Light in a dark Universe

Why we need dark matter to form galaxies

Albert Izard (UC Riverside / Jet Propulsion Laboratory, California Institute of Technology)

Cosmic Thursdays, May 24th 2018

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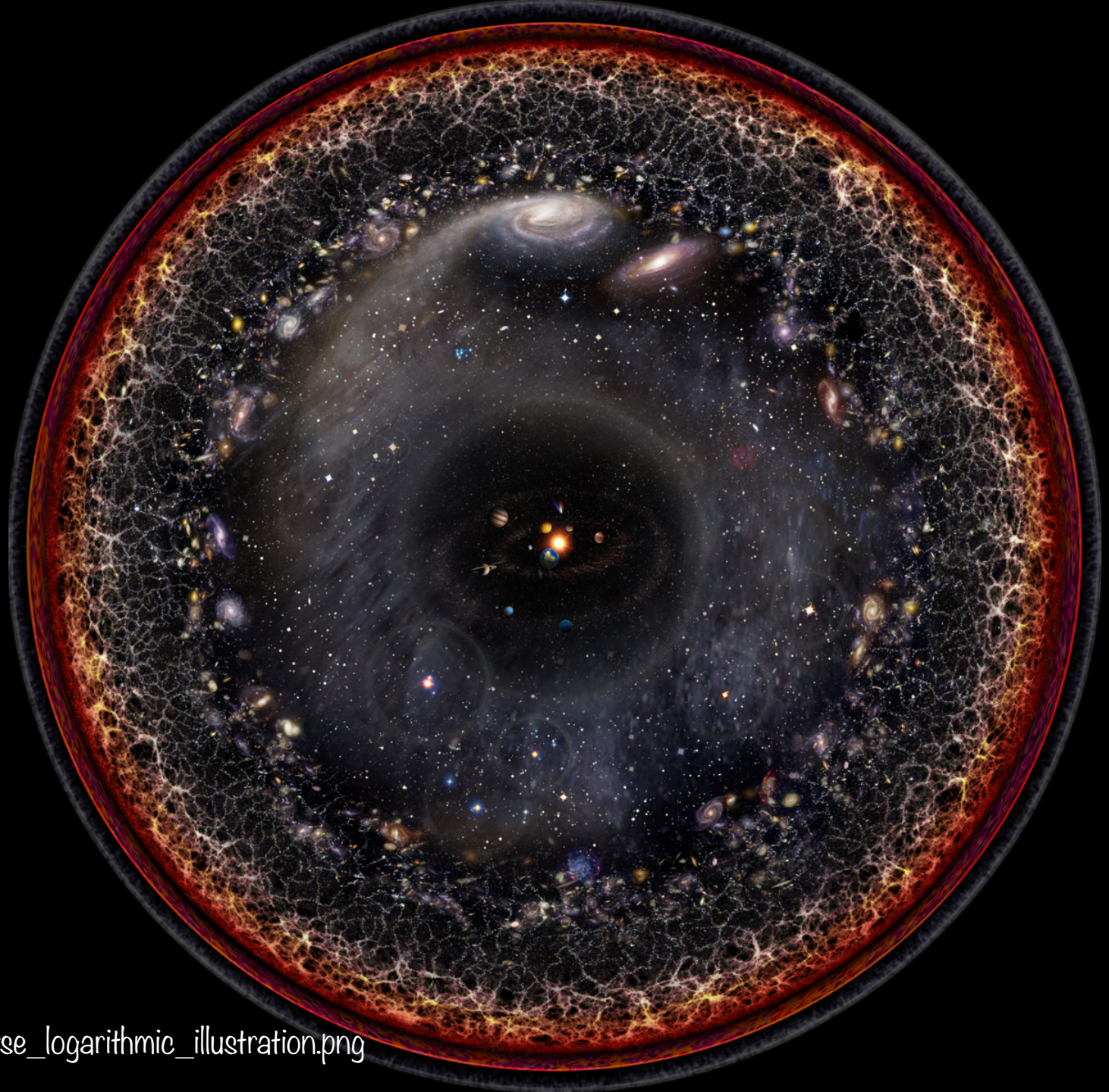
X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

The observable Universe

Copernican Principle:
we are not observing the Universe
from a preferred location



https://commons.wikimedia.org/wiki/File:Observable_universe_logarithmic_illustration.png

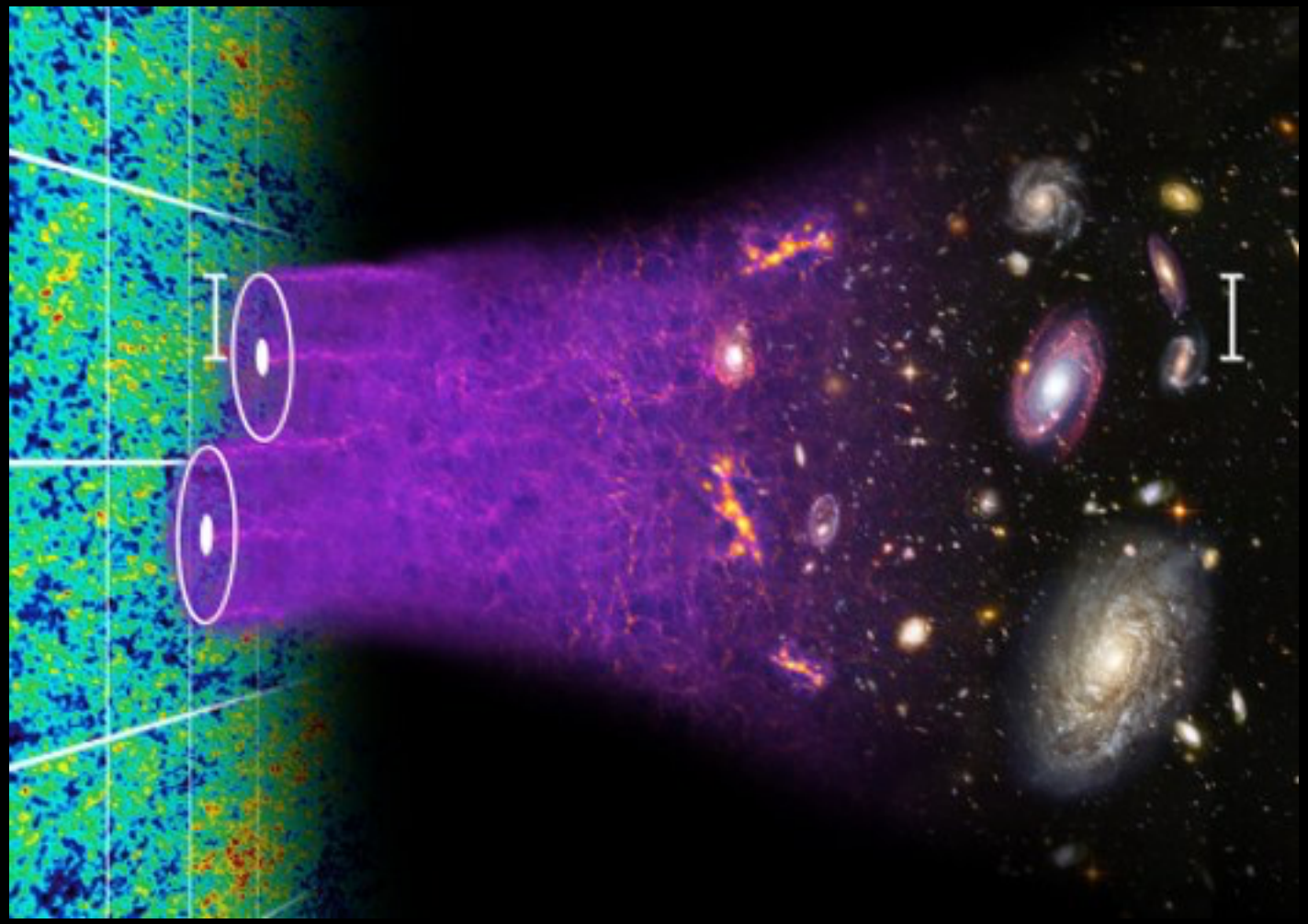
How do stars form?

