

4 Some more about Big Bang theory

- One thing I did not tell you last time ...
- The third pillar of the Big Bang theory: Nucleosynthesis
- Quasar Absorption Lines
- History of the Universe
- Something Intriguing

Tom Abel

Kavli Institute for Astroparticle Physics and Cosmology

Stanford Physics Department

Stanford Linear Accelerator Laboratory

Type Ia Supernovae as cosmological probes

- Characterized by no Hydrogen, but with Silicon
- Progenitor C/O White Dwarf accreting from companion
- Just before Chandrasekhar mass, thermonuclear runaway

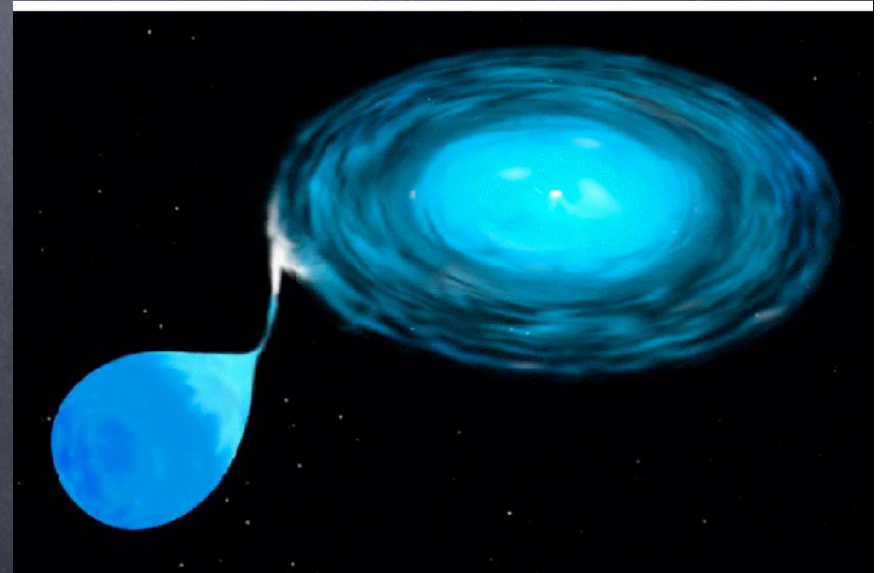
Standard explosion from nuclear physics

Insensitive to initial conditions:

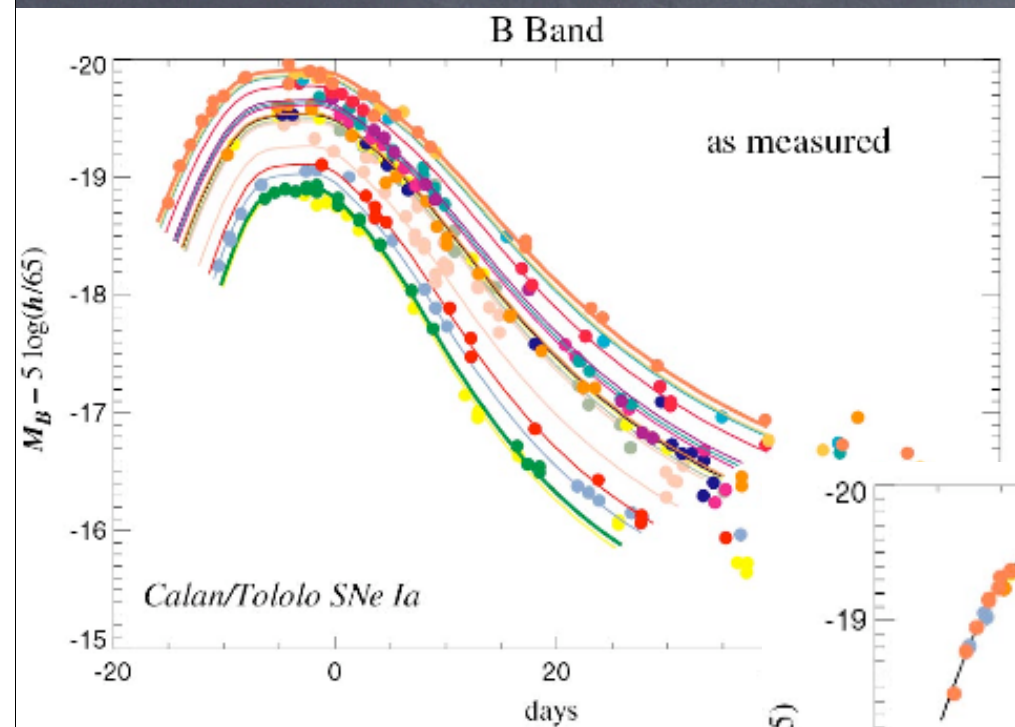
"stellar amnesia"

