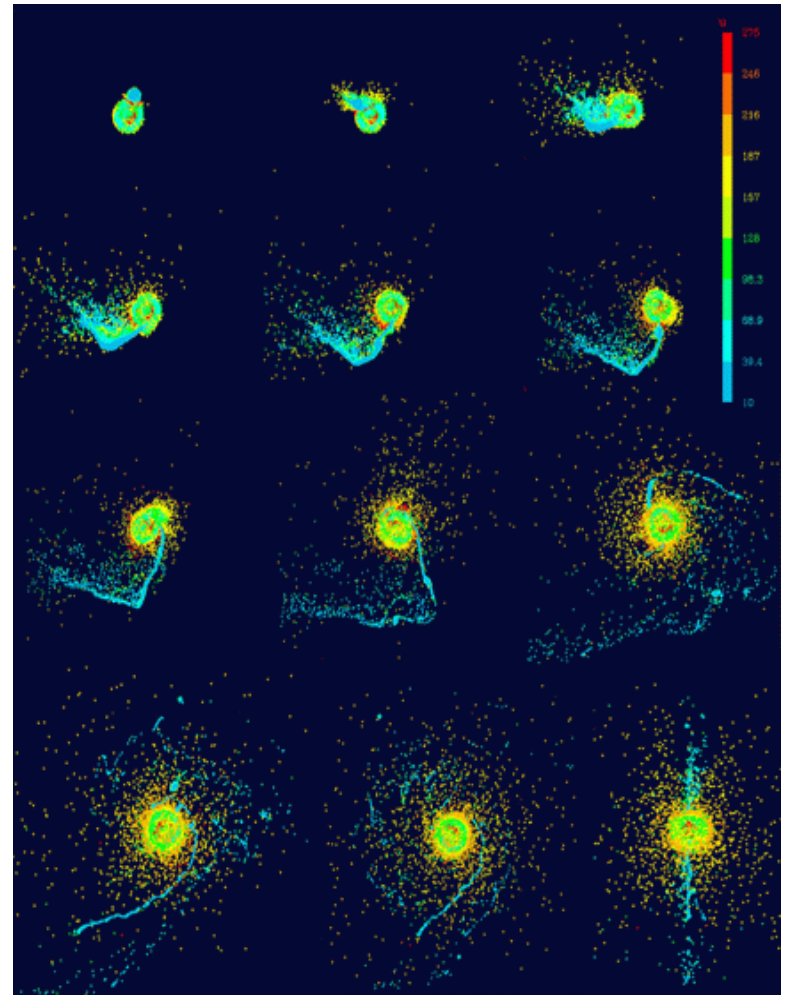


Are We Just So Lucky To Be Around?

STAR Workshop
Bar Harbor, Maine
June 18, 2002

Earth is a very special planet

- Asteroid impact created the moon
- Asteroid eliminated the dinosaurs
- Long-lived, stable star
- Ideal distance from sun
- Atmosphere & water



Are we alone ?

The universe contains 10^{12} galaxies, each one made up of 10^{11} stars, many of which are surrounded by planets. How many harbor intelligent life?

Drake's equation (1960) for number of planets with intelligent life in our galaxy (simplified):

$$N = R_* \times p_{\text{Earth}} \times p_{\text{Life}} \times p_{\text{intell}} \times L$$

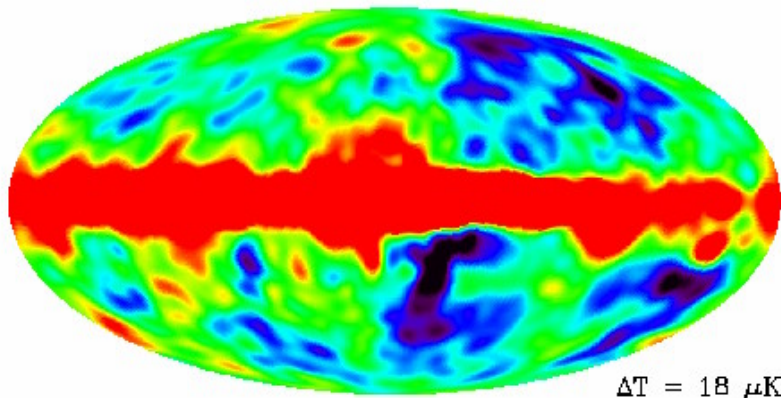
See: <http://www.seds.org/~rme/drakeeqn.htm>

Overview

- Some facts about the universe
- Life: A cosmic accident ?
- The anthropic principle
- Laws of nature and the vacuum
- How did the universe get so large ?
- Re-creating Big Bang conditions in the lab

