Computing Our Universe

Special Topic IV – Particle Astrophysics

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0 WHY PARTICLE ASTROPHYSICS

- Constraints on Particle Physics
- Dark Matter
- Structure Formation
- Nucleosynthesis
- Early Universe
- Inflation
- Cosmological Constant
- Fate of Universe
- Origin of Universe
- Origin of Physics

1 INTERACTIONS, EQUILIBRIUM, AND FREEZEOUT

Early universe was ferment of particle interactions.

Was in **thermal equilibrium** – reaction rates equal forward and backward.

Expansion of universe gave **Hubble dilution**

- diluted particle density: $n \sim a^{-3}$
- reduced particle energies: $T \sim a^{-1}$

Freezeout

If interaction rate Γ rapid then quick transition from equilibrium to *no* reactions – **freezeout**

$$N_{int}(>t) = \int_t^\infty dt'\,\Gamma(t')$$
$$= (n-2)^{-1}(\Gamma/H)_t$$

$$\Gamma \sim T^n \qquad T \sim a^{-1} \sim t^{-1/2} \qquad H = (1/2)t^{-1}$$

Freezeout condition is $\Gamma < H$.

Excellent description since after freezeout time t_f: $N_{int}(>t_f) < 1$

Interaction rate $\Gamma = n\,\langle\sigma v\rangle$

- Cross section generically goes as

$$\sigma = \frac{\alpha^2(\hbar c)^2}{(Mc^2)^\beta}$$

coupling constant α, interaction strength $G = \alpha\,(\hbar c)$, carrier mass M

Dimensionally, $\sigma \sim [\text{length}]^2$ so

$$\sigma = \sigma_0\,(E/E_0)^x \sim T^{\beta-2}$$

Only characteristic energy scale is temperature T of universe.

- Number density goes as $n \sim a^{-3} \sim T^3$

$\Rightarrow$ Interaction rate $\Gamma \sim T^{\beta+1}$

Examples

- Electromagnetism: carrier = photon (massless) ; $\sigma \sim \alpha^2 T^{-2}$

$$\Gamma \sim T \quad ; \quad H \sim T^2 \quad \Rightarrow \quad \Gamma/H \sim T^{-1}$$

$\Rightarrow$ Frozen in early universe, Equilibrium today

- Weak Force: carrier = W, Z bosons (massive) ; $\sigma \sim G_F^2 T^2$

$$\Gamma \sim T^5 \qquad ; \qquad H \sim T^2 \qquad \Rightarrow \qquad \Gamma/H \sim T^3$$

$\Rightarrow$ Equilibrium early, Frozen out today

- Generic Interaction:

  Weaker Interactions $\longrightarrow$ Earlier Decoupling ($\Gamma < H$ earlier)

  Earlier Decoupling $\longrightarrow$ Lower Abundance and Temperature

Particle Relics

- Hot relic: relativistic, energy shared among degrees of freedom

  favorite candidate – light neutrino

$$n_X \approx n_\gamma$$

$$\Omega_X h^2 = \frac{M_X}{92\,eV} \qquad (\textbf{Cowsik – McClelland bound})$$

- Cold relic: decouples when nonrelativistic

  favorite candidates – lsp (neutralino), axion

$$\Omega_X h^2 < 1 \quad \Rightarrow \quad M_X > 2\,GeV \qquad (\textbf{Lee – Weinberg bound})$$

2 SCALAR FIELD PHYSICS

2.1 Lagrangian and Equation of State

Electromagnetism is vector field, gravitation is tensor field. Lagrangian of scalar field ϕ is extremely simple:

$$\mathcal{L} = (1/2)\partial^\mu \phi \partial_\mu \phi - V(\phi)$$
$$\approx (1/2)\dot{\phi}^2 - V$$

Form energy-momentum tensor thru functional variation (Noether)

$$T^{ab} = \partial^a \phi \partial^b \phi - \mathcal{L}\, g^{ab}$$

and read off density and pressure in terms of kinetic and potential energies

$$\rho_\phi = (1/2)\dot{\phi}^2 + V \equiv K + V \qquad ; \qquad p_\phi = (1/2)\dot{\phi}^2 - V \equiv K - V$$

Special Cases

- Free Field V=0 ; $p = \rho$ $\rightarrow$ Equation of state $w = +1$
  Sometimes called *kination* in opposition to inflation.
- Slow Roll K=0 ; $p = -\rho$ $\rightarrow$ Equation of state $w = -1$
  Causes exponential inflation.
  One example is **cosmological constant**.
- Coherent Oscillations $\langle V \rangle = \langle K \rangle$; $p = 0$ $\rightarrow$ EOS $w = 0$
  Acts like nonrelativistic matter!
  One example is (pseudoscalar) **axion**.

