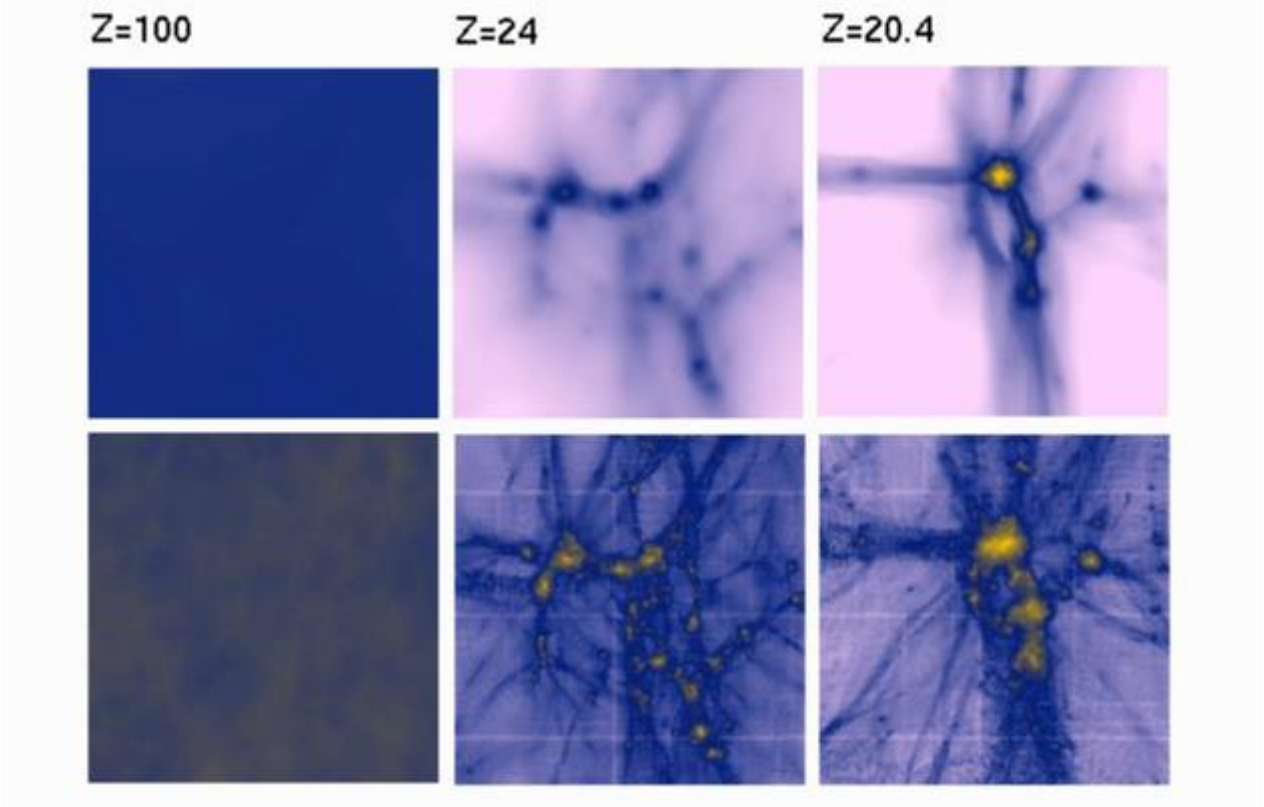
Evolution To The Present Day



The First Stars

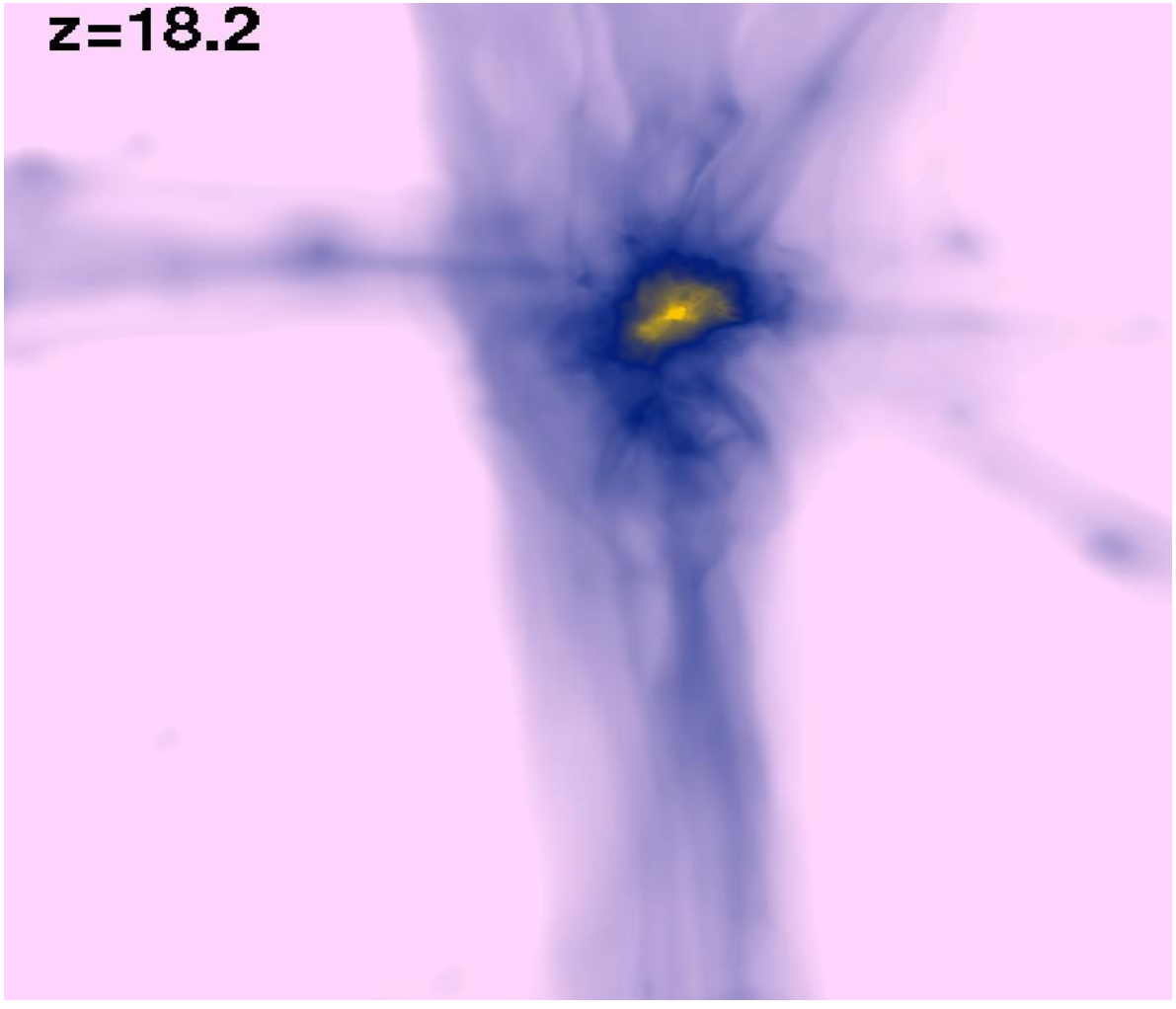
Overview I

- Use the work of Tom Abel, Penn State, as illustration



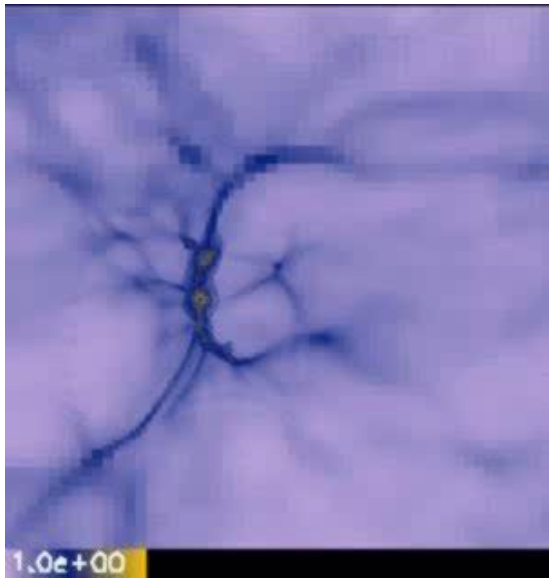
Overview II

- 155 million years after Big Bang; we zoom in on a million solar mass “protogalaxy” which has formed at the apex of filaments



baryons

Movie: 10 orders in scale



Baryons can **cool**, thus collapse; so stars are **much** smaller than dark matter halos

First Stars: Summary

- The dark matter does not cool, because it interacts only gravitationally, and so cannot collapse
- The baryons cool, and so sink within the dark matter halos

- Form in the first 100s million years, within
- 100,000 million solar mass protogalaxies which are 30-100 light years across

Role Of First Stars

- Seeded the growth of supermassive black holes
  - that allowed formation of galaxies
- Generated/dispersed the first heavy elements
  - permitting formation of solar systems
- Heated and reionized the gas