Höflich, Gerardy, Linder, & Marion

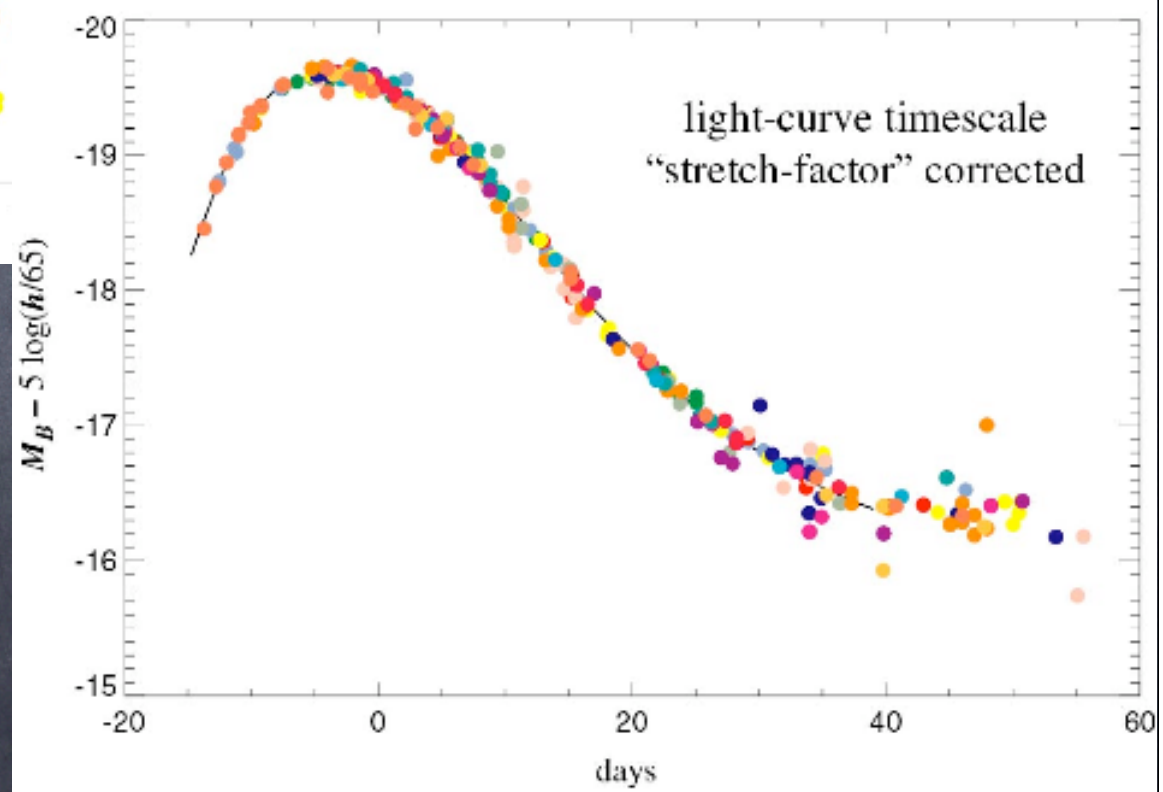
astro-ph/0301334



1 Parameter Family Homogeneity

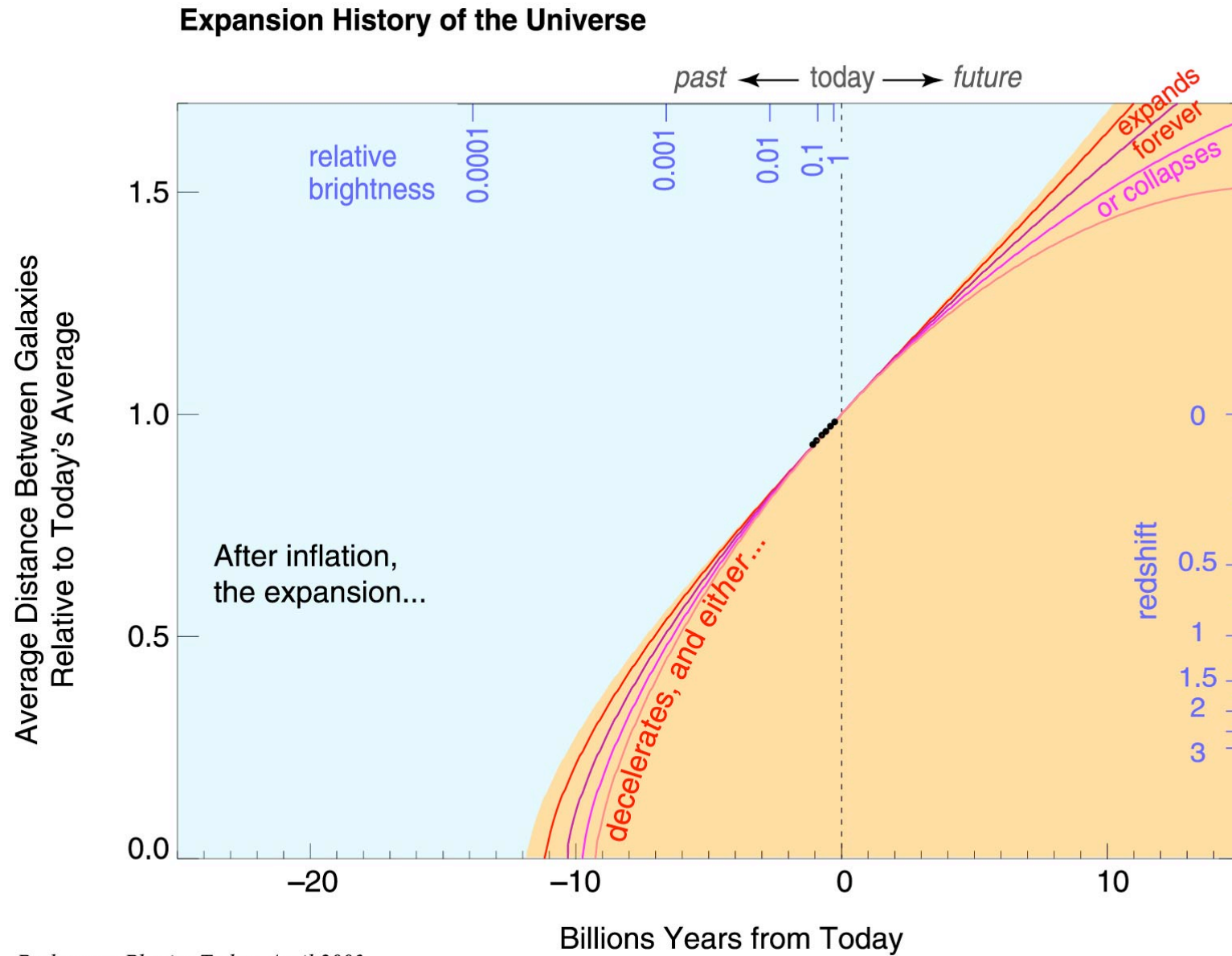


$$L = L_s 10^{(-0.4[M - M_{\text{sun}}])}$$
$$= 10^{(-.4[M - 5.46])}$$
$$L(M = -20) \sim 1.5e10 L_{\text{sun}}$$

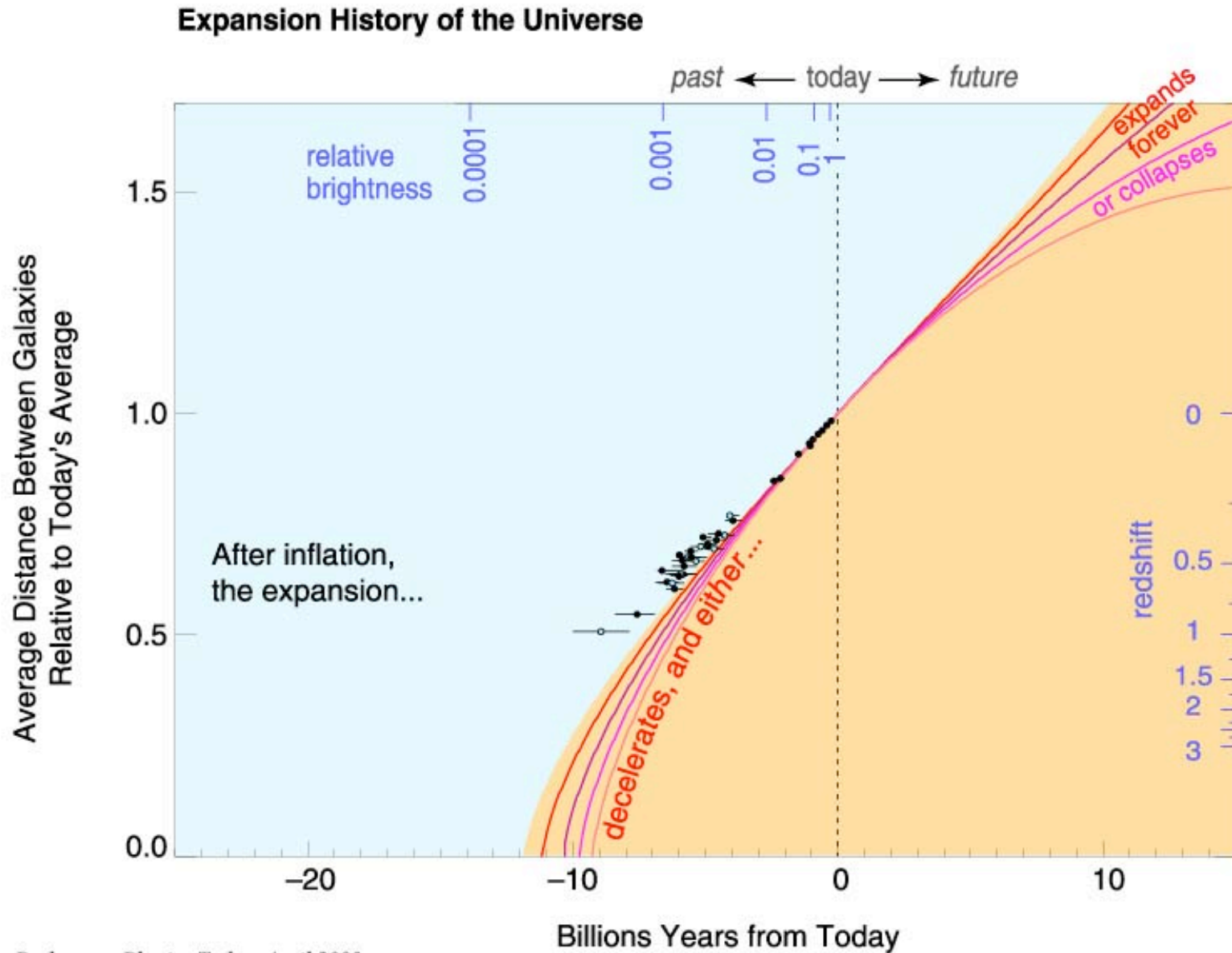


Kim, et al. (1997)