Standard Model of Cosmology

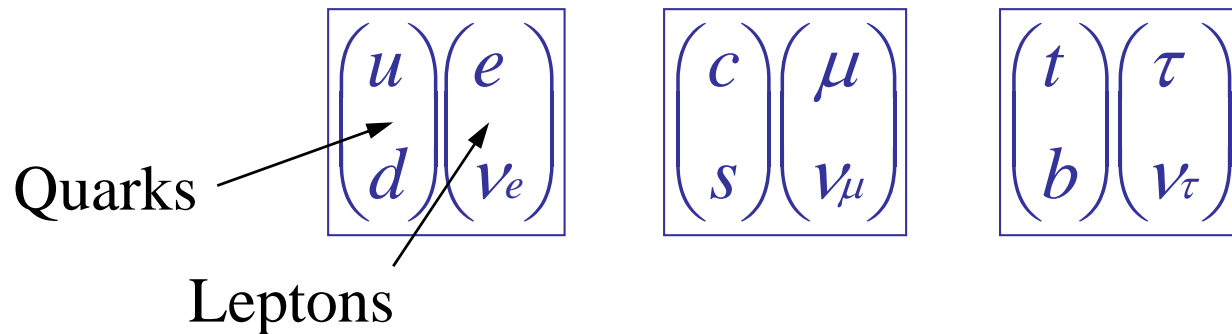
- Hubble expansion
 - Age: 14 billion years
 - $T = 2.73\text{K}$
- † Isotropic (1:100,000)
 - † 97% “dark” mass
 - † Total energy = 0



Background radiation
from COBE satellite

17 Elements of matter and force

Matter Particles



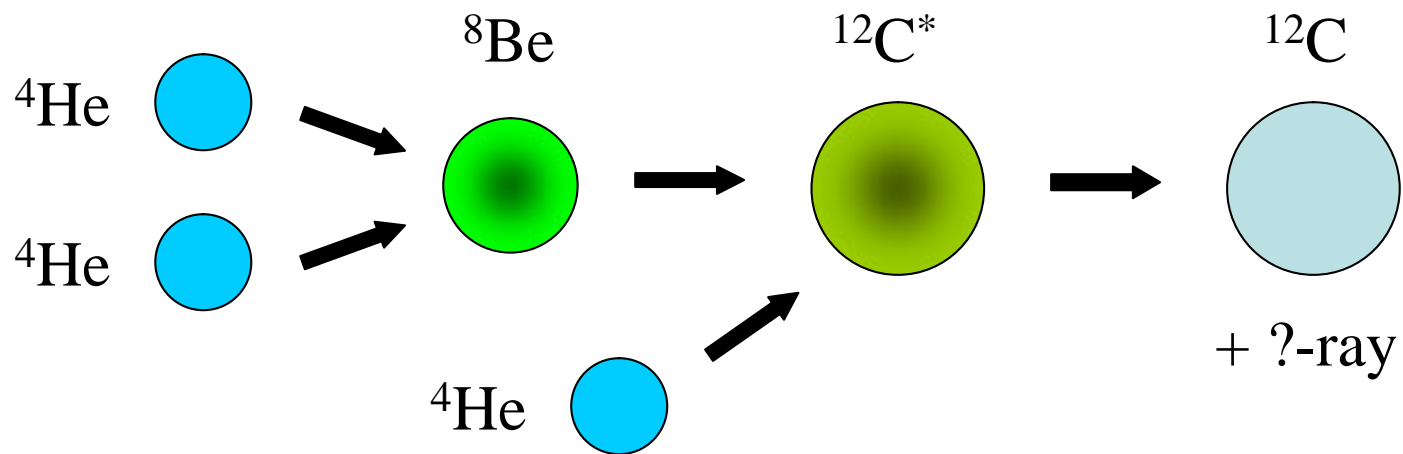
Force Particles

Photon (?), gluon (g), weak boson (W/Z)

Higgs boson (H), graviton (G)

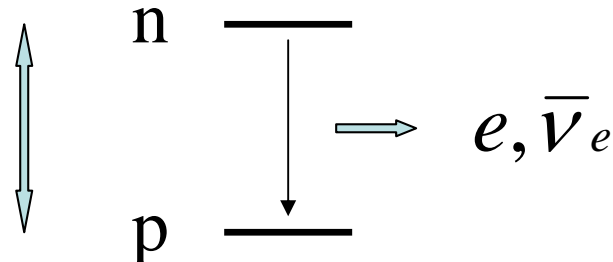
Life: A cosmic accident ?

- † Life is carbon (^{12}C) based.
- † ^{12}C is produced in stars:



Fusion process requires a resonance in ^{12}C at 7.65 MeV

If the neutron were ...

$$\frac{\Delta m}{m} = 0.18\%$$


The diagram illustrates the mass difference between a neutron (n) and a proton (p). A vertical double-headed arrow indicates the mass difference Δm . A downward arrow from the n level to the p level is labeled with an arrow pointing to the products $e, \bar{\nu}_e$.

- Free neutron decays with 15 minutes half-life.
- Neutrons bound in atomic nuclei can be stable.
- If the neutron were only 0.15% **lighter** or 0.3% **heavier**, the stability of nuclei would be seriously affected.

More cosmic miracles ...

- Delicate balance between energy production in the stellar core and energy radiation from the surface.
- Existence of long-lived stars like our sun requires:

$$\frac{Gm_p^2}{\hbar c} \approx 6 \times 10^{-39} \approx \alpha^{12} \left(\frac{m_e}{m_p} \right)^4$$

The Anthropic Principle

Our existence implies that the laws of nature and the properties of the universe permit the formation of intelligent life forms. (B. Carter, 1974)

Observed values of cosmological parameters and constants of nature can be “justified” by the anthropic principle.

But: Who “ordered” those values?
Do we need a creator, after all?

The New Anthropic Principle

A more radical alternative:

The physical laws of nature and the properties of the universe must allow for the probable emergence of intelligent life forms.

