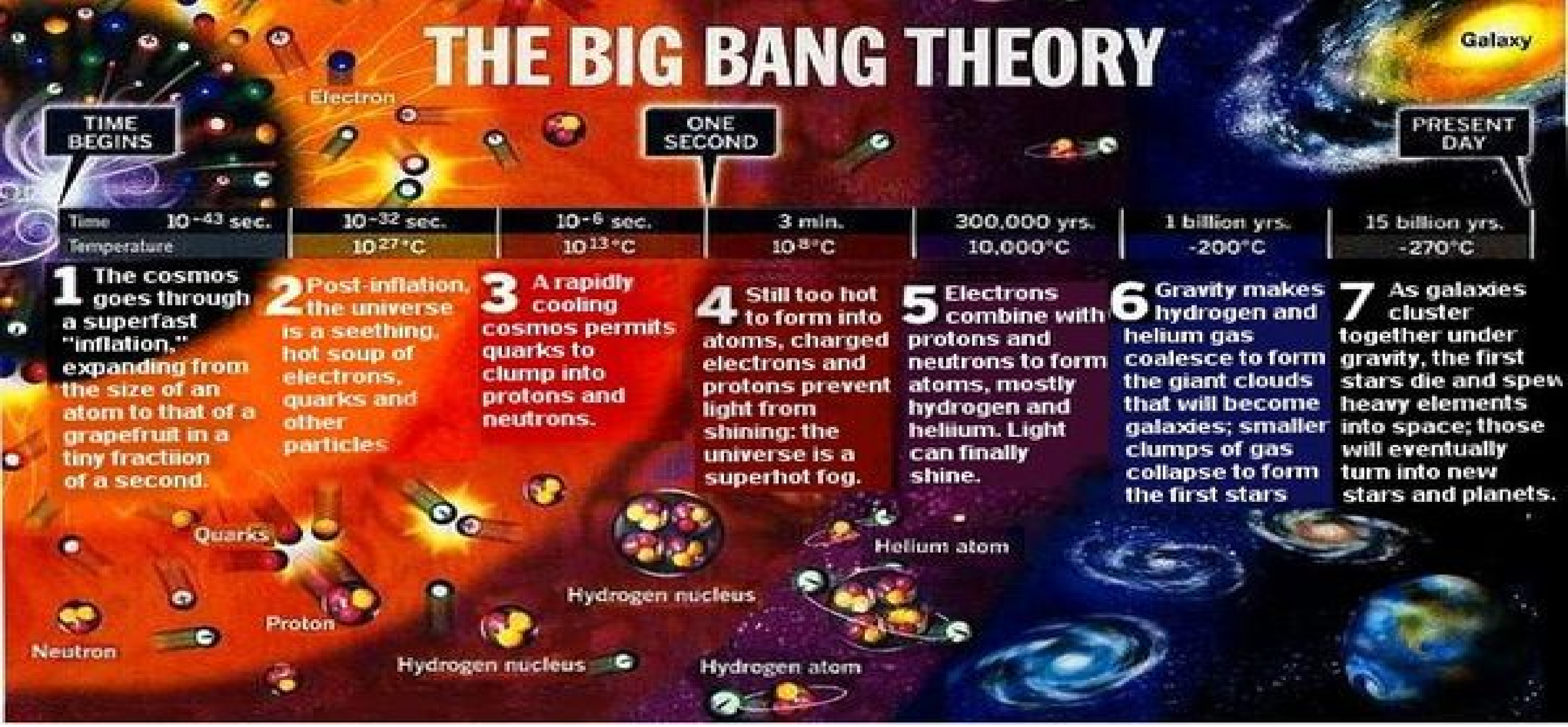
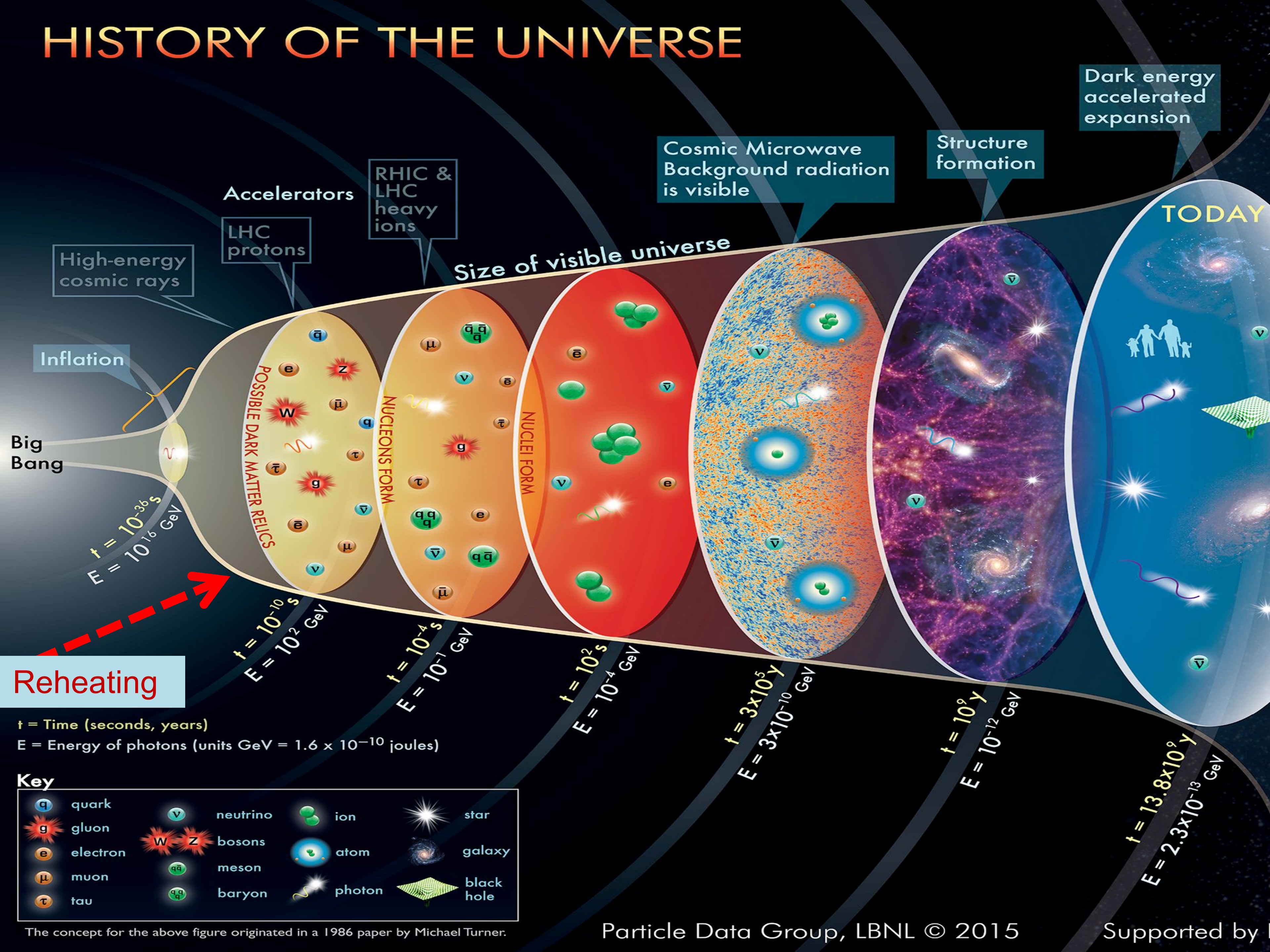
Matter and radiation creation era: Merging the macroscopic and microscopic views

