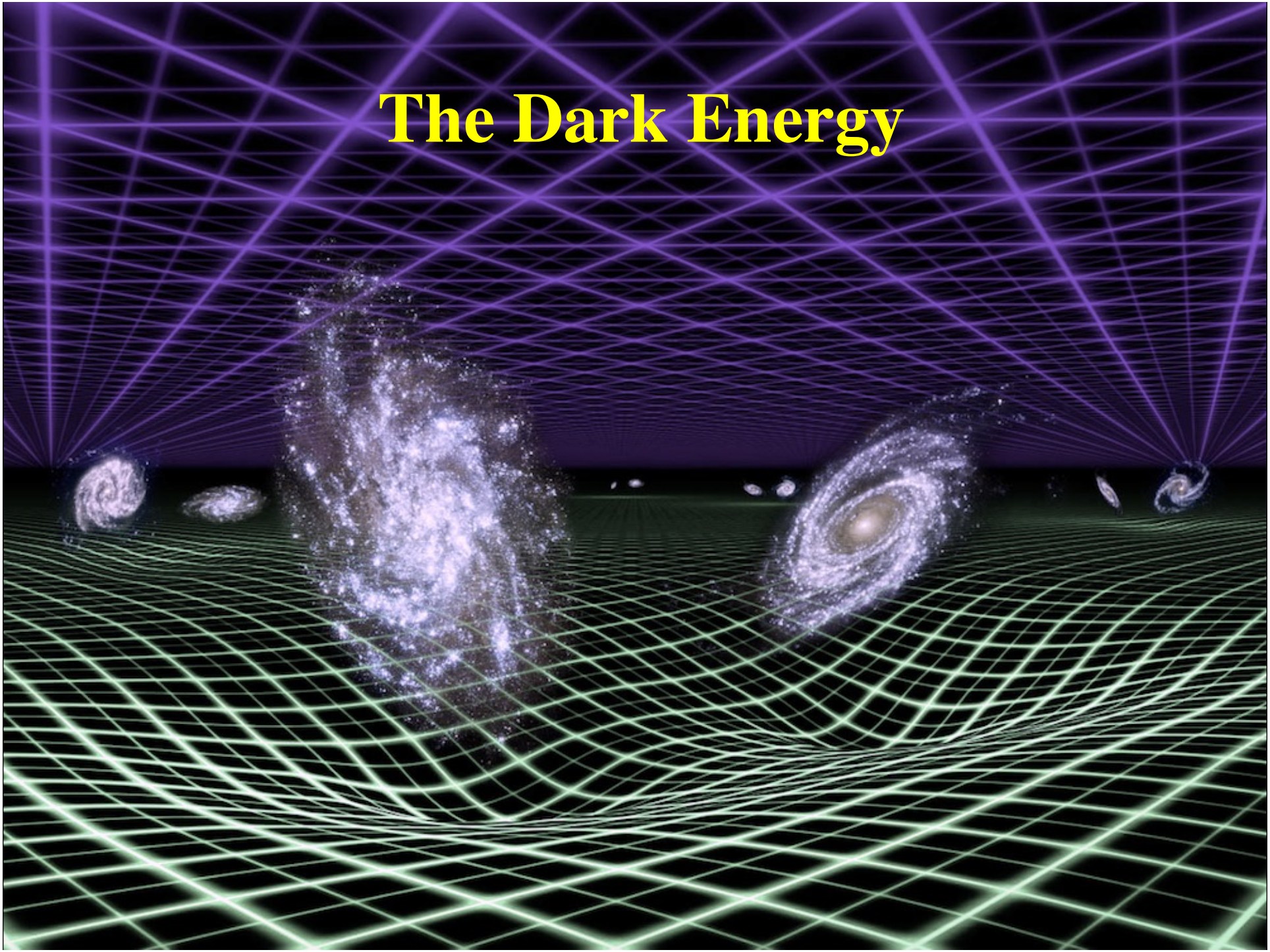
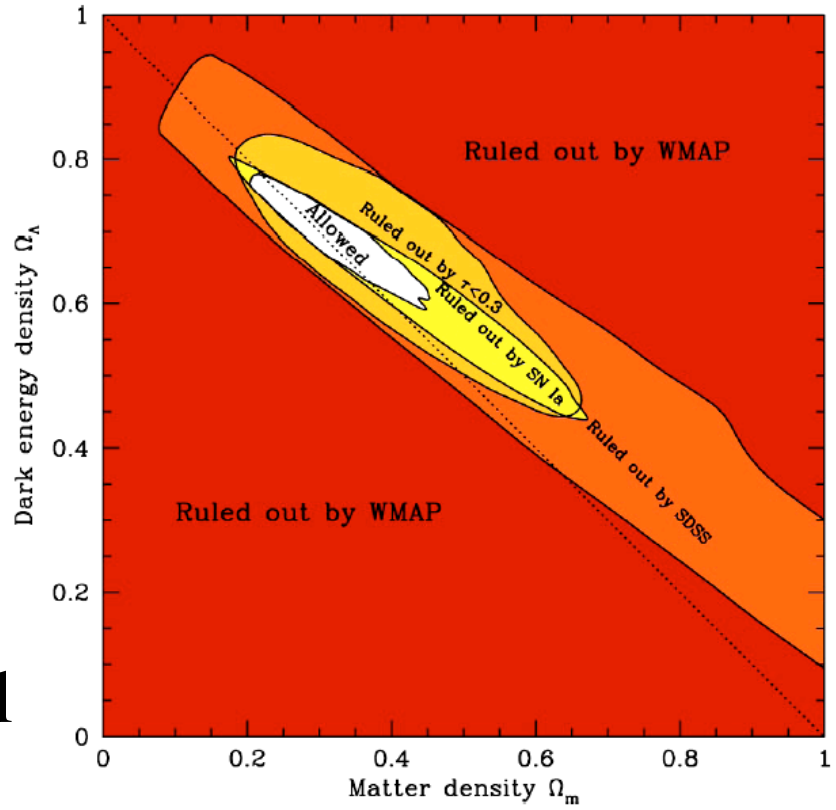
The Dark Energy