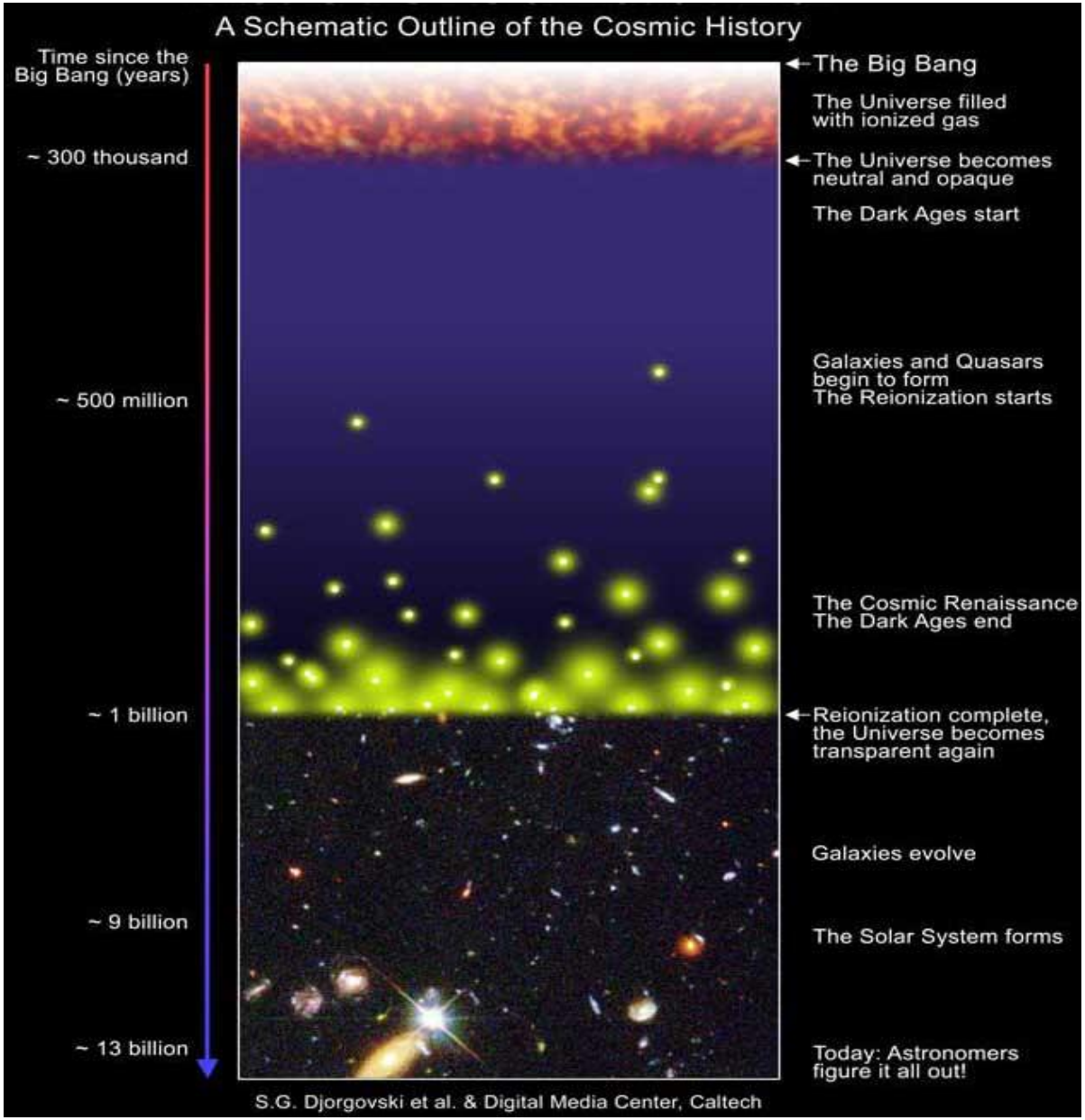


"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

Cosmic Dark Ages

Universe becomes transparent to what is today the CMB.

But it would be opaque to visible light unless reionization occurred.

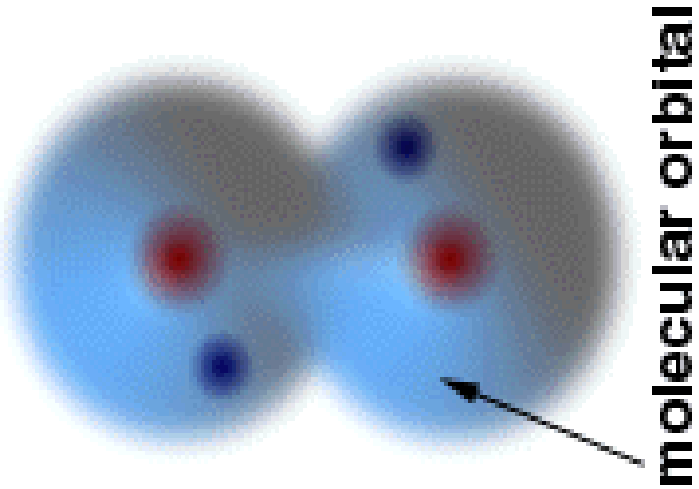


First Stars: Cooling I

- Gravitational collapse releases energy
- The collapse proceeds only as fast as this can be radiated away
- How can a gas radiate energy in today's Universe?
- Through
  - dust, which can glow
  - electrons (particularly of heavy elements) which can radiate at certain energies
  - molecules such as CO, H_20.... which emit energy in jumping from one to another state of rotation/vibration

First Stars: Cooling II

- In the first stars we don't have any of these, except, maybe H_2, if not destroyed by UV light
- Even then:
  - Collisions of H and He transfer energy to some H_2, and that radiates, but ineffectively – inefficient because this molecule is more or less one structure

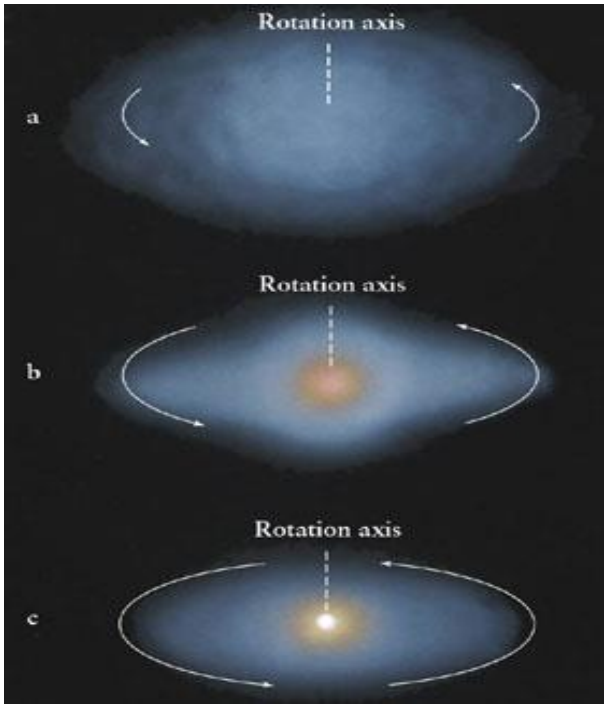


Big Is Better

- In the Galaxy today, a cloud can collapse only if its mass is greater than the “Jeans mass” – only then can gravity win over pressure
- Cooling being efficient, star forming regions are at 10s K – the Jeans mass is quite small (about a solar mass)
- The first stars don't cool as effectively, the Jeans mass is much higher – 1000 x that today
- **Only massive stars can form**

First Stars: Collapse

- Collapse heats baryon gas to about 1000 K
- Cooling reduces temp. of densest parts to 200 – 300K – reduces pressure, thus contraction further increases density....
- Disk-like clump forms inside dark matter halo



And Future Generations…

- First generation of stars would live only 1 million years
  - The lower mass stars die violently, “polluting” the Universe with heavy elements
  - Higher masses give us black holes – seeds for galaxies
- The Sun has only 2% heavy elements – need only 1/1000th of that for cooling to be dramatically enhanced – after only a few generations star formation would become 'normal' and we would get the low mass stars of today

The First Galaxies

Galaxy Formation



- Which came first?
  - SMBH?
  - galaxy?
- A major subject of research – it seems the SMBH came first
- SMBH are the seeds of galaxies, and activity feeds back on the growing galaxy and controls its growth