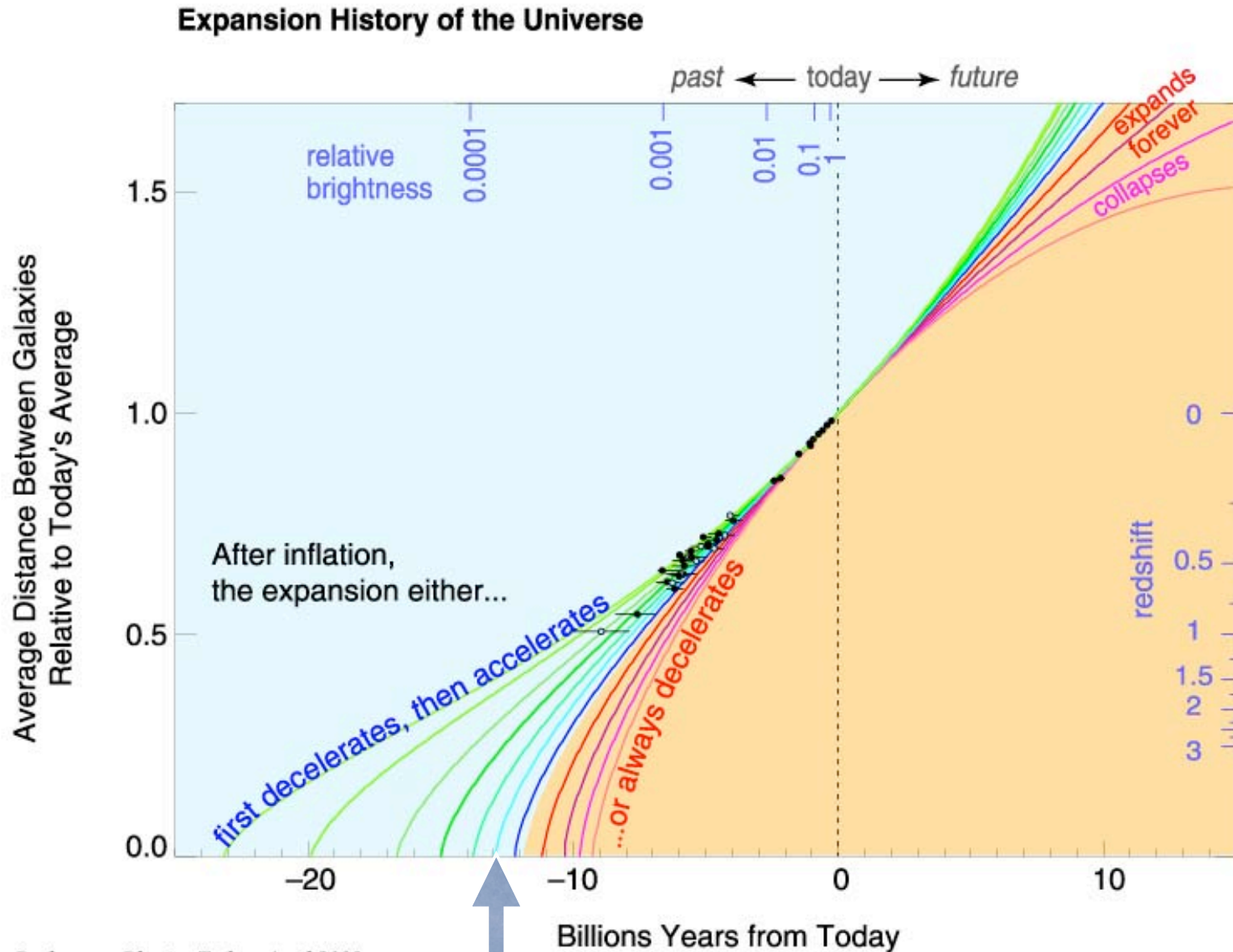
Supernovae: Local



Supernovae: Mapping Expansion



Supernovae: Acceleration



Perlmutter, *Physics Today*, April 2003

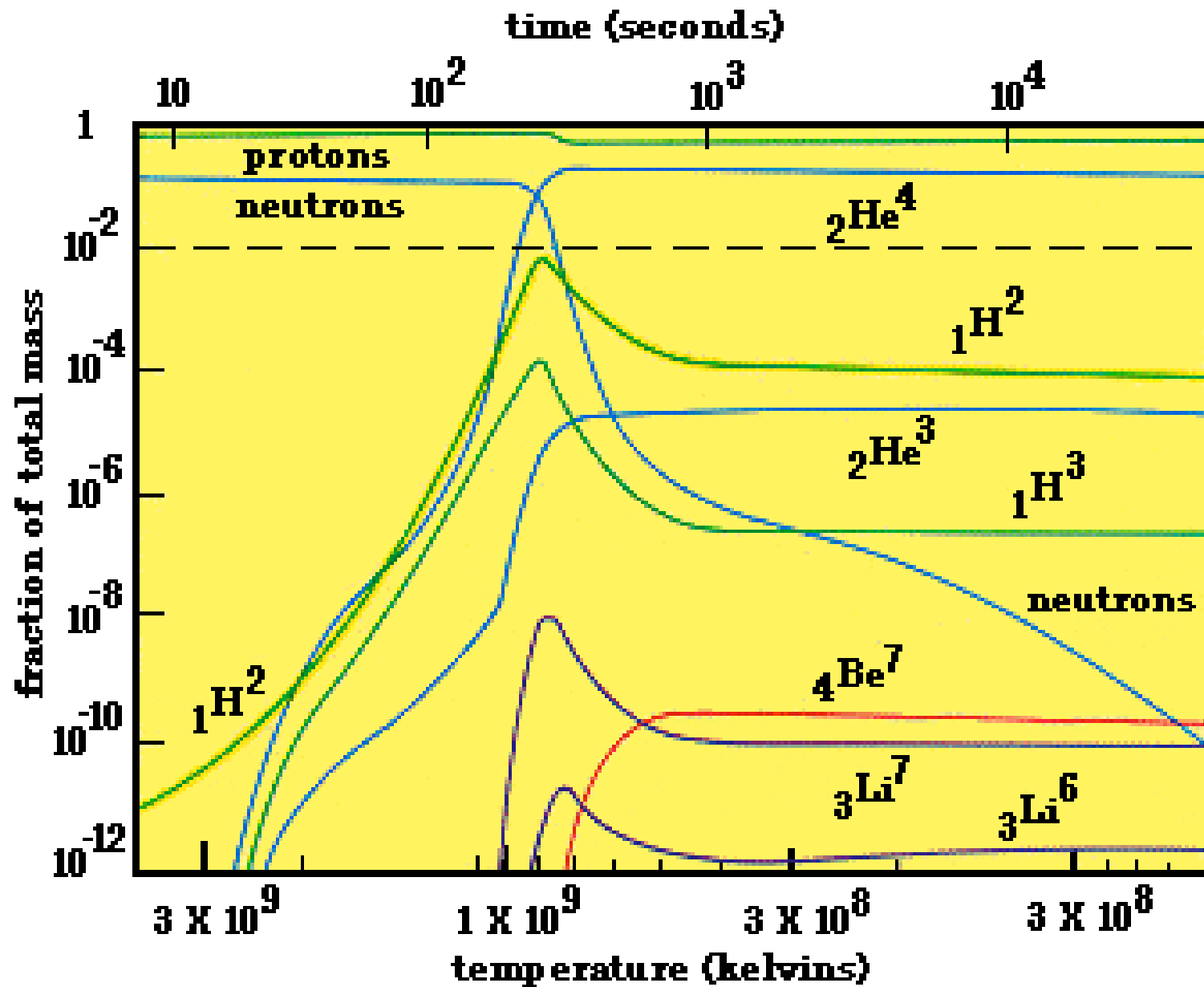
Big Bang Nucleosynthesis (BBN)

- 1940s: Gamow, Alpher & Herman proposed all chemical elements synthesized via nuclear reactions in hot early universe “ylem”
- predicted existence of CBR