The Dark Energy

- The **dominant component** of the observed matter/energy density: $\Omega_{0,DE} \approx 0.7$
- Causes the accelerated expansion of the universe
- May affect the growth of density perturbations
- Effective only at cosmological distances



- Its physical nature is as yet ***unknown***; this may be the biggest outstanding problem in physics today
- ***Cosmological constant*** is just one special case; a more general possibility is called ***quintessence***

Cosmological Constant

It classically appears as an integration constant in Einstein Eqs:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

where

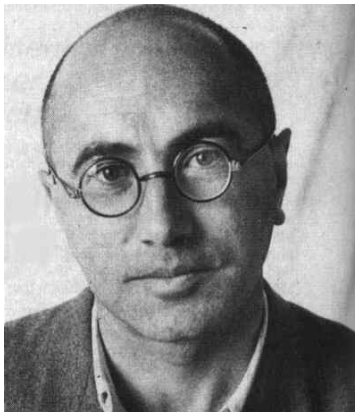
$$\Lambda = 1/L^2, \;\; \rho = \Lambda/4\pi G$$

Note that it does not have a preferred value or explanation in GR (and thus cannot be declared a priori to be zero); it becomes a new constant of nature, and joins G in defining the gravity

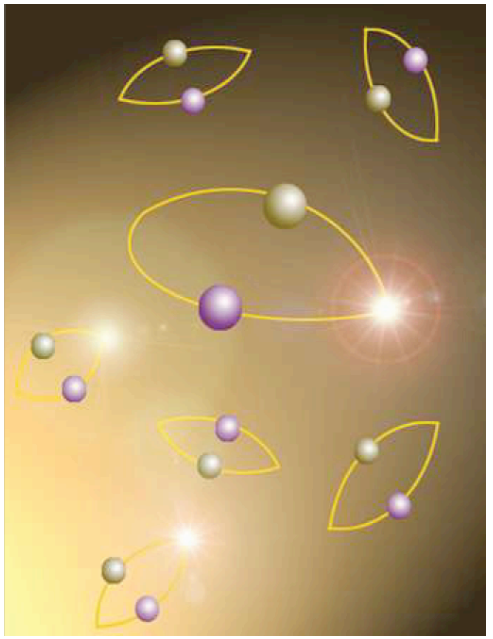
In the Friedmann Eq., it acts as an elastic force, proportional to the distance; so you can think of it as the *elasticity of the physical vacuum*.

By the standard convention, $\Lambda > 0$ (positive energy density) corresponds to a repelling force, and vice versa.