By gravitational collapse: the cycle of gas

Video of the Voyage to Virgo
https://www.youtube.com/watch?v=D_WSeR2sdII

How do galaxies form?

By gravitational collapse too!

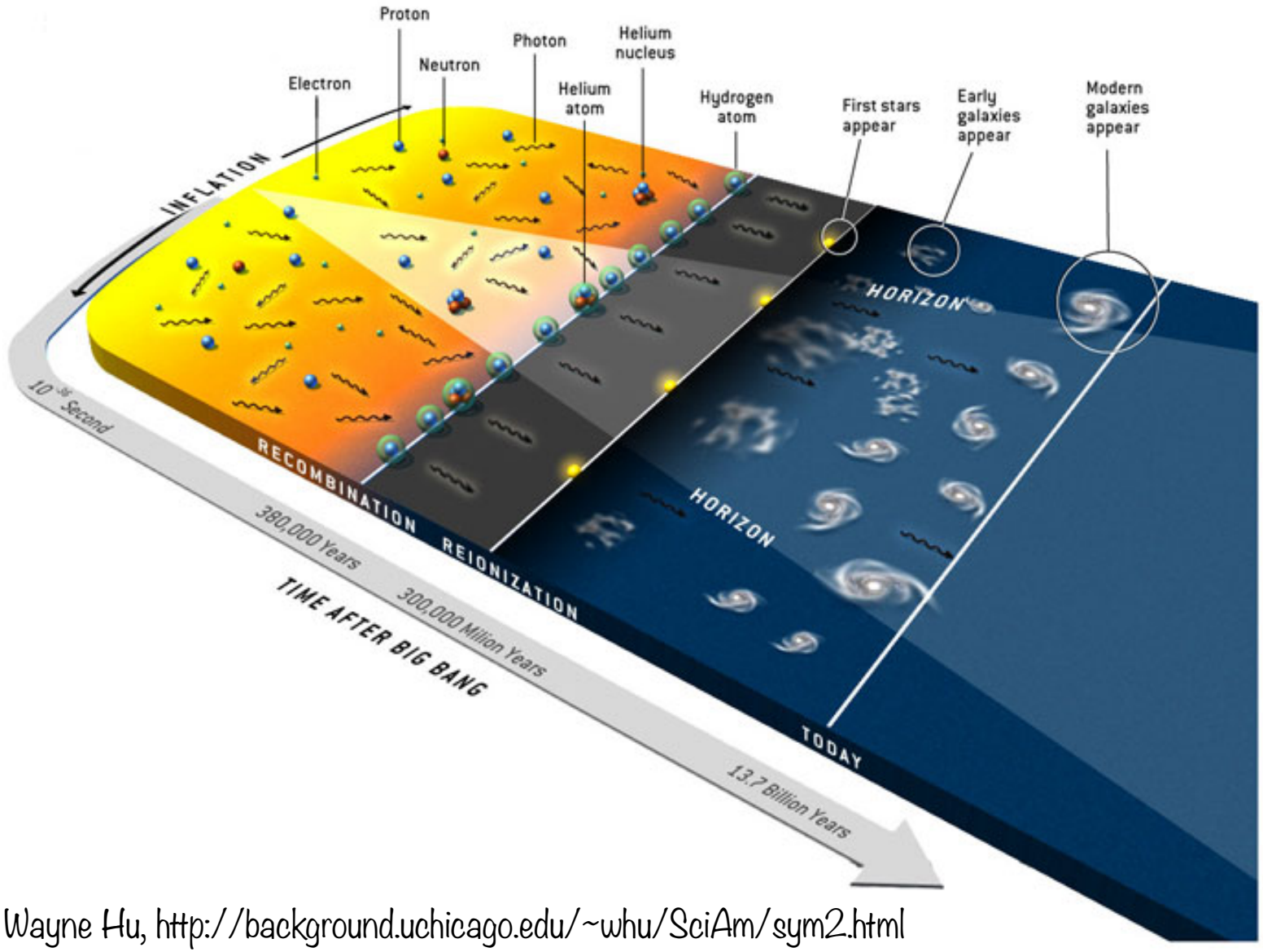


Credit: Chris Blake & Sam Moorfield

The cosmic web

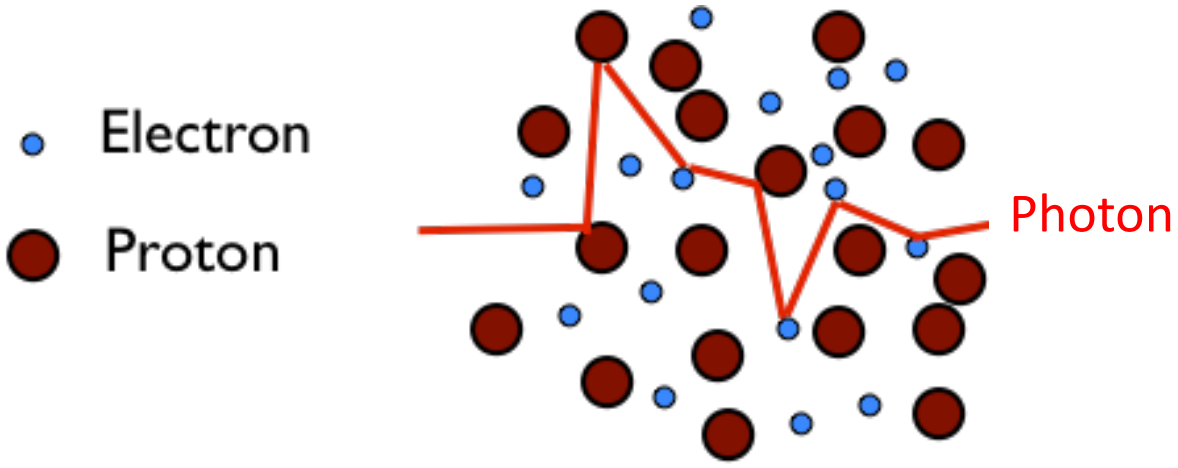
https://www.youtube.com/watch?v=lJXG5zfTL2A

