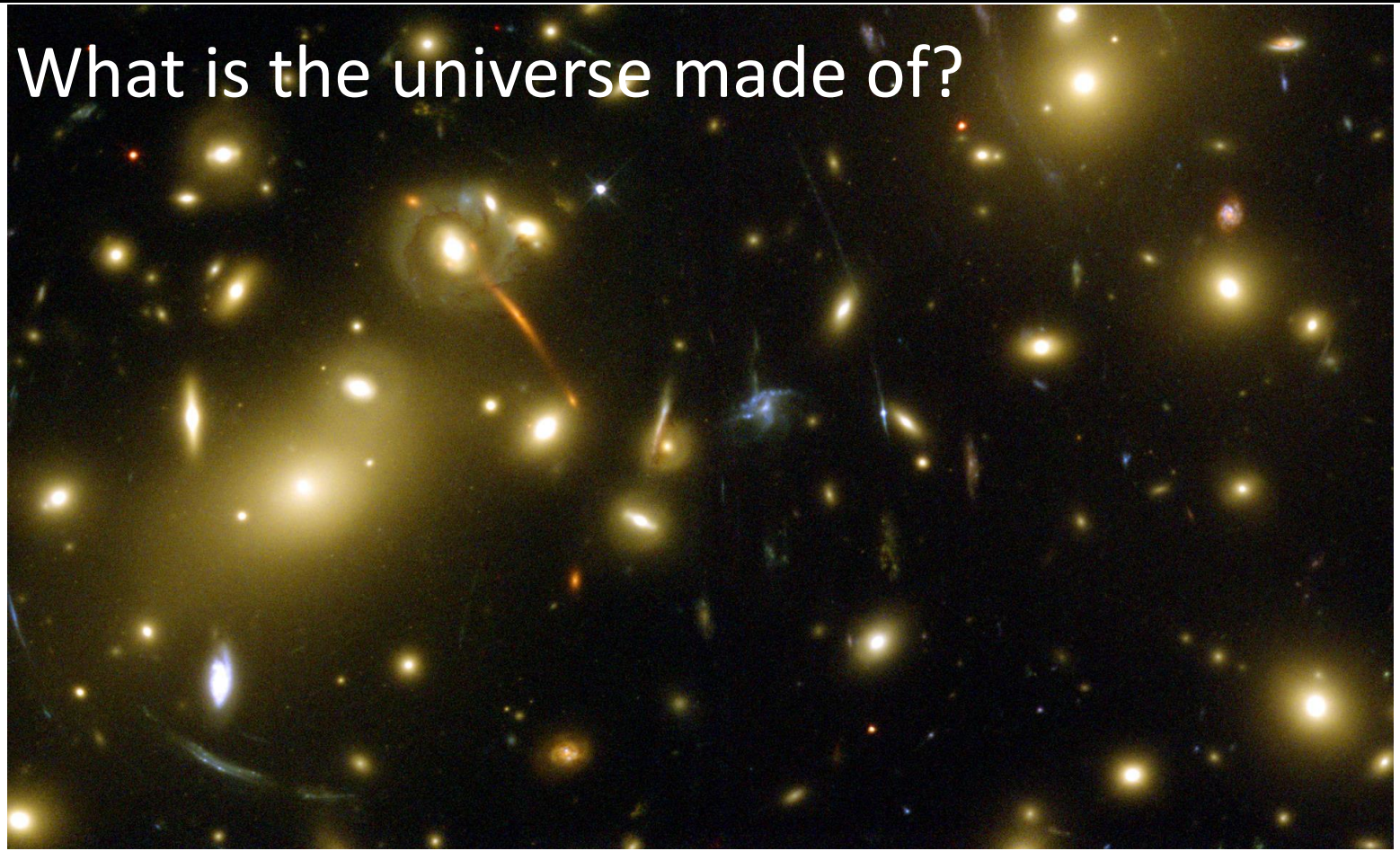
Question: What is the universe made of?



Composition & Structure

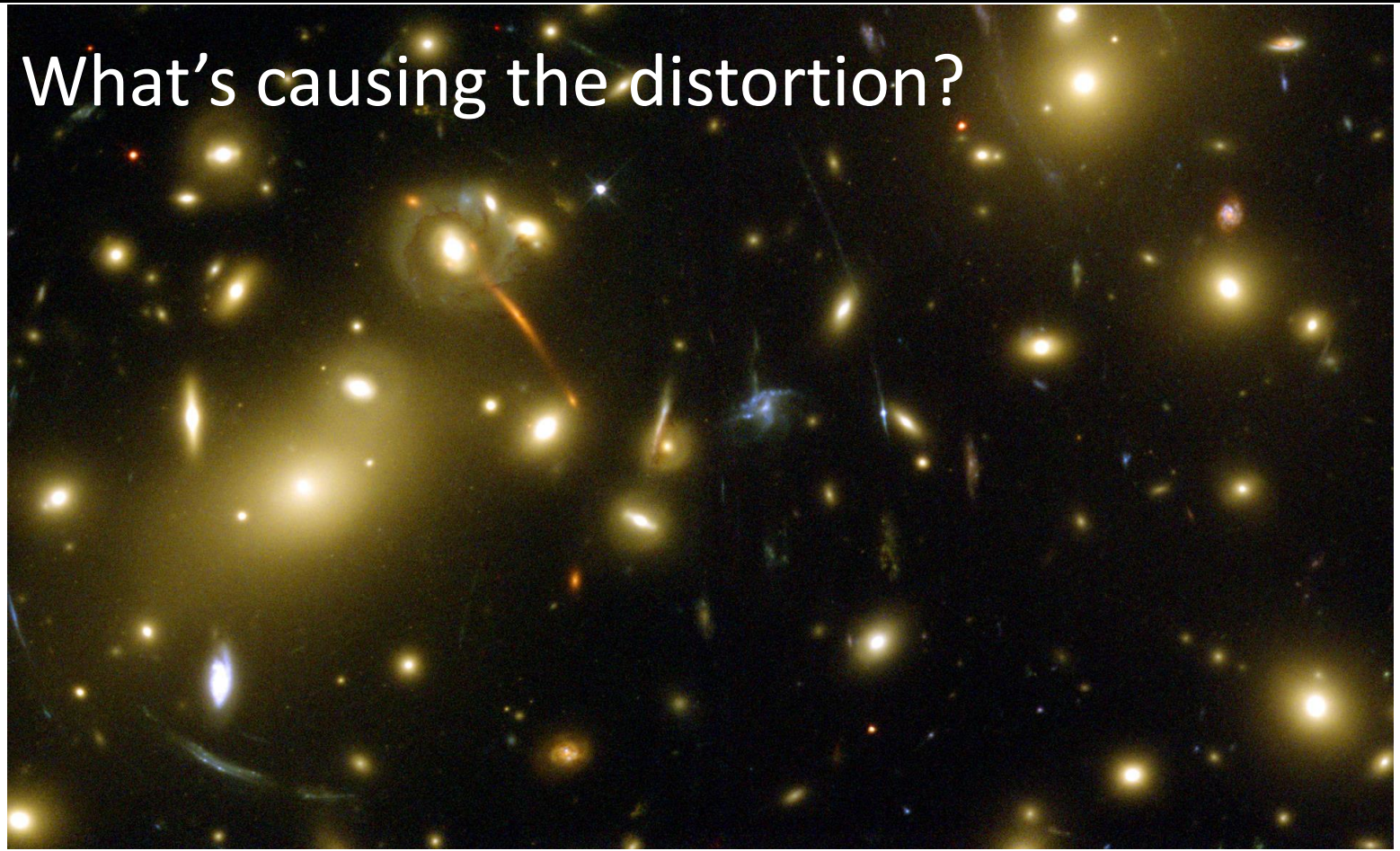
- Taking pictures of the universe in many wavelengths of light

  …and analysing them in the context of a wealth of understanding about astronomy, physics, and astrophysics (light, gravity, stellar models, behaviour of gasses, etc.)

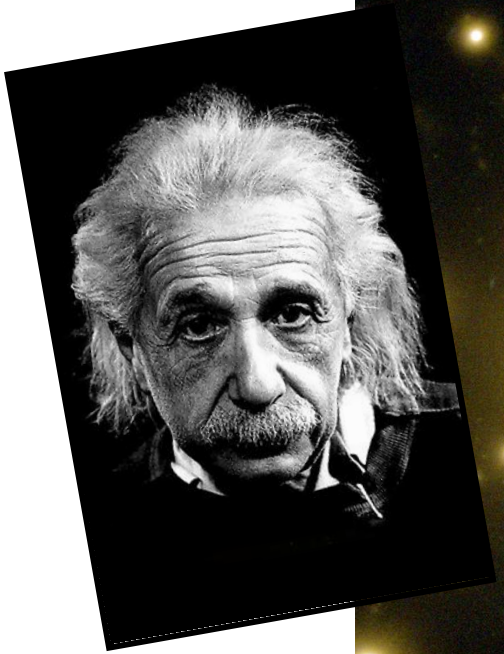
  …tells us the universe contains a lot of **stars**, **gas**, and **dust**, composed of:

  - 74% hydrogen
  - 24% helium
  - 2% heavier elements (“dust”)

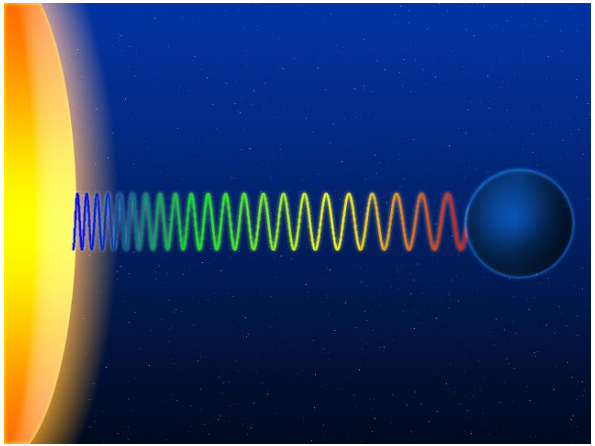
But wait: What's causing the distortion?