Cosmological Constant as a Quantum Field Phenomenon



- Proposed by Yakov Zeldovich (1967)
- A modern view of the physical vacuum is that it is not really empty - it is filled with virtual particle-antiparticle pairs, which annihilate within $\Delta t < \hbar/mc^2$, and their fluctuations give rise to a net energy density - a ground(?) state of the physical vacuum



- This is essentially the same mechanism proposed as the origin of the inflation
- But to really estimate the value of this vacuum energy density, we need a quantum theory of gravity, which we don't have yet
- Nevertheless, eager minds do try …

The Worst Scientific Prediction Ever

- A "natural" Planck system of units expresses everything as combination of fundamental physical constants; the Planck density is:

$$\rho_{Planck} = c^{5} / (\hbar G^{2}) = 5.15 \times 10^{+93} \text{ g cm}^{-3}$$

- The observed value is:

$$\rho_{vac} = \Omega_{\text{vac}} \rho_{crit} \approx 6.5 \times 10^{-30} \text{ g cm}^{-3}$$

Ooops! Off by 123 orders of magnitude …

- This is modestly called "the fine-tuning problem" (because it requires a cancellation to 1 part in 10^{123})
- The other "natural" value is zero
- So, lacking a proper theory, physicists just declared the cosmological constant to be zero, and went on…

Cosmological Constant or Quintessence?

- **Cosmological constant:** energy density constant in time and spatially uniform
  - Corresponds to the energy density of the physical vacuum
  - A coincidence problem: why is $\Omega_\Lambda \sim \Omega_m$ just now?
- **Quintessence:** time dependent and possibly spatially inhomogeneous; e.g. scalar field rolling down a potential
- Both can be described in the equation of state formalism:

