Les Rencontres de Physique des Particules 2024

Baryogenesis from R^2-Higgs inflation

Yann Cado

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based on 2312.10414

in collaboration with C. Englert, T. Modak & M. Quirós

SORBONNE UNIVERSITÉ

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LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

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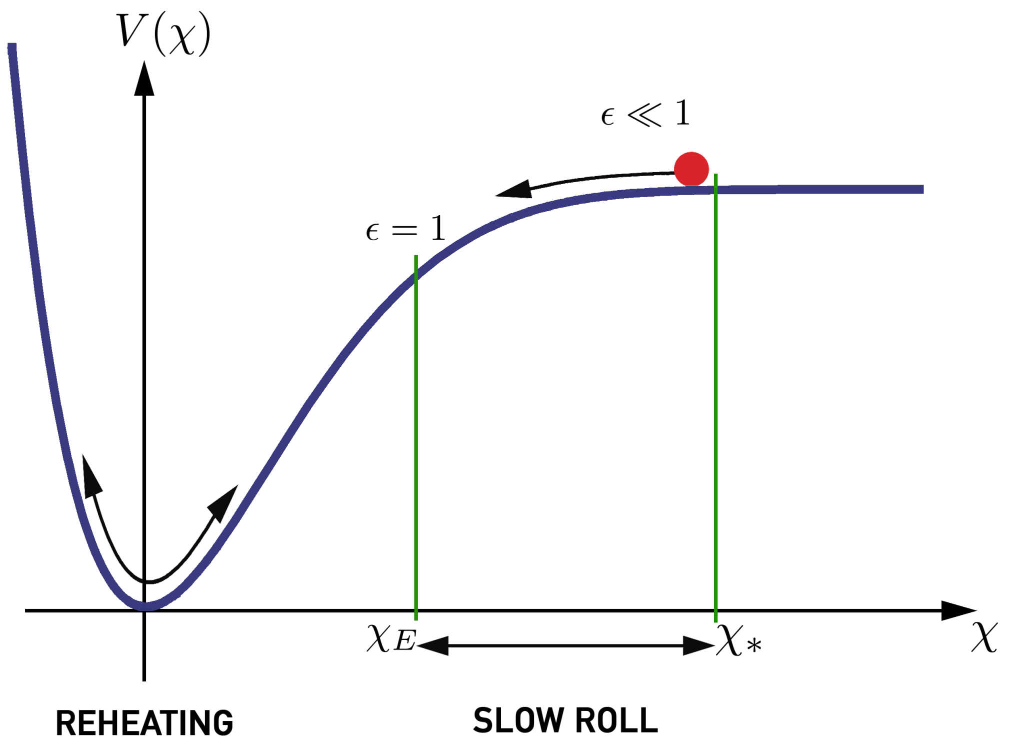
OUTLINE

- Introduction
  - Slow roll inflation
  - Baryogenesis
- R^2-Higgs Inflation
- Gauge fields production
- The Schwinger effect
- Results for baryogenesis
- Conclusion

SLOW ROLL INFLATION

Introduce new scalar field

$$\mathcal{L} = \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - V(\chi) \qquad \Rightarrow \frac{\ddot{a}}{a} \simeq H^2(1-\epsilon)$$



Compute slow roll parameters

$$\epsilon(\chi) = \frac{M_{\rm pl}^2}{2}\left(\frac{V'(\chi)}{V(\chi)}\right)^2 \qquad \eta(\chi) = M_{\rm pl}^2 \frac{V''(\chi)}{V(\chi)}$$

evaluated at the field value $\chi_* = \chi(N_*)$ with

$$N_* = \frac{1}{M_{\rm pl}^2}\int_{\chi_E}^{\chi_*} \frac{V(\chi)}{V'(\chi)}\, d\chi$$

the number of *e*-folds

Guth (1981), Linde (1982), Albrecht-Steinhardt (1982)