Recai Erdem, VIA-lecture, February 03, 2017



This image is taken from http://prancer.physics.louisville.edu/astrowiki/index.php/The_Story_of_the_Universe

The subject of this lecture will be the era between inflationary and radiation dominated eras i.e. the first part of the era between 1 and 2 in the above image, namely, the first part of reheating before thermalization.


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
Reheating
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
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- **I will discuss how an additional insight about this era may be gained (as a possible future direction of research) in the light of the papers;**
- **R. Erdem, "Single scale factor for the universe starting from the creation of radiation and matter till the present", Eur. Phys. J. C 74 (2014) 3066. (One of the main points of this paper is to introduce a scheme to include the era of the creation of radiation and matter in a unified model of cosmology that accounts for all eras of cosmology).**
- **R. Erdem, "Is it possible to obtain cosmic accelerated expansion through energy transfer between different energy densities?", Phys. Dark Univ. 15 (2017) 57. (I will comment how to use some expressions obtained in this paper to relate the macroscopic view (i.e. The one at the level of energy densities) and the microscopic views (i.e. the one at the level of particle physics processes) describing this era. Although this paper focuses mainly on the late times the tools obtained there may be also used for the early universe)**

Why is it important to study the era of the creation of matter and radiation (i.e. the first phase of the Reheating before thermalization)?