Timeline of the Universe

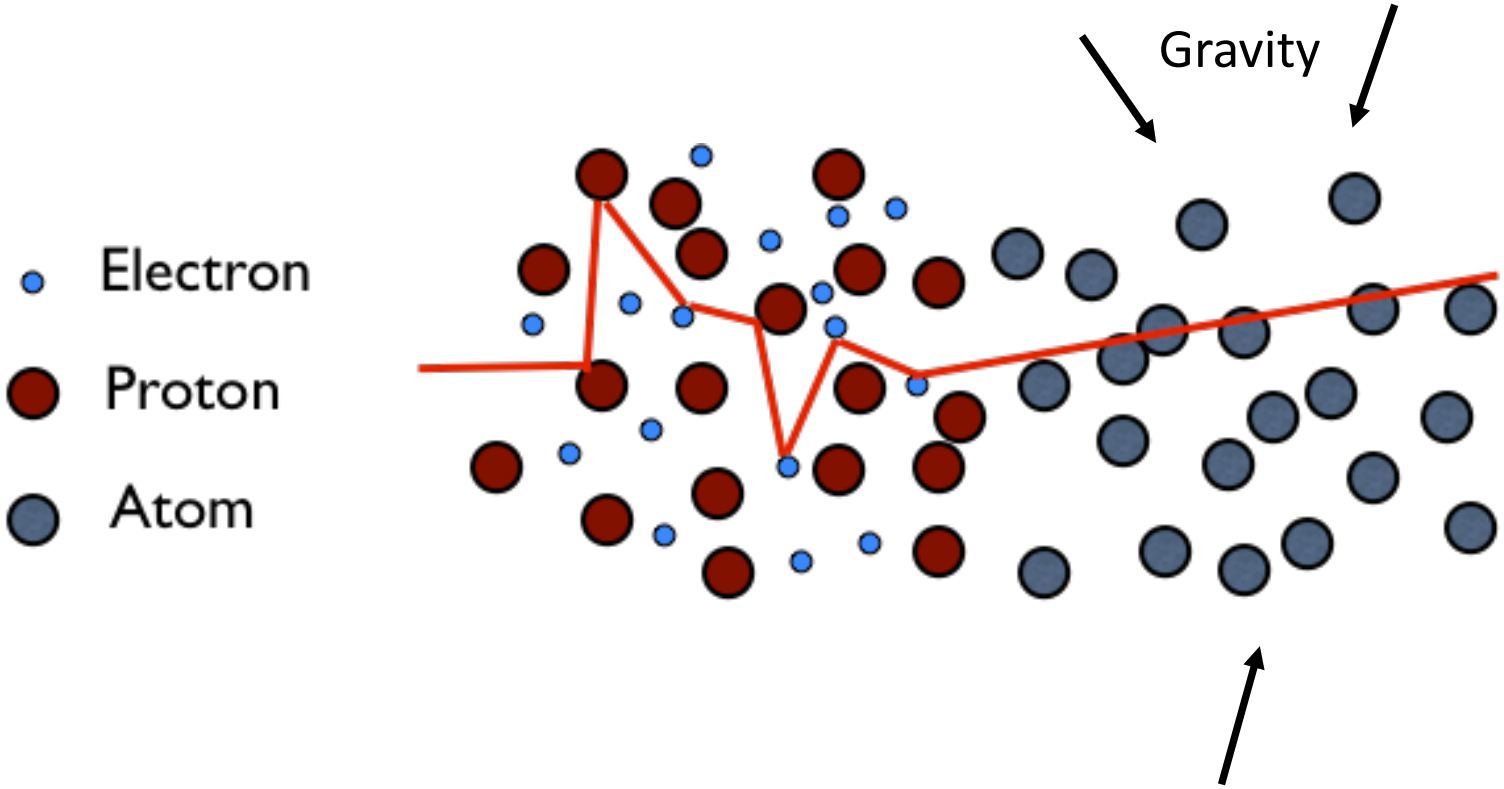


Wayne Hu, http://background.uchicago.edu/~whu/SciAm/sym2.html

The hot Universe



Cosmic microwave background (CMB)



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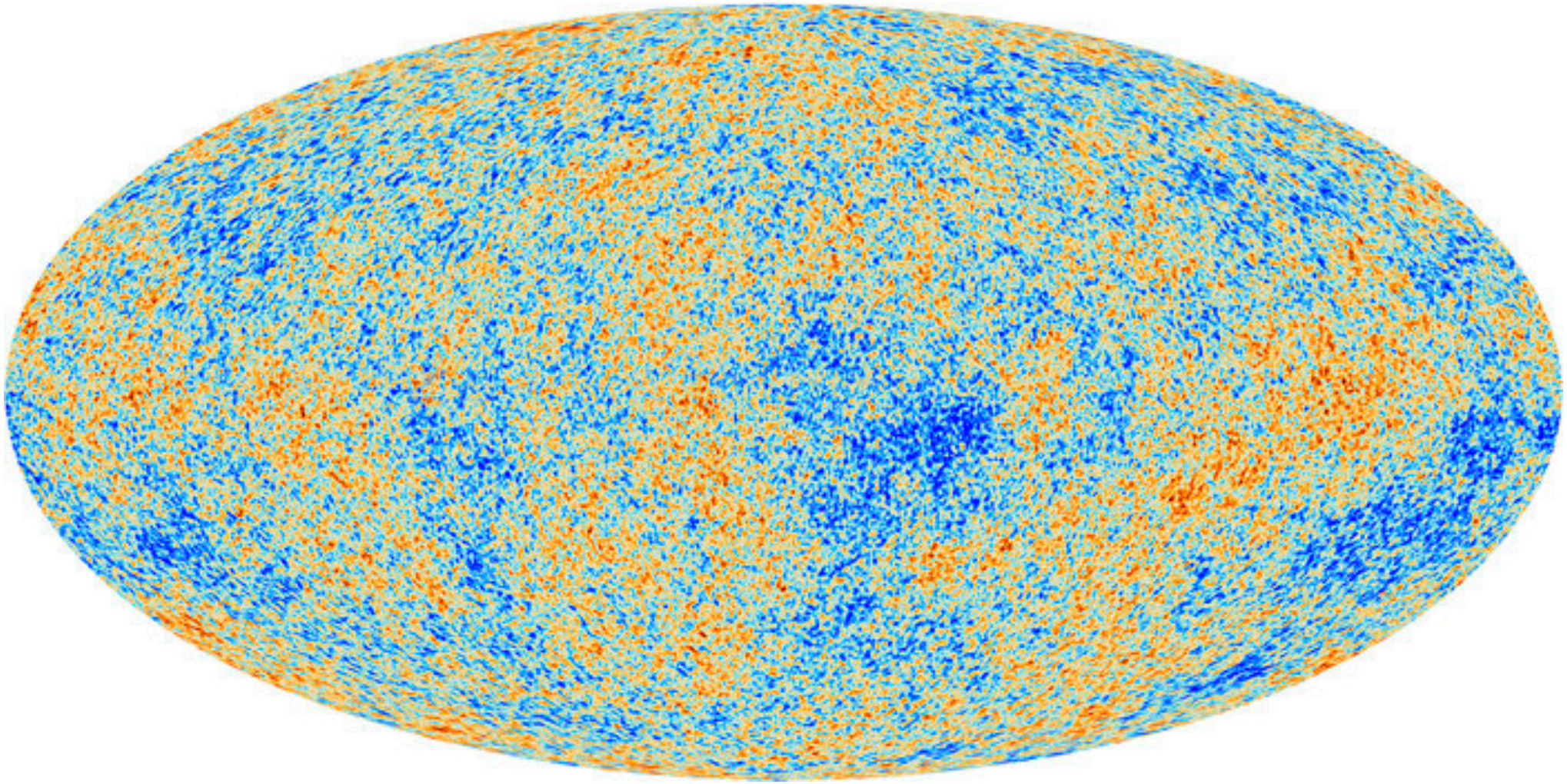
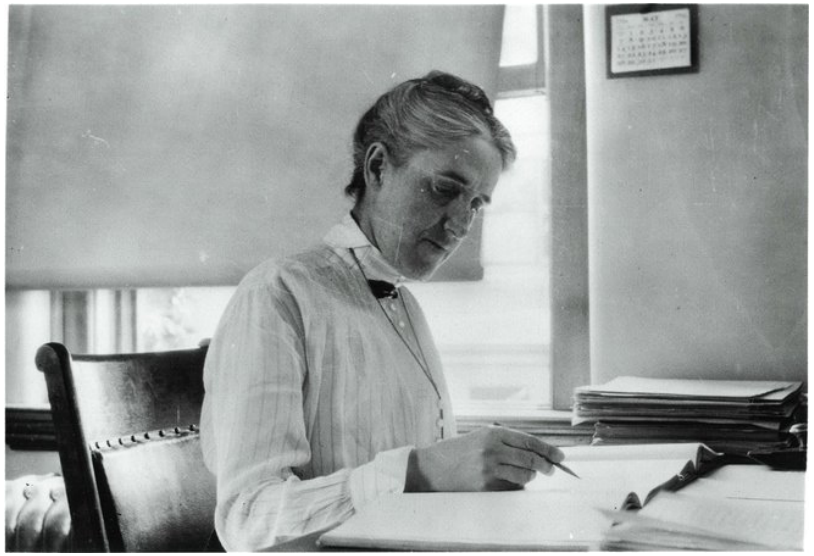


