The energy densities $\rho$ associated with different cosmological components (matter, radiation, vacuum energy, etc.) with different equations of state scale differently with the scale factor $a$ under cosmic expansion. As a result, except during brief transition periods, the energy density of the universe is dominated by one such component.

This is the case not only in the standard cosmology, but typically in the case of modified cosmologies (e.g., with epochs of early matter- or vacuum-energy-domination) as well.

Is it possible to achieve a stable, mixed-component cosmological era in which multiple $\Omega$ maintain non-negligible, effectively constant values over an extended period? In other words, can we arrange for the partitioning of the cosmic pie to remain effectively fixed over an extended period, with sizable slices corresponding to components with different equations of state?

At first glance, this may seem impossible – or at least attainable only with a tedious amount of fine-tuning. However, the answer is yes! Moreover, such eras, which we call periods of cosmic stasis, can be realized in a straightforward manner and in fact arise naturally in many extensions of the Standard model.

To see how a stasis era can arise, let us consider a universe effectively consisting of a single component, including those with additional mass scales. What we need is a continuous transfer of energy density from matter to radiation.

\begin{align*}
\frac{d\Omega_M}{dt} &= -3H\rho_M - 3H\rho_R \\
\frac{d\Omega_R}{dt} &= -4H\rho_R - 3H\rho_M
\end{align*}

Particle decays provide a natural mechanism for obtaining these source/sink terms. However, the exponential decay of a single matter species, which occurs over a relatively short time period, is insufficient for achieving stasis.

What we need is a tower of matter states $\psi$, where $\ell = 0, 1, 2, \ldots, N - 1$, whose decay widths $\Gamma_{\psi,\ell}$ and initial abundances $\Omega_{\psi,\ell}$ scale across the tower in such a way that the effect of decays on $\Omega_M$ and $\Omega_R$ compensates for the effect of cosmic expansion over an extended period. In particular, we consider a tower of $N$ such states with...

<table>
<thead>
<tr>
<th>Masses</th>
<th>Decay Widths</th>
<th>Initial Abundances</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\psi = m_o + (\Delta m)^{\ell}$</td>
<td>$\Gamma_{\psi,\ell} = \frac{m_\psi}{\Delta m} \Gamma_o$</td>
<td>$\Omega_{\psi,\ell} = \Omega_o^\ell = \frac{m_\psi}{m_o} \Omega_o$</td>
</tr>
</tbody>
</table>

- Towers of states with mass spectra of this form arise naturally in many extensions of the Standard Model, including those with extra spacetime dimensions or additional strongly-coupled gauge groups.
- The Boltzmann equations for the individual $\psi$ in conjunction with the relevant Friedmann equation, yield an equation of motion for $\Omega_M$.

\begin{align*}
\frac{d\Omega_M}{dt} &= -3H\rho_M - 3H\rho_R \\
\frac{d\Omega_R}{dt} &= -4H\rho_R - 3H\rho_M
\end{align*}

We want this to vanish for an extended period.

\begin{align*}
\frac{d\Omega_M}{dt} &= - \frac{1}{3} \Omega_M + \frac{1}{3} \Omega_R \\
\frac{d\Omega_R}{dt} &= - \frac{4}{3} \Omega_R + \frac{1}{3} \Omega_M + \frac{1}{3} \sum \Gamma_{\psi,\ell} \Delta \tau_{\psi,\ell} + \frac{1}{3} \sum \Gamma_{\psi,\ell} \Delta \tau_{\psi,\ell}
\end{align*}

- In order to achieve an extended period of stasis, we need $\Delta \tau_{\psi,\ell}$ to vanish over a significant range of $\ell$.

\begin{align*}
\frac{d\Omega_M}{dt} &= - \frac{1}{3} \Omega_M + \frac{1}{3} \Omega_R \\
\frac{d\Omega_R}{dt} &= - \frac{4}{3} \Omega_R + \frac{1}{3} \Omega_M + \frac{1}{3} \sum \Gamma_{\psi,\ell} \Delta \tau_{\psi,\ell} + \frac{1}{3} \sum \Gamma_{\psi,\ell} \Delta \tau_{\psi,\ell}
\end{align*}

- Indeed, for any $\psi$, $\rho$, and $\Gamma$, we find that a tower of decaying matter states with the scaling relations above is capable of satisfying this criterion and gives rise to a period of stasis with matter and radiation abundances given by:

$\Omega_M = \frac{3(1 + \Delta)}{2(1 + \Delta) + 3} \Omega_{M(0)}$ 

Conclusions and Implications of Stasis

- A stasis epoch can be spliced into the cosmological timeline in a variety of places – for example, immediately prior to reheating or immediately after a period of early matter domination.
- The comoving Hubble radius grows more slowly in cosmologies with a stasis era, so perturbation modes re-enter the horizon at a later time. This has implications for inflationary observables.
- Density perturbations grow more quickly during stasis than in an radiation-dominated era. As a result, compact objects (e.g., compact minihalos) can potentially form during stasis, as they do in an early matter-dominated era.
- A stasis era can also be realized involving matter and vacuum energy. The staggered transitions from overdamped to underdamped oscillation of scalars which acquire abundances from vacuum misalignment convert vacuum energy to matter.
- A population of primordial black holes, which transfer energy density to radiation as they evaporate, can also yield a period of stasis.

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