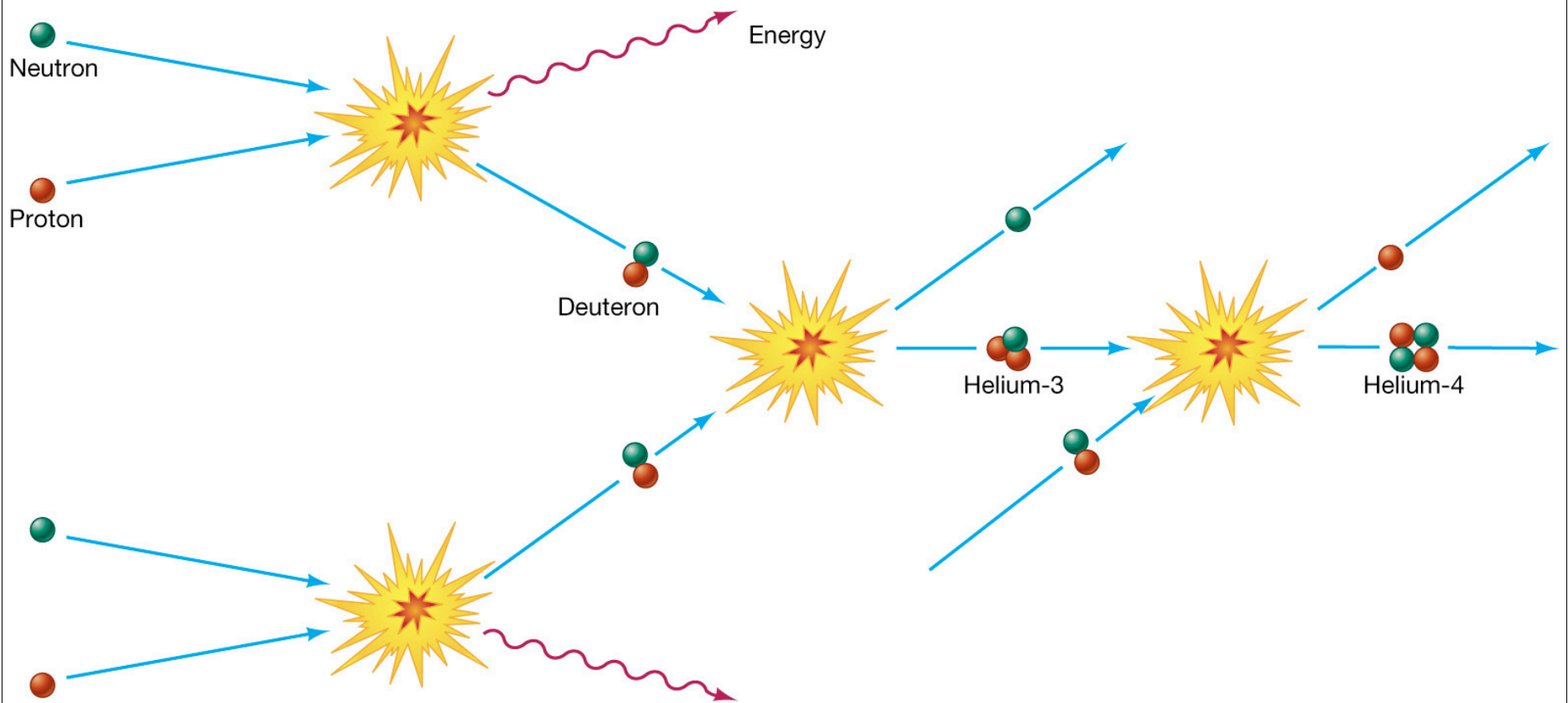


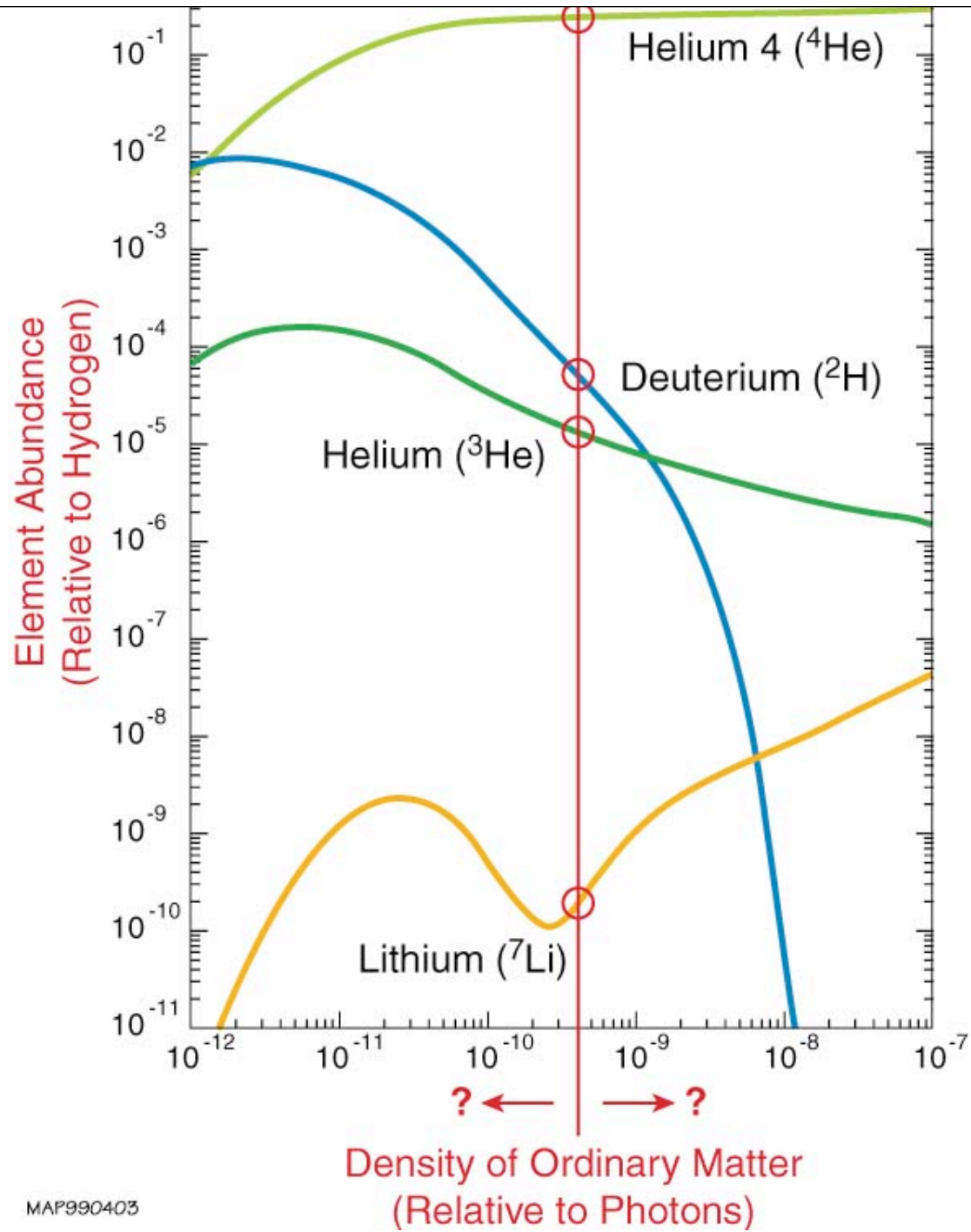
George Gamow (1904-1975)