$$P = w\,\rho$$

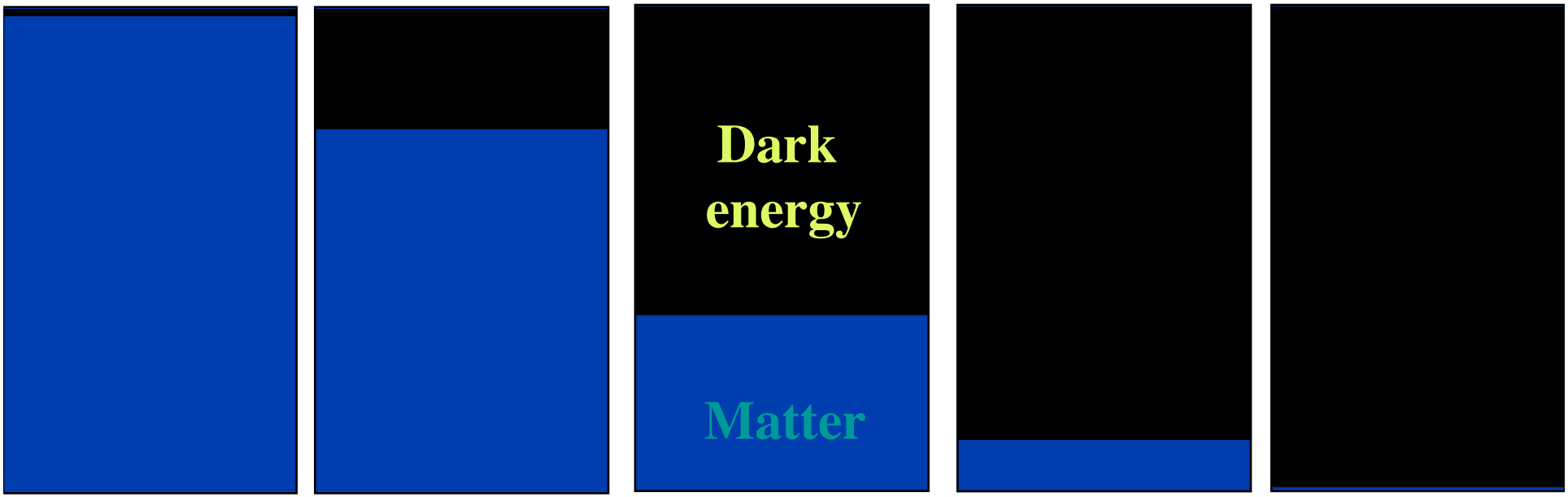
$$\rho \sim R^{-3(w+1)}$$

Cosmological constant: $w = const. = -1$, $\rho = const.$

Quintessence: w can have other values and change in time

The Cosmic Coincidence Problem

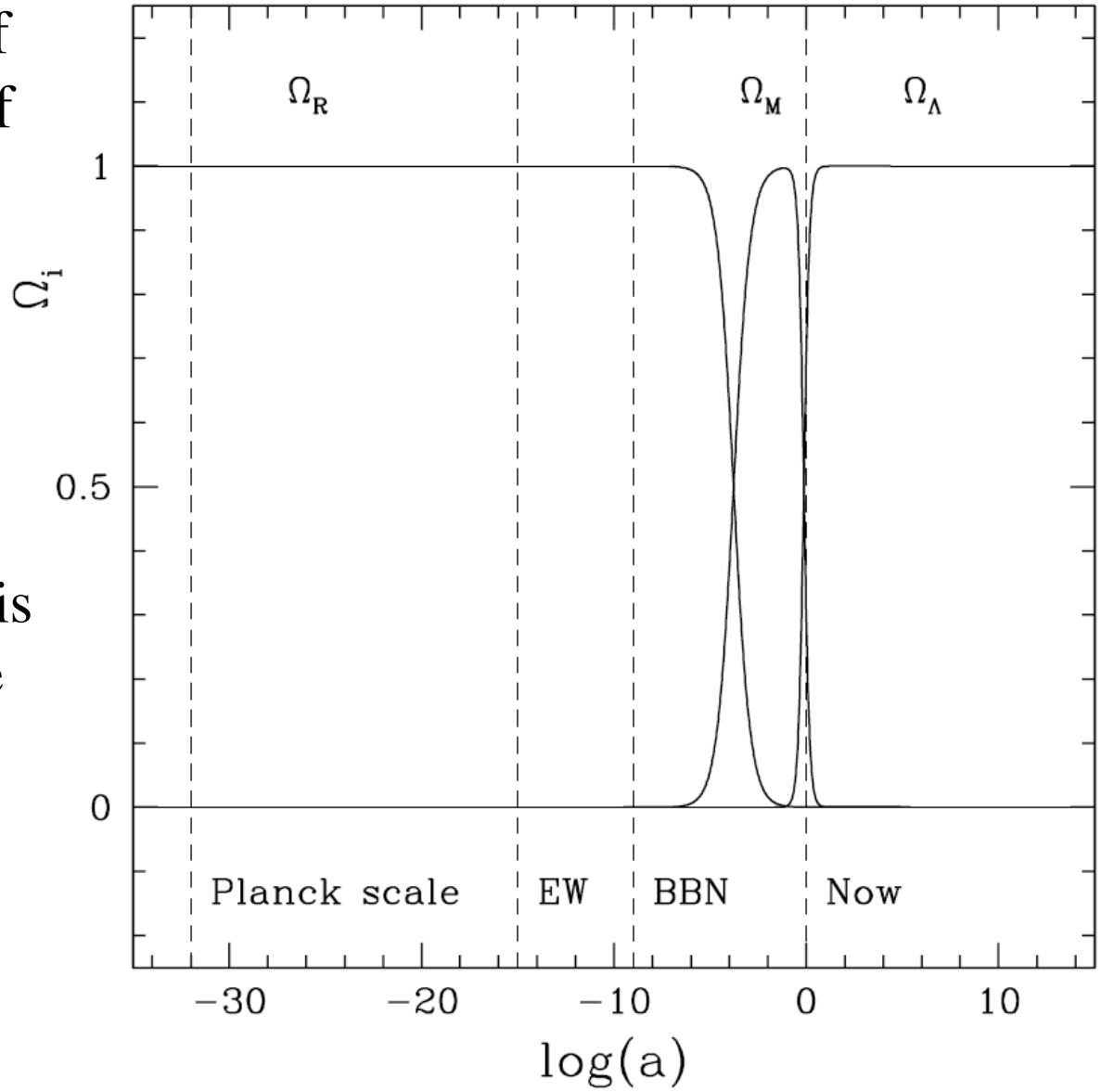
If the dark energy is really due to a cosmological constant, its density does not change in time, whereas the matter density does - and they just happen to be comparable today! Seems un-natural …



The Cosmological Coincidence Problem

The time dependence of the density parameter of various mass/energy density components:

We seem to live in a special era, when the vacuum energy density is just starting to dominate the dynamics of the universe …