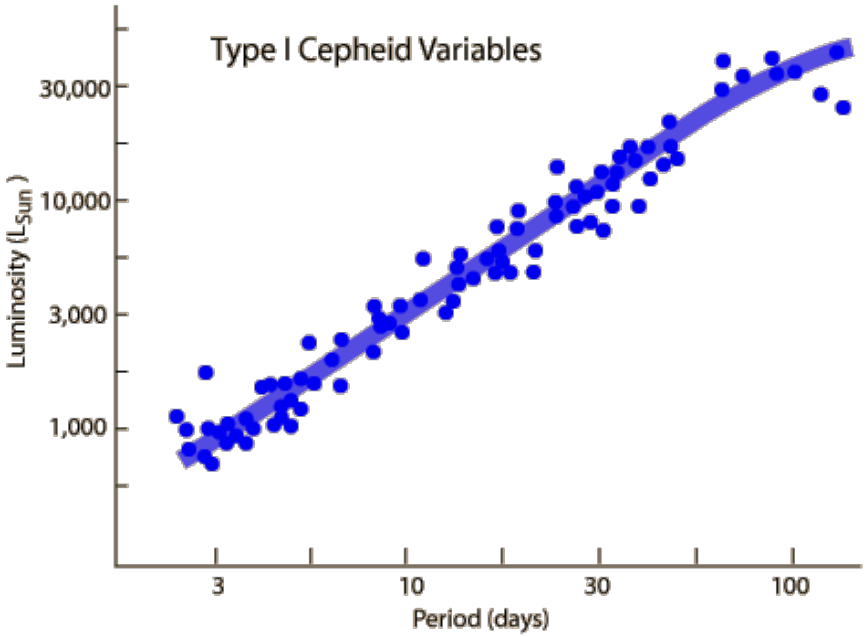
ESA and the Planck collaboration

The foundations of the Big Bang theory (I)



Credits: Harvard-Smithsonian Center for Astrophysics

- 1912: Henrietta Leavitt discovers the properties of cepheid stars
- 1920: Edwin Hubble
- 1927: Georges Lemaitre
- 1929: Hubble



From http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/cepheid.html

The foundations of the Big Bang theory (I)

Credits: Observatories of the Carnegie Institution of Washington

- 1912: Henrietta Leavitt
- 1920: Edwin Hubble finds cepheids in Andromeda (later in more galaxies)
- 1927: Georges Lemaitre
- 1929: Hubble

The foundations of the Big Bang theory (I)

Credits: WordPress

- 1912: Henrietta Leavitt
- 1920: Edwin Hubble
- 1927: Georges Lemaitre proposes the "primeval atom" theory:
  - Galaxies are receding
  - With a velocity proportional to the distance
  - The Universe has to be expanding
- 1929: Hubble

The foundations of the Big Bang theory (I)

Credits: Observatories of the Carnegie Institution of Washington

- 1912: Henrietta Leavitt
- 1920: Edwin Hubble
- 1927: Georges Lemaitre
- 1929: Hubble measures the distance to cepheids at Mt. Wilson
  - He finds a relationship between velocity and distance

The foundations of the Big Bang theory (II)

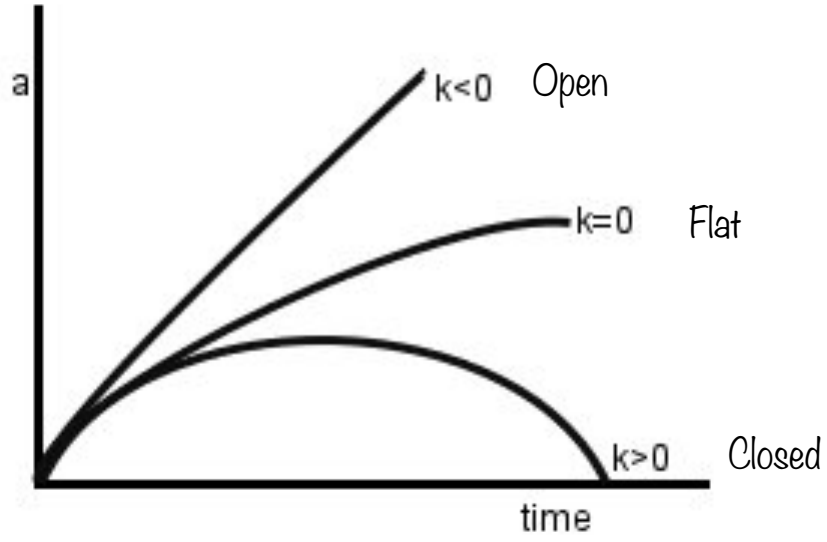
- 1915: Albert Einstein publishes the Theory of General Relativity
- 1917: Einstein
- 1924: Alexander Friedmann
- 1927: Lemaitre
- 1929: The Big Bang theory

The foundations of the Big Bang theory (II)

- 1915: Albert Einstein
- 1917: Einstein adds the cosmological constant
- 1924: Alexander Friedmann
- 1927: Lemaitre
- 1929: The Big Bang theory

The foundations of the Big Bang theory (II)

- 1915: Albert Einstein
- 1917: Einstein
- 1924: Alexander Friedmann finds 3 possible solutions when he applies GR to the Universe
- 1927: Lemaitre
- 1929: The Big Bang theory