Abundance Evolution

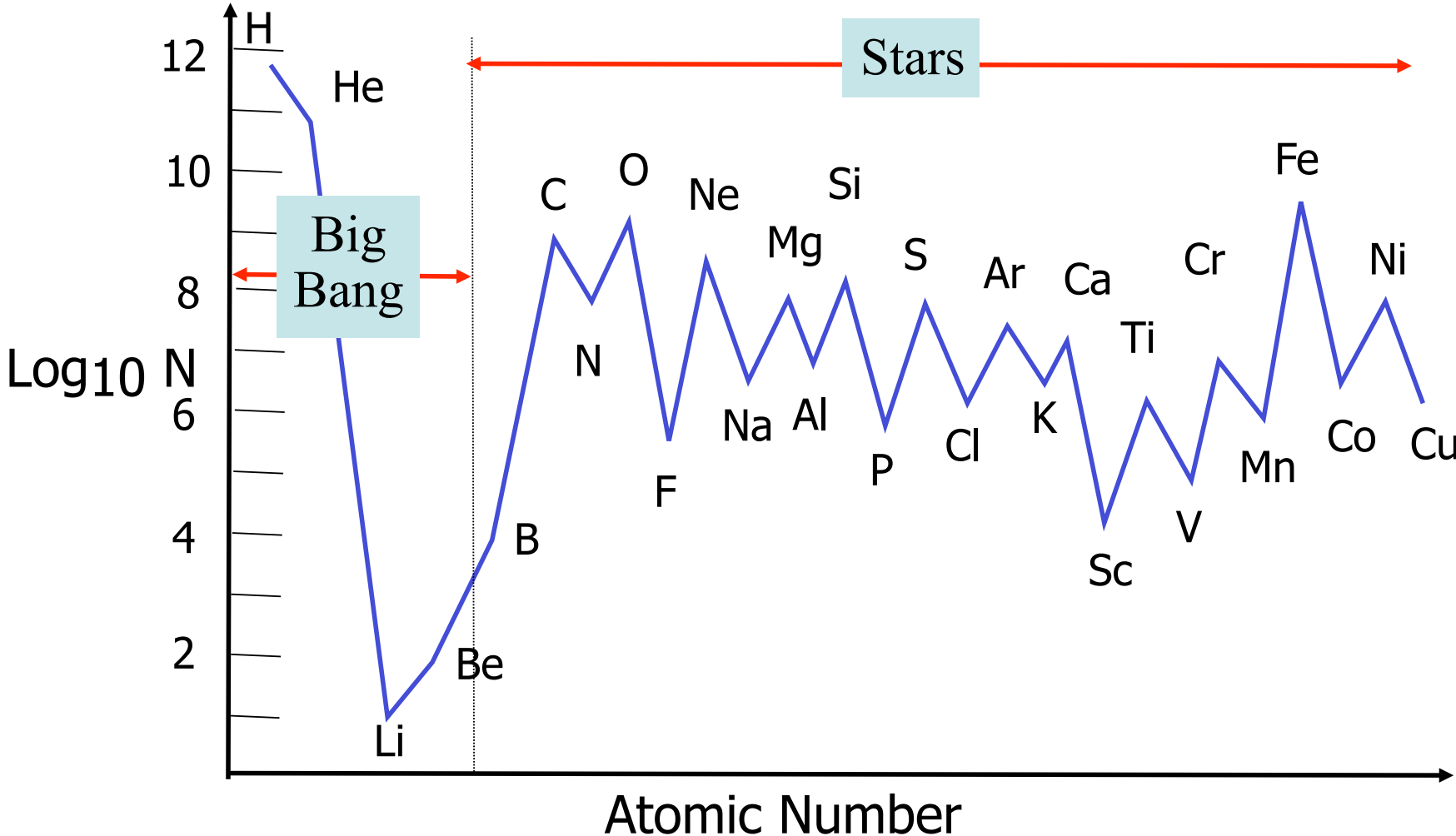


Helium Formation





Cosmic Chemical Abundances



Three Pillars of Big Bang Theory

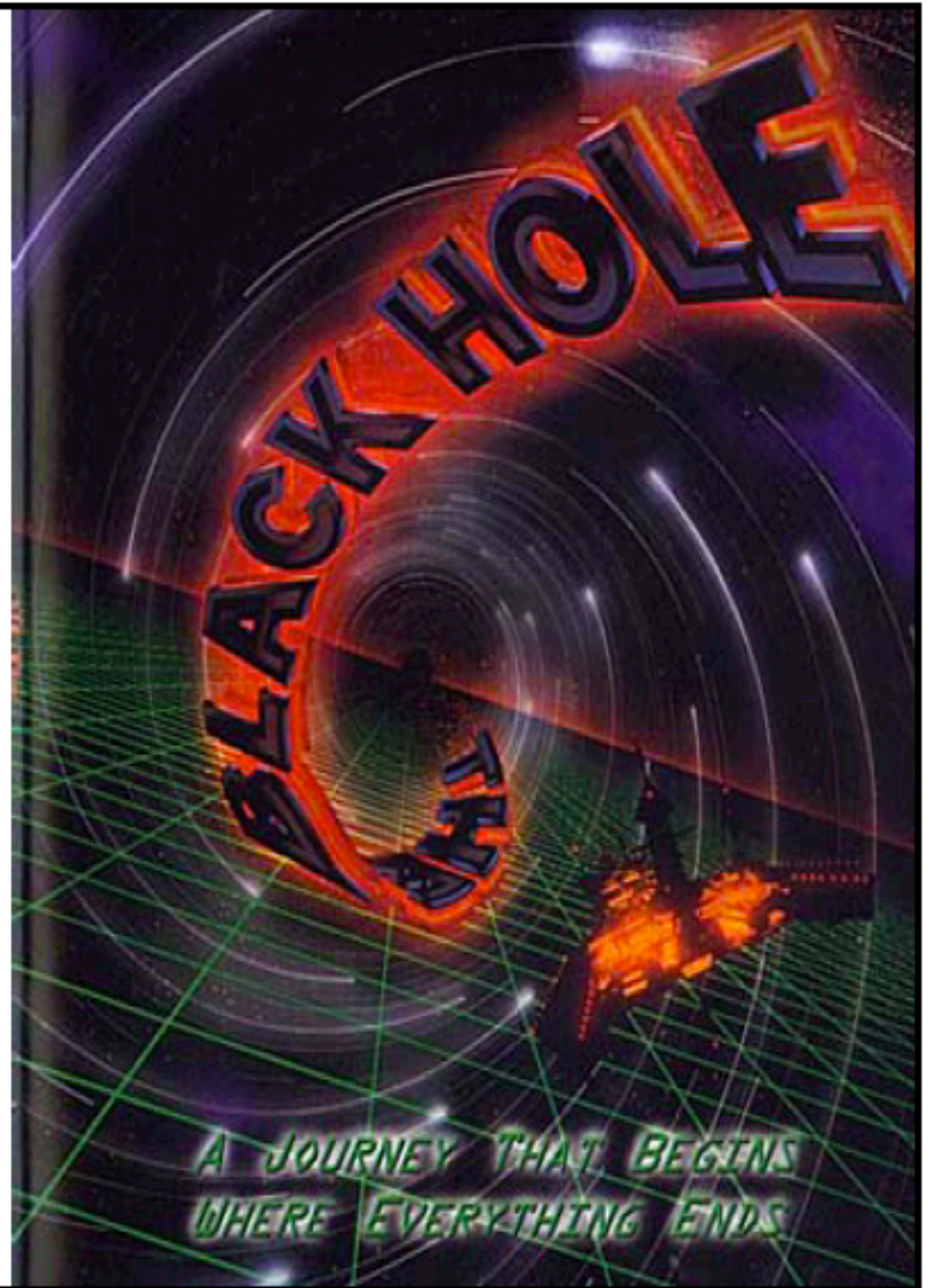
- Hubble's Law: The Expanding Universe
- Cosmic Microwave Background Radiation
- Light Element Nucleosynthesis