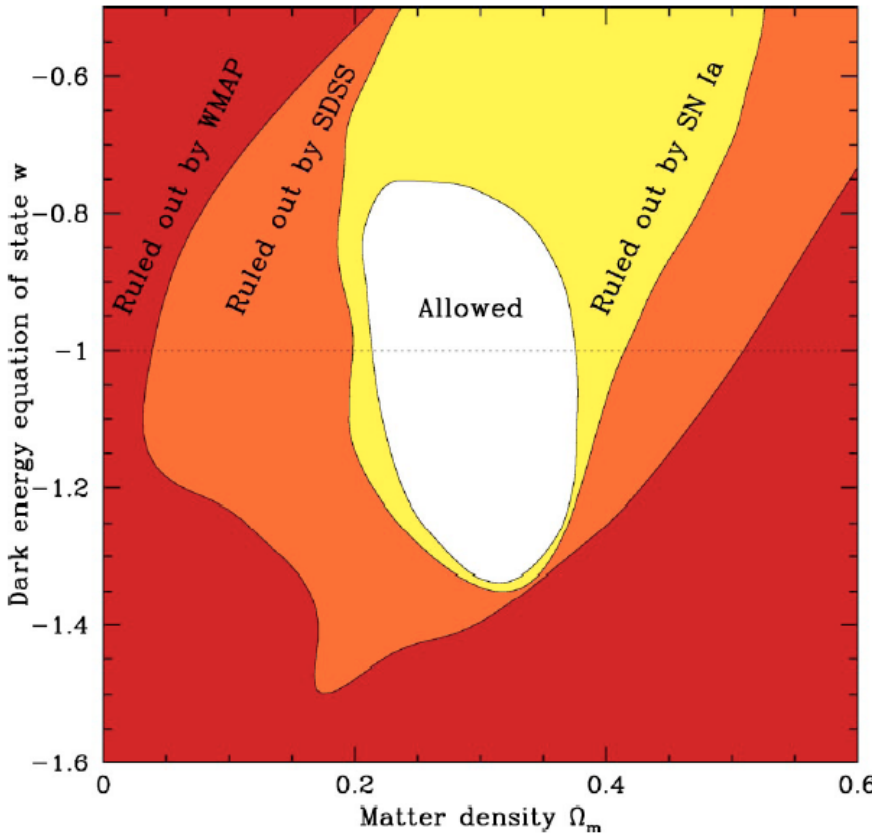
Physical Origins of the Dark Energy

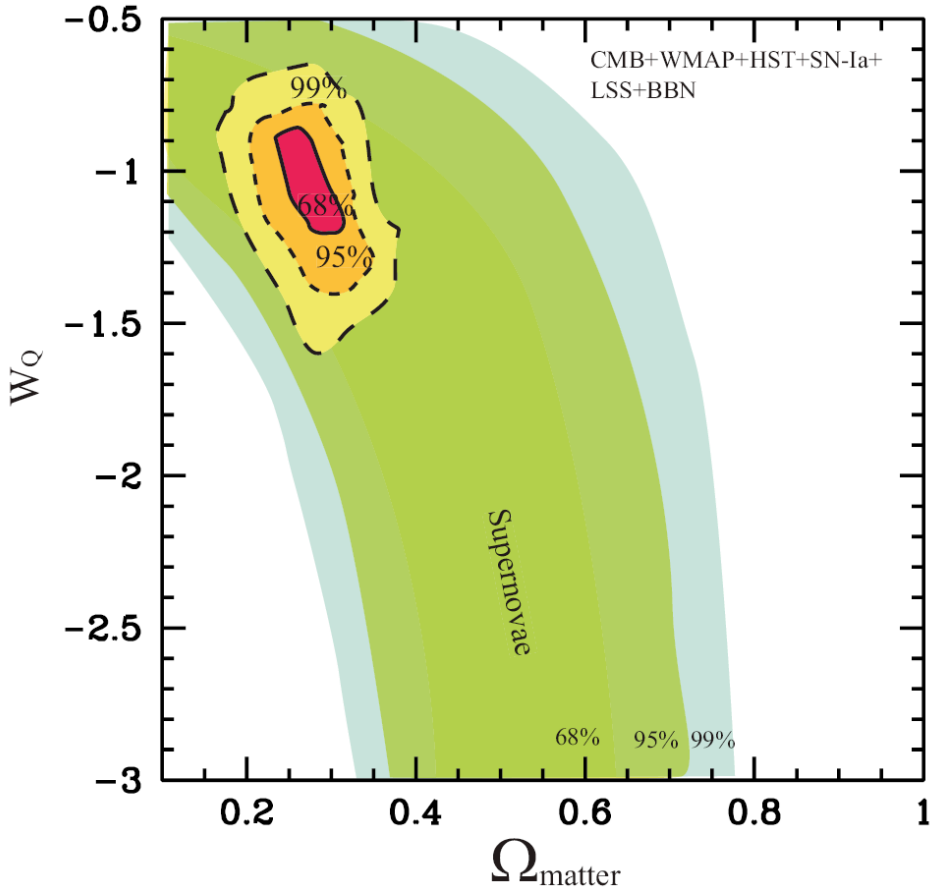
… are completely unknown at this time, and not for the lack of trying: there are literally thousands of papers about it, and more being published every day