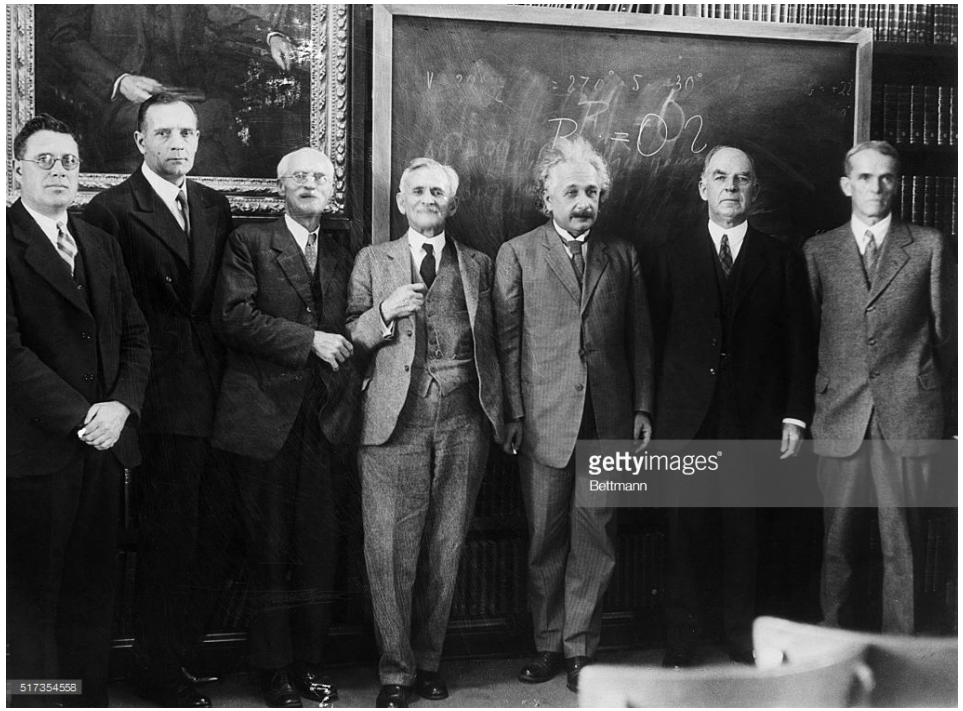


The foundations of the Big Bang theory (II)

- 1915: Albert Einstein
- 1917: Einstein
- 1924: Alexander Friedmann
- 1927: Lemaitre finds independently the same 3 solutions
- 1929: The Big Bang theory

The foundations of the Big Bang theory (II)

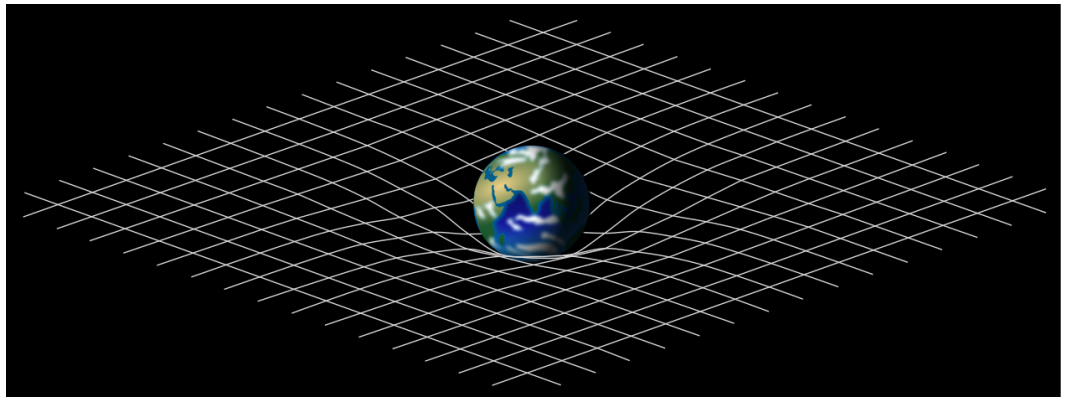
- 1915: Albert Einstein
- 1917: Einstein
- 1924: Alexander Friedmann
- 1927: Lemaitre
- 1929: The Big Bang theory becomes the most accepted theory thanks to Hubble's work. Einstein retracts from the cosmological constant



General Relativity

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

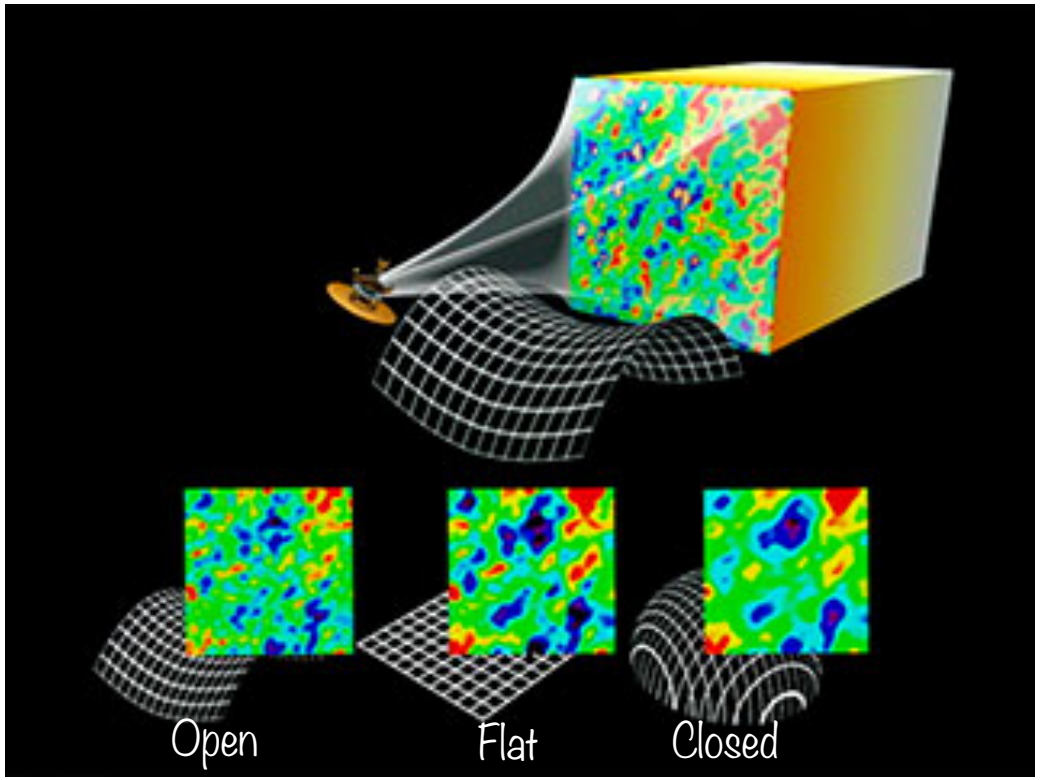
Geometry ~ matter



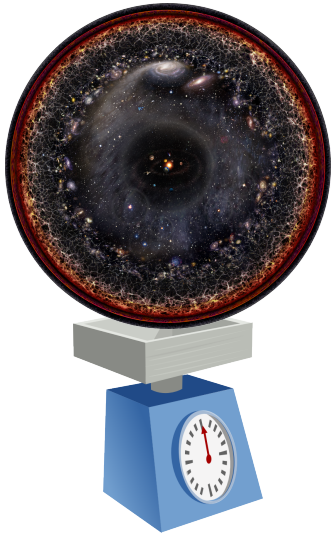
https://commons.wikimedia.org/wiki/File:Spacetime_lattice_analogy.svg

First method to weigh the Universe

- Observe the size of the spots in the CMB
- It will tell you the geometry of the Universe
- The Universe is flat! Therefore it should have the critical density