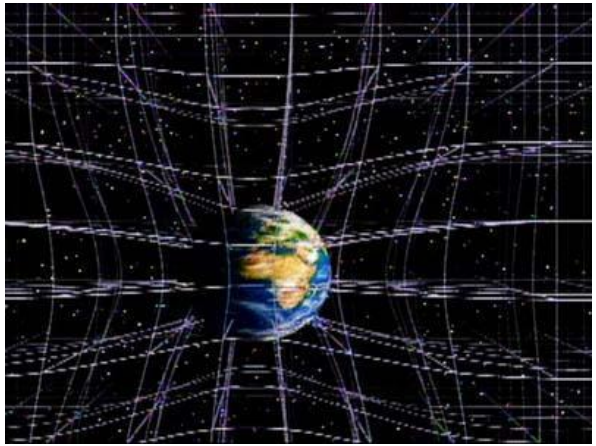


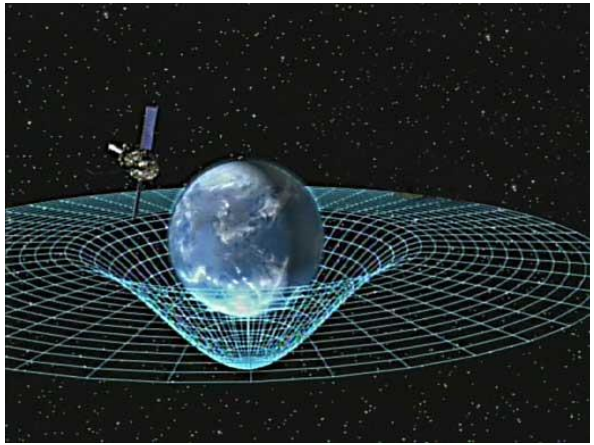
Einstein: Gravity bends light!



- Mass-energy **warps** space and time (actually, **spacetime**)
  - **Time slows down** closer to massive objects →
  - Massive objects have **extra space** in their vicinity

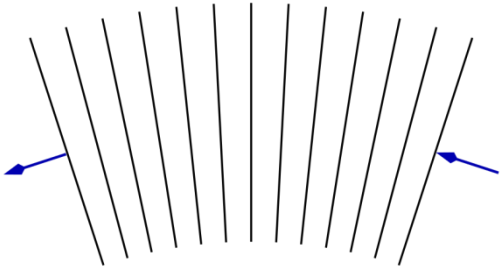


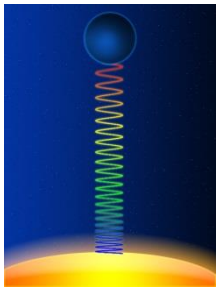




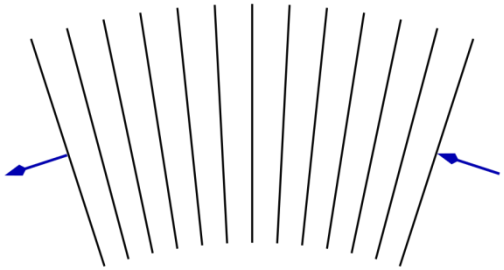
← 3D and 2D representations of extra space

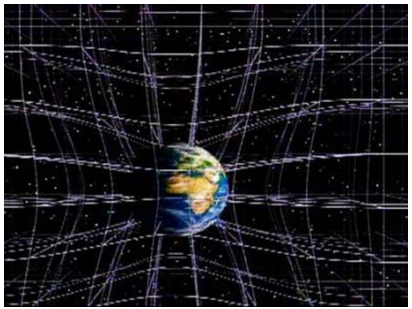
- Mass-energy **warps** space and time (actually, **spacetime**)
  - The **local** speed of light is always c.
  - During 1 second, the part of a light wave-front farther from a mass can move a certain distance at speed c.
  - But because of **time warping**, when 1 second elapses farther out, **less** than 1 second elapses closer in.
  - Thus, the part of the light wave-front closer in, also **locally** moving at speed c, but for **less** time, can move a **lesser distance**, causing the wave-fronts to tilt, and the light ray to "bend" as it travels.



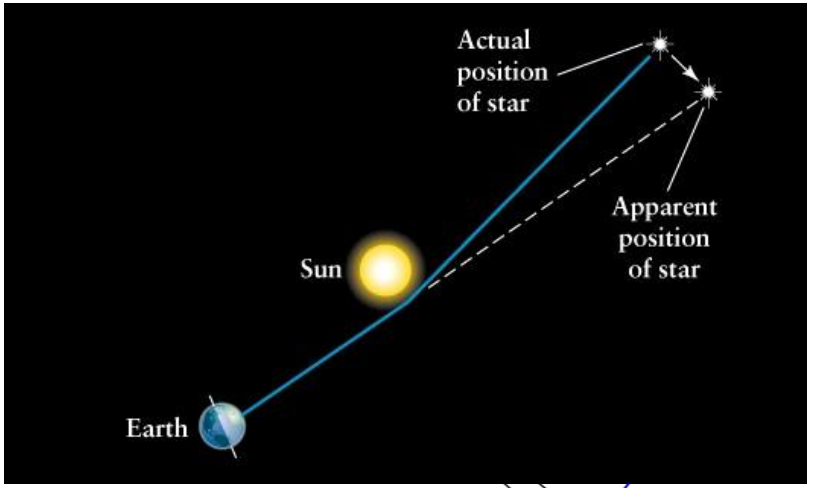


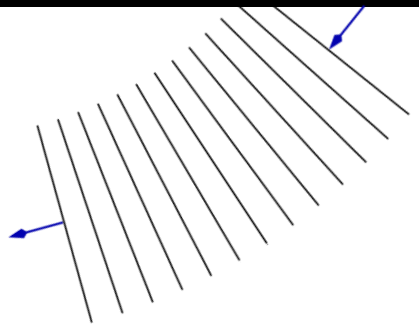
- Mass-energy **warps** space and time (actually, **spacetime**)
  - The **local** speed of light is always c.
  - During 1 second, the part of a light wave-front farther from a mass can move a certain distance at speed c.
  - But because of **space warping**, that distance appears **smaller** in this picture when it is closer in.
  - This also causes the wave-fronts to tilt, and the light ray to "bend" as it travels.
  - For light, the two effects (time warp and space warp) contribute equal amounts to the "bending"