- † Our universe must be one in a multitude of universes (the “multi-verse”).
- † Constants of nature and cosmological parameters must have different values in different universes.
- † We happen to live in a universe that permits the formation of intelligent life.

From science to fiction - and back

- The universality and immutability of the fundamental laws nature in our universe is well established by observation.
- How can this be reconciled with the concept of many universes governed by different laws?
- A possible resolution: The amazing role of the **vacuum** = structure of “empty” space.

The vacuum is not empty

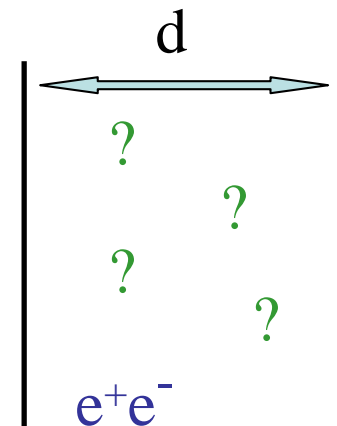
The **uncertainty principle** of quantum physics

$$\Delta E \cdot \Delta t \geq \hbar$$

forbids an empty state, even in “void” space.

Vacuum fluctuations can be measured:

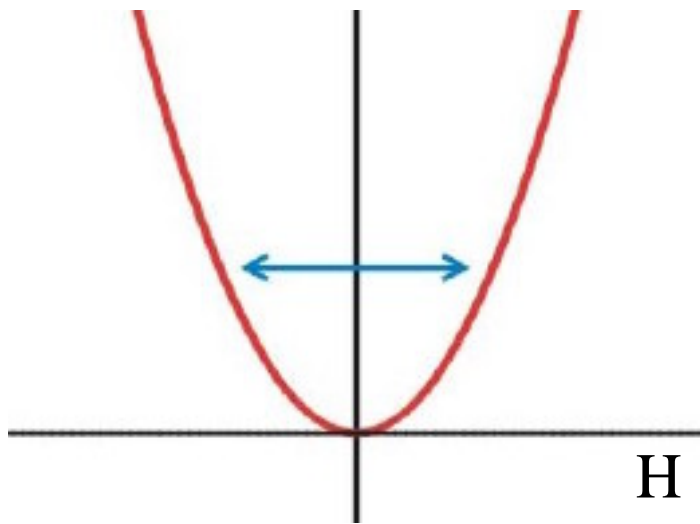
Attractive force between
two adjacent metal plates
(Casimir force, 1948)



The vacuum as a medium (I)