Because

1- The usual matter and radiation we around us is created in this era.

2- To be able to have a true, realistic unified model for all cosmological eras one must be able to give a detailed enough desciption of this era and must be able to embed this era to the cosmic evolution of the universe.

Although there are many studies on reheating in literature,

a standard, well established, and simple description of reheating era, especially a simple, clear, model independent picture that relates the macroscopic (i.e. the one at the level of energy densities) and the microscopic (i.e. the one at the level of particle physics processes) views is still missing.

The standard tools for the particle production for reheating

- 1- The perturbative approach where (in a somewhat ad hoc way) one introduces a decay width Γ into the evolution equation for the energy densities for inflaton ϕ and decay product χ

$$(d^2\phi/dt^2) + 3H(d\phi/dt) + \Gamma(d\phi/dt) + (\partial V/\partial\phi) = 0$$

$$(d^2\chi/dt^2) + 3H(d\chi/dt) - \Gamma(d\chi/dt) + (\partial V/\partial\chi) = 0$$

This formulation is only approximately valid, and is valid at level of perturbative quantum field theory, [L. Kofman, A. Linde, A.A. Starobinsky, ″Towards the theory of reheating after inflation ″, PRD 56 (1997) 3258], and is model dependent.

The standard tools for the particle production for reheating are

- 2- Parametric resonance where the amplitude of a field (other than inflaton or the perturbations of inflaton) is exponetially amplified due to the oscillation of inflaton in the background as an driving source after the inflationary era e.g.

$(d^2\phi/dt^2) + (\partial V/\partial\phi) \cong 0$

$(d^2\chi_k /dt^2) + (k^2 + g^2\sigma^2 + 2\,\sigma^2 k\Phi)\chi_k = 0$

(for $V = (m^2/2)(\phi - \sigma)^2 + ((m_\chi(0)^2/2)\chi^2 + (g^2/2))\phi^2\chi^2$)

and the number of χ's grows as exponentially. This mechanism is efficient only in some cases, and in most these cases it is efficient only in some time interval. The calculations are model dependent, and usually tedious and need numerical tools.

Is there an easier way to see the evolution of the energy densities?

- Both the perturbative approach and the parametric resonance need a detailed study of the specific model considered to get information about the evolutions of energy densities. Therefore obtaining the evolution of the energy densities is tedious and the results are somewhat obscure because of the resulting complicated picture.
- Instead one may adopt a more practical approach to obtain an approximate evolution of the energy densities in an easier way by using some expressions in my recent paper as will be discussed in the following slides.

An observation:

- After the inflationary era the Hubble parameter H gets small enough so that one approximately has $(d^2\phi/dt^2) + (\partial V/\partial\phi) \cong (d^2\phi/dt^2) + m(\phi-\sigma) = 0$ i.e. inflaton ϕ oscillates about its minimum σ with zero average pressure, $<p> = 0$ i.e. inflaton behaves like dust in this era. Therefore the energy transfer in this era may be considered to be from (non-relativistic) matter to radiation.
- This observation will be our starting point to obtain the evolution of the energy densities in the era of the creation of matter and radiation (i.e. in the first part of reheating) in the following slides.

Another observation

- The equation for an energy density that has some energy transfer Q (in a FLRW universe) $(d\rho/dt) + 3H(1+\omega)\rho = Q$

may be expressed as

$(d\rho/dt) + 3H(1+\omega+\Delta\omega)\rho = 0$

i.e. an energy transfer modifies EoS of the energy density.

- Hence one may make an energy density mimic another energy density by coupling the original to another energy density through an energy transfer Q.

- **Therefore, for example, the energy densities of (extremely non-relativistic matter) and radiation may be expressed in general as**
- $\rho_m = C_m(t)/a^3, \ \ \rho_r = C_r(t)/a^4$

where C_m (C_r) is constant if ρ_m (ρ_r) is not coupled to any energy density,
and $C_m = C_m(t)$, $C_r = C_r(t)$ are time-dependent in general.

- The explicit forms of $C_m(t)$ and $C_r(t)$ are found in terms of the rate of energy transfer in comoving frame $d\rho'/dt$ in my recent (2017) paper. For example, in the case of energy transfer from matter to radiation in the case of instantenous interactions

  $C_m(t) = C_m(t_1) - \int^t (d\rho'/du)\, a^3(u)\, du,$

  $C_r(t) = C_r(t_1) + \int^t (d\rho'/du)\, a^4(u)\, du$

- Therefore the evolution of energy densities in a coupled system may be obtained once the rate of the energy transfer in the comoving frame $d\rho'/dt$ is known.One may show that
- $(d\rho'/dt) = -(dC_m/dt)/\, a^3(t)$

For example, in the case where the conversion of matter to radiation is through the following 2-body inelastic scattering processes, $d\rho'_m/dt$ may be determined as follows:

One may show that
$(d\rho'_m/dt) = -(dC_m/dt)/a^3$.