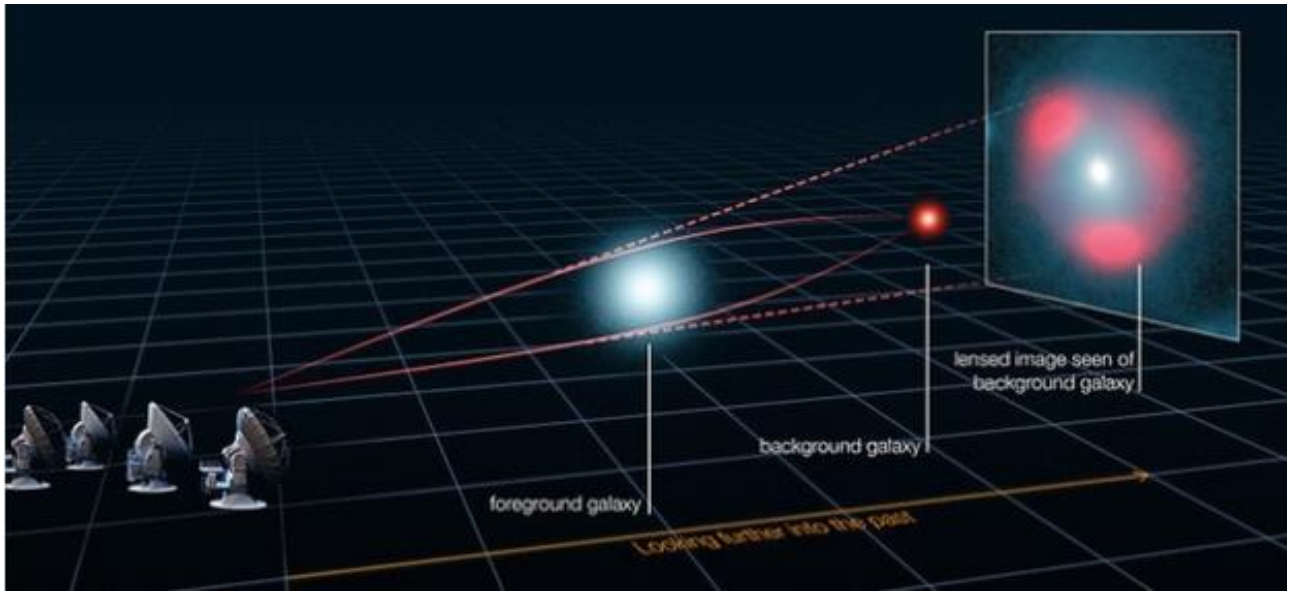


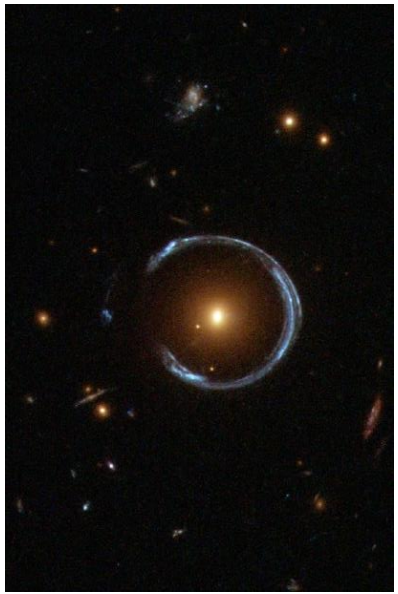
- Mass-energy **warps** space and time (actually, **spacetime**)
  - "Bend" is not the right word: **Locally**, light always moves in a **straight line** at **speed c**, and it is spacetime that is bent.
  - When moving from one region of flat spacetime to another, through a region of warped spacetime, a light ray will emerge moving in a different direction **relative** to its original direction.
  - This distorts the view of objects seen through the warped region—called a ***gravitational lens.*** But in popular science we just say "gravity bends light".

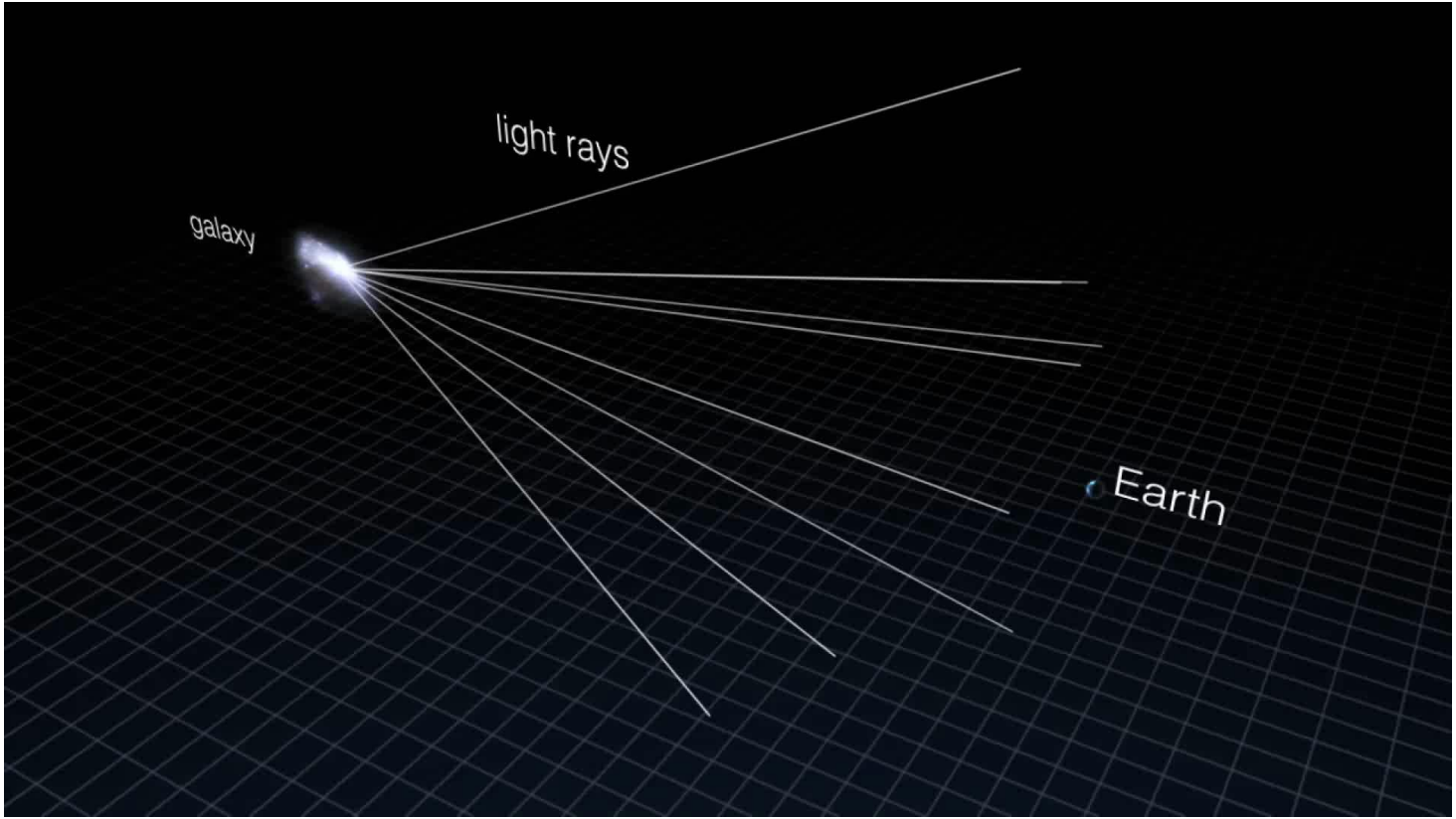




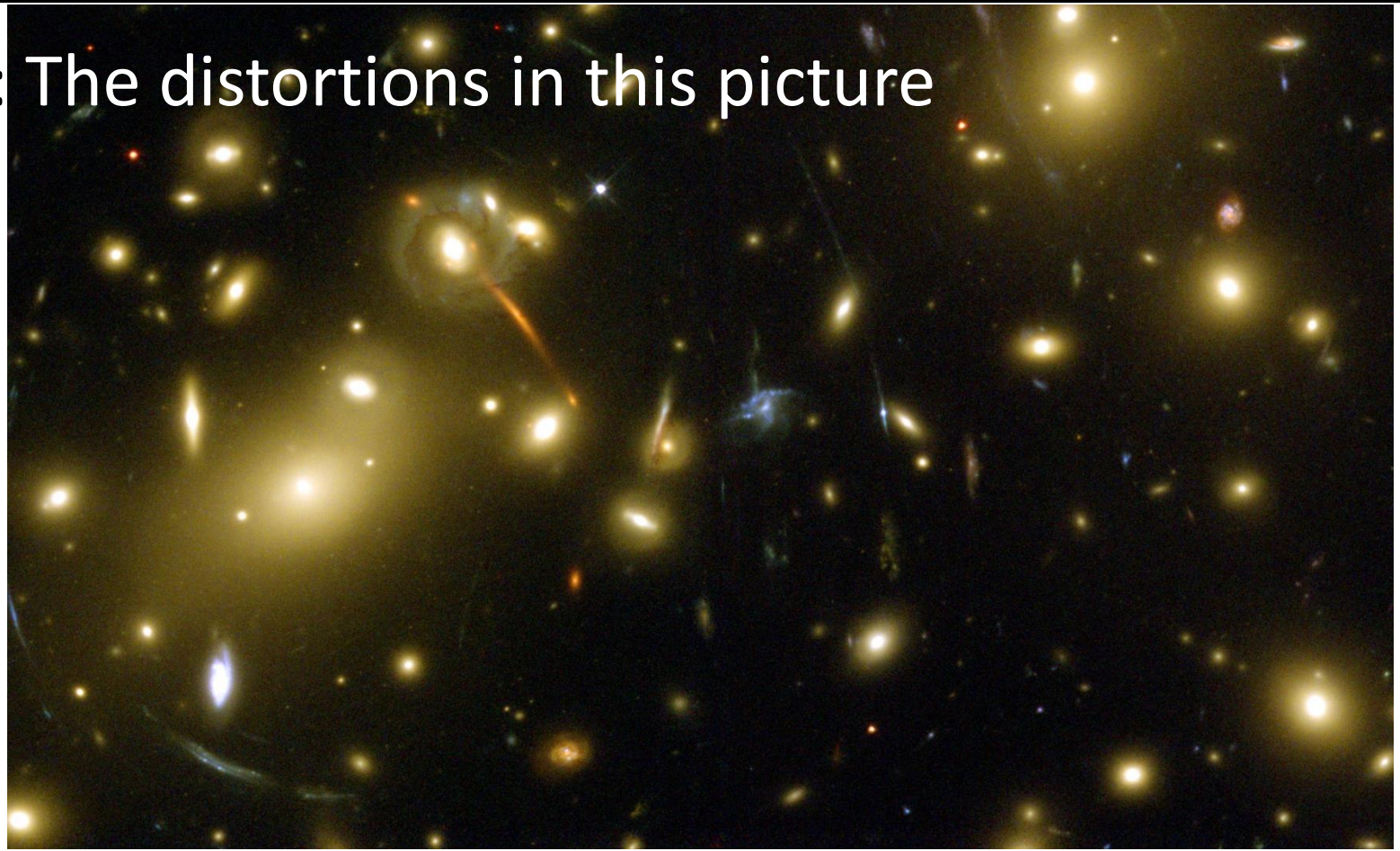
- **Any** form of mass-energy can create a gravitational lens: planets, stars, black holes, galaxies, clusters of galaxies, gas between galaxies, etc., as well as any **invisible** forms of mass. Gravity is **universal**: it measure **all mass**, visible or not.
- **All** these gravitational lenses distort the images of further away objects.



