Dark Matter and Baryon Asymmetry from the very Dawn of Universe

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Inflation does a good job!

- Resolves horizon/homogeneity problem.
- Makes Universe flat.
- Washes out heavy relics (e.g., monopoles), which would overclose the Universe.

  Starobinsky'79 Sato'80 Guth'81
- Provides with primordial perturbations—seeds for the future structure formation.

  Mukhanov and Chibisov'81

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Still, plenty of mechanisms of producing DM and baryon asymmetry at preheating and later stages.

Mechanisms are different and operate at different times $\Longrightarrow$ coincidence problem $\frac{\rho_{DM}}{\rho_B} \simeq 5$.

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(NB. Beware: populistic statement!)

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We would have the economical model, where basically all the "mysteries" are resolved by inflation.

Consider free complex scalar field $\Psi = \Psi_1 + i\Psi_2 = \lambda \cdot e^{i\varphi}$

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}|\partial_\mu \Psi|^2 - M^2|\Psi|^2\right]$$

$$\langle \Psi \rangle \neq 0$$

If Ψ is non-interacting with Standard Model fields, it could serve as DM with the energy density $\rho_{DM} \propto M^2\lambda^2$.

Alternatively, if there is non-zero Noether charge density $\boxed{Q = \lambda^2\dot{\varphi}}$, it can be converted into baryon asymmetry a la in the Affleck-Dine mechanism.

$$U(1) - \text{symmetry} \Longrightarrow \nabla_\mu J^\mu = 0 \Longrightarrow \frac{1}{a^3}\frac{d}{dt}\left(a^3 Q\right) = 0 \; .$$

Noether charge density: $\quad Q \equiv J^0 = \lambda^2 \dot{\varphi}$

during inflation $\quad Q \propto \frac{1}{a^3} \to 0 \Longrightarrow$ No Baryon Asymmetry!

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$\rho_{DM} \simeq M^2\lambda^2 \to 0 \Longrightarrow$ No Dark Matter for $M \gtrsim H$!

$$\ddot{\lambda} + 3H\dot{\lambda} - \frac{Q^2}{\lambda^3} + M^2\lambda = 0 \qquad Q = 0 \Longrightarrow \lambda \to 0$$

$M \ll H \Longrightarrow$ DM survives, but with large isocurvature perturbations

To get non-trivial λ, one should have $Q \neq 0$.

$U(1)$-symmetry breaking interaction with the inflaton!

$$S_{int} = \int d^4x\sqrt{-g} \cdot \beta \cdot \varphi \cdot T_{infl} \Longrightarrow \frac{1}{a^3}\frac{d}{dt}\left(Qa^3\right) = \beta T_{infl}$$

$$Q(t) \simeq \frac{1}{a^3(t)} \int_{a_{in}}^{a(t)} \frac{d\ln a(t')}{H(t')} \cdot a^3(t') \cdot U(t') \Longrightarrow Q(t) \simeq \beta \frac{U(t)}{H(t)} \quad Q \simeq \text{const}$$

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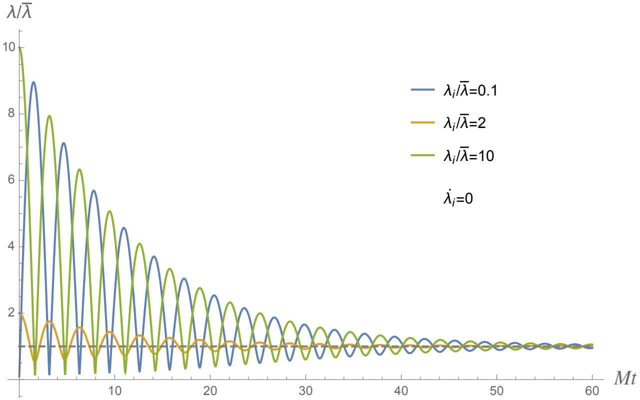
Good news for baryon asymmetry

$$\ddot{\lambda} + 3H\dot{\lambda} - \frac{Q^2}{\lambda^3} + M^2\lambda = 0 \Longrightarrow$$

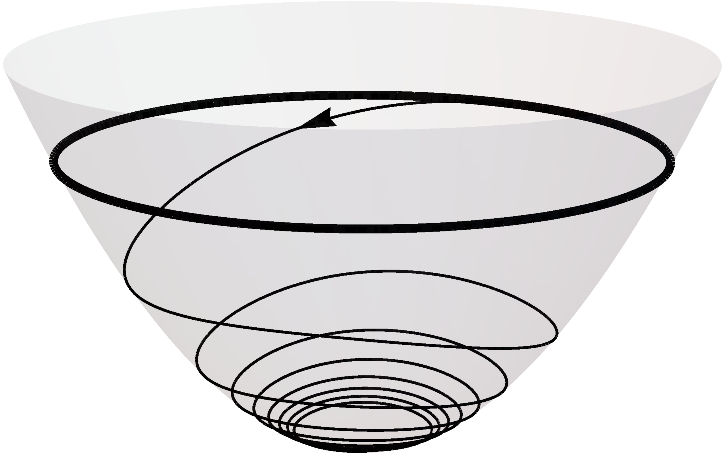
$$V_{eff} = \frac{Q^2}{2\lambda^2} + \frac{M^2\lambda^2}{2} \Longrightarrow \bar{\lambda} = \sqrt{\frac{Q}{M}}$$

Good news for DM

$\lambda = \bar{\lambda} = \sqrt{\frac{Q}{M}}$ is an attractor solution for $M \gtrsim H$



$\boxed{\lambda \to \bar{\lambda} = \sqrt{\frac{Q}{M}}}$ within a few Hubble times $\Longrightarrow$ $\boxed{\dot{\varphi} \to M}$



After inflation the $U(1)$-symmetry breaking term is switched off $\Longrightarrow Q \propto \frac{1}{a^3}$.

$\Delta_B \simeq \frac{Q}{s} = \text{const}$ or $\rho_{DM} \simeq MQ \propto \frac{1}{a^3}$.

Contribution from preheating?

The essence of the mechanism—DM and baryon asymmetry are generated during quasi-de Sitter expansion of the Universe and remain constant.

Generically, non-zero contribution during preheating,

$$S_{int} = \int d^4x\sqrt{-g} \cdot \beta \cdot \varphi \cdot T_{infl} \neq 0$$

The contribution is suppressed, if preheating is instant or $T_{infl} \to 0$ during preheating. The latter is possible, e.g., in

$$S_{infl} = \int d^4x\sqrt{-g} \left[\frac{1}{2}(\partial\phi)^2 + \frac{\xi}{2}R\phi^2 - \frac{h}{4}\phi^4\right] .$$

$T_{infl} \to 0$ following the restoration of the approximate conformal symmetry.

Evolution after inflation: DM

Right after inflation $\rho_{DM} \simeq M \cdot Q \simeq \frac{\beta M U}{H}$

Generically U is huge $+ \quad \rho_{DM} \propto \frac{1}{a^3} \Longrightarrow \frac{\rho_{DM}}{\rho_{rad}} \propto a$.

To satisfy $\rho_{DM} \simeq \rho_{rad}$ at $T_{eq} \simeq 1$ eV ,

one should have a tiny coupling constant $\beta \simeq \frac{T_{reh}}{M_{Pl}} \cdot \frac{T_{eq}}{M}$

For $T_{reh} \simeq 10^{16}$ GeV and $M \sim H \sim 10^{-5}\ M_{Pl}$, one gets

$$\boxed{\beta \simeq 10^{-26}}$$

Evolution after inflation: baryon asymmetry

Generating baryon asymmetry is *a la* in the Affleck–Dine mechanism.

$$\mathcal{L} = y\bar{n}S\Psi + h.c. \Longrightarrow \Delta_B = \frac{Q}{s},$$

$$\Delta_B = 0.87 \cdot 10^{-10}$$

Assume that inflaton energy density is immediately converted into radiation right after inflation.

$$\beta \simeq 10^{-10}\sqrt{\frac{H}{M_{Pl}}}$$

High scale inflation $H \simeq 10^{14}$ GeV $\Longrightarrow$ $\boxed{\beta \simeq 10^{-12}}$.

β is enhanced by the ratio $\sim \frac{M}{m_p}$ compared to DM case.

Perturbations are adiabatic!

$$\boxed{\delta\lambda = \delta\lambda_{ad} + \delta\lambda_{iso}} \qquad \boxed{\delta\varphi = \delta\varphi_{ad} + \delta\varphi_{iso}}$$

Adiabatic perturbations $\delta\lambda_{ad}$ and $\delta\varphi_{ad}$ are due to inflaton fluctuations $\delta\phi$.

Isocurvature fluctuations are the ones, which Ψ has on its own.

Adiabatic perturbations have the standard form

$$\frac{\delta\varphi_{ad}}{\dot{\varphi}} = \frac{\delta\lambda_{ad}}{\dot{\lambda}} = \frac{\delta\phi}{\dot{\phi}}$$

$$\frac{\delta\Psi_{1,ad}}{\dot{\Psi}_1} = \frac{\delta\Psi_{2,ad}}{\dot{\Psi}_2} = \frac{\delta\phi}{\dot{\phi}}$$

Adiabatic perturbations are the same as in the picture with non-interacting scalar fields Polarski and Starobinsky'94

Isocurvature perturbations: $\delta\phi = 0 \quad \Phi = \Psi = 0$

$$\delta Q_{iso} = \delta(\lambda^2 \dot{\varphi})_{iso} = \frac{C}{a^3} \to 0 \Longrightarrow \frac{\delta\dot{\varphi}_{iso}}{\dot{\varphi}} = -\frac{2\delta\lambda_{iso}}{\lambda}$$

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$$\delta\ddot{\lambda}_{iso} + 3H\delta\dot{\lambda}_{iso} + M^2_{eff}\delta\lambda_{iso} = 0 \; .$$

$$M^2_{eff} = M^2 + 3\dot{\varphi}^2 \gtrsim H^2 \; .$$

Perturbations $\delta\lambda_{iso}$ are in the fast roll regime $\Longrightarrow$ decay behind the horizon within a few Hubble times.

We end up with adiabatic perturbations.

Light DM with $M \ll H \implies$ isocurvature perturbations

$$\delta\lambda_{iso} \simeq \frac{H}{2\pi} \Longrightarrow \mathcal{P}_{S_{DM}} = \frac{H^2}{\pi^2\lambda^2}$$

$$\mathcal{P}_{S_{DM}} \ll \mathcal{P}_{\mathcal{R}} = \frac{H^2}{\pi\epsilon M_{Pl}^2} \Longrightarrow \lambda \gtrsim 10 M_{Pl}\sqrt{\epsilon}$$

$\rho_{DM} \simeq M^2\lambda^2$ tends to be overproduced, unless

$$M \lesssim \frac{10^{-34}\ \text{eV}}{3\epsilon^2}\ .$$

Either tiny M or a low scale inflation (similar to the case of axions).

This is one reason, why we considered the super-heavy field Ψ with $M \gtrsim H$.

Non-minimal coupling to gravity

The mechanism requires very small β and very large masses $M \gtrsim H$.

This is not necessary, if there is the non-minimal coupling to gravity.

$$S_{non-min} = \int d^4x\sqrt{-g} \cdot \frac{\xi}{2} \cdot R \cdot \lambda^2 \, .$$

Effective mass during inflation $\quad M_{eff}^2 = M^2 - \xi R \qquad R \approx -12H^2$.

For $\boxed{\xi \gtrsim 1}$, one has $\boxed{M_{eff}^2 \gtrsim H^2}$ even if $M^2 \ll H^2$.

The rest of the story is as in the model with the super-heavy field Ψ.

β is enhanced compared to the minimal case: $\beta \simeq 10^{-3}$ for $M \simeq 10^{-21}$ eV.

Yet another variation of the scenario

The field Ψ interacts with the inflaton $\sim \varphi \cdot T_{infl} \Longrightarrow$ potentially unstable.

Another issue: the interaction $\sim \varphi \cdot T_{infl}$ should be regularized in the limit $\lambda \to 0$ (the phase is badly defined in this limit).

- $\Gamma(\Psi \to \text{inflatons}) \ll H_0 \Longrightarrow$ the field Ψ is stable.
- $\Gamma(\Psi \to \text{inflatons}) \gg H_0 \Longrightarrow$ the field Ψ is unstable.

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$$\mathcal{L} = y_{ij}\bar{S}_i S_j \Psi + h.c.$$

$Q = n_S$ the coupling constant β is larger by the factor $\frac{M}{m_S}$.

Conclusions

- Universal mechanism of producing Dark Matter and baryon asymmetry from inflation is discussed
- Both can be generated during quasi-exponential expansion of the Universe (rather than preheating).
- The coupling to inflaton is very weak $\beta \simeq 10^{-26}$ and $\beta \simeq 10^{-12}$.
- Isocurvature perturbations decay exponentially fast behind horizon.
- The couplings can be made larger, if there is the non-minimal coupling to gravity.

Thanks for your attention!