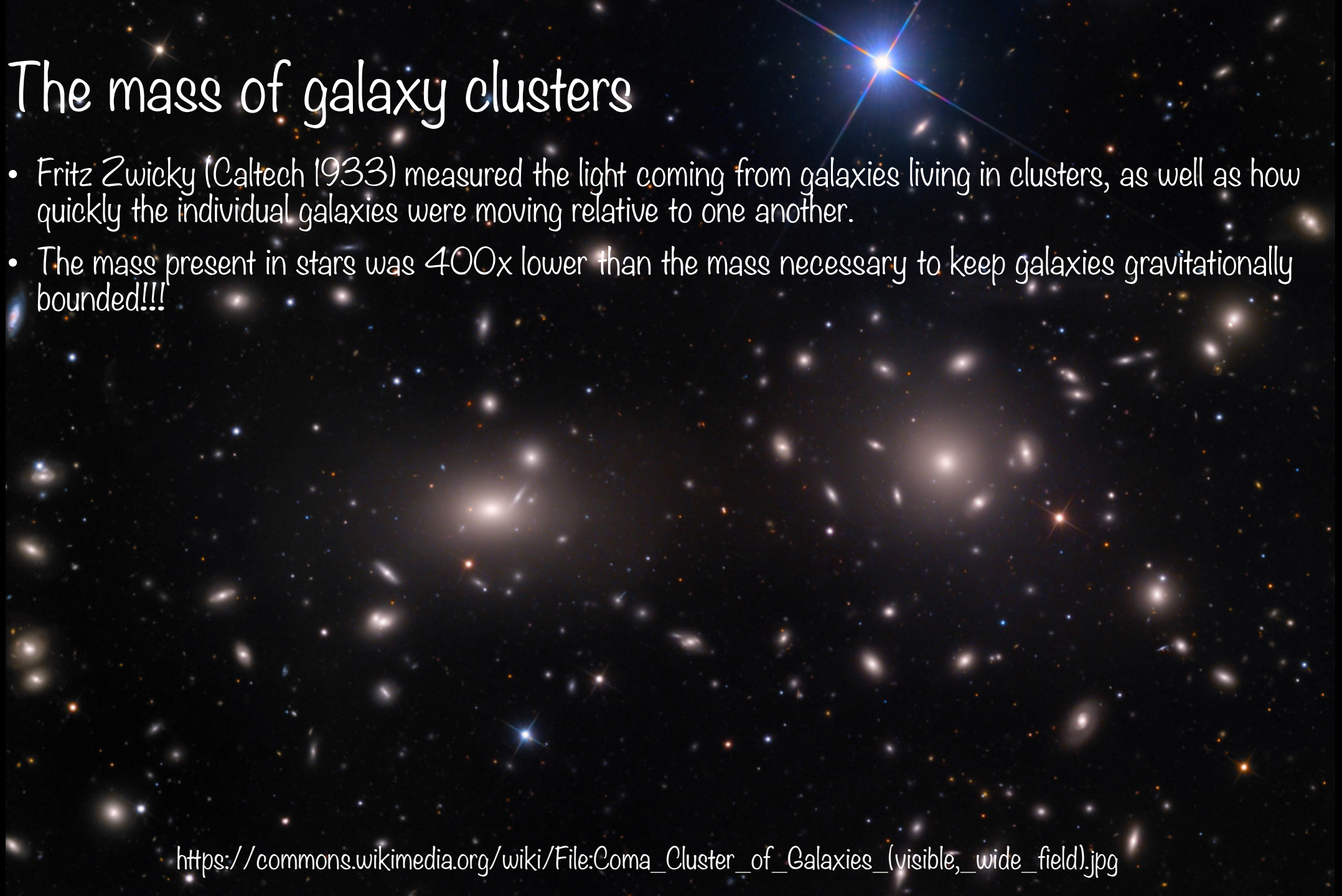


NASA/WMAP science team



The mass of galaxy clusters

- Fritz Zwicky (Caltech 1933) measured the light coming from galaxies living in clusters, as well as how quickly the individual galaxies were moving relative to one another.
- The mass present in stars was 400x lower than the mass necessary to keep galaxies gravitationally bounded!!!



https://commons.wikimedia.org/wiki/File:Coma_Cluster_of_Galaxies_(visible,_wide_field).jpg

The mass of galaxies

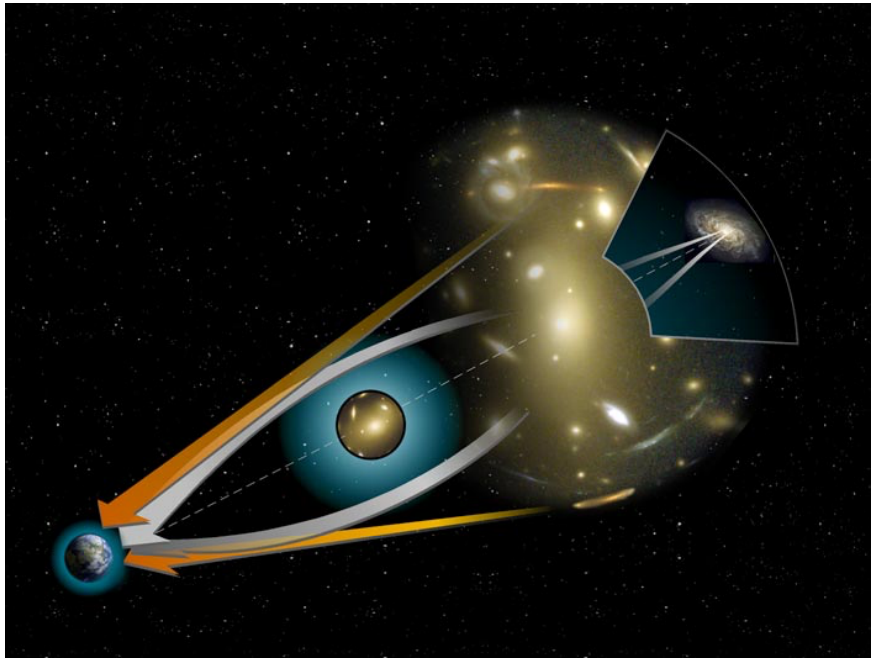
- Vera Rubin (1970s) studied the rotation of galaxies and her findings suggested the presence of dark matter

http://www.spacetelescope.org/static/archives/images/large/heic1104a.jpg

Credit: Carnegie Institution, Department of Terrestrial Magnetism

Gravitational lensing

- General relativity predicts gravitational lensing

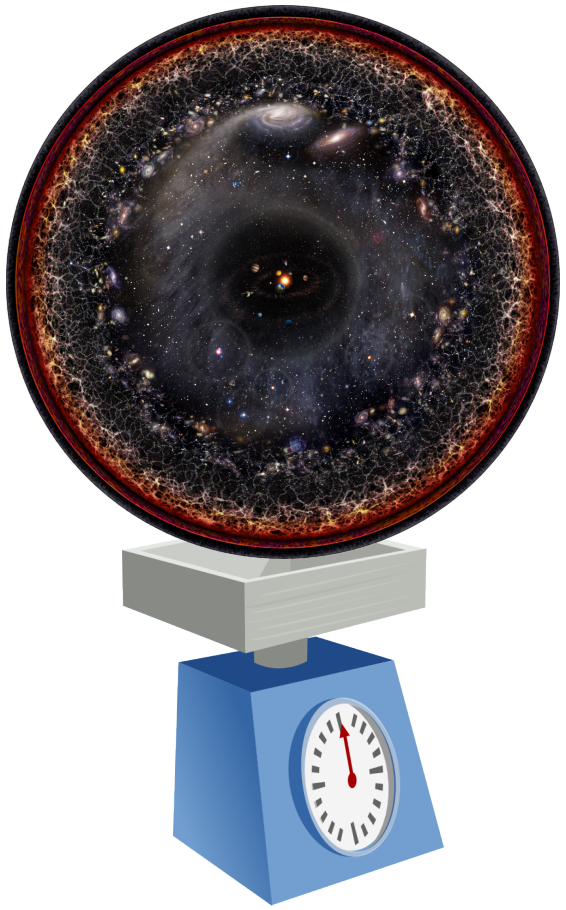


https://commons.wikimedia.org/wiki/File:Gravitational_lens-full.jpg

The bullet cluster (2005): The smoking gun of dark matter

- Red: gas (X-rays)
- Blue: density (weak gravitational lensing)

