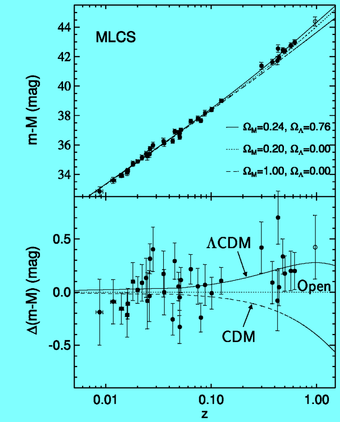
8.286 Lecture 21
November 26, 2013

PROBLEMS OF THE CONVENTIONAL (NON-INFLATIONARY) HOT BIG BANG MODEL

Summary of Lecture 20: Supernovae Ia as Standard Candles



Supernova Data of Hi-Z Supernova Search Team, 1998

Summary of Lecture 20

Evidence for the Accelerating Universe

1) Supernova Data: distant SN Ia are dimmer than expected by about 20–30%.
2) Cosmic Microwave Background (CMB) anisotropies: gives $\Omega_{\rm vac}$ close to SN value. Also gives $\Omega_{\rm tot} = 1$ to 1/2% accuracy, which cannot be accounted for without dark energy.
3) Inclusion of $\Omega_{\rm vac} \approx 0.70$ makes the age of the universe consistent with the age of the oldest stars.

☆ With the 3 arguments together, the case for the accelerating universe and $\Omega_{\rm dark\ energy} \approx 0.70$ has persuaded almost everyone.

☆ The simplest explanation for dark energy is vacuum energy, but "quintessence" is also possible.

Summary of Lecture 20: Particle Physics of a Cosmological Constant

☆ $$u_{\rm vac} = \rho_{\rm vac} c^2 = \frac{\Lambda c^4}{8\pi G}$$

☆ Contributions to vacuum energy density:

1) Quantum fluctuations of the photon and other bosonic fields: positive and divergent.
2) Quantum fluctuations of the electron and other fermionic fields: negative and divergent.
3) Fields with nonzero values in the vacuum, like the Higgs field.

Summary of Lecture 20

- ☆ If infinities are cut off at the Planck scale (quantum gravity scale), then infinities become finite, but

> 120 orders of magnitude too large!

- ☆ For lack of a better explanation, many cosmologists (including Steve Weinberg and yours truly) seriously discuss the possibility that the vacuum energy density is determined by "anthropic" selection effects: that is, maybe there are many types of vacuum, with different vacuum energy densities, with most $\sim$ 120 orders of magnitude larger than ours. Maybe we live in a very low energy density vacuum because it is conducive to life.

Summary of Lecture 20: Einstein and Friedmann

June 29, 1922: Alexander Friedmann's paper received at *Zeitschrift für Physik.*

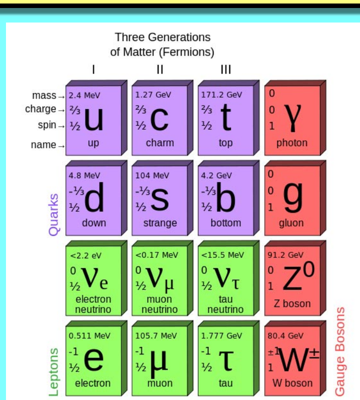
September 18, 1922: Einstein's refutation received at *Zeitschrift für Physik*: claimed that Friedmann failed to notice that $\dot{\rho} = 0$.

May, 1923: Einstein met Friedmann's friend, Yuri A. Krutkov, at retirement lecture by Lorentz in Leiden, and Krutkov convinced Einstein of his error.

May 31, 1923: Einstein's retraction of his refutation is received at *Zeitschrift für Physik.*

The handwritten draft of Einstein's retraction included the phrase "a physical significance can hardly be ascribed to them," referring to Friedmann's solutions, but Einstein crossed it out before submitting.

The Standard Model of Particle Physics



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Gauge Theories

$$\vec{E} = -\vec{\nabla}\phi - \frac{1}{c}\frac{\partial \vec{A}}{\partial t} ,$$

$$\vec{B} = \vec{\nabla} \times \vec{A} .$$

$$A_\mu = (-\phi, A_i) .$$

$$\phi'(t, \vec{x}) = \phi - \frac{\partial \Lambda}{\partial t} ,$$

$$\vec{A}'(t, \vec{x}) = \vec{A} + \vec{\nabla}\Lambda ,$$

$$A'_\mu(x) = A_\mu(x) + \frac{\partial \Lambda}{\partial x^\mu} .$$

Combining gauge transformations: $\Lambda_3 = \Lambda_1 + \Lambda_2$.