Morevover one has

$(dn'_m/dt) = -(dC_m^{(n)}/dt)/a^3 = -\beta' n_m^2 \sigma v$, $d\rho'_m/dt \cong m(dn'_m/dt)$;

so $(d\rho'_m/dt) \cong - \beta\rho_m^2(t)\, a^{r-1}(t)$

where $\beta = [\beta'/m]\,[a(t_1)]^{1-r}\sigma(t_1)\, v(t_1)$, $\sigma = \sigma(t_1)[a(t)/a(t_1)]^r$, $v = v(t_1)[a(t_1)/a(t)]$.

- In other words if one can find $\rho_m(t)$, σ at t_1 and its evolution with $a(t)$ then we can determine $(d\rho'_m/dt)$.

- $\rho_m(t)$ can be found from

$(dc_m/dt)/a^3 = \beta\rho_m^{\,2}(t)a^{r-1}(t) \;\Rightarrow$

$dc_m/c_m^{\,2} = \beta\, a^{r-4}(t)\, dt = \beta\, a^{r-5}(t)\, da/H$

for $t > t_1$.

The integration of this expression gives $c_m(t)$ i.e. $\rho_m(t)$ can be found once H and r are fixed.

For example, for $H = \xi\, a^s(t)$ we have found

$c_m(t) = \xi c_{m1}/\{\xi + \beta c_{m1}[a^{r-s-4}(t_1) - a^{r-s-4}(t)]/\,(4-r+s)\}$

$(d\rho'_m/dt)$

$\quad = c_{m1}^{\,2}\beta^2 a^{r-7}(t)]/\,/\{1 + \beta c_{m1}[a^{r-s-4}(t_1) - a^{r-s-4}(t)]/\,\xi(4-r+s)\}^2$

for $t > t_1$ where $c_{m1} = c_m(t_1)$.

- $\rho_r = C_r(t)/a^4$ can be determined by

$C_r(t) = C_r(t_1)+\int(d\rho'/du\ )a^4(u)du.$

Thus one may obtain a solid approximate evolution of the energy densities of matter and radiation, at least, when the universe is matter or radiation dominated.

(A similar procedure can be followed for the cases where there is a resonance in the intermediate state as done in Phys. Dark Univ. 15 (2017) 57 (although the it is more complicated).)

- **In many cases, at a given time, one may write**

$$\rho_m = C_m(t)/a^3(t) \approx \alpha_m\, a^p(t)$$

$$\rho_r = C_r(t)/a^4(t) \approx \alpha_r\, a^q(t)$$

where α_m, α_m, p, q are constants.

- **Then if q > p then reheating will occur otherwise it will not.**

- **In general if $(d\rho_r/dt) > (d\rho_m/dt)$ then reheating will occur otherwise it will not.**

A Comment

- The procedure followed here may be considered to be a simple method for solving the equations
- $(d\rho_m/dt) + 3H\rho_m = Q_1$, $(d\rho_r/dt) + 4H\rho_r = Q_2$ by using $C_m(t)$, $C_r(t)$, and obtaining $Q_1 = -Q_2$ (that may be guessed in this simple case while Q_1, Q_2 are not so evident in general) and finding the form(s) of Q_1, Q_2 by considering the situation at the microscopic level (i.e. at the level of particle physics). In the example considered we have found Q_1 proportional to ρ_m^2 while it is phenomenologically is usually taken to be proportional to ρ_m (that corresponds to decays). Moreover the content of the results is easy to see.

Summmary

- In this lecture I have summarized a simple general procedure to relate the microscopic and the macroscopic views of conversion of (extremely non-relativistic) matter to radiation through the simplest case, namely, through instantenous interactions (while in Phys. Dark Univ. 15 (2017) 57, I have mainly used this approach to study the case where there is a resonance in the intermediate state as a possible source of an accelerated cosmic expansion).

Conclusion

I hope, the procedure mentioned here will get more sophisticated in future and become a good tool to relate the microscopic and macroscopic descriptions of the particle creation era in a simple and clear way.