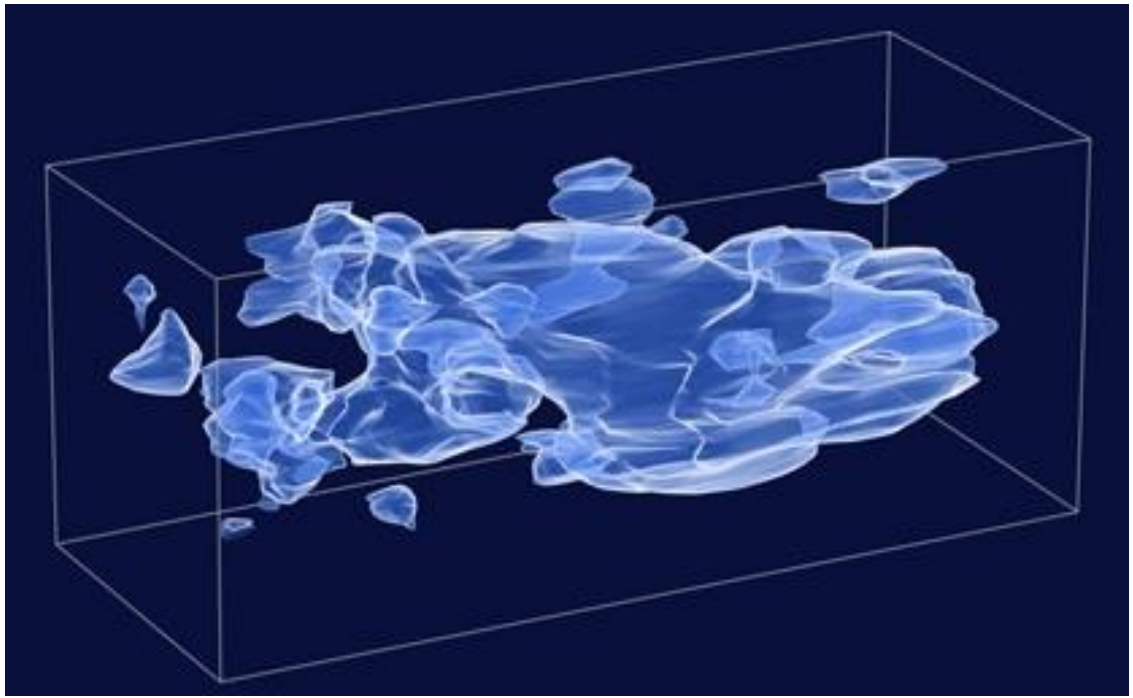



light rays
galaxy
Earth

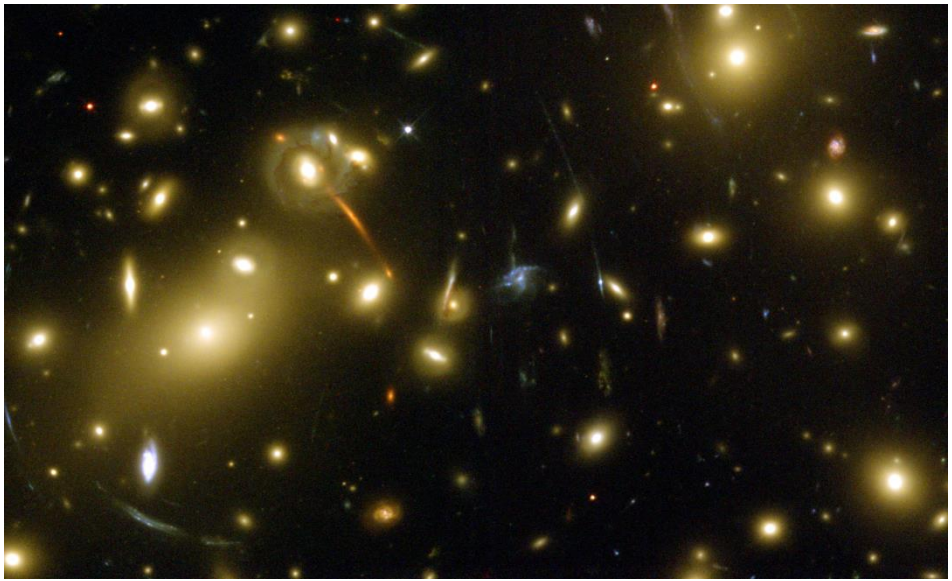
Hence: The distortions in this picture



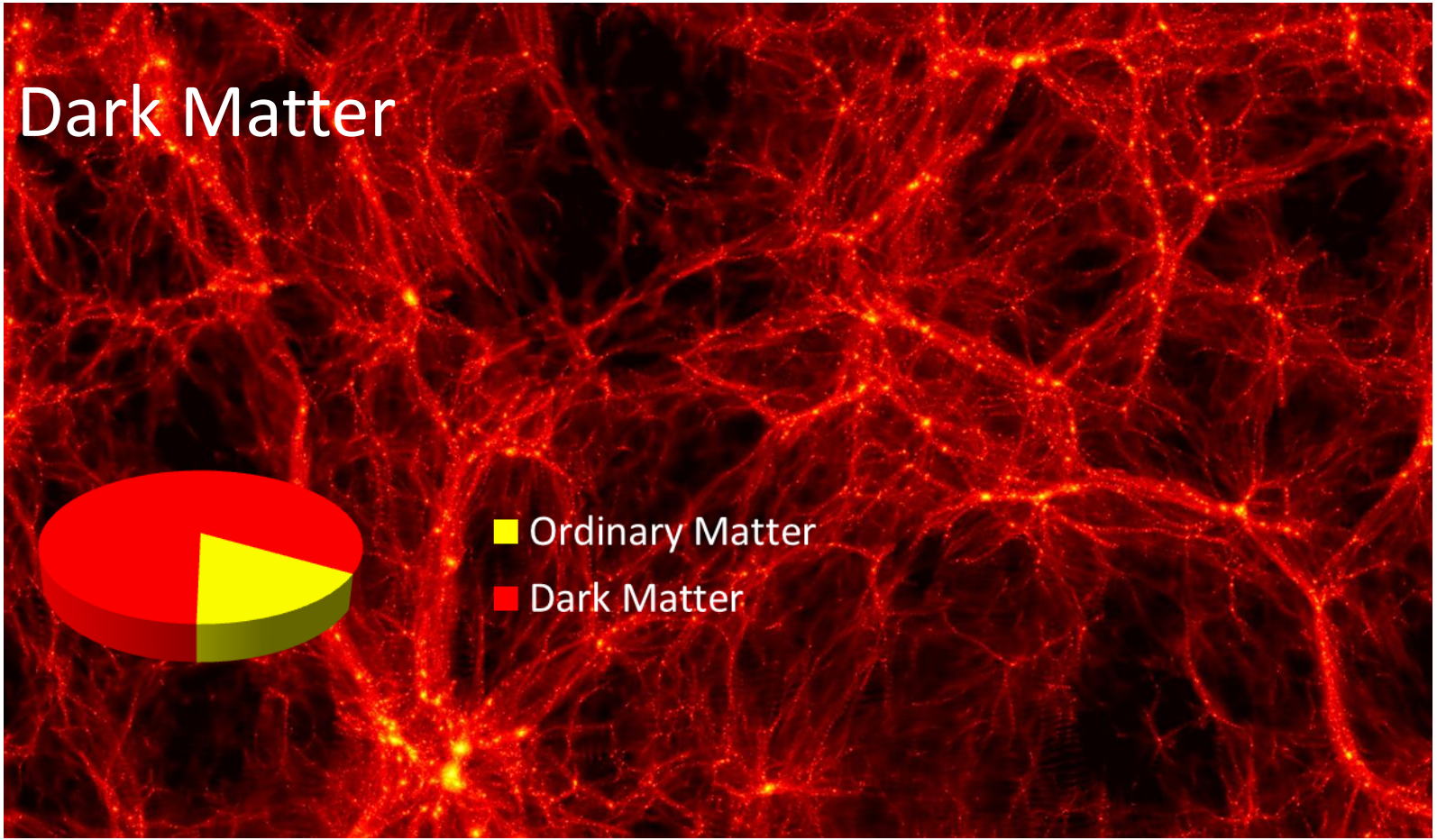
- By measuring the distortions in detail, physicists can construct a detailed 3D map of **all** the mass-energy in a given region of space, **seen and unseen**.