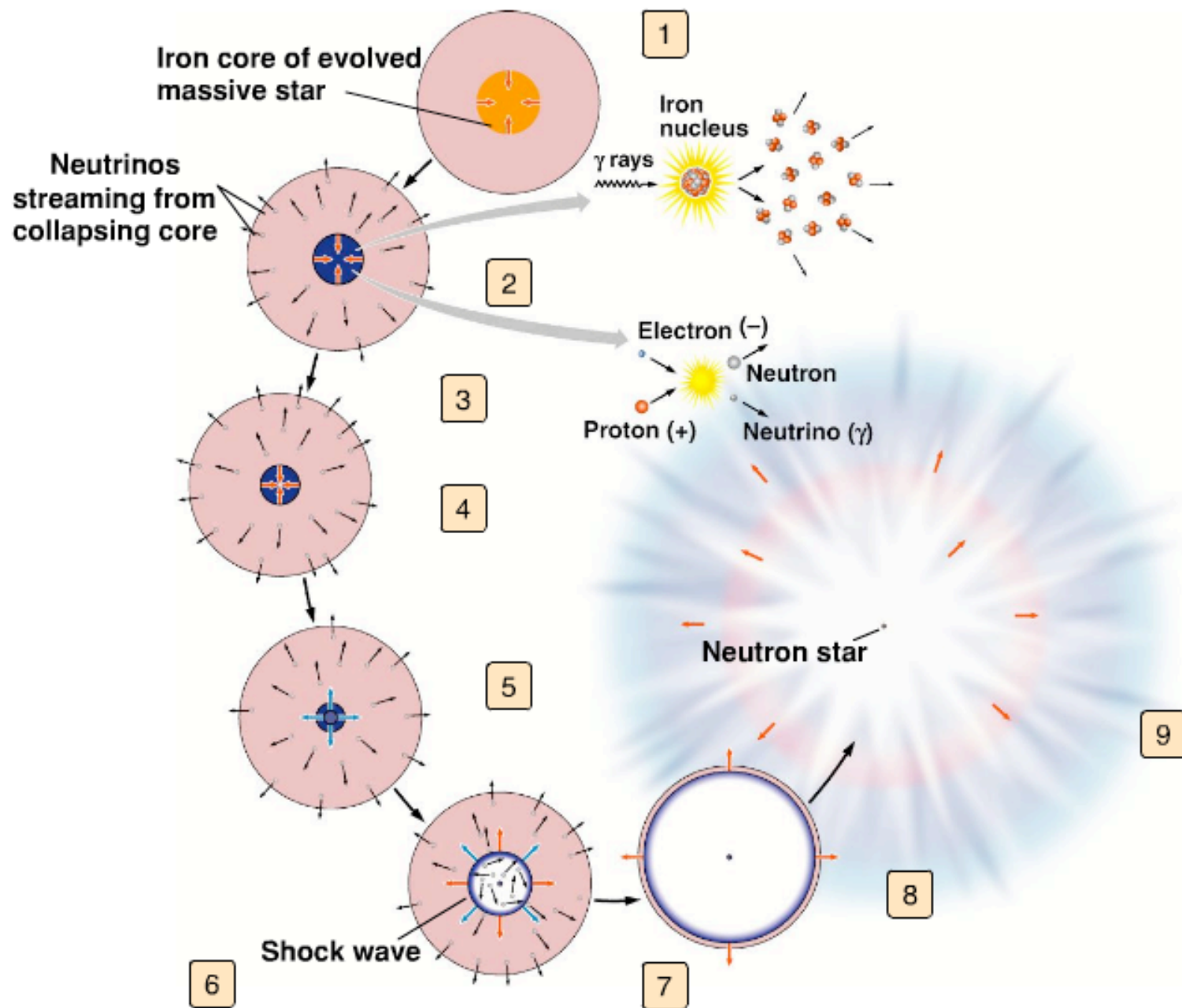
Black Holes: Gravity's Ultimate Victory

If $M_{\text{core}} > 3M_{\text{sun}}$, Pauli
exclusion for Neutrons
fails. Nothing can prevent
complete collapse.