SMBH = Supermassive Black Hole

SMBH Formation/Growth I

There is currently no true consensus

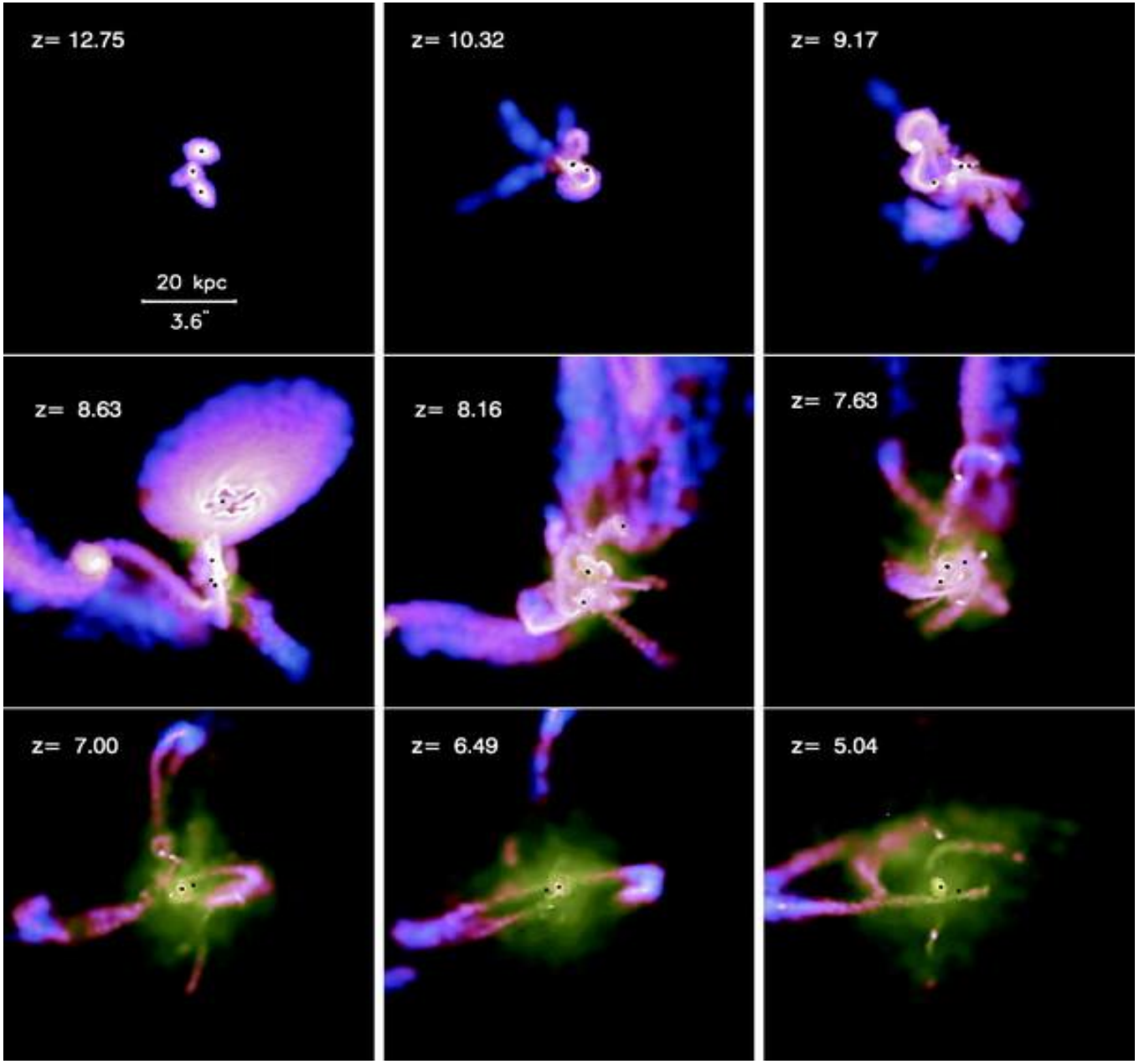
- Pure accretion? This is really problematic:
  - Inflow is limited by outflow of radiation arising from energy released by inflow
  - If the radiation pushes with an efficiency of 10%, and we start with a 100 solar mass object, it will take at least 0.5 billion years to make a billion solar mass SMBH
  - but such SMBHs must have been in place at z=7, when the Universe was only 0.8 billion years old, because we see luminous active galaxies back then

SMBH Formation/Growth II

- **Mergers followed by accretion, with the remnants of the 1st massive stars as seeds?**
- This looks more promising
- In the same way that we think the `cosmic web' arises in a bottom up scenario – small stuff first, building to bigger structures – it's suggested that protogalaxies with one or a few BHs from the 1st stars merge hierarchically
- Once a sufficiently massive BH exists, accretion can `finish the job'