- **Surprise!**
  - All the mass that can be **seen** (or reasonably inferred), is **not nearly enough** to cause the amount of gravitational lensing that is observed.
  - Any typical picture like this contains:
    - ✓ 15% ordinary matter (stars, gas, dust, i.e., atoms)
    - ✓ 85% ***dark matter***
  - If the dark matter in space could be made visible, it would look like this…

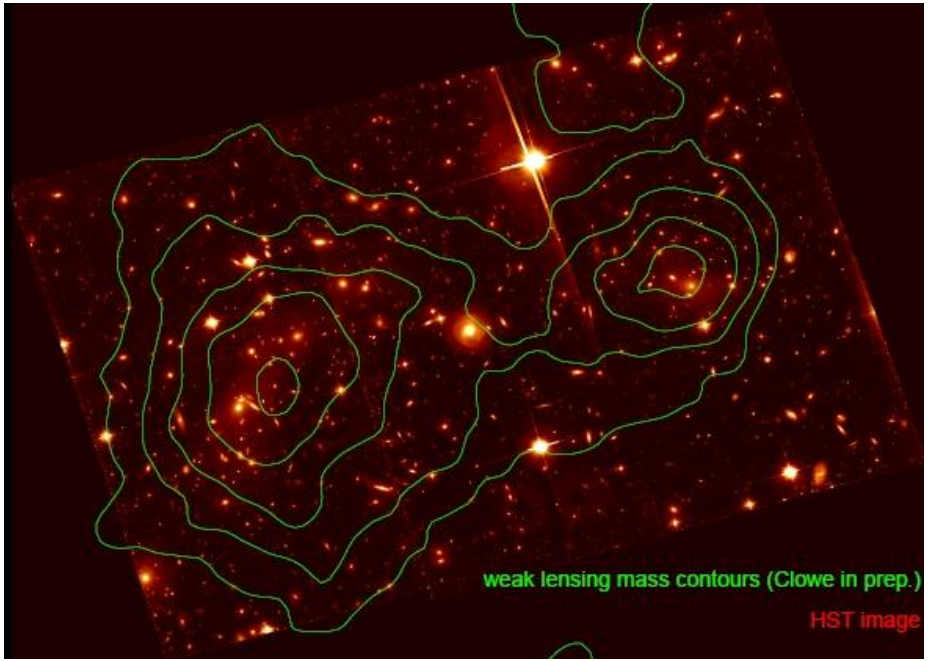


Mystery: Dark Matter



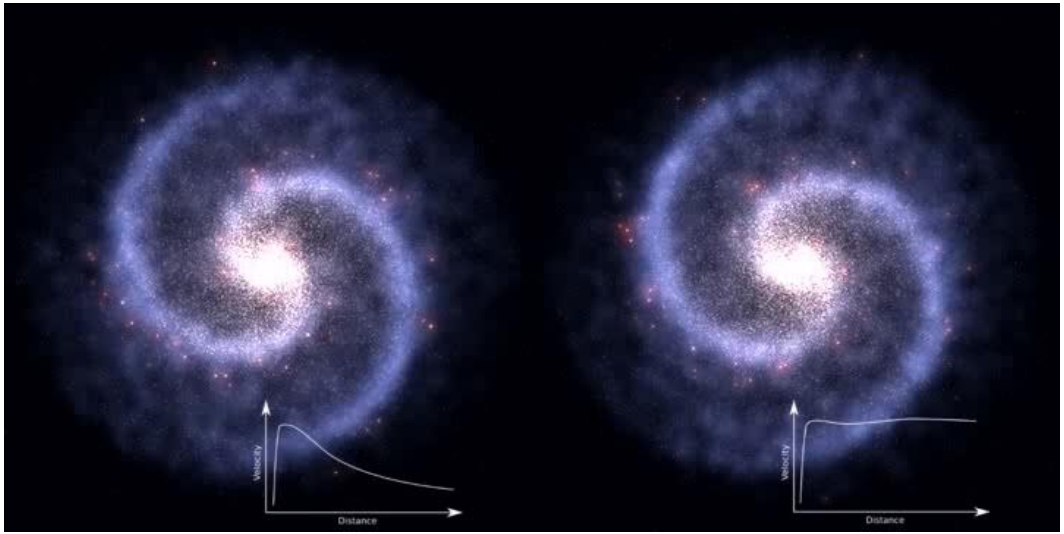
- Basic properties:
  - Dark matter is called “dark” because it appears to **emit no light** of its own. Nor does dark matter appear to **reflect** or **absorb** light. Thus it is **transparent**.
  - The existence and properties of dark matter are **inferred** from its **gravitational effects** on things we **can** see.
  - Dark matter has not been detected **directly**, making it one of the **greatest mysteries** of our times. Currently a worldwide race for first direct detection!

- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
    - **Gravitational lensing**



- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
  - **Galaxy rotation curves** (Vera Rubin)