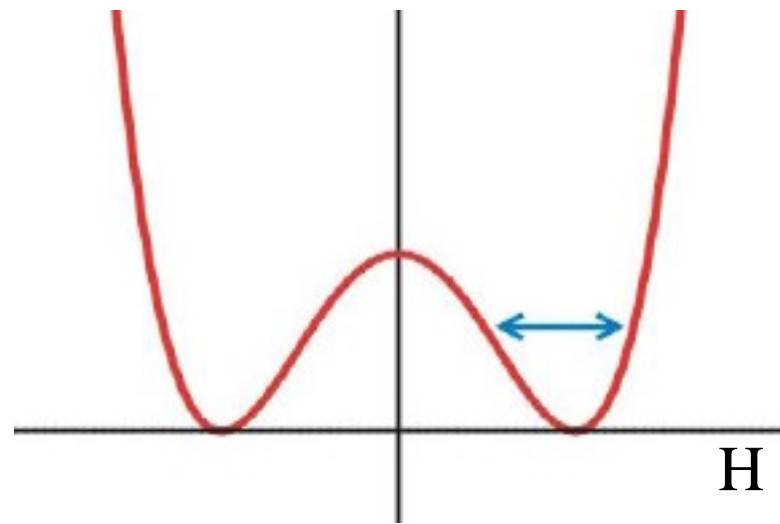
Trivial vacuum

$$\langle H \rangle = 0$$



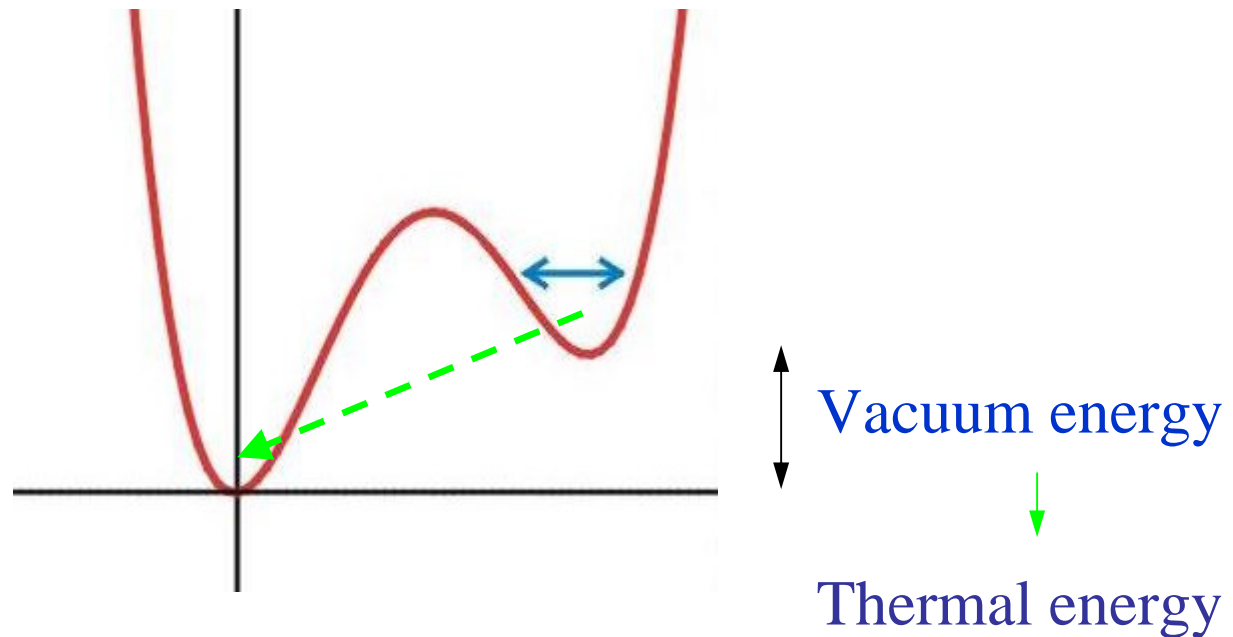
Higgs vacuum

$$\langle H \rangle \neq 0$$



The vacuum as a medium (II)

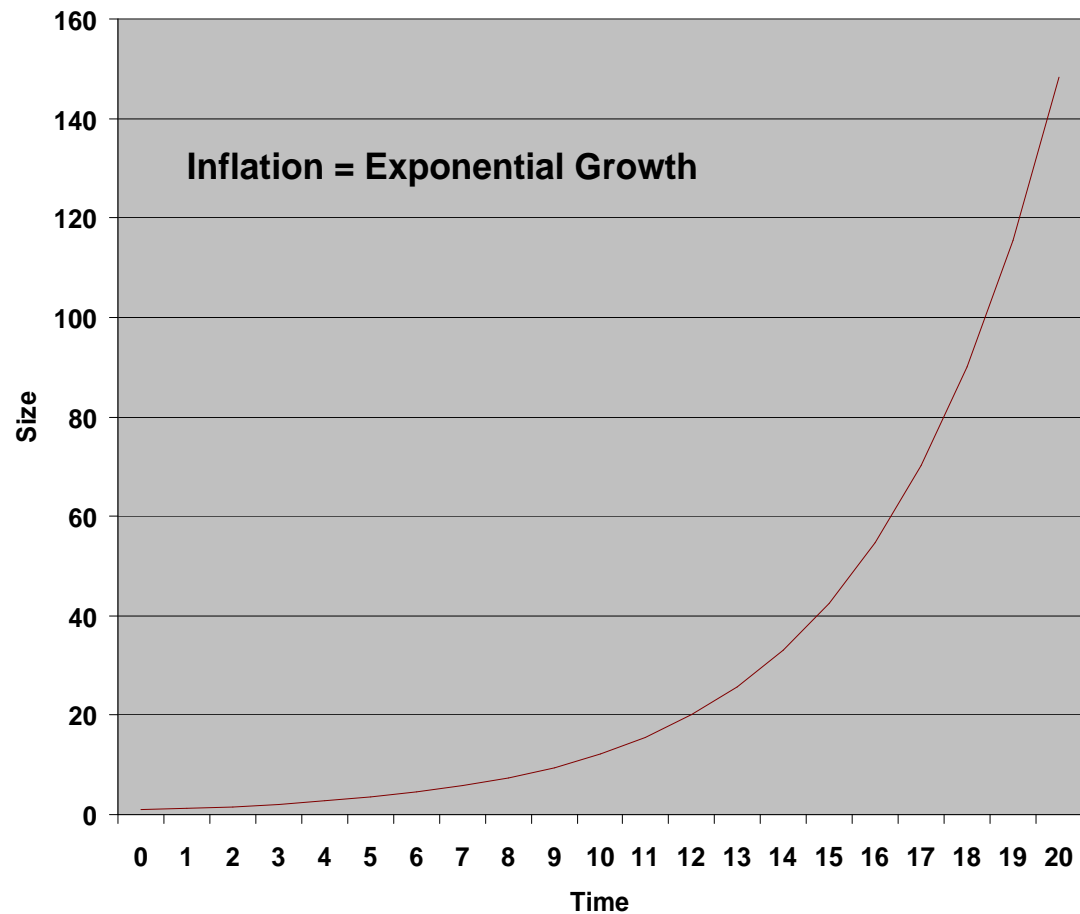
False vacuum: Metastability



The inflationary universe

The vacuum energy drives growth of the cosmic size according to Hubble's law:

$$\frac{dR}{dt} = H \times R$$



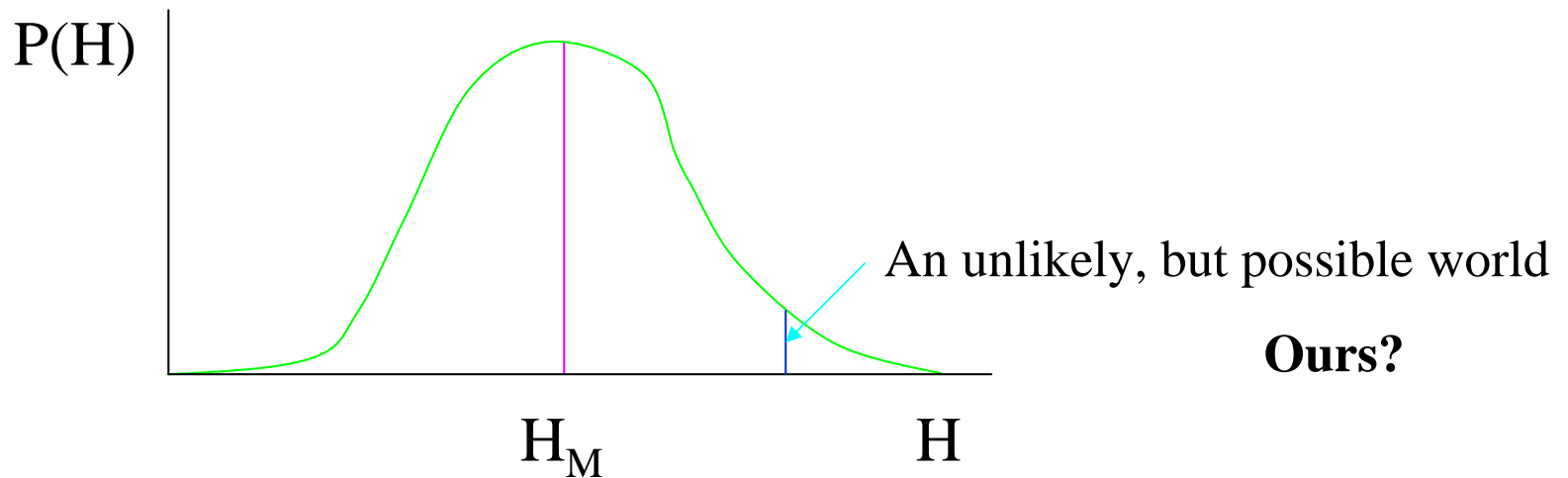
Many worlds - unlike ours ?

- Cosmic inflation, once started, never ends.
- An endless series of bubbles of true vacuum develop and grow into universes.
- The laws of physics can be different in each universe, if their vacua differ.
- Intelligent life can develop in *some* universes, by necessity, we happen to live in one of these.

No reason for being average

Mediocrity Principle (Vilenkin, 1995)

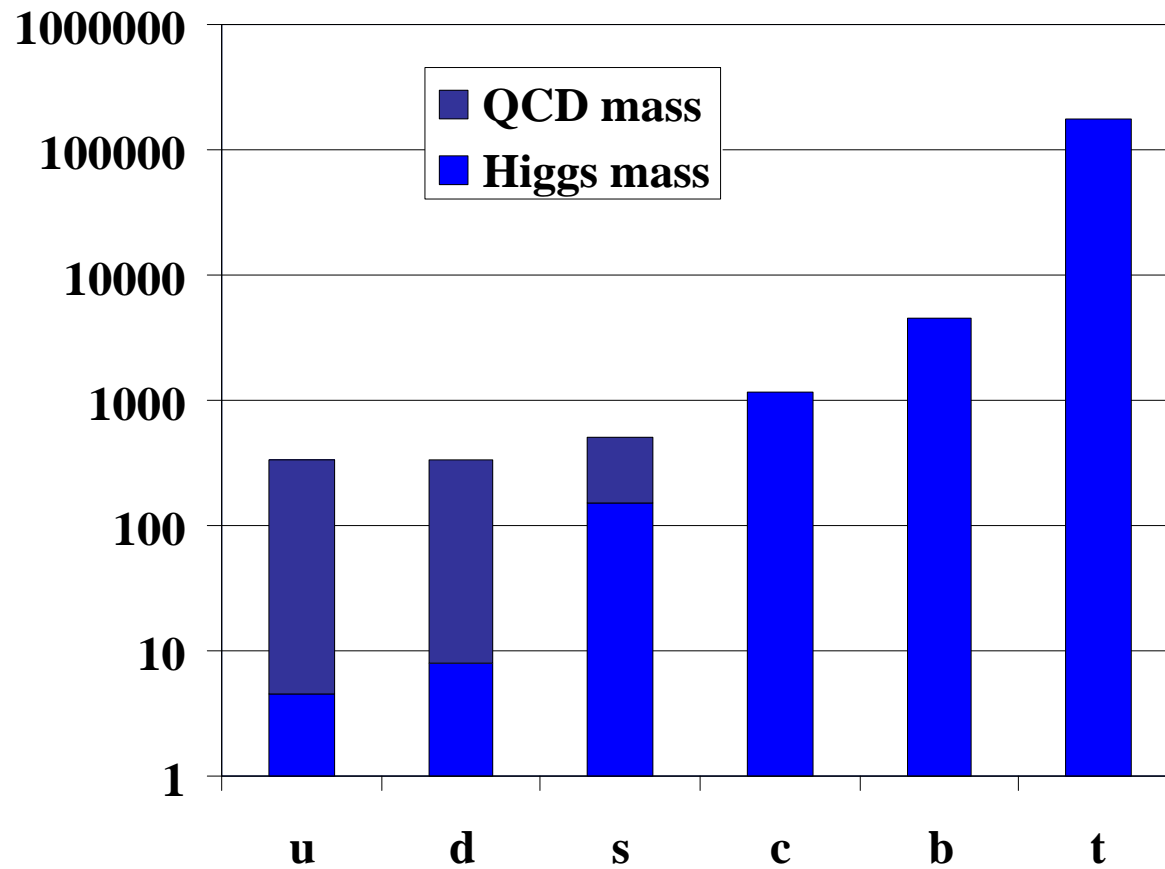
$$P(H) \sim V(H) \times n_g(H) \times n_i(H)$$