- Many of the proposed models are based on one of the following:
  - Decay of some scalar field, similar to the inflation mechanism
  - Modified theories of gravity
  - Holographic models, connecting the vacuum energy density to the area of the event horizon and thermodynamics
  - Landscape or multiverse models that postulate the existence of $\sim 10^{500}$ separate universes, with different (random) values of the physical constants, Λ included
  - Models connecting DM and DE … ***etc., etc.***
- One measurement that might help eliminate some possibilities is a possible deviation (evolution) of the EOS parameter w

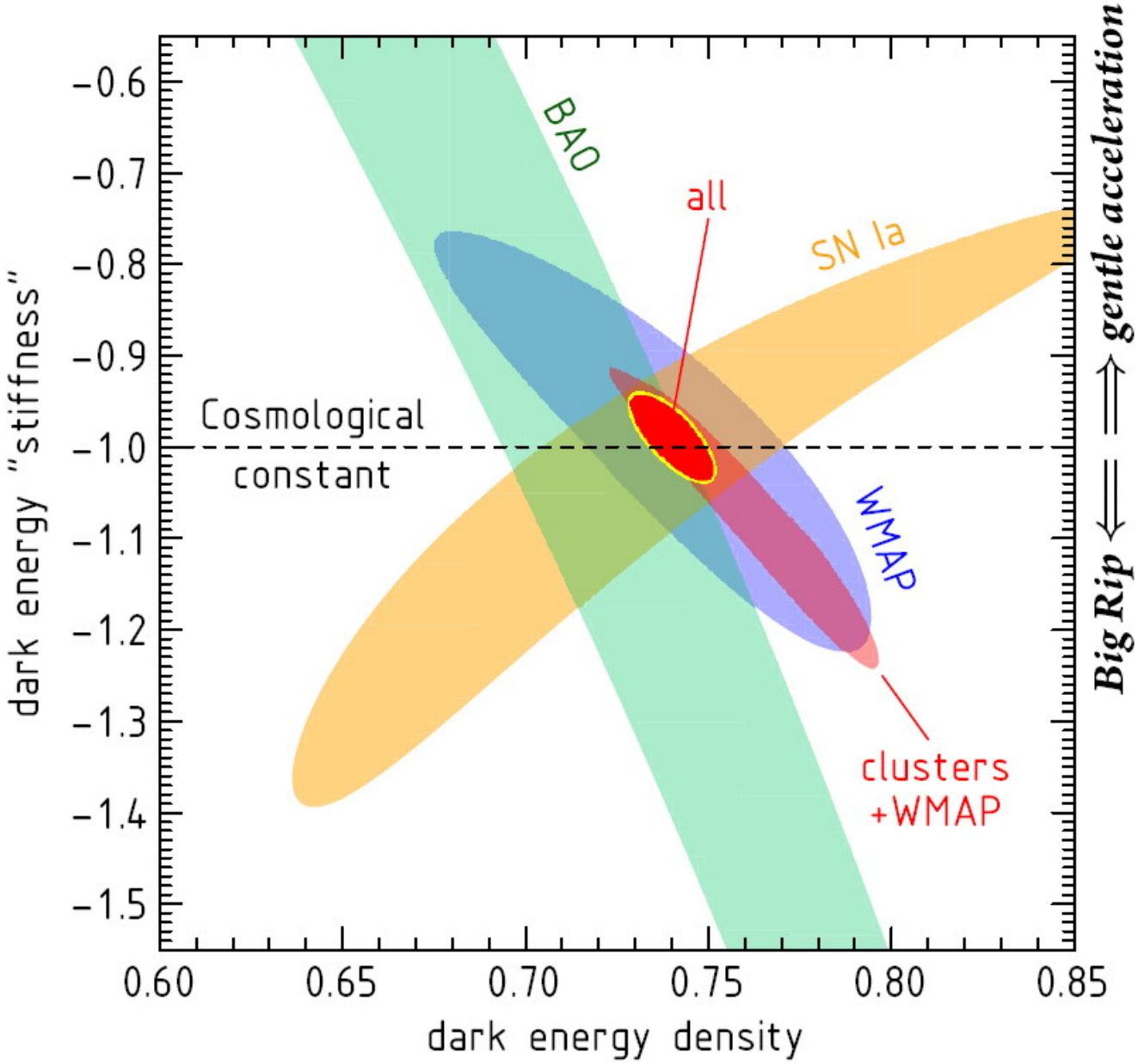
Observational Constraints on *W*

Strongly favor values of $w \sim -1$, i.e., *cosmological constant* like dark energy. Some models can be excluded, but there is still some room for $\rho_{vac} \neq const.$ models