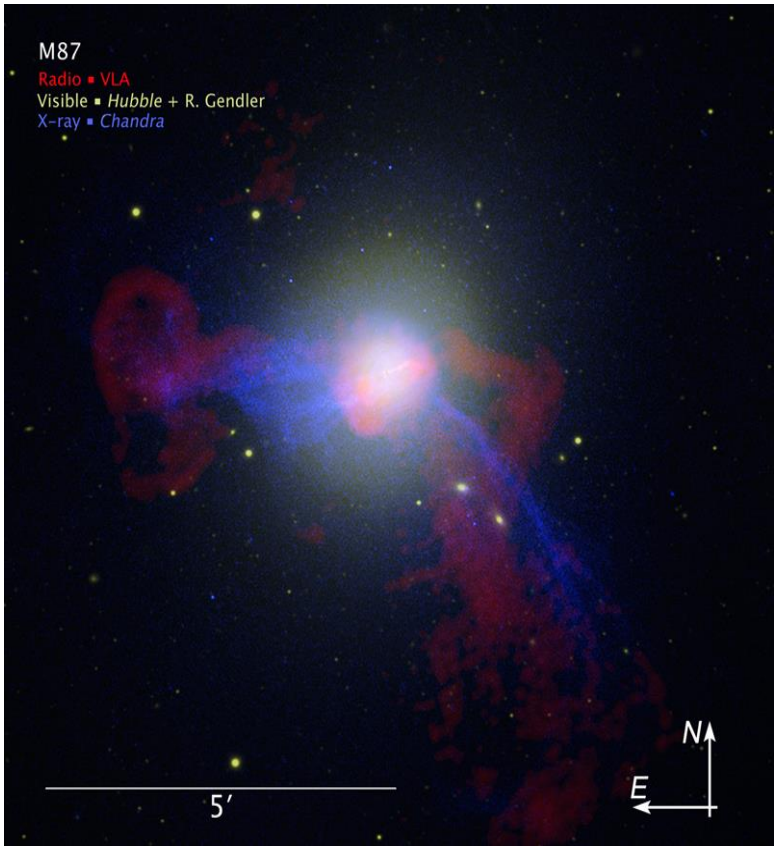
SMBHs – Getting The Ball Rolling

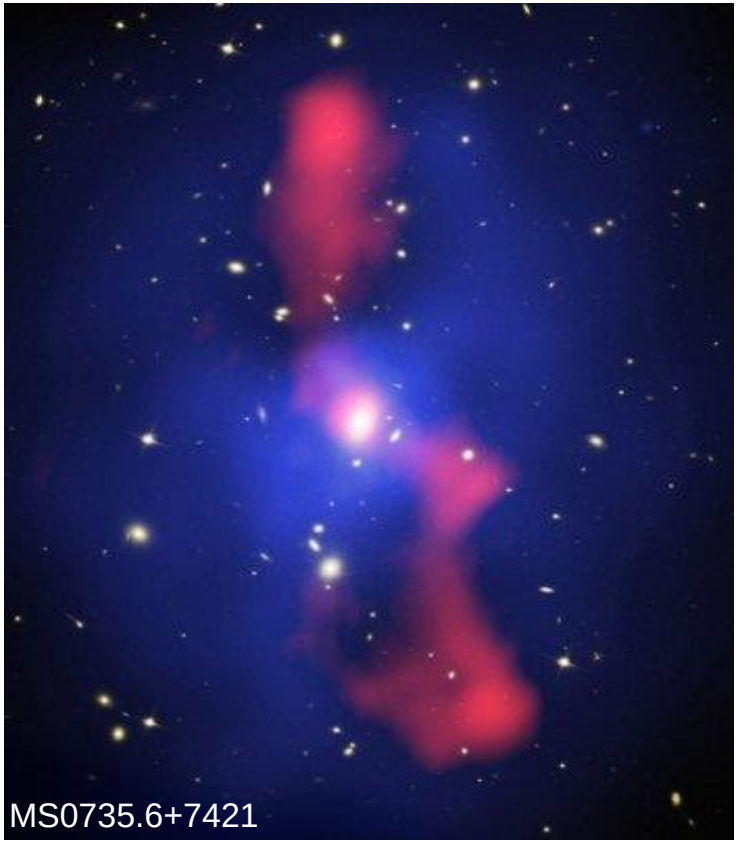
- A plausible view is the hierarchical picture:
  - Mergers between protogalaxies with BHs from 1st stars which existed only 100s million years after Big Bang,
  - rapidly build intermediate mass BHs, starting maybe 1/3 billion years after Big Bang
  - Active galaxies formed by z ~ 7 when the Universe was less than 1/10th its present age – about 0.8 billion years old
  - These – and their host galaxy – continue to grow by accretion, in a self-regulating way


z= 12.75
20 kpc
3.6"
z= 10.32
z= 9.17
z= 8.63
z= 8.16
z= 7.63
z= 7.00
z= 6.49
z= 5.04

The Feedback Mechanism I

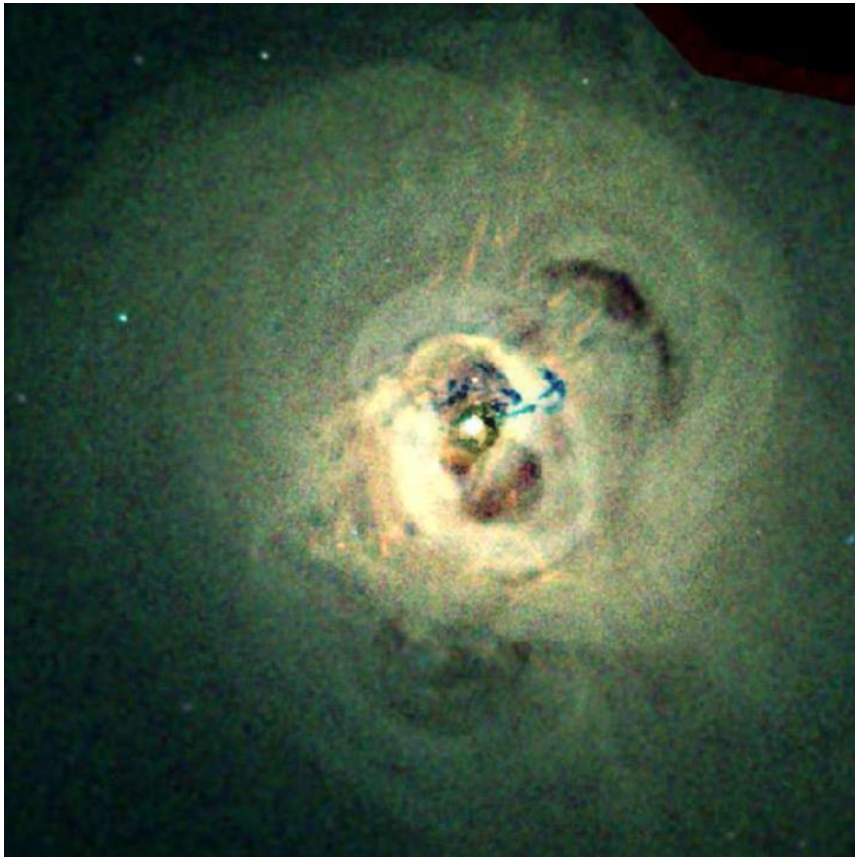
- Wind/jet is more important than radiation when the output is not close to maximum efficiency