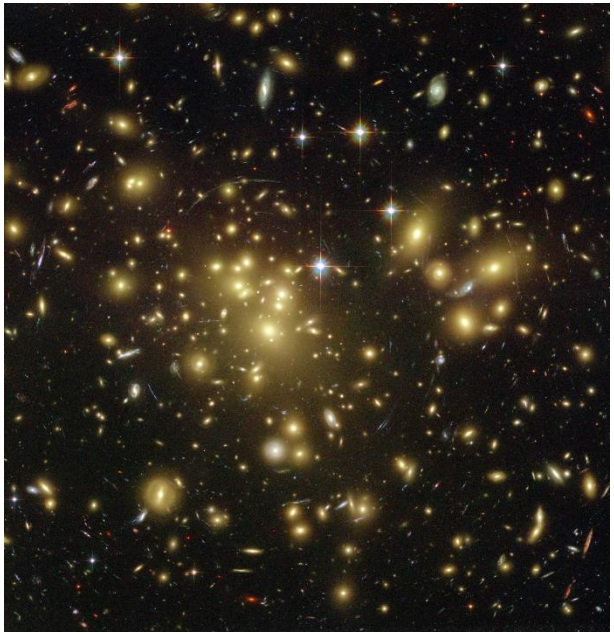
Solar System Analogy

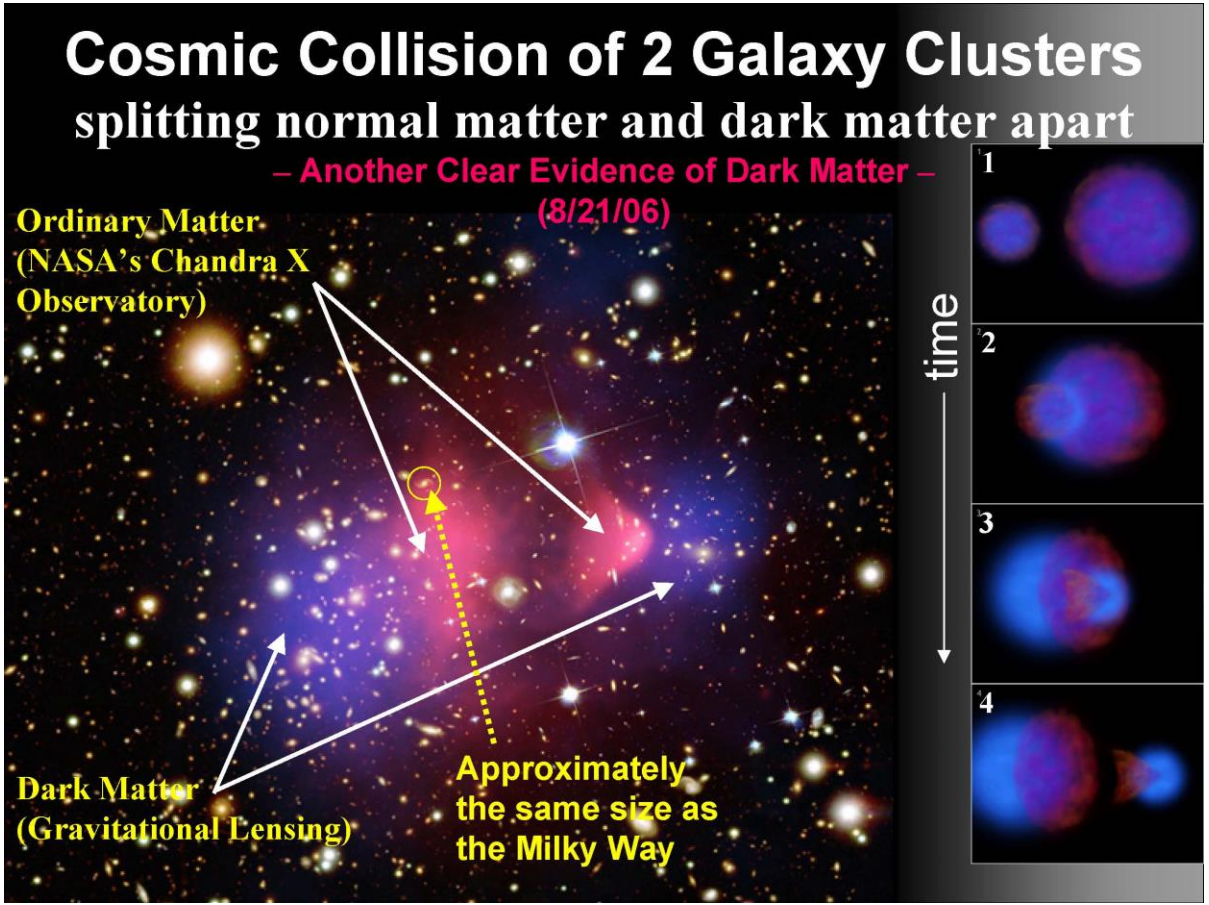


Expected Observed

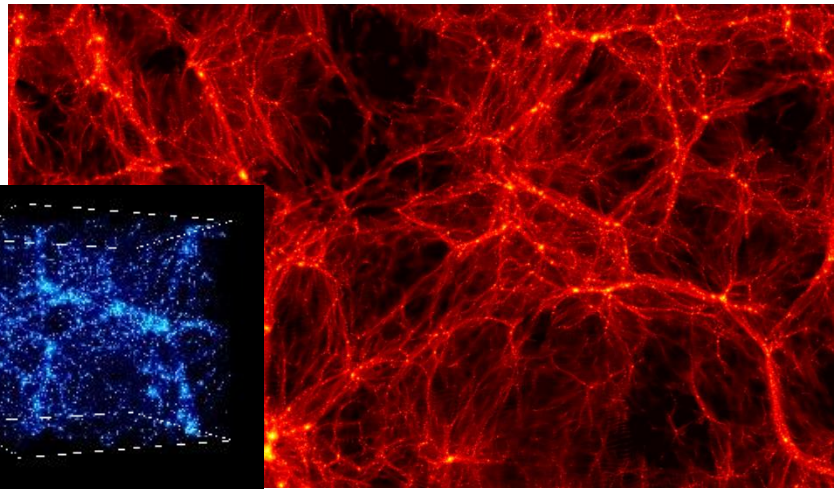
- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
    - **Galaxy rotation curves** (Vera Rubin)

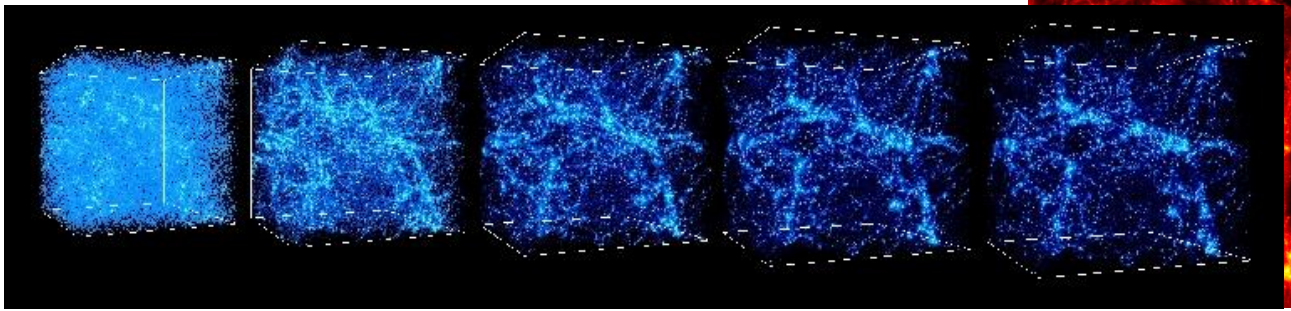
- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
  - **Anomalies in galaxy clusters**
  - **Mass** measured three **independent** ways:
    - ✓ Orbital velocities of individual galaxies
    - ✓ X-rays emitted by hot gas between galaxies (assuming pressure/gravity balance)
    - ✓ Gravitational lensing of background galaxies




Cosmic Collision of 2 Galaxy Clusters
splitting normal matter and dark matter apart
– Another Clear Evidence of Dark Matter –
(8/21/06)
Ordinary Matter
(NASA's Chandra X
Observatory)
time
1
2
3
4
Dark Matter
(Gravitational Lensing)
Approximately
the same size as
the Milky Way

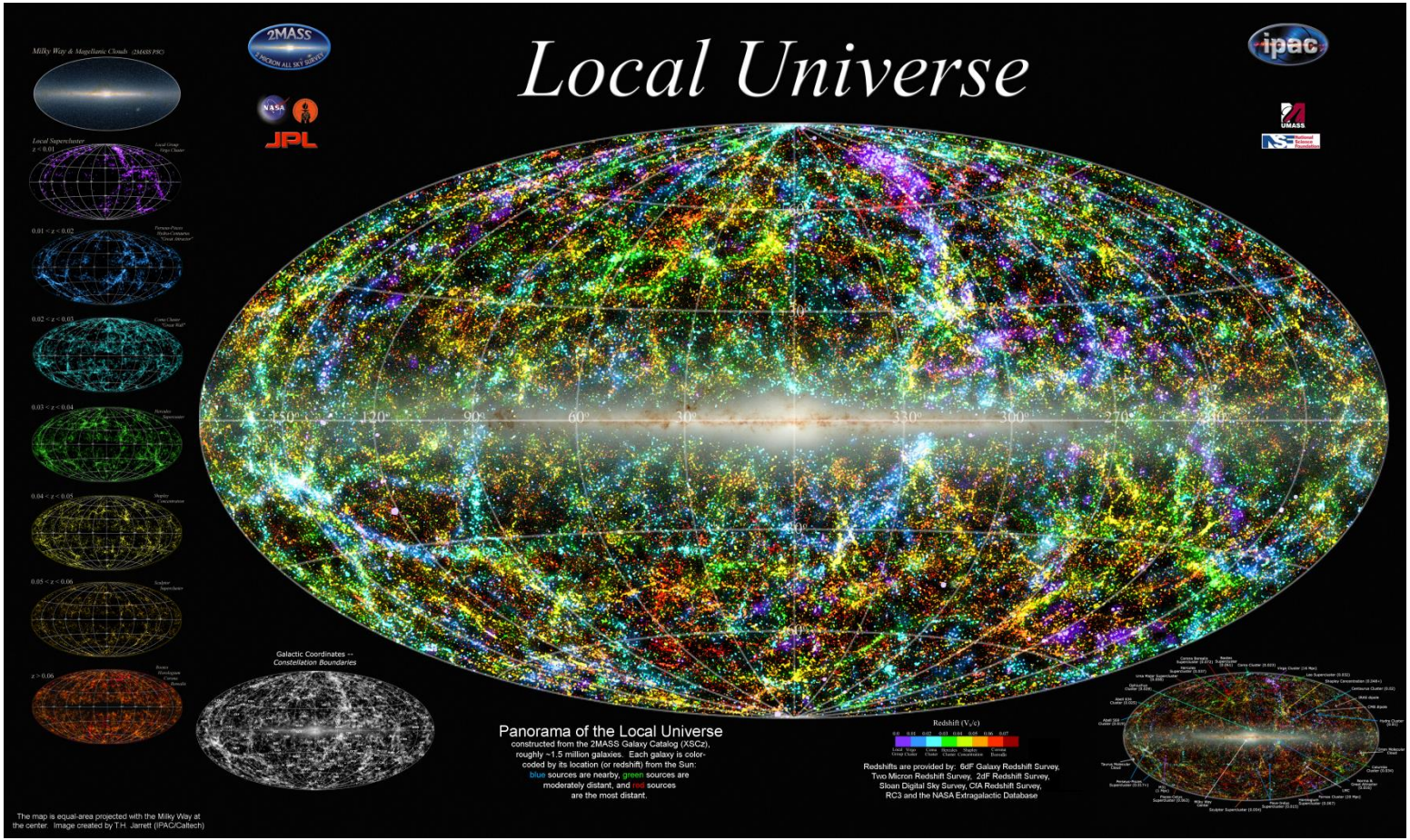
- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
  - **Large scale structure formation**



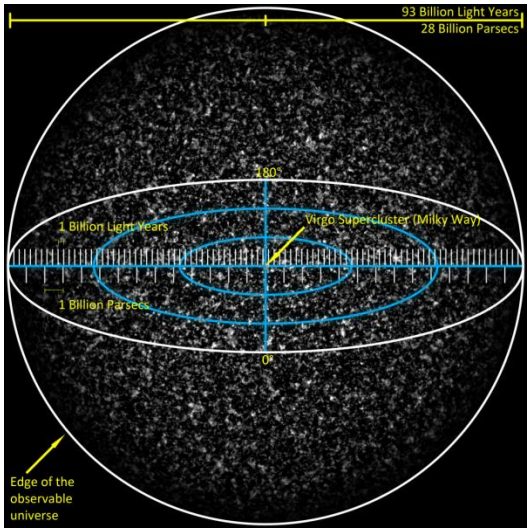


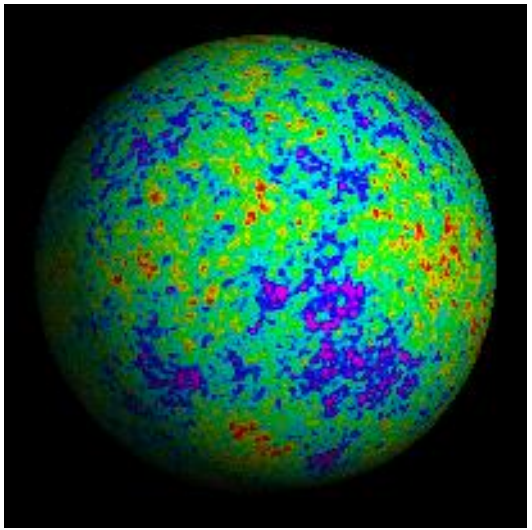
Computer simulation of **evolution of universe** showing gravitational clumping of **dark matter**. Clumped dark matter attracts ordinary matter (H and He gas), facilitating gravitational collapse into stars → stars gravitationally collapse into galaxies → galaxies gravitationally collapse into clusters of galaxies (large scale structure of the universe). *Without dark matter, it's hard to understand how the large scale structure we see could have evolved*.