NB the EOS w is generally not constant in time.

2.2 Cosmological Constant

Equivalent to vacuum energy. Vacuum defined as the energy ground state and must be Lorentz invariant, since all observers must agree on the ground state.

Only Lorentz invariant tensor is Minkowski $\eta^{ab} = \mathrm{diag}(-1, 1, 1, 1)$. Thus the energy-momentum tensor of the vacuum must be $T^{ab} \sim \eta^{ab}$.

From this one can read off directly the EOS of this component:

$$T^{ab} = -\rho\{-1, 1, 1, 1\} \qquad \Rightarrow \qquad p = -\rho \quad (w = -1)$$

The conservation Friedmann equation tells us such a component has no time variation $\dot{\rho}$, so we call it the **cosmological constant** $\Lambda = \rho_{vac}$.

Natural value for such a constant is $\rho_{vac} \approx \rho(t_{Pl}) \approx 10^{92} g\, cm^{-3} \approx 10^{120} \rho_{crit}$. Oops! Is it incredibly small or is it exactly zero? Big debate.

A period of vacuum domination gives an expansion law

$$a(t) \sim e^{Ht}, \qquad H = \sqrt{8\pi\Lambda/3} = \text{const}$$

The resulting form of the metric is called **DeSitter spacetime**.

Too much Λ means no Big Bang could occur.

A brief period of vacuum domination gives an inflationary epoch (but the inflation field is not the only vacuum field).

Exactly enough Λ allows $\Omega_m \approx \Omega_\Lambda$ today.

We can detect a cosmological constant through such observations as the age of the universe, angular scales of CMB anisotropies, and others.

- Statistics of gravitationally lensed objects
  $\Omega_\Lambda = 0.7^{+0.1}_{-0.2}$ Chiba & Yoshii (astro-ph/9808321)
- High z supernovae magnitudes
  $\Omega_\Lambda = 0.68 \pm 0.1$ (if flat) Riess et al. (astro-ph/9805201)
- Lyα forest + cluster mass function
  $\Omega_\Lambda = 0.66^{+0.09}_{-0.13}$ (if flat) D. Weinberg et al. (astro-ph/9810011)

2.3 Dynamical Fields

The constancy of the cosmological constant creates two problems:

- *Fine Tuning:* If Λ is small but nonzero, the only way to explain the 120 orders of magnitude deviation from ρ_{Pl} is to postulate a new energy scale around 1 meV or extreme fine tuning.
- *Coincidence:* $\Omega_\Lambda \approx \Omega_m$ only happens once in history of universe. Why are we now in this unique epoch?

Dynamical fields, that evolve with time, can alleviate these puzzles.

A particularly attractive subset are **tracking fields**. This name is sometimes given to *tracing* or *tuning* fields whose energy density evolves in a way to match the evolution of the dominant component, e.g. $\rho_\phi \sim a^{-4}$ in the radiation era. But it often means fields whose evolution leads them to an attractor solution: a common evolution despite a wide range of initial conditions.

The first type generally can solve the fine tuning but not the coincidence puzzle, while the second type goes a long way toward satisfying both. Fairly simple potentials $V(\phi)$ can give rise to either behavior.

3 QUINTESSENCE (The Fifth Element)

This is a tracking field (of the second type) that can arise from $V(\phi) \sim \phi^{-\alpha}$ or $V(\phi) \sim e^{M_{Pl}/\phi}$. Field theory motivations include dynamical symmetry breaking, Kaluza-Klein, superstrings, supergravity, ...

It solves the fine tuning puzzle for $\alpha > 2$: energy scale $\sim$ GeV.

The EOS w_ϕ(today) is determined by Ω_m, so it can explain why quintessence looks close to, but not exactly like, a cosmological constant today. Also predicts that Ω_Q should not be too drastically different than Ω_m.

FIGURE: Evolution and Tracking of Q Field

Another virtue is that it has easily calculated, observable consequences distinguishable from a cosmological constant. So a real cosmological constant may not be needed.

Measurements of high z supernovae and CMB anisotropies will constrain this model (just as for a cosmological constant) in the next few years. No current cosmological simulations include quintessence yet.