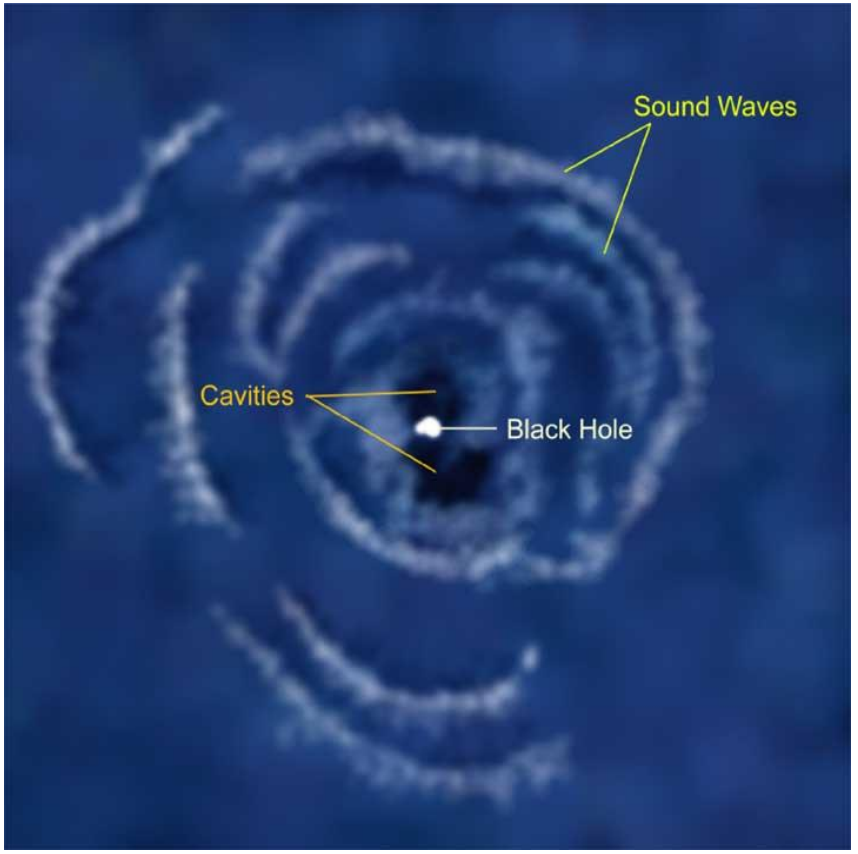




The Feedback Mechanism II

- An example of heating/cavity excavation: Chandra observations of the Perseus cluster

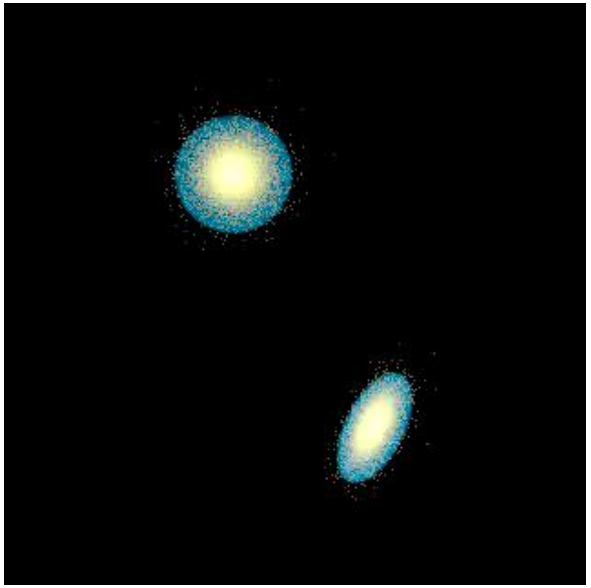




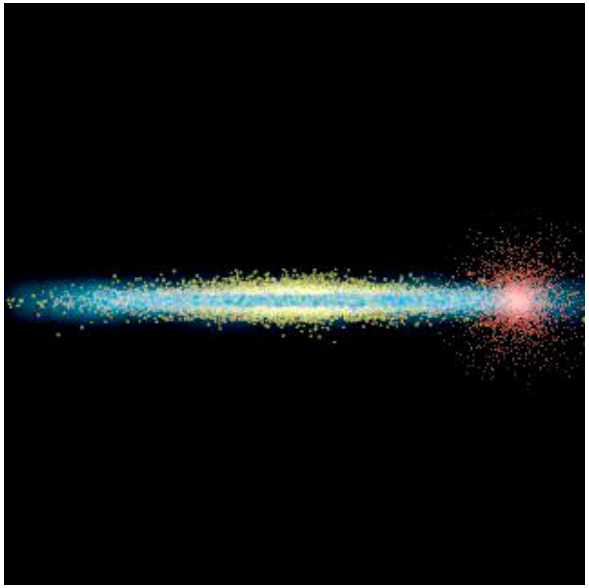
The Final Galaxy: Merging Halos

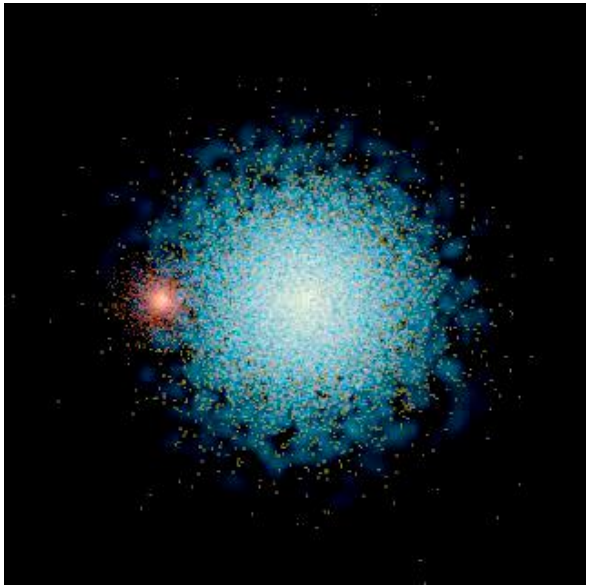
- 'Giant' galaxies form through hierarchical merging of small 'halos'
- **Ellipticals**
- **Spirals**