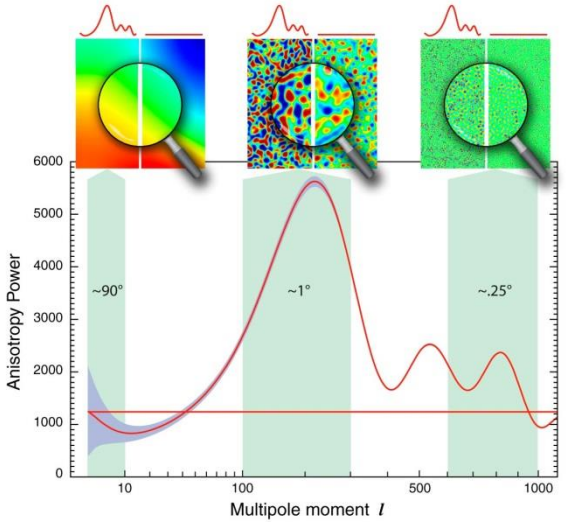
Composition & Structure—Dark Matter



- The **evidence** for dark matter is **strong**. **Independent convergent** lines of evidence include:
  - **Cosmic microwave background**
  - The “afterglow of the Big Bang” contains evidence about the amount of dark matter there should be in the universe (“twenty-sigma detection”!). Discuss this more later…

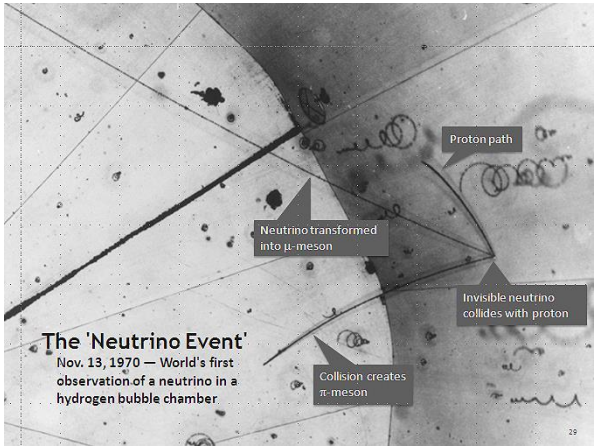






- Strong general consensus: Dark matter is really present. **But what is it?**
  - **Baryonic** dark matter?
    - ✓ ***Baryons*** are mainly **protons and neutrons** making up **ordinary matter** (atoms)
    - ✓ Big Bang nucleosynthesis **limits the amount of ordinary matter** (more later…)
    - ✓ Of this ordinary matter, only about 20% is luminous; **80% is dark**
    - ✓ **Examples** of **dark ordinary matter**: black holes, other dark & dense remnants of dead stars, brown dwarfs, planets, warm or cold gas (most of it)
    - ✓ But in total, the amount of dark ordinary matter is **far short** of what is needed. Most of the dark matter must be ***nonbaryonic*** (not protons & neutrons)

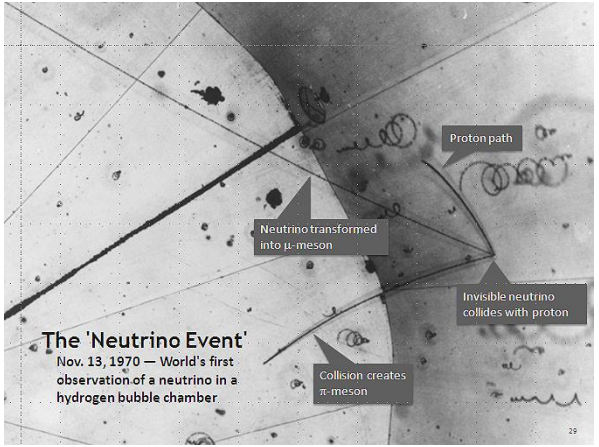
- Strong general consensus: Dark matter is really present.
  But what is it?



  - **Nonbaryonic** dark matter. Two possibilities:
  - **Hot** (fast-moving)
    - ✓ Example: **Neutrinos**.
      - **Second most abundant** particle in the universe (after the photon)
      - More than a **billion** neutrinos for every proton created by the Big Bang
      - Interact only though **gravity** and **weak nuclear force** → hard to detect
      - **Problem:** $m_\nu \ll m_e$: Total mass of neutrinos < 1% total dark matter mass

What is a Neutrino?

- Strong general consensus: Dark matter is really present.
  But what is it?



  - **Nonbaryonic** dark matter. Two possibilities:
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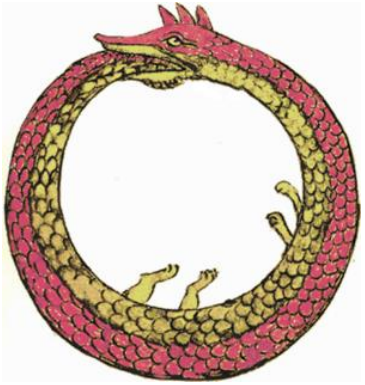
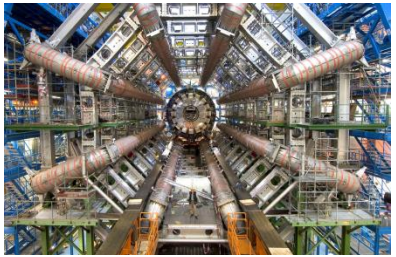
      - ➢ More than a **billion** neutrinos for every proton created by the Big Bang
      - ➢ Interact only though **gravity** and **weak nuclear force** → hard to detect
      - ➢ **Problem:** $m_\nu \ll m_e$: Total mass of neutrinos < 1% total dark matter mass
    - ✓ **Bigger Problem:** Hot dark matter particles **don't gravitationally clump** well, in a way that could explain the large scale structure we observe.

- Strong general consensus: Dark matter is really present. **But what is it?**
  - **Nonbaryonic** dark matter. Two possibilities :
  - **Cold** (slow-moving)
    - ✓ **WIMPs**: Weakly Interacting Massive Particles (like neutrino, but heavier)
    - ✓ **Axions**: Hypothetical particle invented to explain the "strong CP problem in QCD"
    - ✓ And others; this gets deep into particle physics. **Amazing**: *the strong new interplay between particle physics (physics of the **very small**) and cosmology (physics of the **very large**)*

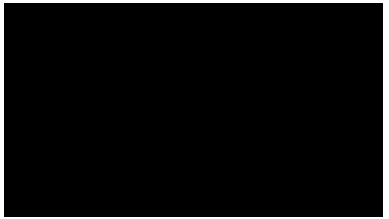


- Strong general consensus: Dark matter is really present. **But what is it?**
  - **Current consensus view** is that dark matter is primarily composed of a mysterious new type of **subatomic particle** that is **slow-moving (cold)**
  - **Other ideas:**
    - ✓ **Alternative theories of gravity:** dark matter reveals itself gravitationally; maybe we just have gravity wrong, and there is no dark matter!
    - ✓ **Matter in extra dimensions**, that interacts only gravitationally with matter in our universe?
    - ✓ **Primordial defects** in the topology of quantum fields, which contain energy and therefor gravitate?
    - ✓ **Etc.** Very active area of physics. Symmetry Magazine article.

- **Searching** for dark matter particles:
  - **Direct** detection:
    - ✓ Detect naturally-occurring dark matter particles in labs deep underground (to reduce background cosmic rays), e.g., SNOLAB
    - ✓ Generate & detect dark matter particles in accelerators (LHC)

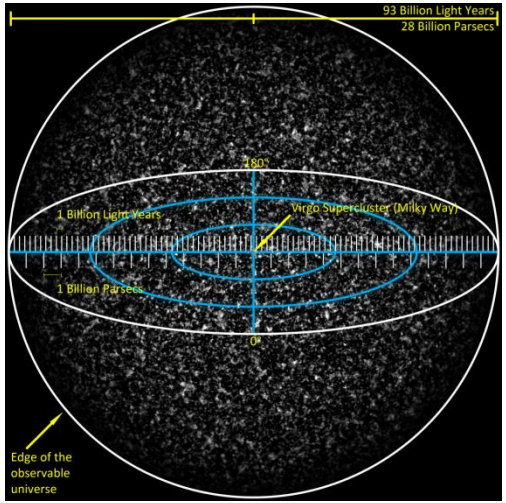


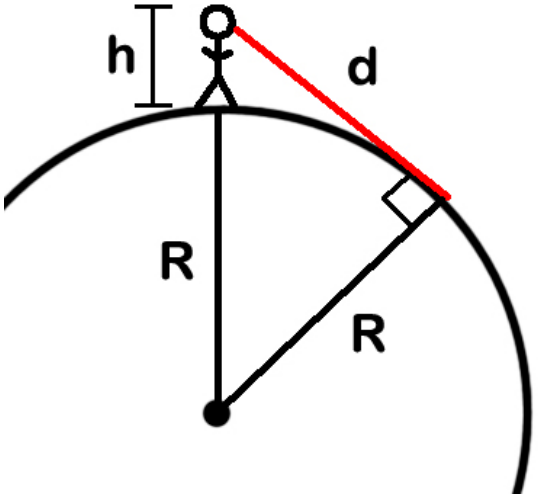
  - **Indirect** detection:
    - ✓ Dark matter annihilation or decay can produce gamma rays or particle-antiparticle pairs. Excess gamma rays or antimatter from regions of high dark matter density might provide indirect evidence.



  - **No conclusive evidence** so far…

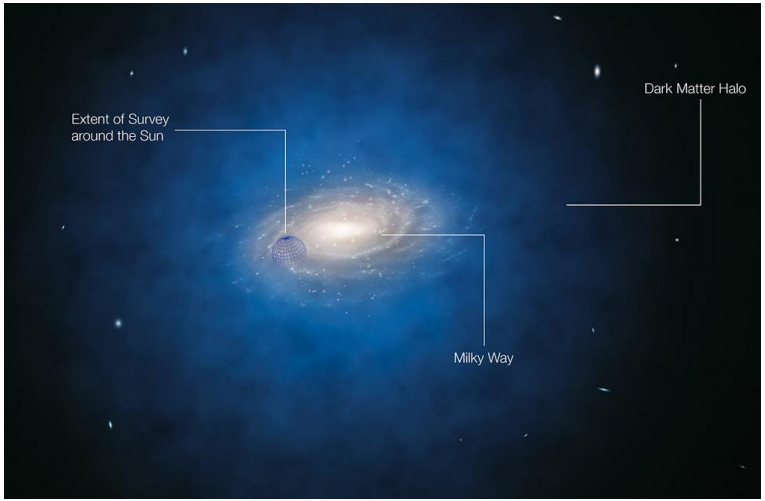
- Summary:
    - The **observable** universe is **big**: about **46 billion light-years** in radius. It almost certainly extends **beyond our cosmological horizon**, how far no one knows. Estimates range from at least 100s of times larger than the observable universe (by measure of **flatness**…) to at least 10^{10s} of times larger than the observable universe (by **inflation theory**).

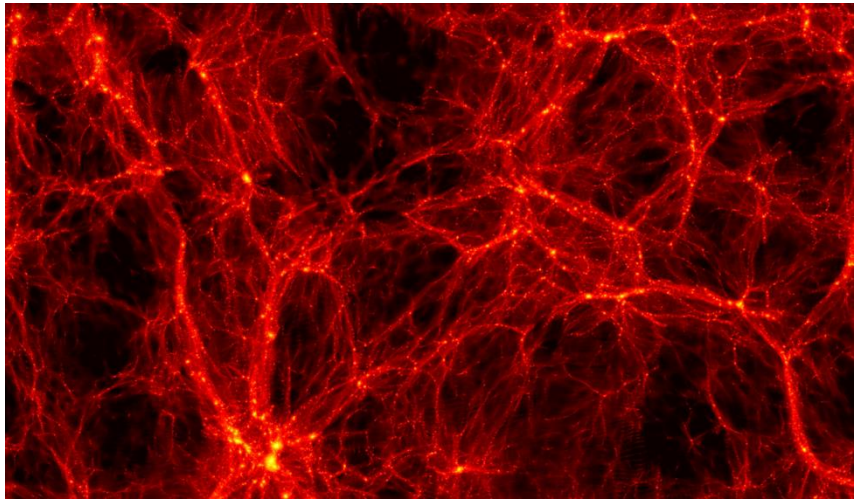




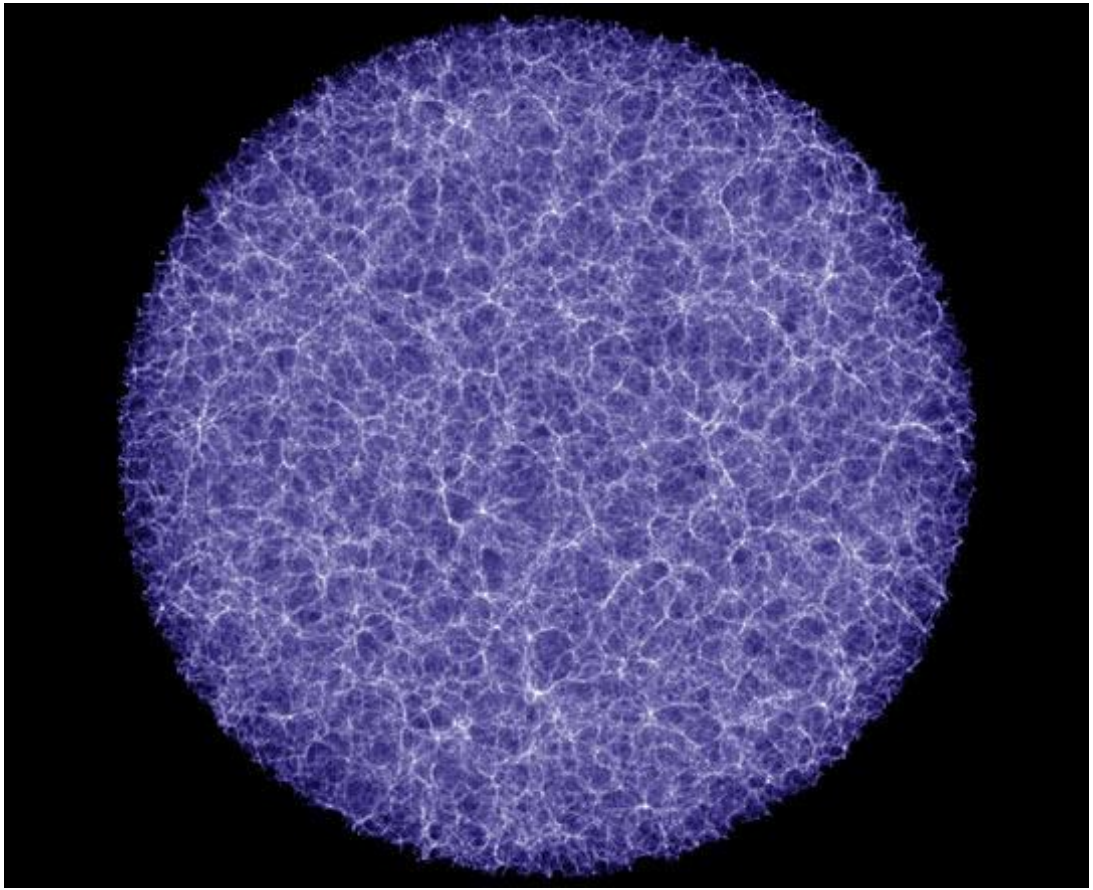
- Summary:
    - **15%** of the matter in it is **ordinary (baryonic) matter** in the form of stars, gas, and dust. There are **several hundred billion** galaxies in the observable universe, many (like our own Milky Way galaxy) having **several hundred billion** stars or more and a central **supermassive black hole** (more later…).

- Summary:
  - **85%** of the matter in it is invisible **nonbaryonic dark matter**, inferred to exist by its **gravitational effect** on stuff we *can* see. No one knows what it is, but **best guess** is a new type of subatomic particle that is slow-moving (cold). It is one of the **greatest mysteries** of our times, with a worldwide race to unravel it…





- Summary:
  - This matter has **structure on all scales**: people, planets, solar systems, galaxies, galaxy clusters and galaxy superclusters (and voids).
  - **Dark matter** forms the **backbone** of this structure, onto which ordinary matter gravitationally collapsed.
  - Averaged over very large distances, this matter (ordinary & dark) fills all of space **almost perfectly uniformly**.



- Summary:
    - Observable universe on **logarithmic scale**, with the Solar System at the center, inner & outer planets, Kuiper belt, Oort cloud, Alpha Centauri, Perseus Arm, Milky Way galaxy, Andromeda galaxy, nearby galaxies, Cosmic Web, Cosmic microwave background radiation, near the edge of the observable universe. (Wikipedia)

Composition & Structure