Phy16-04-6-21

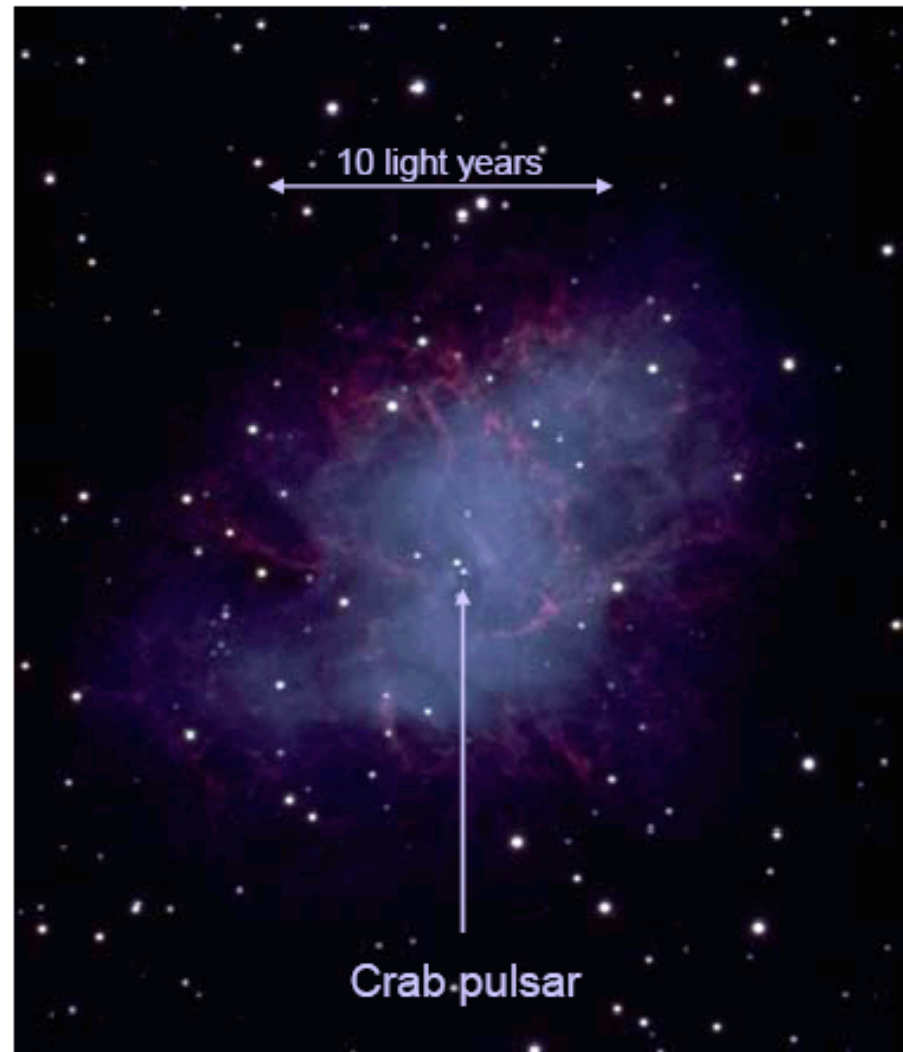
Disney 1979





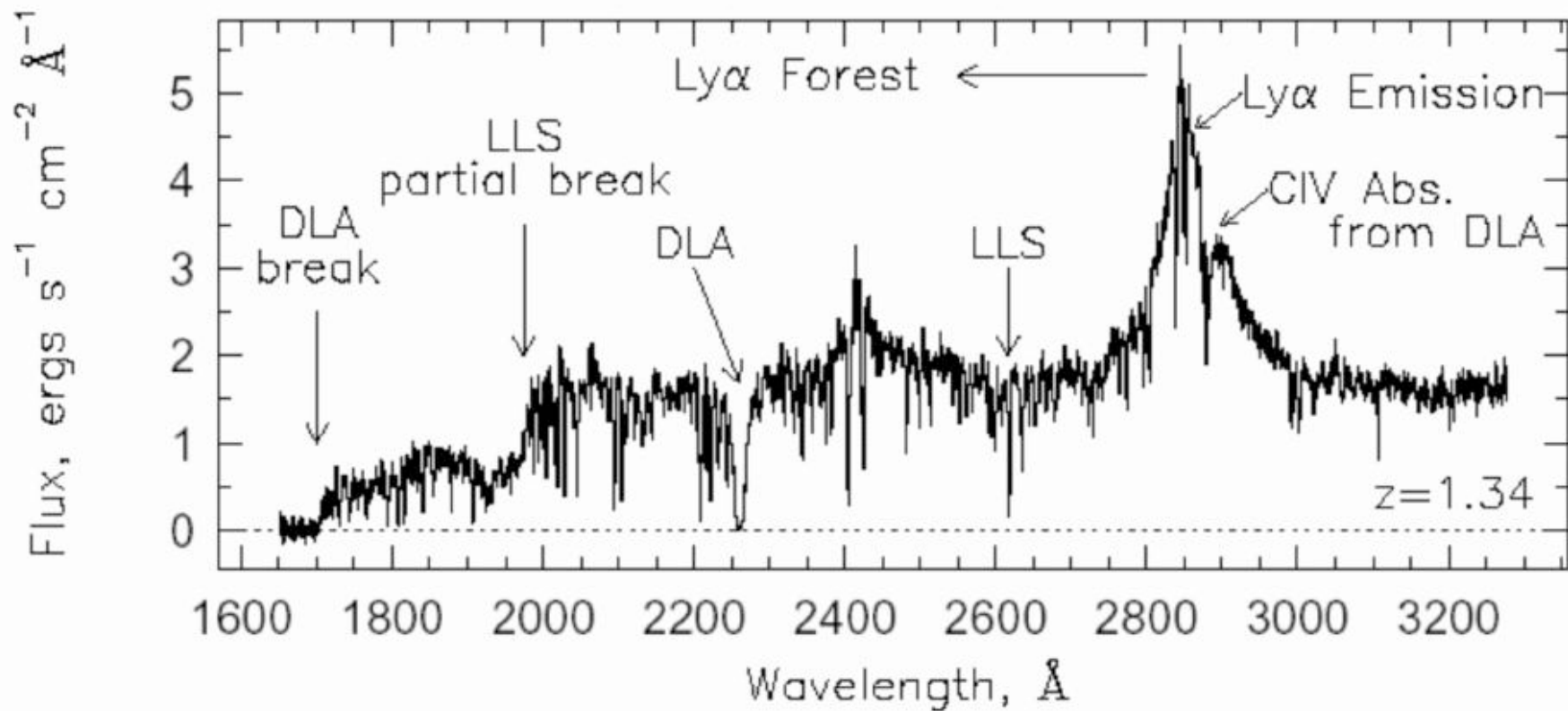
Crab Supernova in 1054

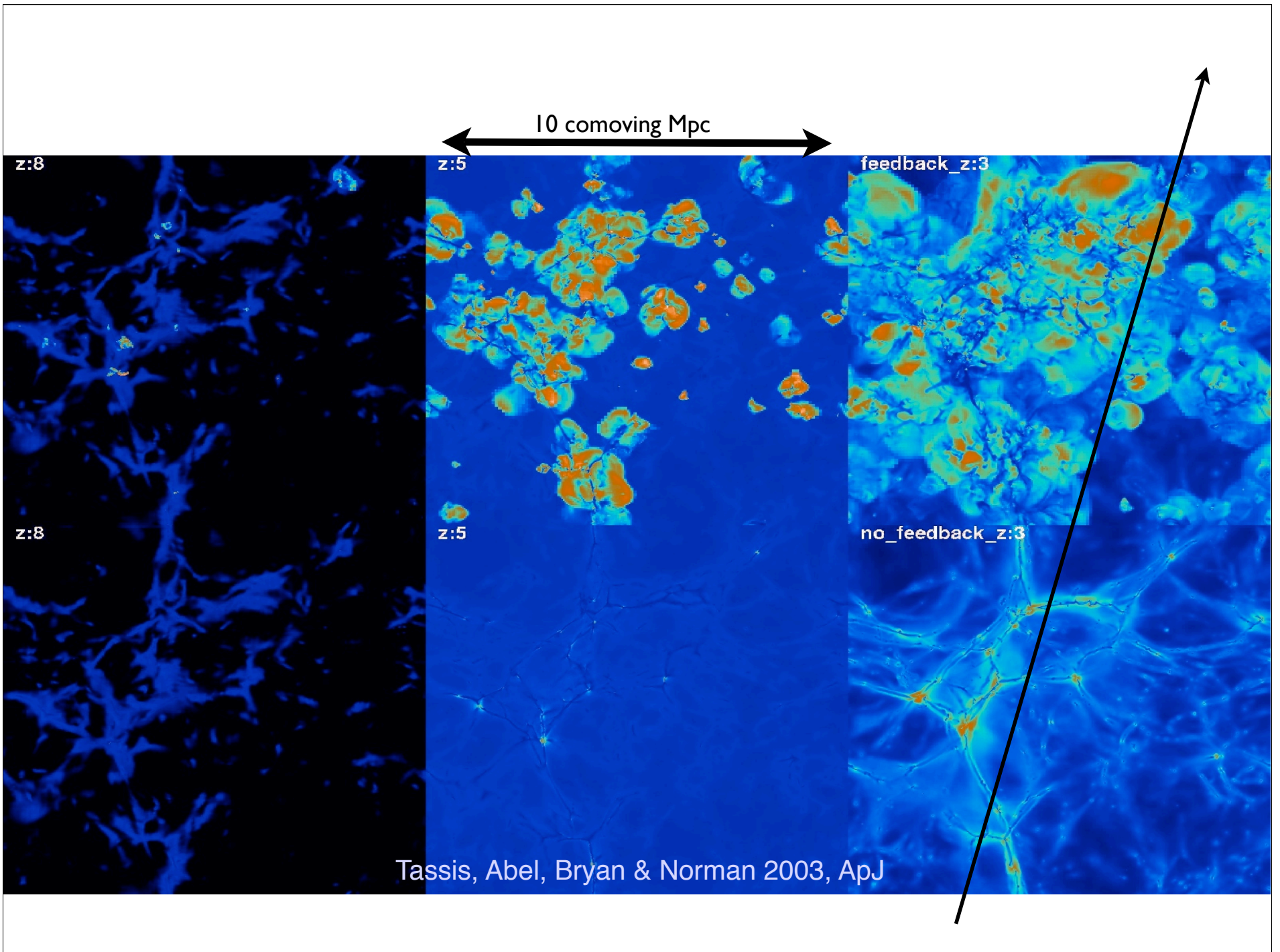
- Supernova remnant formed from explosion seen in 1054 just above Orion
- 7,200 light years away
- Formed a neutron star – now a pulsar spinning 30 times per sec
- Has diameter of about 10 km



Quasar Absorption Lines

- First big success for Cosmological Hydrodynamics : 1994 - now








The History of the Universe

- **0 seconds.** The Big Bang. Space begins expanding.
- **10^{-43} seconds. The Planck time.** The universe has a radius of 10^{-35} cm (the Planck length) and a temperature of about 10^{32} K. Prior to this time the universe had complete symmetry: all 4 forces we know today were unified. We do not know what happened before this time, because our knowledge of physics breaks down at this point. Gravity becomes a distinct force. The other forces are still unified as the GUT (Grand Unified Theory) force. We have entered the **GUT era**.
- **10^{-35} seconds.** The temperature has fallen to 10^{28} K. The electro-weak and the strong nuclear forces become distinct. The universe enters a state called a "false vacuum", during which the energy of the vacuum drives inflation. By 10^{-32} seconds, the universe has expanded by about a factor of 10^{60} , becoming the size of the Solar System.
- **10^{-32} seconds.** Inflation stops. The universe undergoes a phase transition to a lower-energy state ("the true vacuum"). The inflation smooths out all irregularities, ensuring that the entire visible universe was in causal contact, and makes the geometry of the universe flat. This is the **electro-weak era**

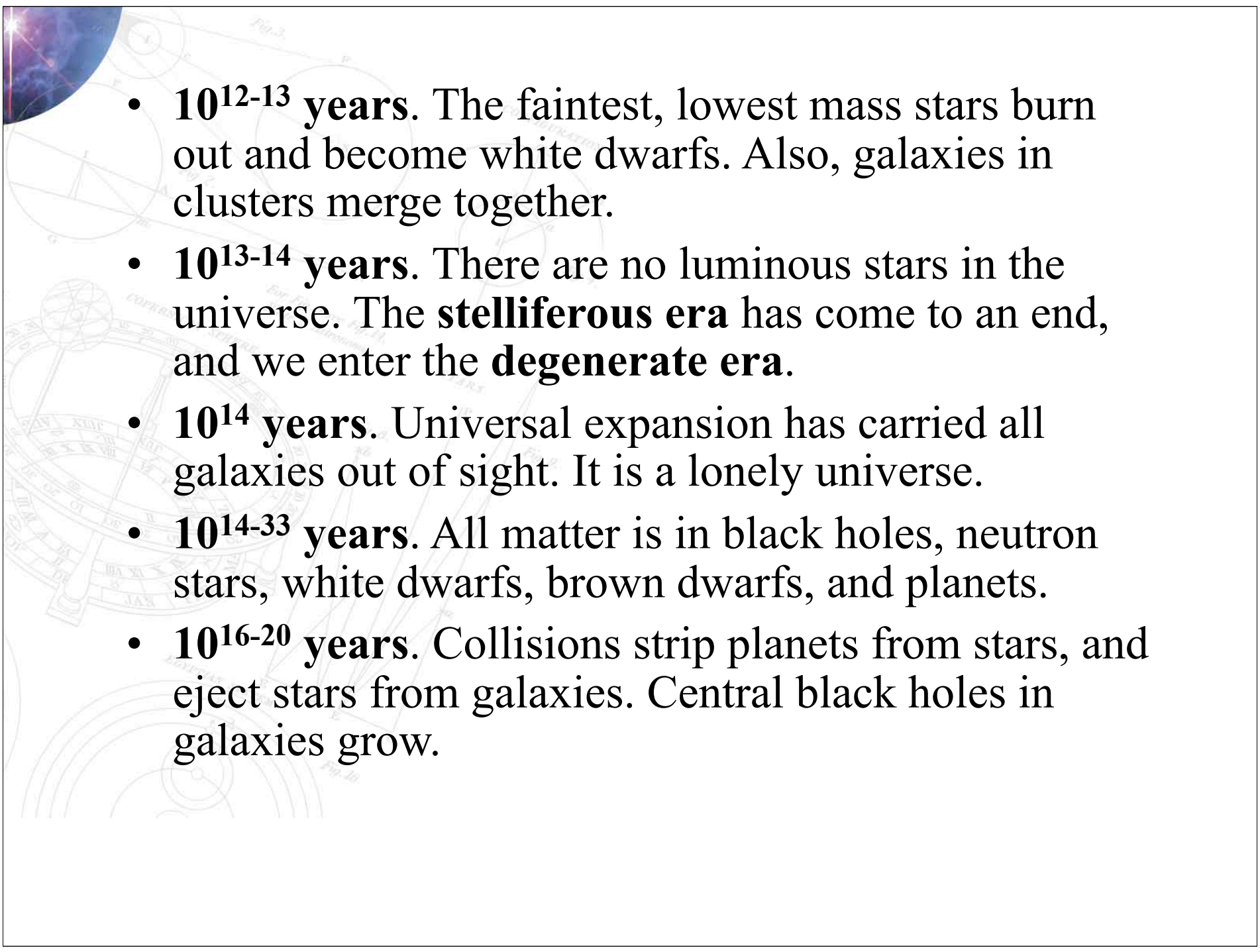
- **10^{-4} seconds.** The temperature has cooled to 10^{13} K. The energy density is no longer sufficient to create quarks, so quarks freeze out of the universe.
- **10^{-3} seconds.** The temperature has cooled to 10^{12} K. The energy density is no longer sufficient to create protons. All protons that will ever exist have been made. Due to an asymmetry in the electro-weak force, for every 10^9 antiparticles made, 10^9+1 particles are made. The 10^9 particle/antiparticle pairs annihilate, leaving 10^9 photons for every proton in the universe.
- **10^{-3} to 100 seconds. The era of nucleosynthesis.** Protons react with other protons to create Deuterons and alpha particles (helium nuclei). At the end of this era, the matter in the universe is 70% hydrogen and 25% helium (by mass), with traces of deuterium, lithium, boron, and beryllium.
- **100 seconds to 400,000 years. The era of nuclei.** The universe is fully ionized, and continues to expand. The universe is opaque to radiation because free electrons are good absorbers. The universe is in thermal equilibrium.


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- **400,000 years. Recombination.** The temperature has cooled to 3000K. The redshift z is 1090. electrons and protons can combine to form atoms. The universe becomes transparent. We see 3000K photons redshifted by a factor of 1000 to 3K. We cannot see any further back in time with light.
 - **about 10^8 years.** The first generation of stars (population III) forms from clouds of gas. We enter the **Stelliferous era**. Massive stars create the metals (everything heavier than hydrogen and helium) and return them to the interstellar medium.
 - **about 10^8 years.** Galaxies form. Dust (made of metals) is abundant. The earliest galaxies probably have redshifts of 10-30.
 - **7 billion years.** The Sun and solar system form.
 - **13.7 billion years.** Now.



The Future of the Universe

- **15 billion years.** (1 billion years from now). The Solar luminosity has increased to the point where the average temperature on Earth reach the boiling point of water. It may be time to move to cooler climates!
- **19 billion years.** (5 billion years from now). The Sun leaves the main sequence. Its radius approaches one Astronomical Unit. Mercury is vaporized. The planets spiral outwards as the red giant Sun loses mass in a solar wind. Venus may survive; the Earth ends up near where Mars is now.
- **21 billion years.** (7 billion years from now). The Sun becomes a white dwarf.

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- **10^{12-13} years.** The faintest, lowest mass stars burn out and become white dwarfs. Also, galaxies in clusters merge together.
 - **10^{13-14} years.** There are no luminous stars in the universe. The **stelliferous era** has come to an end, and we enter the **degenerate era**.
 - **10^{14} years.** Universal expansion has carried all galaxies out of sight. It is a lonely universe.
 - **10^{14-33} years.** All matter is in black holes, neutron stars, white dwarfs, brown dwarfs, and planets.
 - **10^{16-20} years.** Collisions strip planets from stars, and eject stars from galaxies. Central black holes in galaxies grow.

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- **10^{14-20} years.**
 - Binary stars spiral together and merge.
 - Collisions between white dwarfs produce supernovae.
 - Collisions between brown dwarfs produce low mass stars.
 - Typical galaxies shine with one solar luminosity.
 - **10^{20} years.** The only luminosity in the universe comes from white dwarfs absorbing dark matter. White dwarfs glow at a temperature of 64K.
 - **10^{33-37} years. The end of matter.** Protons decay. White dwarfs glow with an luminosity of 400 Watts.
 - **$>10^{60}$ years. The Black Hole era.**
 - **10^{65} years.** Stellar mass black holes evaporate.
 - **10^{100} years.** Galactic mass black holes evaporate.
 - *This is how the world will end. not with a bang, but a whimper.*



Where Did the Universe Come From?

- What is the universe and where did it come from? Although that question has been and continues to be the province of philosophy and theology, physics is coming closer to its own answer. And the physical answer is might awesome. Our universe may be nothing more than a fluctuation in *The Vacuum*.
- Now, *The Vacuum* that cosmologists speak of is not the common vacuum, the absence of matter. *The Vacuum* can be thought of as a substrate underlying the universe, or of as space itself. *The Vacuum* is not empty: it contains energy (the so-called vacuum energy). This energy can be utilized to create virtual particles, subject to the **Heisenberg Uncertainty Principle**.

Heisenberg's Uncertainty Principle

- This application of Heisenberg's Uncertainty Principle says that you can create something of energy E for a time T so long as the product $ET < h$, where h is Planck's constant. This does not violate the law of conservation of energy, basically because the violation is too small to be measured. In our universe, this leads to the spontaneous creation and annihilation of what are called **virtual particles**. One consequence of virtual particles is the evaporation of black holes.



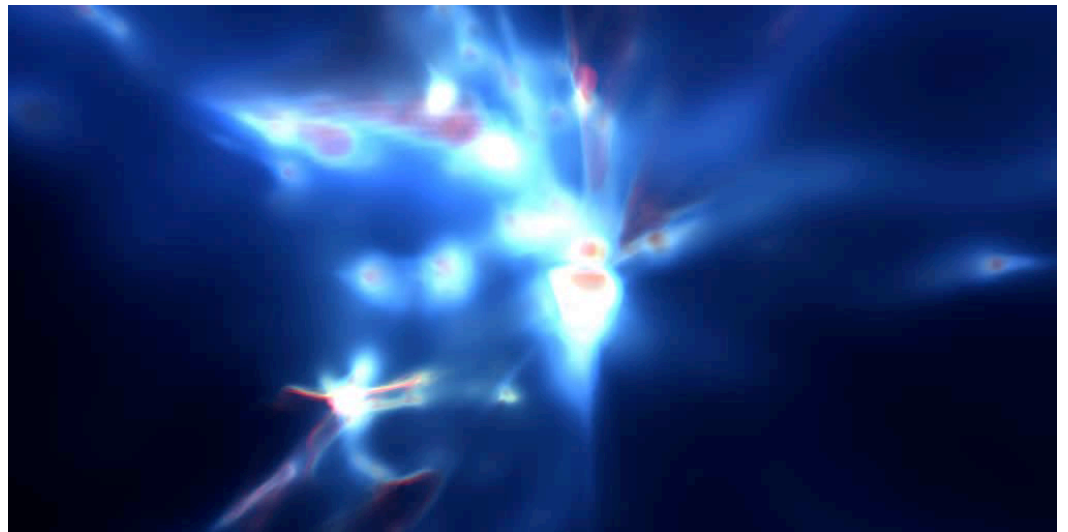


The universe a fluke?

- How does this apply to the universe? The total energy of the universe is composed on rest-mass energy ($E=mc^2$), kinetic energy, and potential energy. Potential energy is negative, while rest-mass and kinetic energies are positive. If the universe is exactly balanced (or flat), then the potential energy will offset the kinetic energy, and the net energy of the universe may be zero. Now, zero times anything is less than Planck's constant, so a zero-energy universe could conceivable appear out of nothing (*The Vacuum*) and exist for a very long time.

Summary

- The golden age of Cosmology is now!
- Discoveries are being made with Telescopes as well as super-computers



Simulation: Marcelo Alvarez, John Wise & Tom Abel 2007
Visualization: Ralf Kähler, Marcelo Alvarez & Tom Abel