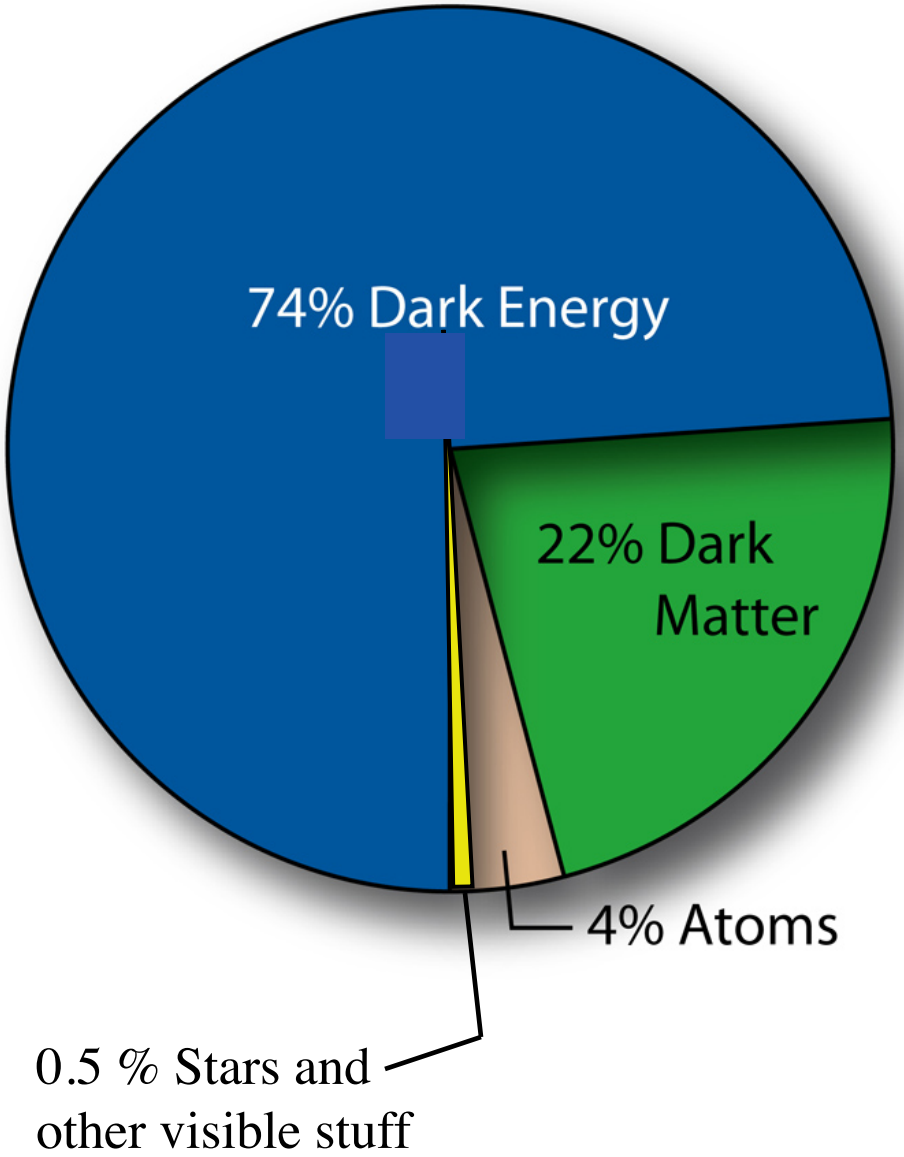




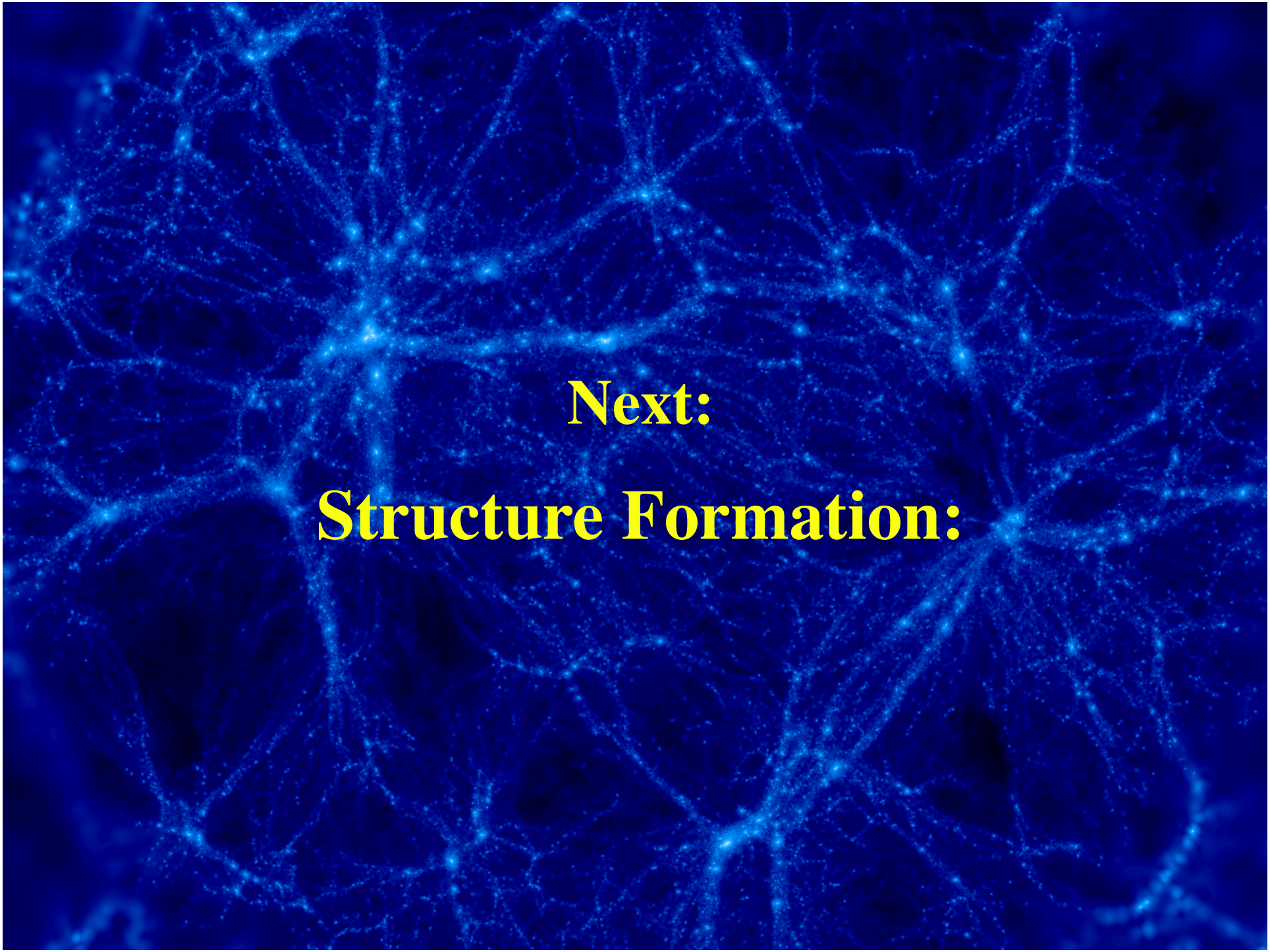
Observational Constraints on *W*



Contents of the Universe: Summary



- $\Omega_0 = 1.00 \pm 0.02$
- $\Omega_m \approx 0.27 \pm 20\%$
  - $\Omega_b \approx 0.045 \pm 10\%$
    - Includes $\Omega_{visible} \approx 0.005$
  - $\Omega_{non\text{-}b} \approx 0.22$
    - Includes $\Omega_\nu < 0.005$
  - $\Omega_{CMBR} \approx 0.0001$
- $\Omega_{de} \approx 0.73 \pm 10\%$
- The physical nature of the DE is currently completely unknown


Next:
Structure Formation: