Baryogenesis from Quark - Gluon Plasma?

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Talk based on paper
"Late Reheating, Hadronic Jets and Baryogenesis" by Takehiko Asaka, D.G., Vadim Kuzmin and Mikhail Shaposhnikov, hep-ph/0310100, PRL 92:101303 (2004)

The main question:

Inflaton is a heavy particle.
What can its decay products do with early Universe' plasma?
(Answer: they overheat the plasma, strongly and in a highly nonuniform way)

The answer depends on and has implications for:

Cosmology

- No preheating (inflaton must decay perturbatively, i.e. as a particle)
- Late reheating preferable (makes getting observable effects easier)
- A new opportunity for electroweak baryogenesis provided
- Gravitational waves (?)
- Late inflaton decays may (?) affect BBN $\Rightarrow$ lower limit for $T_{rh} > \mathcal{O}(10 \ldots 100)\,\text{MeV}$

QFT

- Calculations heavily dependent on QGP physics
- QCD effects dominating
- theory of QGP cascades needs to be developed
- are non-abelian effects really important?
- what happens below deconfinement temperature?

Outline:

1. Introduction

2. High-energy partons in (QGP) plasma: why QGP cascades are so different from atmospheric showers!

quark-gluon

   - multiple scattering and Landau-Pomeranchuk-Migdal effect
   - cascade formation
   - thermalisation and overheating

3. Baryogenesis

   - dynamics of electroweak phase transition not important
   - sphaleron rate and overheating time
   - net estimate: $\frac{n_B}{s} \gtrsim (1 \ldots 10) \cdot 10^{-7} \delta_{CP}$

Introduction

"Old" (circa 1990) paradigm:

* inflation → reheating → further expansion near thermal equilibrium
* Out-of-equilibrium effects (e.g. baryogenesis) due to phase transitions

Preheating (1994):
Strongly non-thermal dynamics is perfectly possible

(Soon after that): Various other nonthermal affects* <u>are</u> possible, even for perturbative inflaton decays within hot primordial plasma.

* including the one considered here

Inflation model: low T_{RH} required

(*) inflaton mass $M_\varphi \gg T_{RH}$

otherwise plasma effects directly affect inflaton decay, E. Kolb et al. PRD 68, 123505 (2003)

(**) $T_{RH} \lesssim T_{EW} \sim 100$ GeV

to exploit EW phase transition (perhaps even QCD deconfinement phase transition, $T_{QCD} = 130$ MeV)

Low naturally occurs in certain inflation models, e.g. K.-I. Izawa, T. Yanagida, Phys. Lett. B 393, 331 (1997). Generally, such models involve certain fine-tuning of parameters. Also, WMAP data provide noticeable restrictions for these.

Some standard estimates

$$\Gamma_\varphi = f_\varphi M_\varphi \quad \text{(inflaton decay width)}$$

$$t^{decay} = \frac{1}{\Gamma_\varphi} \sim \frac{1}{H^{decay}}$$

$$\Downarrow$$

$$\Gamma_\varphi^2 \sim \left(H^{decay}\right)^2 = \frac{8\pi}{3}\frac{\rho^{decay}}{M_{Pl}^2} = \frac{8\pi}{3}\frac{1}{M_{Pl}^2}\,\frac{g^* \pi^2}{30} T_{RH}^4$$

$$\Downarrow$$

$$T_{RH} \sim \sqrt{f_\varphi M_\varphi M_{Pl}} \left(\frac{90}{8\pi^3 g_*}\right)^{1/4}$$

where $g_* \sim 100$

if $T_{RH} \lesssim 100$ GeV

$M_\varphi \gtrsim 10^9$ GeV (Izawa, Yanagida)

then $f_\varphi \lesssim 10^{-23}$

Late reheating means a very slow inflaton decay (of course!)

In our case:

inflaton $\varphi \to q\bar{q}$ (just for simplicity)

$$E_q = M_\varphi / 2 \gtrsim 10^{10}\,\mathrm{GeV}$$

Decay products (partons) are out of thermal equilibrium if $T < 10^{10}\,\mathrm{GeV}$

$\Rightarrow$ T can be neglected when the parton energy loss per unit length is calculated:

radiative loss due to gluon emission $\quad -\dfrac{dE}{dz} \sim \sqrt{E}$ $\quad$ very high!

$\Rightarrow$ High-E partons experience extremely strong interaction with the medium. Where all this lost energy dissipates?

Option 1: wide shower, ΔT negligible
- atmospheric showers
- cascades in ordinary matter (e.g. inside particle detectors)

Option 2: energy remains localized within $O(1)$ thermal correlation lengths
$\Rightarrow$ explosive local overheating of plasma

Why this is the case: QGP physics

Multiple Scattering and LPM suppression

Bethe-Heitler spectrum for radiated gluons (independent scattering):

$$\omega \frac{dI^{BH}}{d\omega\, dz} = \frac{3\alpha_s C_R}{2\pi \lambda_g} \sqrt{\log \frac{1}{\mathcal{H}}}$$

$C_R = C_F = 4/3$ if parton is a quark

$C_R = C_A = 3$ — " — gluon

Neglecting log term, one would obtain huge energy loss

$$-\frac{dE^{BH}}{dz} = \int_0^E \omega \frac{dI^{BH}}{d\omega dz} d\omega \sim E$$

However, this isn't the case (except for $\omega \to 0$ when thermal effects modify the result anyway). Because of LPM suppression:

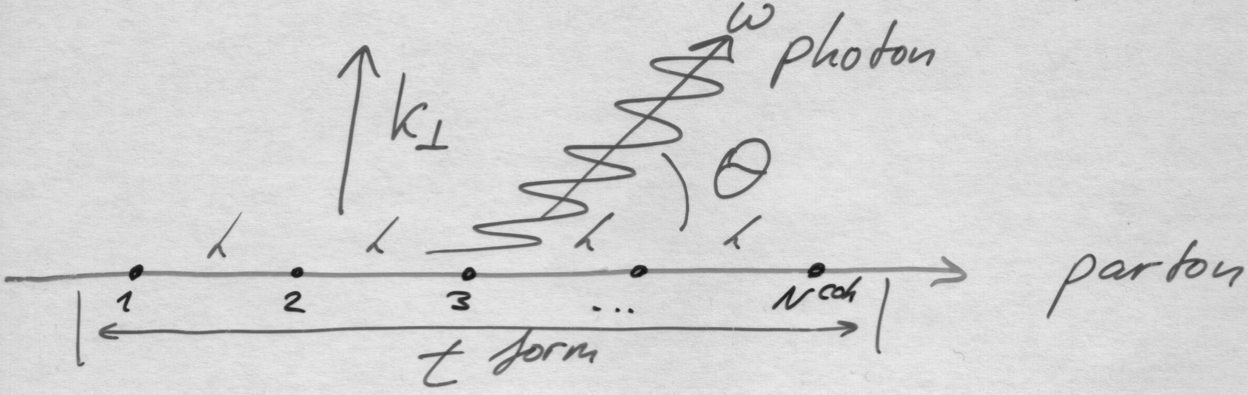
$$\boxed{\text{The scattering takes place coherently on many centres (= multiple scattering).}}$$

Landau–Pomeranchuk–Migdal effect in QCD/QED

'1953 (Landau–Pomeranchuk), '1956 (Migdal)

QCD case: R. Baier, Yu. L. Dokshitzer, S. Peigné and D. Schiff, 1995 – ongoing

Yu. L. Dokshitzer and D.E. Kharzeev, PLB 519 (2001) 199



Formation (= coherency) time:

c.m. frame: large scattering angles, so $k^{total}_{c.m.} \sim k_\perp$ $\qquad t^{form}_{cm} \sim \frac{1}{k^{total}_{cm}} \sim \frac{1}{k_\perp}$

plasma frame: $\underline{t^{form}} = t^{form}_{cm}\, \Gamma = \underline{\frac{\omega}{k_\perp^2}}$ (i) $\qquad \Gamma \sim \frac{\omega}{k_\perp}$

# of scatterings

$$N^{coh} = \frac{t^{form}}{\lambda} \quad \text{(ii)}$$

Accumulated $k_\perp^2$: random walk approximation (not so easy for QED!)

$k_\perp^2 = \mu^2 N^{coh}$ (iii) $\quad \mu^2$ – typical momentum transfer

$\mu \sim M_{Debye} \sim gT$ for $T \neq 0$ QCD

From (i) – (iii) one obtains

$$N^{coh} = \sqrt{\frac{\omega}{\mu^2 \lambda}} = \sqrt{\frac{\omega}{\omega_{BH}}}$$

so

$$\omega \frac{dI^{LPM}}{d\omega\, dz} = \underbrace{\frac{1}{N^{coh}}} \omega \frac{dI^{BH}}{d\omega\, dz}$$

we have 1 independent scattering per N^{coh} centres

Scattering angle:

$$\theta \sim \frac{k_\perp}{\omega} \sim \frac{(\mu^2 N^{coh})^{1/2}}{\omega} = \lambda \omega_{BH} \left(\frac{\omega_{BH}}{\omega}\right)^{3/4}$$

Total energy loss:

$$\omega \frac{dI}{d\omega\, dz} = \frac{3C_R}{2\pi} \frac{\alpha_s}{\lambda_g} \sqrt{\mathcal{H} \log \frac{1}{\mathcal{H}}}$$

$$\mathcal{H} = \frac{\lambda_g \mu^2}{\omega} \ll 1 \quad QCD$$

$$\mathcal{H} = \frac{\lambda \mu^2 \omega}{2E^2} \ll 1 \quad QED$$

so

$$-\frac{dE}{dz} = \int_0^E \omega \frac{dI}{d\omega\, dz} d\omega = \frac{3C_R \alpha_s \mu^2}{\pi} \sqrt{\frac{E}{\omega_{BH}} \log \frac{E}{\omega_{BH}}}$$

$$-\frac{dE}{dz} \sim \sqrt{E} \text{ both for } \begin{array}{ll} QCD & \int_0^E \frac{d\omega}{\sqrt{\omega}} \\ QED & \int_0^E \sqrt{\omega}\, d\omega \end{array}$$

Stopping distance:

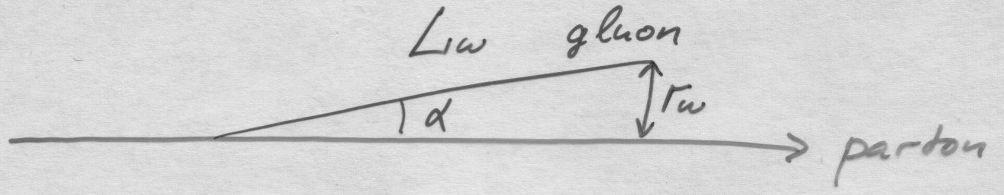
$$L = \frac{2E}{\frac{dE}{dz}} = \frac{2\pi}{3C_R} \frac{\lambda_g}{\alpha_s} \sqrt{\frac{E}{\omega_{BH}} \frac{1}{\log \frac{E}{\omega_{BH}}}}$$

$$\int \frac{dE}{\sqrt{E}}$$

Cascade formation

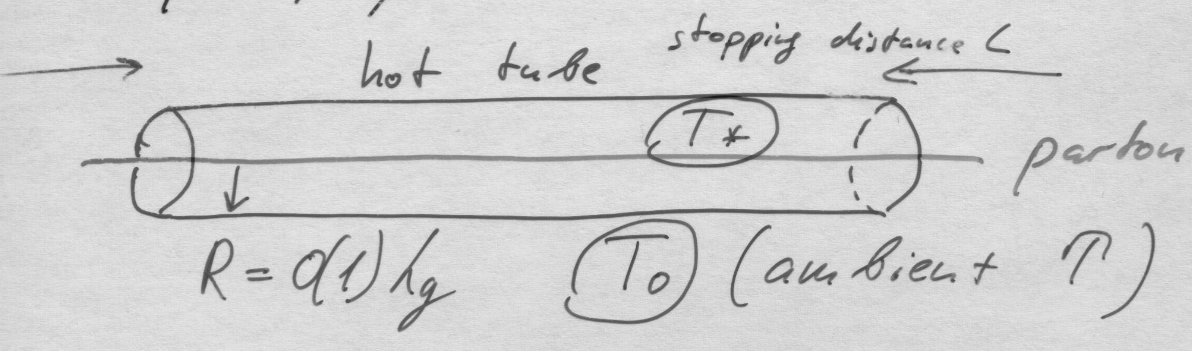
Complicated process which allows for some simple estimates.

Key point: hard processes do not propagate the energy away from the proton trajectory:



$$r_\omega = L_\omega \alpha \sim \sqrt{\omega}\,\frac{1}{\omega^{3/4}} \sim \frac{1}{\omega^{1/4}} \xrightarrow[\text{large } \omega]{} 0$$

$\Rightarrow$ shower doesn't develop. Transverse Energy transfer done by soft particles which promptly thermalise.



Heating the plasma:

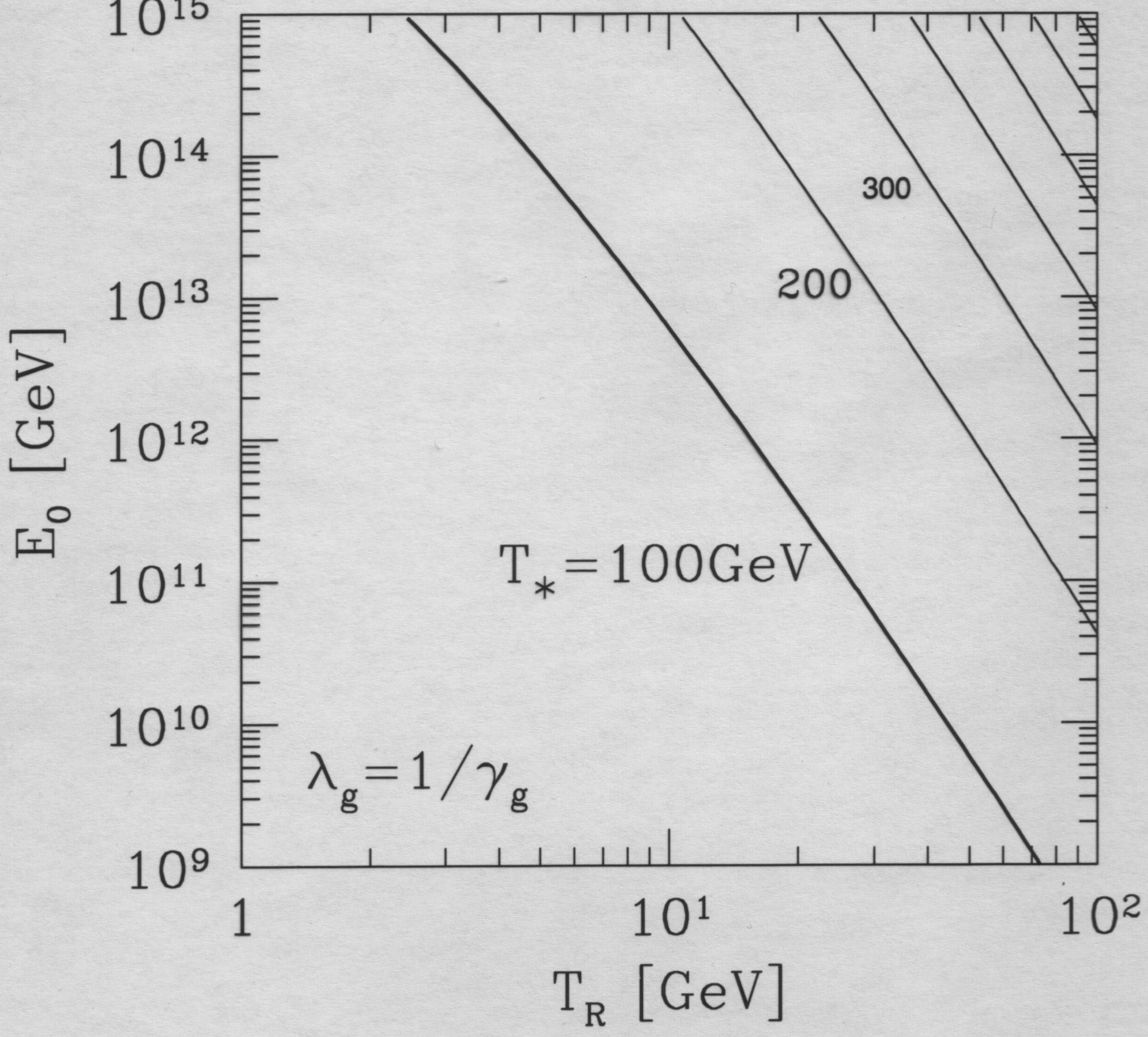
$$\frac{\pi^2 g_*}{30} T_*^4 = \frac{E}{V}$$