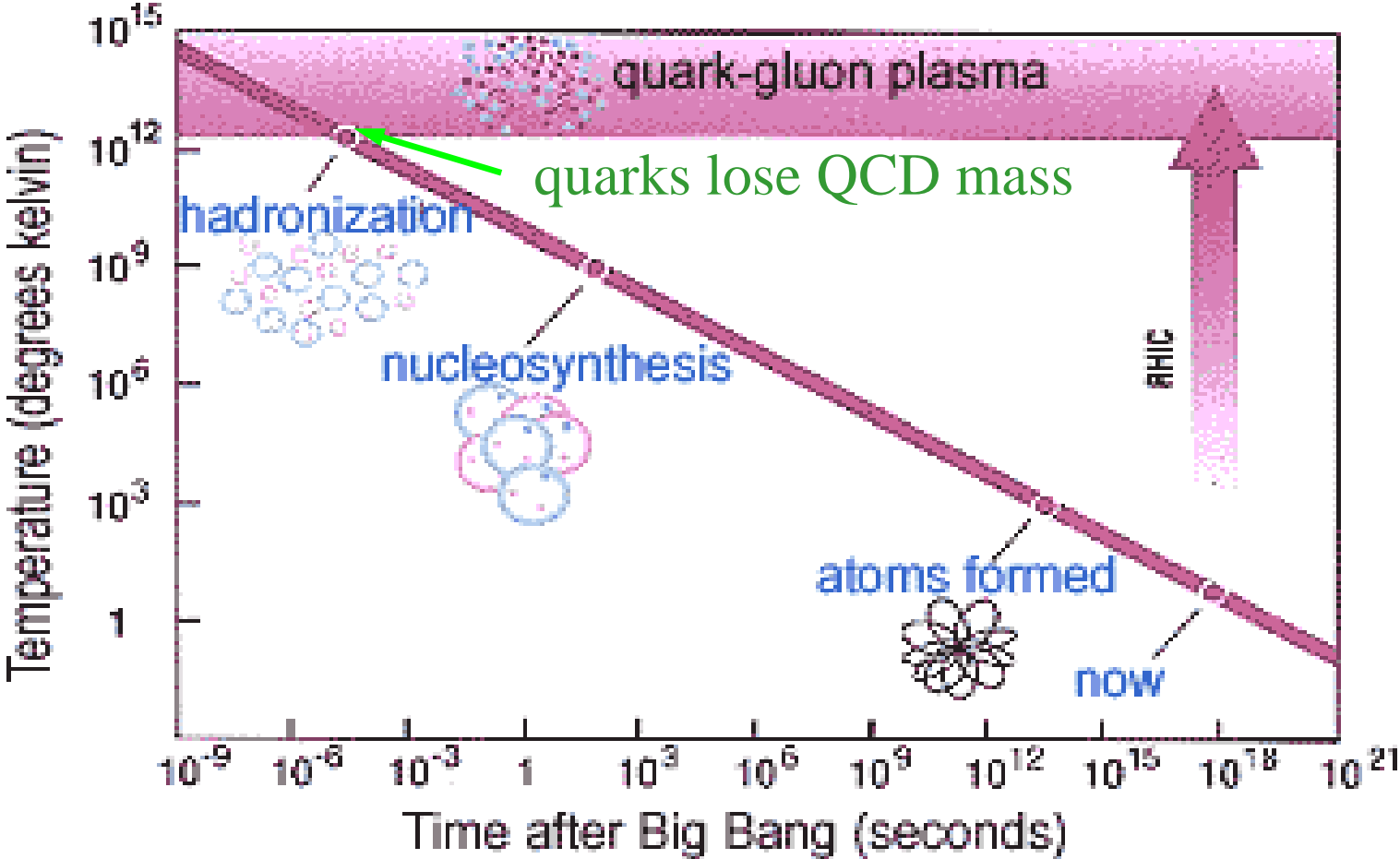
Probing the vacuum

- Astronomers measure the vacuum fraction of the energy balance of our universe: 70%.
- Nuclear physicists create conditions, similar to those after the Big Bang, in collisions of nuclei at Brookhaven National Lab (RHIC).
- High energy physicists search for the Higgs boson in particle collisions at Fermilab (Tevatron).
- String theorists construct models of complex vacuum states in higher dimensions.