How To Make An Elliptical

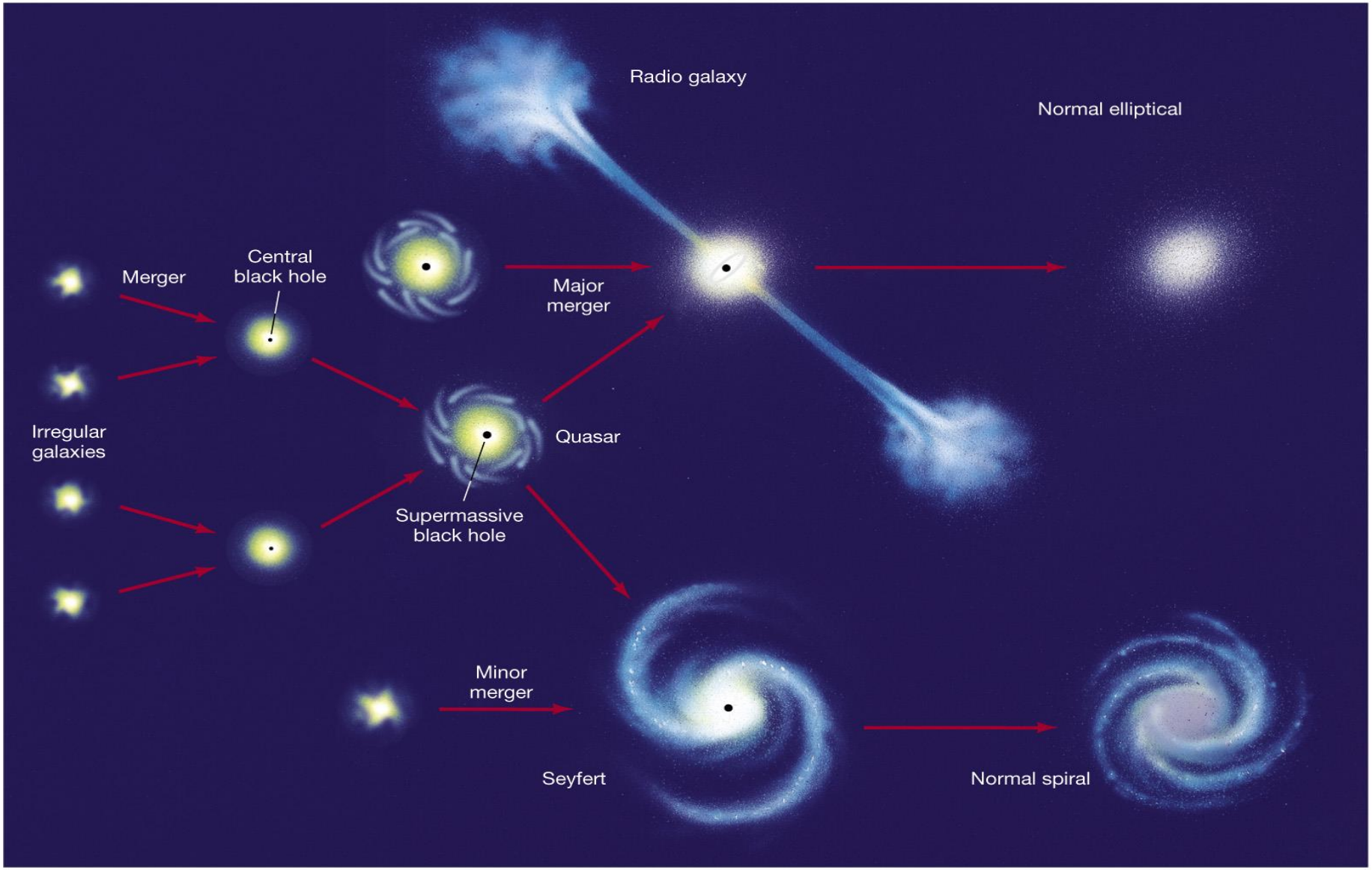


How To Make A Spiral



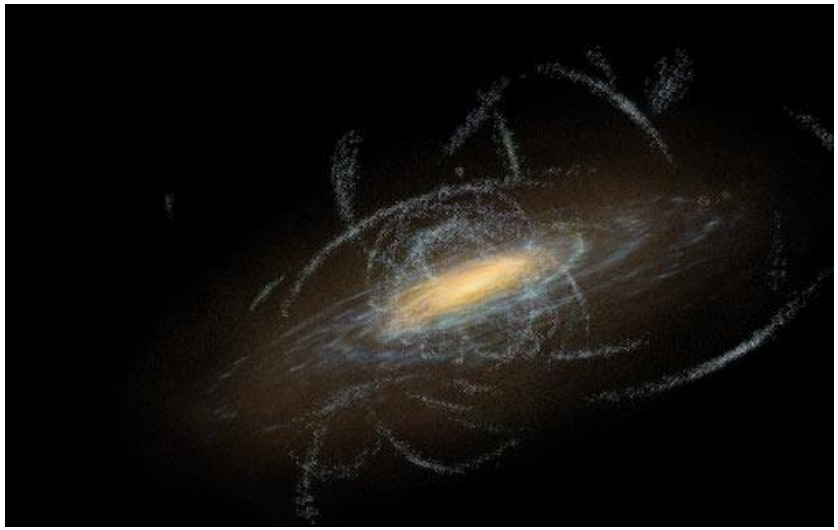


Formation Summary



Relic Streams I

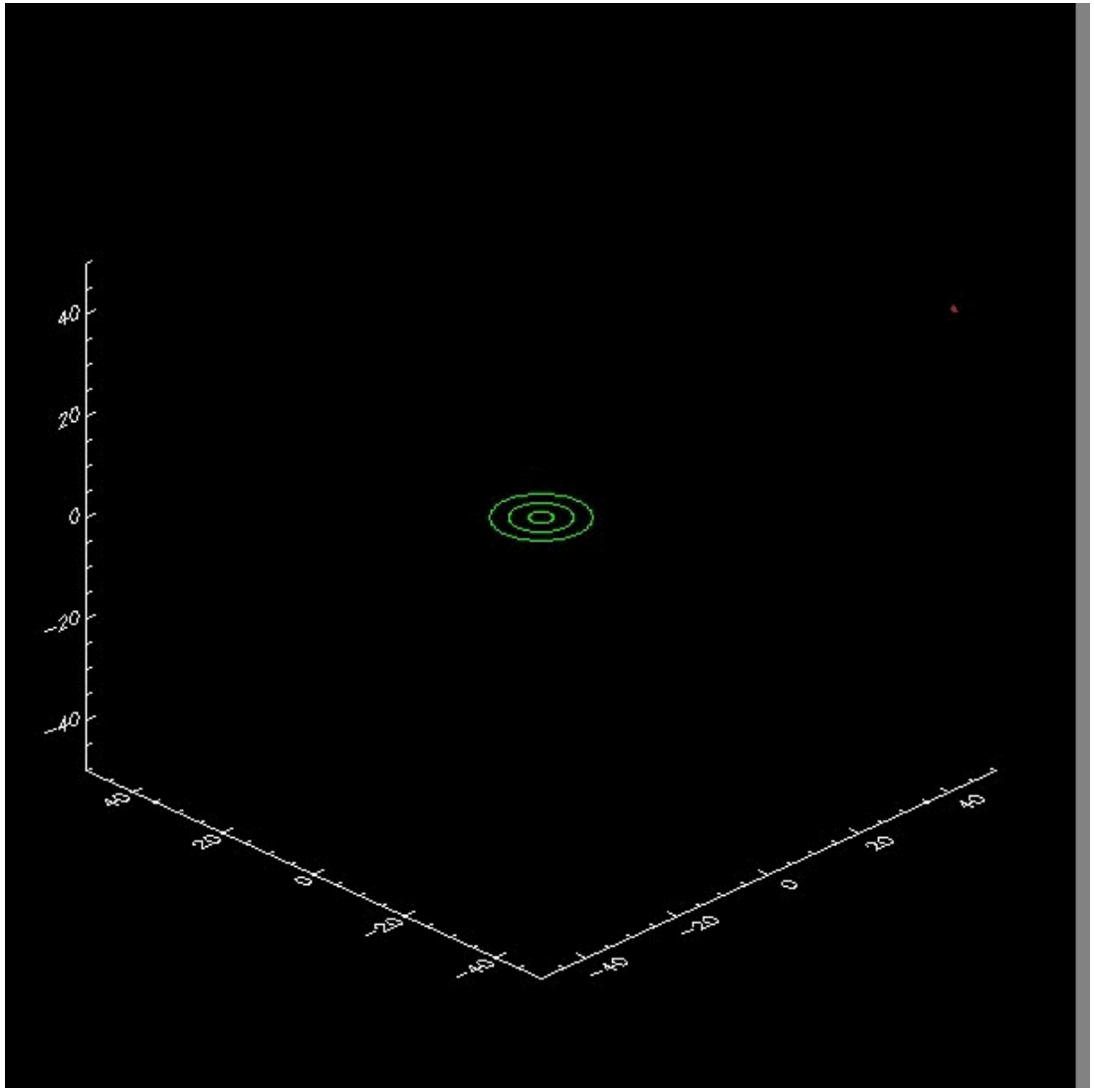
- Merging of 'dwarf halos' should lead to 'relic streams'



(artwork)



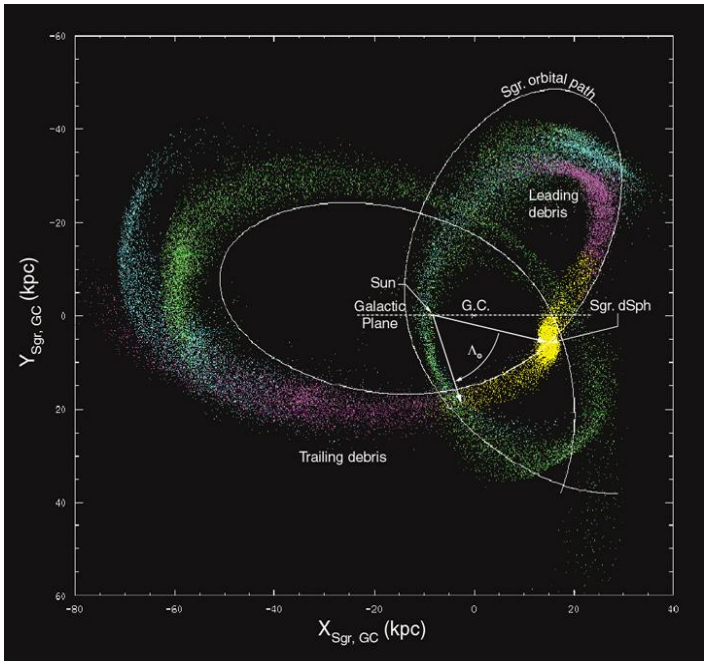
(reality)

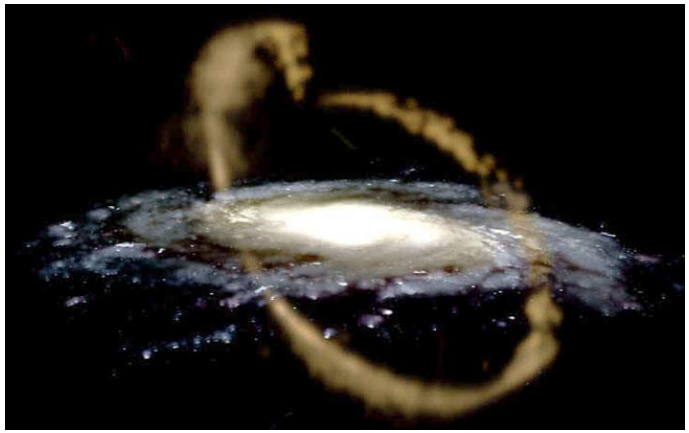

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Relic Streams II

- We can see the 'relic streams' from halo merging in the Milky Way
- Sagittarius dwarf is disrupting in gravitational field of Milky Way – Sgr dwarf is part of Sgr tidal stream







Wrap Up!

- We are seeing the late stages of evolution of our galaxy – The Milky Way
- The Universe is continuing to evolve
- What does the future hold? That's another class!


The James Webb Space Telescope
Seeing Farther
Launch: December 18!
NASA
CSA ASC
esa
nasa.gov/webb