$$V = \pi L R^2 \sim \pi L \lambda_g^2$$

$$T_* \simeq 5 \cdot 10^{-2} \left(\frac{100}{g_*}\right)^{1/4} \mu^{3/4} \left[\frac{E_0}{\lambda_g} \log \frac{E_0}{\lambda_g \mu^2}\right]^{1/8}.$$

factor of 2 increase in T for $E_0 \sim 10^{11}$ GeV
10 $E_0 \sim 10^{13}$ GeV

$\Rightarrow$ to get any noticeable outcome, one needs to get just below a phase transition.



10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
E_0 [GeV]
300
200
$T_* = 100$GeV
$\lambda_g = 1/\gamma_g$
1
10^1
10^2
T_R [GeV]

Observational Effects

- heating is not typically very strong:

$$\frac{T^*}{T_{RH}} \sim \begin{matrix} 2 & E_0 \sim 10^{11}\,\text{GeV},\ T_{RH} \sim 100\,\text{GeV} \\ 10 & E_0 \sim 10^{13}\,\text{GeV},\ T_{RH} \sim 100\,\text{GeV} \end{matrix}$$

(possibly more for $T_{QCD} \approx 130\,\text{MeV}$!)

$\Rightarrow$ thermal effects can be observed near phase transitions:

- EW phase transition (even crossover!) $\Rightarrow$ EW baryogenesis

- QCD deconfinement phase transition $\Rightarrow$ BBN corrections possible

  $\rightarrow$ T_{RH} limit

- But: a non-thermal effect!

  - Gravitational wave emission (potentially possible)

Electroweak Baryogenesis from QGP

(WMAP:) $$\frac{n_B}{n_\gamma} = 6.5^{+0.4}_{-0.3} \cdot 10^{-10}$$

Licia Verde's talk, Thursday

- The baryon asymmetry is (potentially) perfectly obtainable within the standard electroweak theory via aesthetically attractive topological effects

  Sakharov 1966 Kuzmin, Rubakov, Shaposhnikov 1985
  t'Hooft 1977

- The values of fundamental constants (CKM matrix etc.) seem to be just wrong for that:

  - too little CP violation (physics beyond the SM is needed)

  - no 1st order EW phase transition, only a crossover, so the easiest source of non-equilibrium is gone (circa 2000)

BUT: inflaton decays give the new, source of non-equilibrium!

EW - baryogenesis from QGP: the key points

- nonequilibrium effects from rapid local heating and cooling down of the plasma tubes
- cooling down the tubes due to heat transfer / hydrodynamic expansion, so the phase order strength is irrelevant
- a few formulas:
  - Sphaleron (= baryoproduction) rate proportional to the energy density:

    $$\Gamma_{sph} = O(10)\, \alpha_{EW}^5 T^{*4} \propto \varepsilon^{thermal}$$

    this eliminates the leading contribution from T^*

  - the final result:

    $$\frac{n_B}{s} \gtrsim O(1) \cdot 10^{-7} \delta_{CP}$$

    compared to $\frac{n_B}{s} = 9 \cdot 10^{-11}$ observed

    $\delta_{CP} \sim 10^{-10}$ measured in the SM

- thus, an interesting possibility still requiring a "new physics" to get $\delta_{CP} \gtrsim 10^{-4}$

Baryogenesis

Important point: time scale defined by energy dissipation from the hot tube or expansion of the tube itself.
Strength of the phase transition is no longer crucial.

Sphaleron rate: $\Gamma_{sph} \sim 10\, \alpha_w^5 T_*^4$

Tube exists for $\Delta t \sim \frac{R^2}{4D}\left(\frac{T_*}{T_0}\right)^4$ overheating time

$$D \sim \frac{1}{\gamma g}$$

$$\Rightarrow \frac{n_B}{s} \sim \frac{n_{parton}}{s} \underbrace{\left(\Gamma_{sph} V \Delta t\right)}_{\text{\# of transitions}} \cdot \underbrace{\delta_{cp}}_{\text{efficiency}}$$

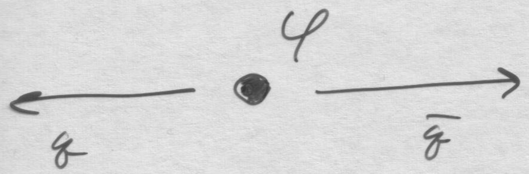
$$\Gamma_{sph} \cdot V \sim T_*^4 V \sim E = \underline{M_\varphi}/2$$

$$\frac{n_{parton}}{s} = \frac{2 n_\varphi}{s} \sim \underline{\frac{3}{2} \frac{T_0}{M_\varphi}} \qquad \left(n_\varphi = \frac{\rho_\varphi}{M_\varphi} \sim T_0^4 \quad s \sim T_0^3 \right)$$

$$\Rightarrow \boxed{\frac{n_B}{s} \sim 10^{-8}\, T_0 \Delta t\, \delta_{cp}}$$

T_* gone!

Gravitational waves from inflaton decay



- Decay products rapidly decelerate, with only L^{stopping} being of relevance

- the process insensitive to other thermal effects

- only classical contribution estimated (calculated):

$$\frac{\delta E}{E} \sim O(10)\, \frac{T_{RH}^2}{M_{Pl}^2} \left(\frac{E_0}{T_{RH}}\right)^{1/2} \sim 10^{-30}$$

@ $E_0 \sim 10^{10}$ GeV
$T_{RH} \sim 100$ GeV

$$\lambda \sim L^{\text{stopping}} \sim O(10)\, \frac{1}{T_{RH}} \sqrt{\frac{E_0}{T_{RH}}} \sim \text{metres (now)}$$

Effects near QCD phase transition:

$$T_{QCD} \sim 130 \text{ MeV} \quad , \quad \frac{T^*}{T_{QCD}} \sim 20$$

- brief emergence of deconfined phase
- variations of quark densities within the remnants of the hot tubes might affect BBN
- this would provide a lower bound for reheating temperature

$$T_{RH} > O(100) \text{ MeV}$$

BUT... too few inflatons per unit volume

Conclusions:

- Late reheating + massive inflaton do introduce a new parameter into consideration:

  $$\frac{E_0}{T_{RH}} \sim \frac{M_\varphi}{T_{RH}} \sim 10^7 \div 10^{15}$$

- there are quite a few effects sensitive to this parameter

- plasma heating factor is $\left(\frac{M_\varphi}{T_{RH}}\right)^{\frac{1}{8}}$ still noticeable around phase transitions

- EW baryogenesis possible at $M_\varphi \gtrsim 10^{10}$ GeV but still not strong enough to overcome small δ^{CP}

- Other effects potentially possible perhaps for heavier inflaton or other supermassive particles