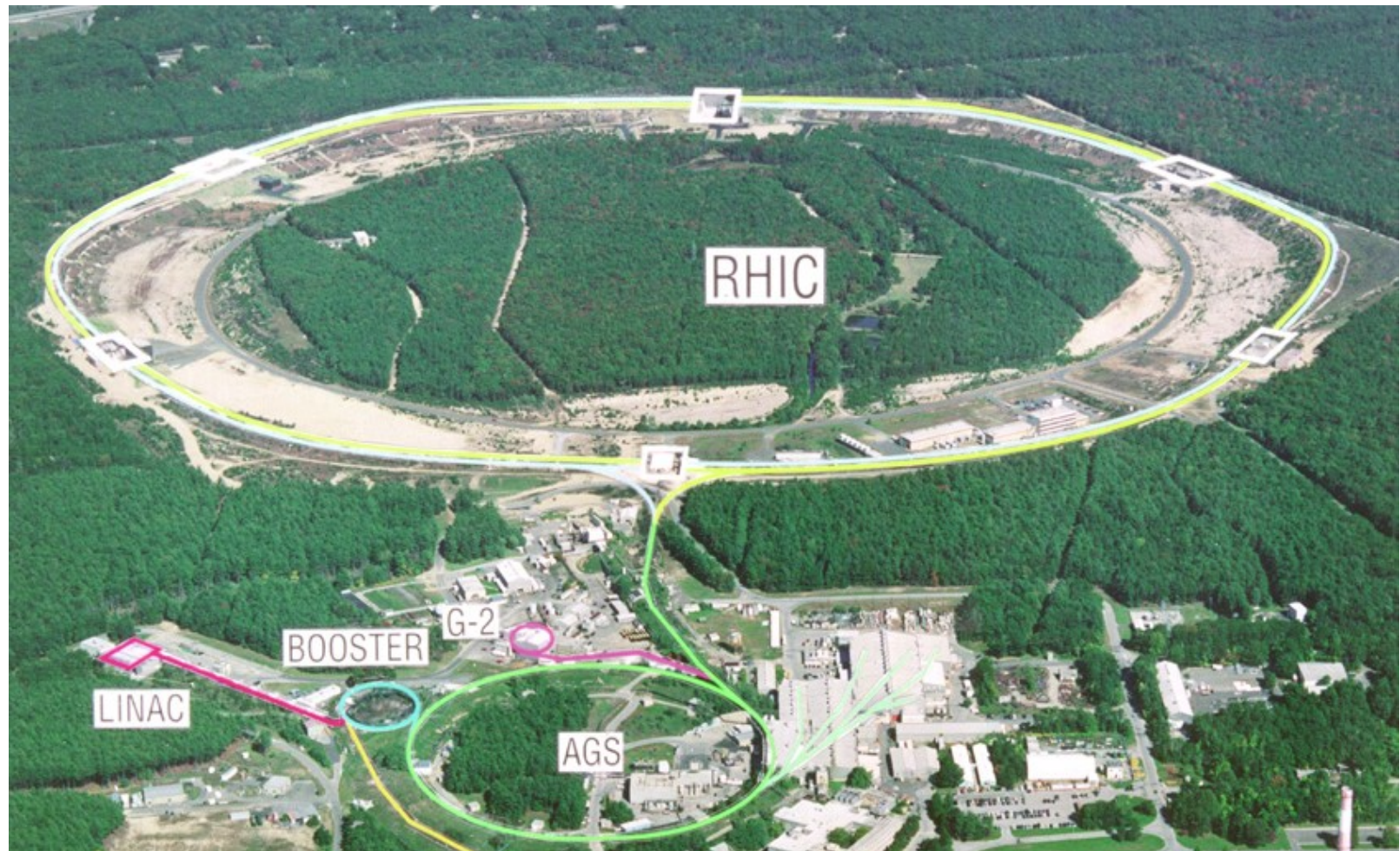
Quark masses from the vacuum



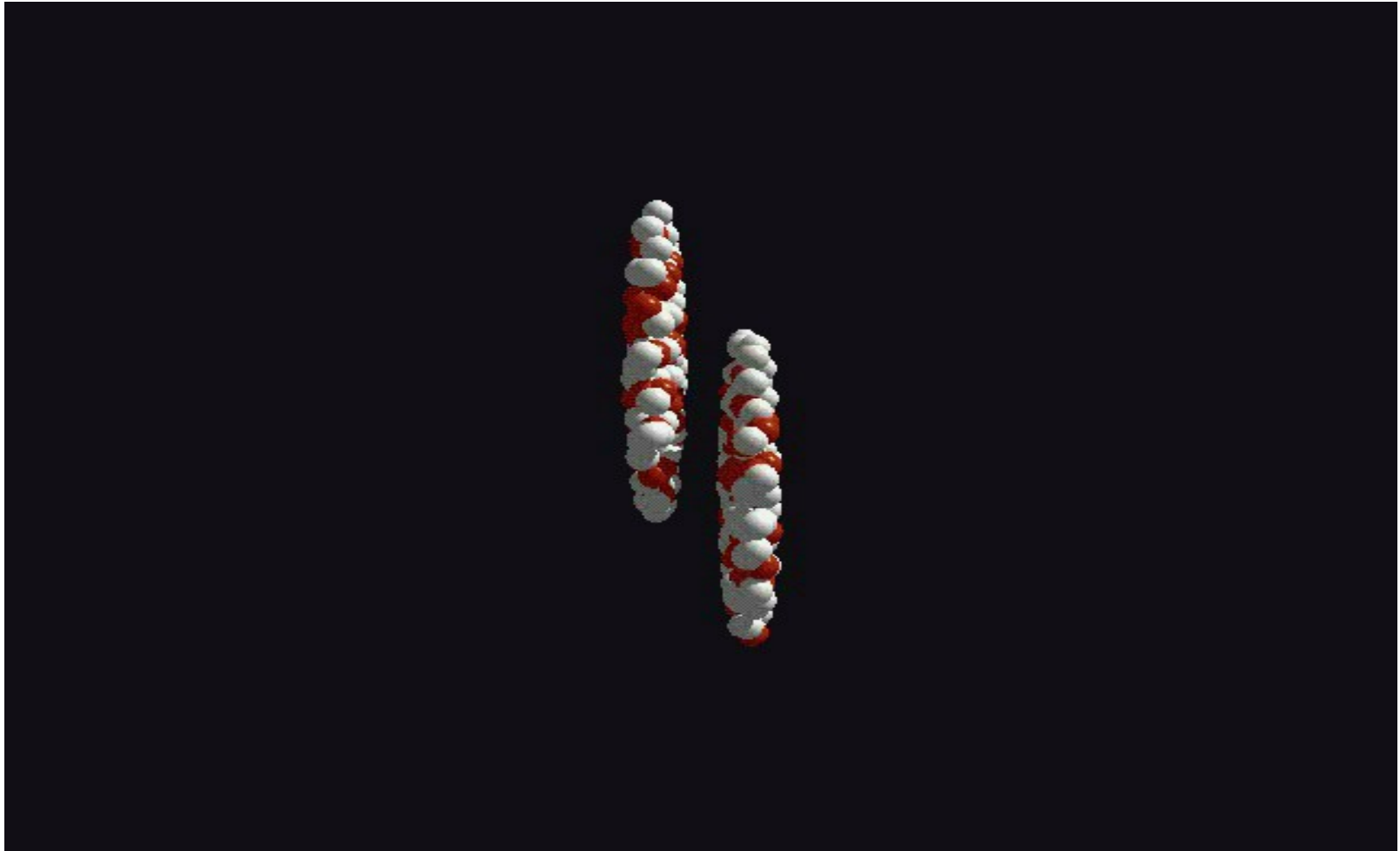
Thermal history of the universe



Relativistic Heavy Ion Collider

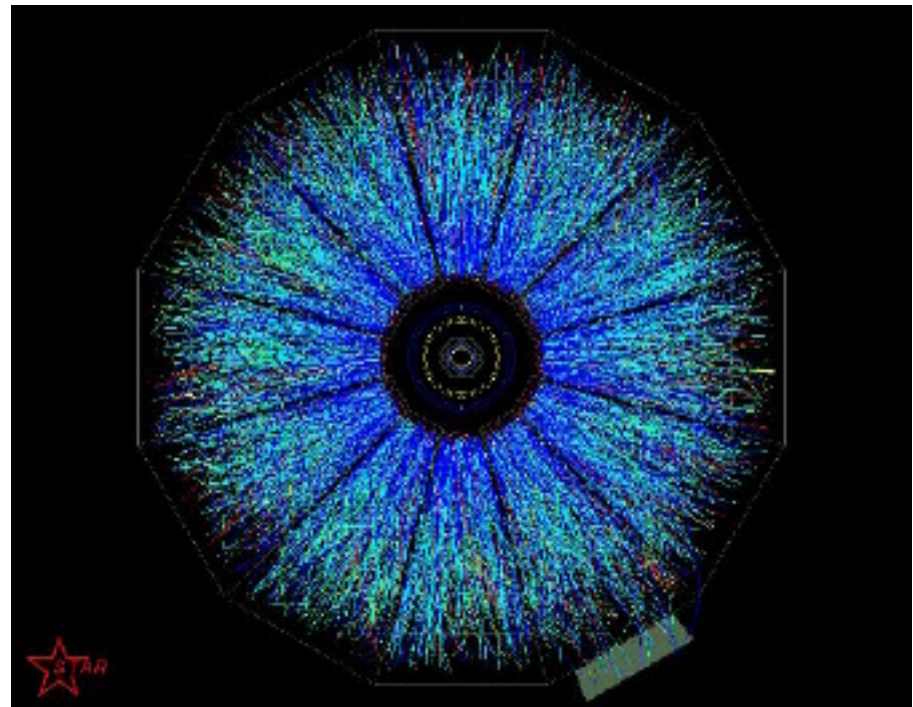


Au+Au Collision at RHIC



Collisions at RHIC

Collisions of gold nuclei heat nuclear matter to temperatures exceeding two trillion degrees, the “melting point” of the vacuum. Quarks move freely within the new vacuum, and the **u**, **d**, **s** quarks lose most of their mass.



As a result, especially, **s** quarks are copiously produced. This signature effect has already been observed.

Current research goals

- Establish the initial conditions reached at RHIC (temperature, energy density,...).
- Develop and refine probes of super-dense matter (s-, c-quarks, jets, flow, fluctuations, ...).
- Demonstrate the disappearance of the QCD generated part of the quark masses (“chiral symmetry restoration”)

What's ahead ?

- Over the next decade, we will explore and find out whether our universe once inflated, and how the masses of particles are generated.
- Requirements for the emergence of life and intelligence will be better understood.
- Is there a miraculous coincidence?
- Are there many different worlds?

<http://www.arxiv.org/astro-ph/0108259>

Finis

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