Let's recap



List of clues for dark matter:

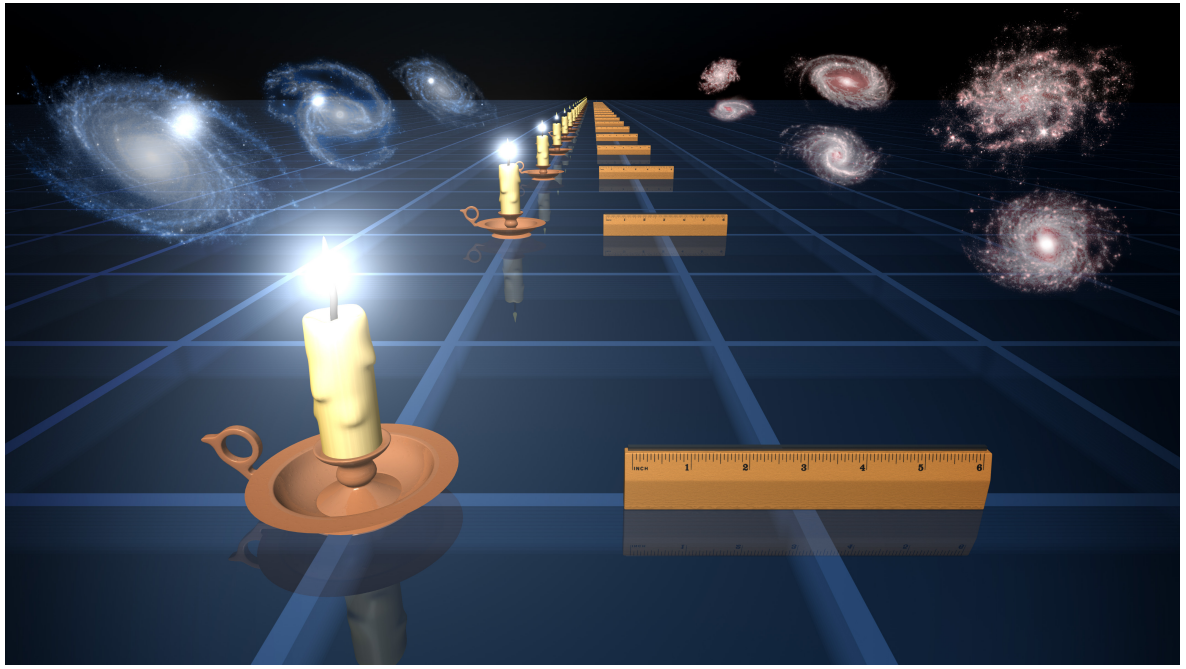
- Rotation of galaxies
- Motions inside galaxy clusters
- Gravitational lenses
- Large scale structure
- Cosmic microwave background observations

What we know about dark matter

- It does not interact electromagnetically. Only gravitationally.
- There are large amounts of dark matter within galaxies and galaxy clusters: dark matter halos.
- It is constituted by an unknown particle yet to be discovered.

But there is more darkness: dark energy!

- The Universe is expanding faster and faster
- Discovered independently by two teams in 1998, Nobel Prize in 2011
- We need a repulsive force



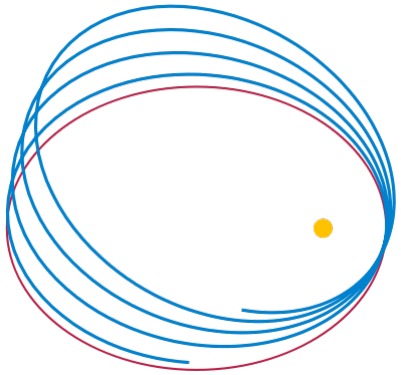
Credit: NASA/JPL-Caltech

Credit: NASA/ESA-HST

The cosmic pie

New discoveries, new science!

Phenomenon	New entity	New theory
Uranus's orbit	Neptune	Bessel's specific gravity
Mercury's orbit	Hypothetical planet Vulcano	General Relativity
Galaxy dynamics large scale structure	Dark matter	Modified Newton Dynamics
Accelerating Universe	Dark energy	Modified General Relativity



https://en.wikipedia.org/wiki/File:Relativistic_precession.svg

We need to conduct galaxy surveys

Video: SDSS flight through the Universe
https://www.youtube.com/watch?v=08LBltePDZw
Abell 68, Hubble Space Telescope

The future is coming

euclid

ESA/NASA

2021

1.2 m (4feet)

1 billion galaxies

WIDE-FIELD INFRARED SURVEY TELESCOPE

WFIRST

ASTROPHYSICS • DARK ENERGY • EXOPLANETS

NASA

mid-2020s

2.4 m (8feet)

The decision to implement WFIRST will not be finalized until NASA's completion of the National Environmental Policy Act process

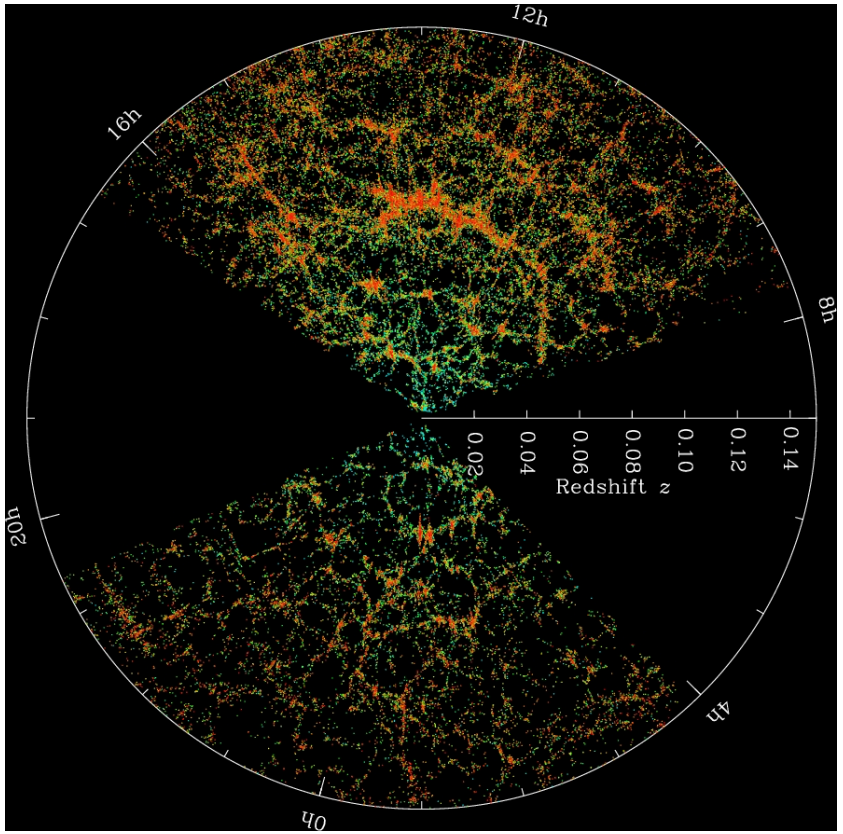
Let's do experiments: simulations!

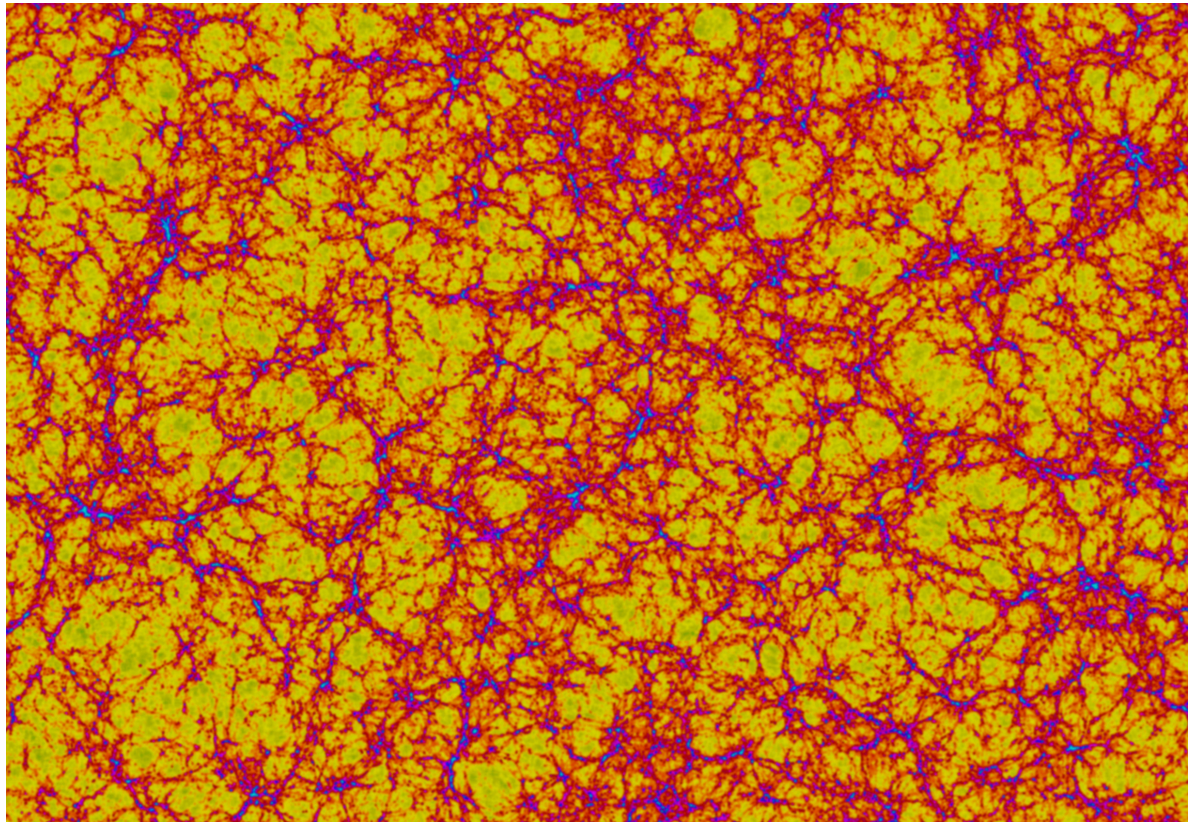
- Videos:

- The Illustris project: https://www.youtube.com/watch?v=NjSFR4OSY58

- The Aquarius project: https://www.youtube.com/watch?v=zLSe7RxtJ4o

Simulations vs observations





Credit: M. Blanton and SDSS

Big simulations = big machines

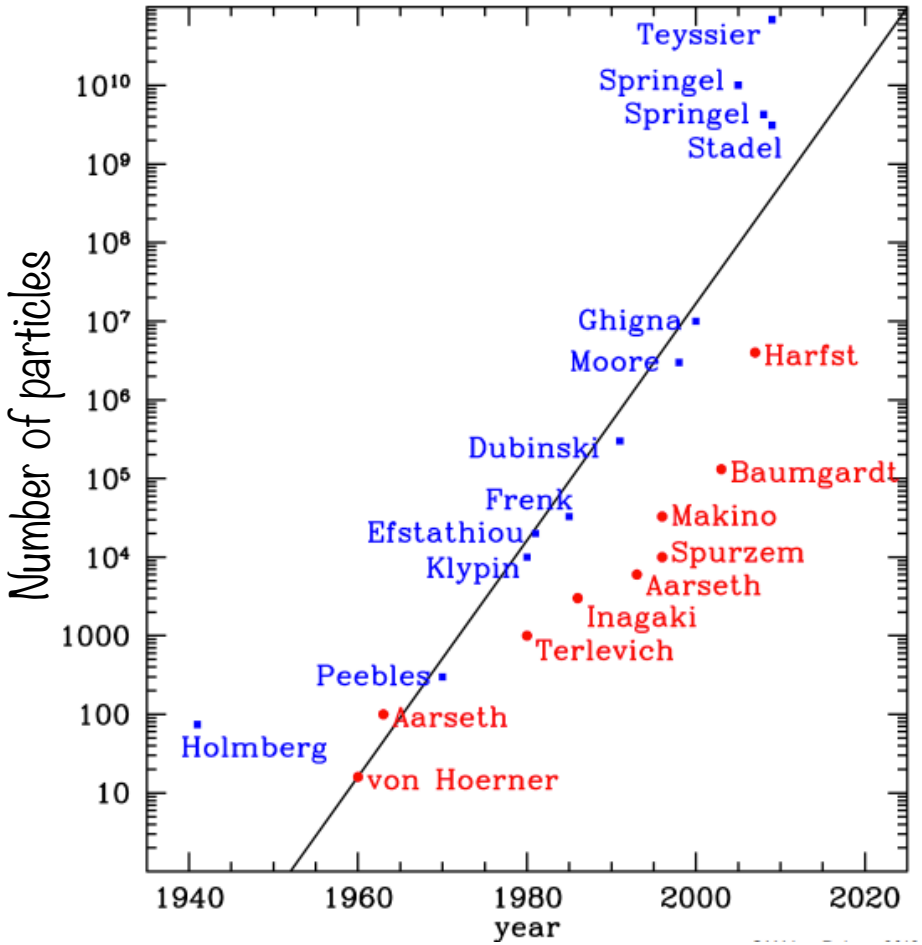
- What is supercomputing?
- What is a parallel algorithm?

The Sequoia supercomputer has 1.5 million cores

Credit: Bob Hirschfeld/LLNL

Moore's law

- To compare:
- 1e13 cells in the human body
- 20 billion neurons in a human brain
- The latest simulations are out of scale



Thanks!