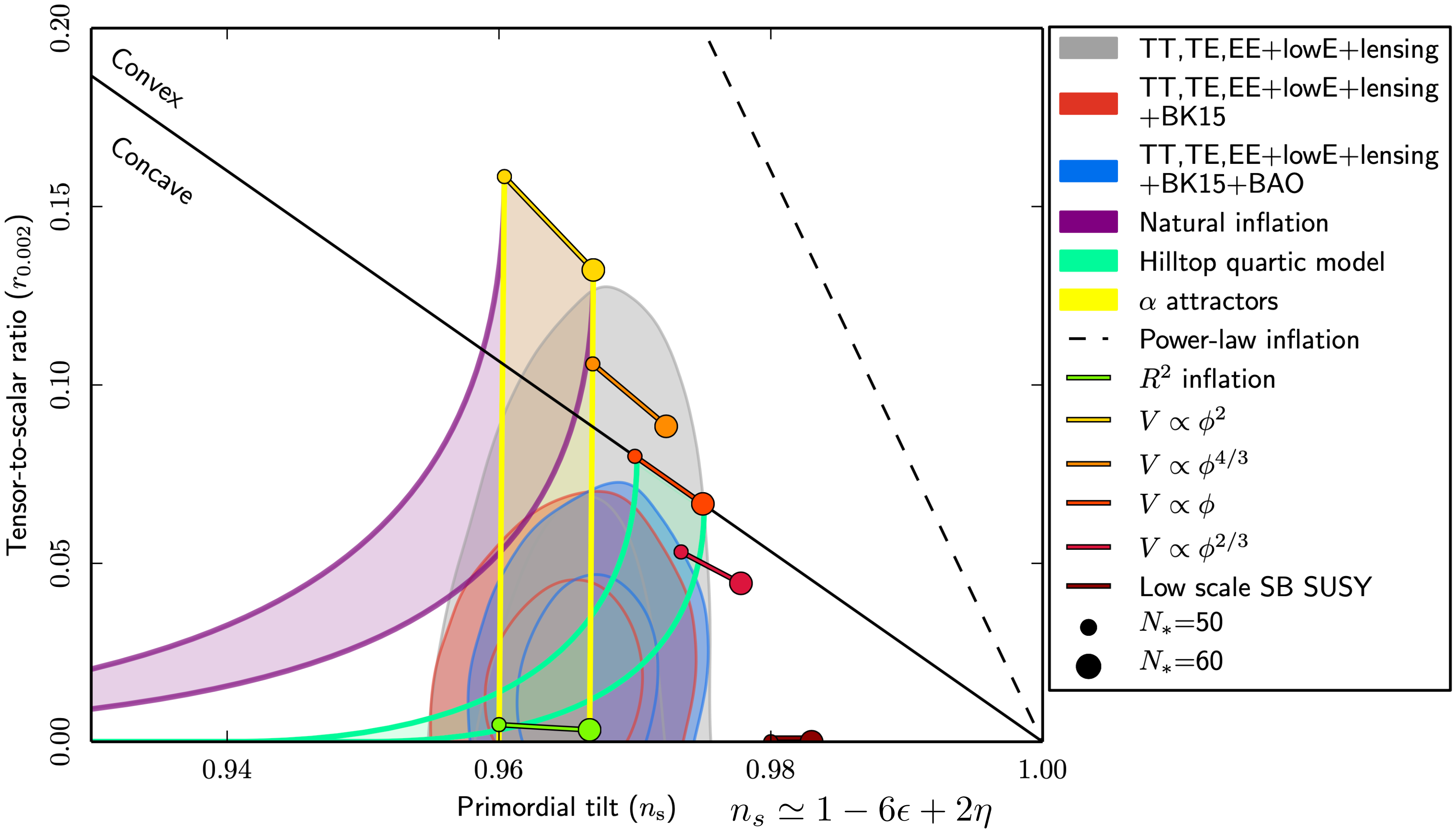
SUCCESS IF

$$\epsilon(\chi_*) < 0.0044 \quad (95\%\text{C.L.})$$
$$\eta(\chi_*) = -0.015 \pm 0.006 \quad (68\%\text{C.L.})$$

$$\epsilon(\chi) = \frac{M_{\rm pl}^2}{2}\left(\frac{V'(\chi)}{V(\chi)}\right)^2$$

$$\eta(\chi) = M_{\rm pl}^2 \frac{V''(\chi)}{V(\chi)}$$

$r = 16\,\epsilon$



$n_s \simeq 1 - 6\epsilon + 2\eta$

PLANCK results X (2018)

One realisation : Higgs Inflation

$$\mathcal{L} = -\frac{M_{\rm pl}^2}{2}R - \frac{\xi_H h^2}{2}R + \frac{1}{2}\partial_\mu h \partial^\mu h - U(h) \qquad U(h) = \frac{\lambda}{4}\left(h^2 - v^2\right)^2$$

JORDAN FRAME

$$g_{\mu\nu} \to \Theta g_{\mu\nu} \qquad \Theta = \left(1 + \frac{\xi_H h^2}{M_{\rm pl}^2}\right)^{-1}$$

PERFORM WEIL TRANSFORMATION

EINSTEIN FRAME

$$\mathcal{L} = -\frac{M_{\rm pl}^2}{2}R + \frac{M_{\rm pl}^2}{2} K(\Theta)\partial_\mu \Theta \partial^\mu \Theta - V(\Theta) \qquad V(\Theta) = \Theta^2 U[h(\Theta)]$$

Bezrukov-Shaposhnikov-Magnin-Sibiryakov (2008-2011)

Starobinsky (1980)

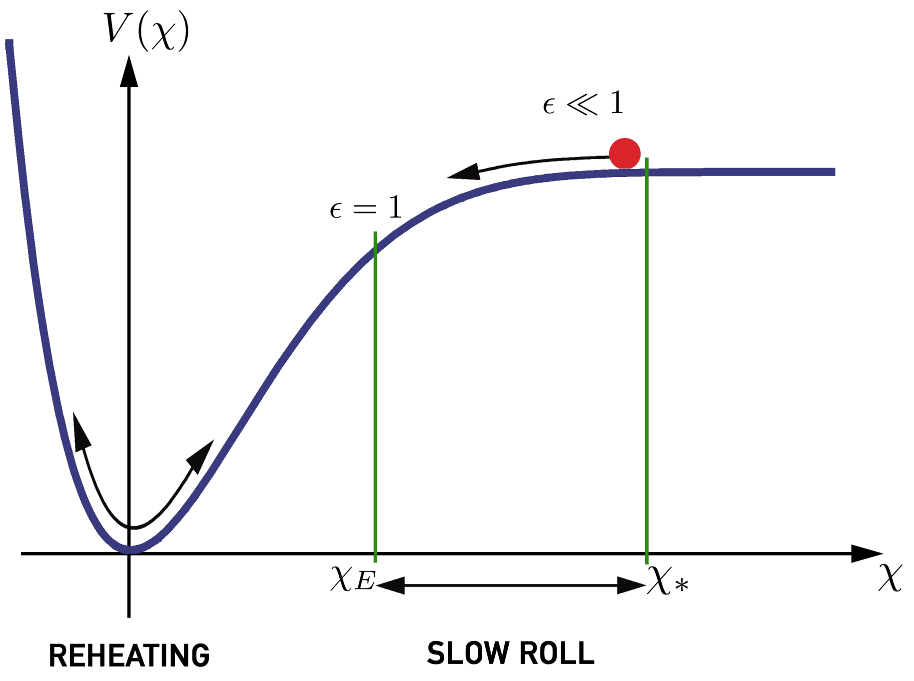
Define χ such that $\left(\frac{d\chi}{d\Theta}\right)^2 = M_{\rm pl}^2 K(\Theta)$

and get

$$\mathcal{L} = -\frac{M_{\rm pl}^2}{2} R + \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - V(\chi)$$

$$V(\chi) \simeq \frac{\lambda M_{\rm pl}^4}{4\xi_H^2}\left[1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{\chi}{M_{\rm pl}}\right)\right]^2$$

STAROBINSKY POTENTIAL



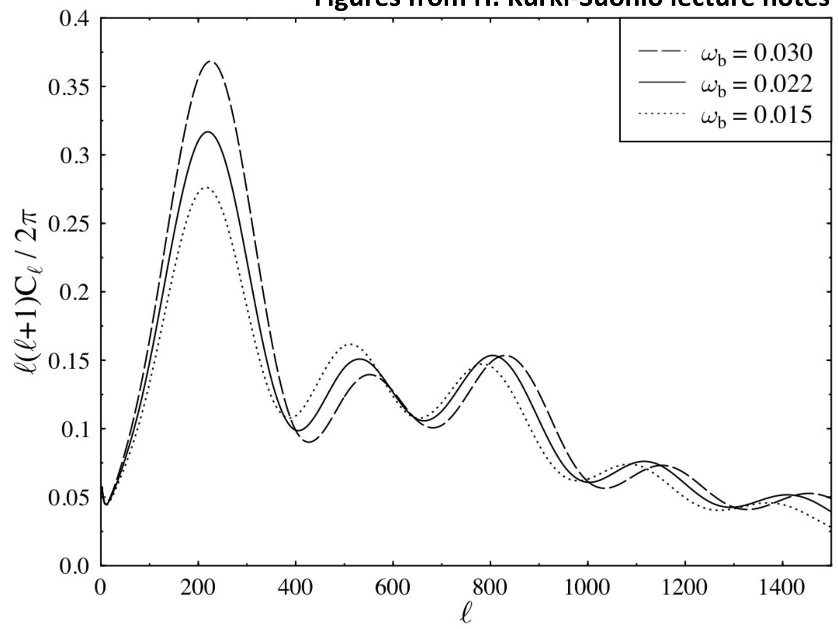
R^2 theory leads to the same class of potential, with similar results & without the HI problems

$$\mathcal{L} \supset \frac{M_{\rm pl}^2}{2} R + \frac{\xi_R}{4} R^2$$

JORDAN FRAME

BARYOGENESIS

Figures from H. Kurki-Suonio lecture notes



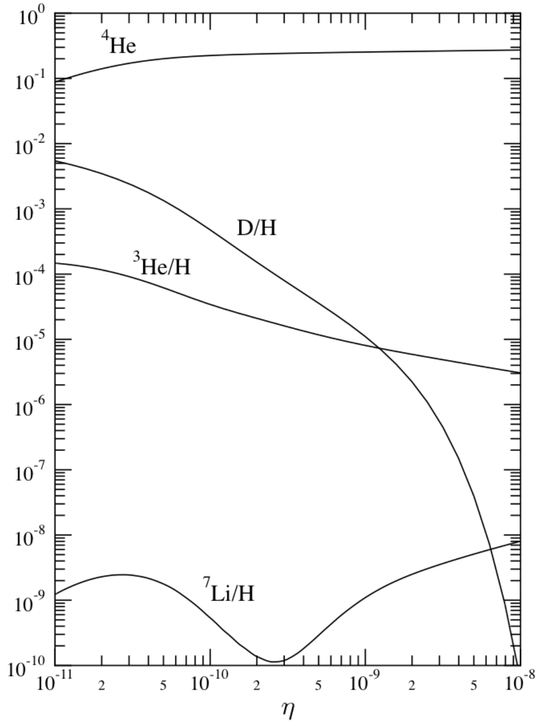
- No matter vs antimatter patches in the Universe
  - No γ rays from annihilation
  - Universe is isotropic and homogeneous

- Relative size of Doppler peaks in CMB are sensitive to

$$\eta = \frac{n_{\text{baryon}}}{n_{\text{photon}}} \qquad \eta_{\text{CMB}} = 10^{-10} \cdot (6.14 \pm 0.25)$$

- BBN predicts observed abundance of lightest elements

for $\eta_{\text{BBN}} = 10^{-10} \cdot \begin{cases} 6.28 \pm 0.35 \\ 5.92 \pm 0.56 \end{cases}$



➡ We need a dynamical process that violates B, C/CP and thermal equilibrium

Sakharov (1967)

ELECTROWEAK BARYOGENESIS

't Hooft (1976)
Rubakov-Shaposhnikov (1996)
Anber-Sabancilar (2015)
Kamada-Long (2016)

Chern-Simons coupling

$$\mathcal{L} \supset f(\phi) B_{\mu\nu} \tilde{B}^{\mu\nu} \qquad F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\langle \mathbf{E}\cdot\mathbf{B}\rangle = 2\frac{d}{d\tau}\langle \mathbf{A}\cdot\mathbf{B}\rangle \qquad \mathcal{H} = \lim_{V\to\infty}\frac{1}{V}\int_V d^3x\,\langle \mathbf{A}\cdot\mathbf{B}\rangle$$

HYPERHELICITY

Chiral anomaly in the SM:

$$\Delta N_B = \Delta N_L = N_g \left(\Delta N_{\text{cs}} - \frac{g_Y^2}{16\pi^2}\,\Delta\mathcal{H}_Y \right)$$

BARYON ASYMMETRY

$$\eta_B \simeq 4\cdot 10^{-12}\, f_{\theta_W}\, \frac{\mathcal{H}_Y}{H^3(t_{\text{end}})} \left(\frac{H(t_{\text{end}})}{10^{13}\,\text{GeV}} \right)^{\frac{3}{2}} \frac{T_{\text{rh}}}{T_{\text{rh}}^{\text{ins}}}$$

Bezrukov-Shaposhnikov-Magnin-Sibiryakov (2008-2011)

Combined R^2 and Higgs Inflation with Chern-Simons coupling

$$\mathcal{L} = \frac{M_{\rm Pl}^2}{2} f(R) + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{SU(2)} + \mathcal{L}_{\rm fermions}$$

$$f(R) = R + \frac{\xi_R}{2M_{\rm Pl}^2} R^2 + \frac{\xi_H}{M_{\rm Pl}^2} |h|^2 R - \frac{2}{\Lambda^2 M_{\rm Pl}^2} \frac{\epsilon^{\mu\nu\rho\sigma}}{\sqrt{-g}} B_{\mu\nu} B_{\rho\sigma} R$$

JORDAN FRAME

$$g_{\mu\nu} \to \Theta^{-1} g_{\mu\nu}, \qquad \Theta = \left.\frac{\partial f(\Psi)}{\partial \Psi}\right|_{\Psi=R}$$

PERFORM WEIL TRANSFORMATION

EINSTEIN FRAME

$$\mathcal{L} = \frac{M_{\rm Pl}^2}{2} R - \frac{1}{2} G_{IJ}\, \partial_\mu \phi^I \partial^\mu \phi^J - V(\phi^I) + \mathcal{L}^E_{SU(2)} + \Theta^{-1} \mathcal{L}_{\rm fermions}$$

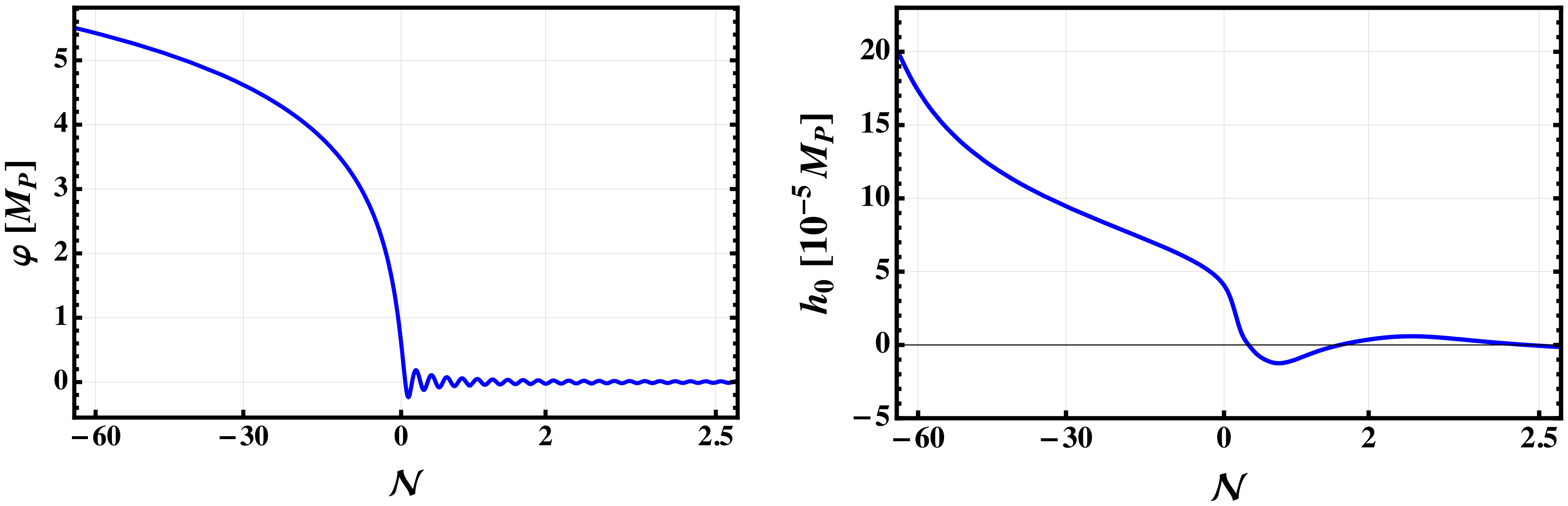
$$\phi^I \in \{\phi, h\} \qquad \phi = M_{\rm P} \sqrt{\frac{3}{2}} \ln \Theta \qquad G = \begin{pmatrix} 1 & 0 \\ 0 & \Theta^{-1} \end{pmatrix}$$

Combined R^2 and Higgs Inflation with Chern-Simons coupling

EINSTEIN FRAME

$$V(\phi^I) = V_0(\phi^I) + \frac{2M_{\rm Pl}^2}{\xi_R \Lambda^2} F(\phi^I)\,\Theta\, B_{\mu\nu}\tilde{B}^{\mu\nu} \qquad \tilde{B}^{\mu\nu} = \frac{1}{2\sqrt{-g}}\epsilon^{\mu\nu\rho\sigma}B_{\rho\sigma}$$

$$V_0(\phi^I) = \frac{\lambda}{4}h^4\Theta^{-2} + \frac{M_{\rm Pl}^4}{4\xi_R}F^2(\phi^I) \qquad F(\phi^I) = 1 + \Theta^{-1}\left(\frac{\xi_H h^2}{M_{\rm Pl}^2} - 1\right)$$

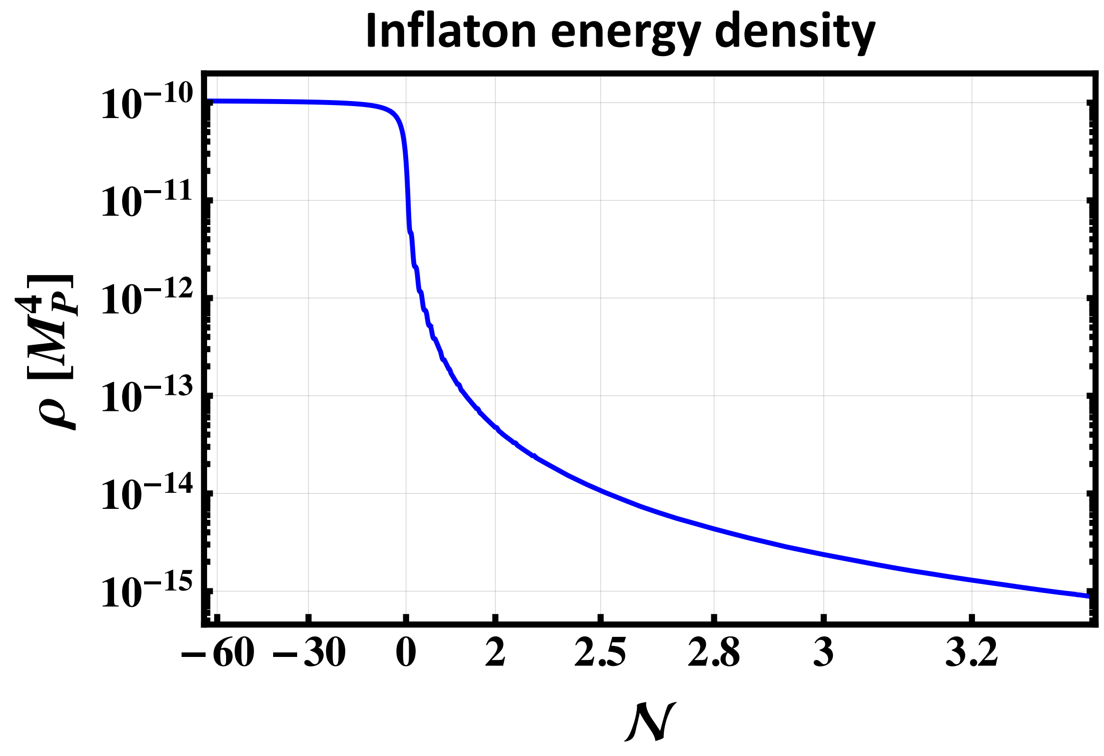


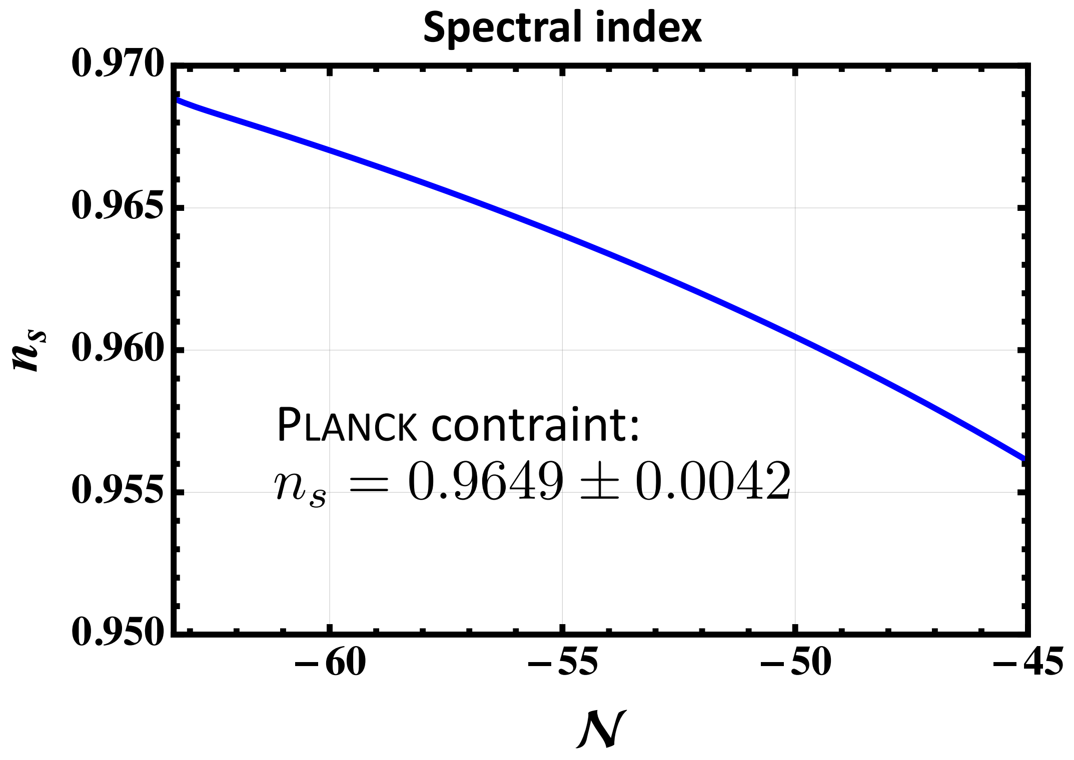
$$\xi_R = 2.35 \times 10^9$$

$$\xi_H = 10^{-3}$$

$$\mathcal{N} \equiv \ln \frac{a(t)}{a(t_{\rm end})}$$

Combined R^2 and Higgs Inflation with Chern-Simons coupling





$\xi_R = 2.35 \times 10^9$ $\xi_H = 10^{-3}$ $\mathcal{N} \equiv \ln \frac{a(t)}{a(t_{\text{end}})}$

Gauge fields production

EoM for the gauge field in radiation gauge in Einstein frame

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}F^{\mu\nu}\right)+\frac{8\cos^2\theta_W M_{\rm pl}^2}{\xi_R\Lambda^2}\partial_\mu\left(F(\phi^I)e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm pl}}}\right)\tilde{F}^{\mu\nu}=j^\nu$$

$U(1)_Y$ projected onto $U(1)_{EM}$ as $\langle h\rangle \neq 0$

Fermion current: $j^\mu=\sum_f ieQ_f\, e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm pl}}} g^{\mu\nu}\bar{f}e^a_\nu\tilde{\gamma}_a f$

$$\mathbf{J}=\sigma_{\rm c}\,\mathbf{E}=-\sigma_{\rm c}\frac{\partial\mathbf{A}}{\partial\tau}$$

Can be neglected if the fermion field values are small

Upon quantization in helical basis

$$\mathbf{A}(\tau,\mathbf{x})=\sum_{\lambda=\pm}\int\frac{d^3k}{(2\pi)^3}\left[\epsilon_\lambda(\mathbf{k})\,a_\lambda(\mathbf{k})\,A_\lambda(\tau,\mathbf{k})\,e^{i\mathbf{k}\cdot\mathbf{x}}+\text{h.c.}\right]$$

Tachyonic instability for one mode:

$$\frac{\partial^2 A_\lambda}{\partial\tau^2}+\sigma_{\rm c}\frac{\partial A_\lambda}{\partial\tau}+k\left[k+\lambda\boxed{\frac{8a\cos^2\theta_W M_{\rm pl}^2}{\xi_R\Lambda^2}\frac{\partial}{\partial t}\left(F(\phi^I)e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm pl}}}\right)}\right]A_\lambda=0$$

Leads to explosive production of **one** helicity mode

Plasma observables

Durrer-Neronov (2013)
Anber-Sabancilar (2015)

We can compute some observables at the end of inflation

$$\rho_E \equiv \lim_{V\to\infty} \frac{1}{2\,V} \int_V d^3x \, \frac{\langle \mathbf{E^2} \rangle}{a^4} = \frac{1}{a^4} \int_0^{k_c} dk \, \frac{k^2}{4\pi^2} \left(|A'_+|^2 + |A'_-|^2 \right)$$

$$\rho_B \equiv \lim_{V\to\infty} \frac{1}{2\,V} \int_V d^3x \, \frac{\langle \mathbf{B^2} \rangle}{a^4} = \frac{1}{a^4} \int_0^{k_c} dk \, \frac{k^4}{4\pi^2} \left(|A_+|^2 + |A_-|^2 \right)$$

$$\mathcal{H} \equiv \lim_{V\to\infty} \frac{1}{V} \int_V d^3x \, \frac{\langle \mathbf{A} \cdot \mathbf{B} \rangle}{a^3} = \frac{1}{a^3} \int_0^{k_c} dk \, \frac{k^3}{2\pi^2} \left(|A_+|^2 - |A_-|^2 \right)$$

$$\mathcal{G} \equiv \frac{1}{2a} \frac{d\mathcal{H}}{d\tau} = -\lim_{V\to\infty} \frac{1}{V} \int_V d^3x \, \frac{\langle \mathbf{E} \cdot \mathbf{B} \rangle}{a^4} = \frac{1}{a^4} \int_0^{k_c} dk \, \frac{k^3}{2\pi^2} \left(|A_+ A'_+| - |A_- A'_-| \right)$$

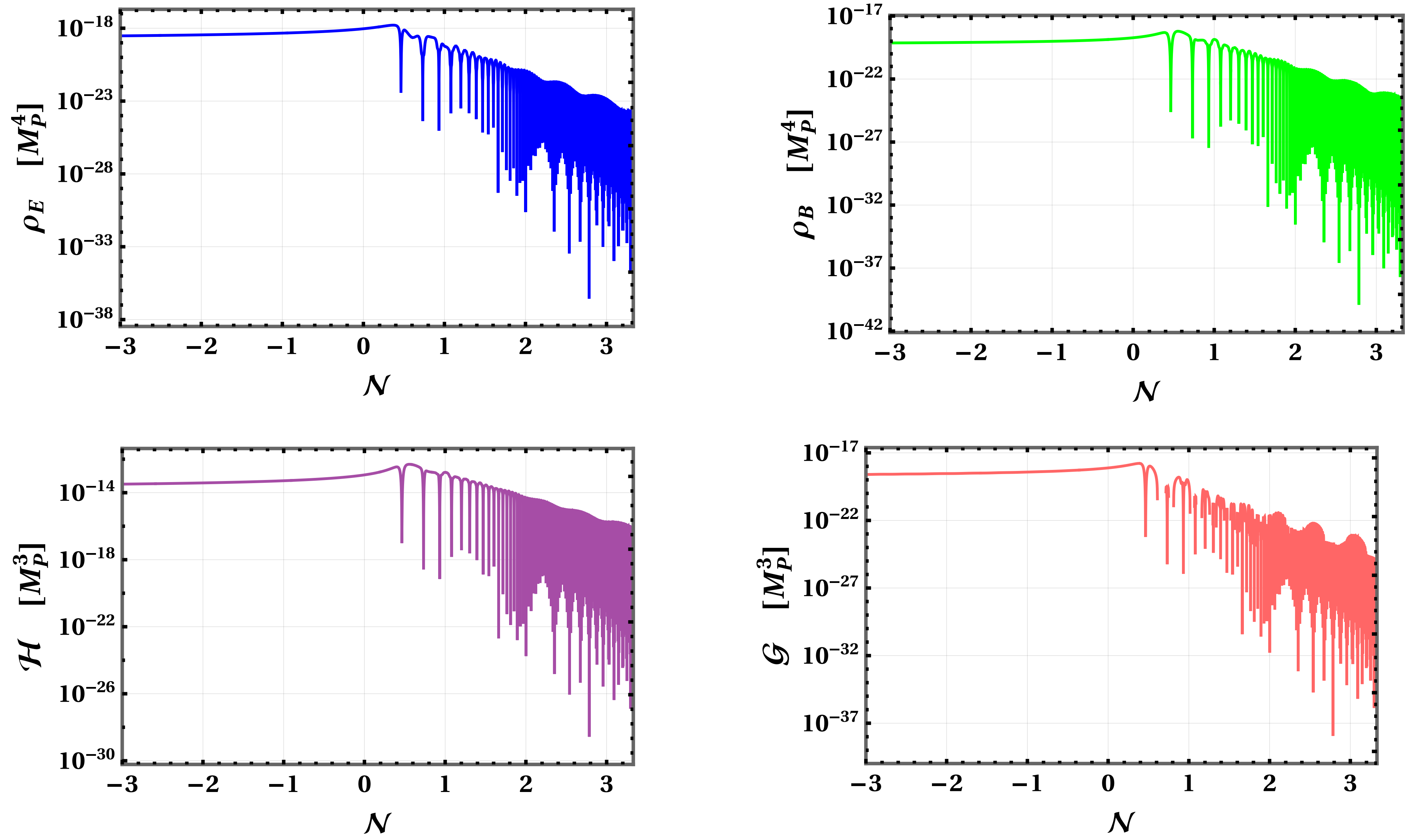
$$k_c = |aH\,\xi| + \sqrt{(aH\,\xi)^2 + \frac{a^2}{2}\left[\dot{\sigma}_{\rm ph} + \sigma_{\rm ph}\left(\frac{\sigma_{\rm ph}}{2} + H\right)\right]}$$

$$\sigma_{\rm c} = a\,\sigma_{\rm ph}$$

$$\xi = \frac{4\cos^2\theta_W M_{\rm pl}^2}{\xi_R \Lambda^2 H} \frac{\partial}{\partial t}\left(F(\phi^I) e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm pl}}} \right)$$

Plasma observables

$\xi_R = 2.35 \times 10^9,\ \xi_H = 10^{-3},\ \Lambda = 2 \times 10^{-5} M_{\rm P}$

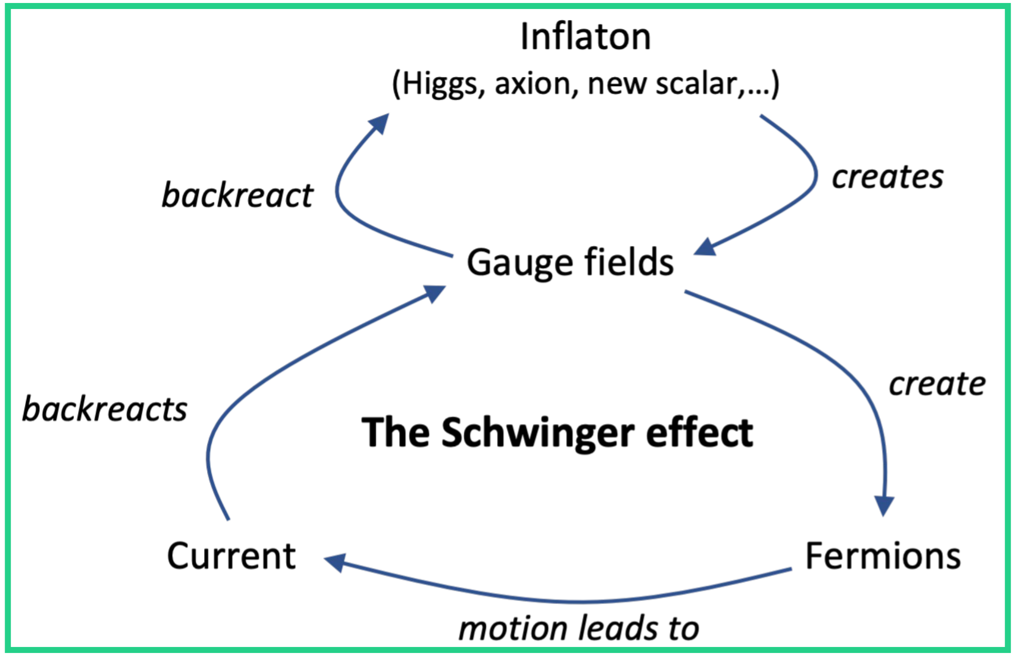


THE SCHWINGER EFFECT

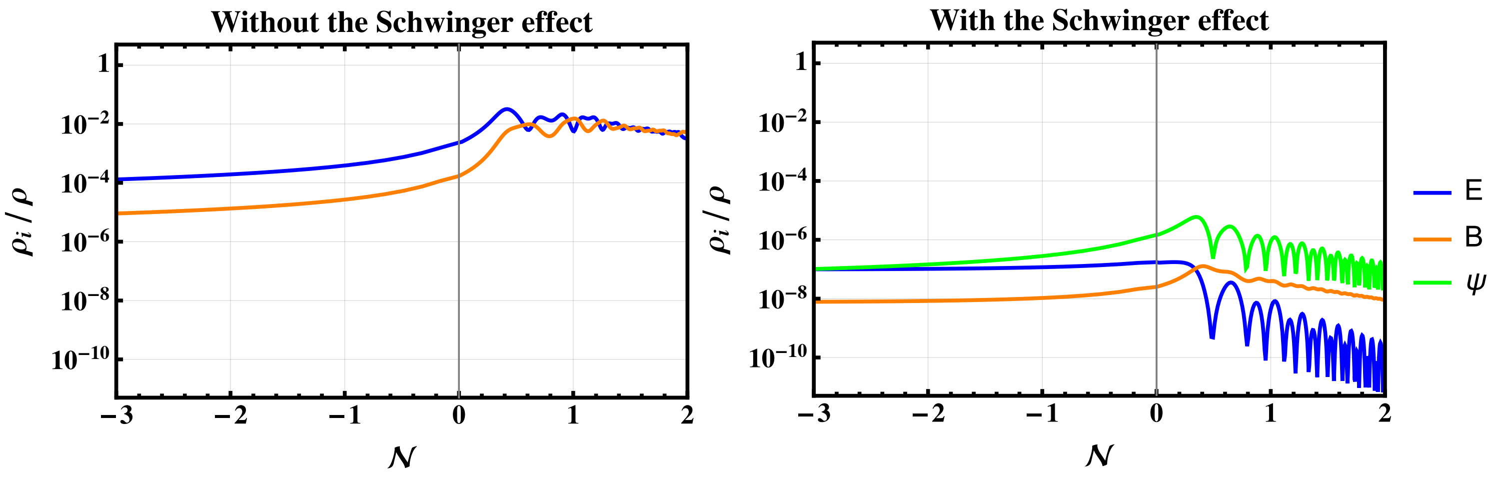
Cohen-McGady (2008)
Domcke-Mukaida (2018)
Kitamoto-Yamada (2022)

The comoving conductivity in the case of one Dirac fermion f with mass m_f and charge Q_f under a U(1) group with coupling g:

$$\sigma_f^{\mathrm{c}} = \frac{|g\,Q_f|^3}{6\pi^2}\,\frac{a}{H}\,\sqrt{2\rho_B}\,\coth\left(\pi\sqrt{\frac{\rho_B}{\rho_E}}\right)\exp\left(-\frac{\pi m_f^2}{\sqrt{2\rho_E}\,|g\,Q_f|} - \sqrt{\frac{2}{3}}\frac{\phi}{M_P}\right), \quad \sigma_{\mathrm{c}} = \sum_f \sigma_f^{\mathrm{c}}$$



Explosive gauge fields production leads to fermion/antifermion pairs creation and their currents backreact on the produced gauge fields.



$$\rho_\psi = \lim_{V\to\infty}\frac{\sigma_{\mathrm{c}}}{V}\int_V d^3x\,\frac{\langle \mathbf{A}\cdot\mathbf{E}\rangle}{a^4} = \frac{\sigma_{\mathrm{c}}}{a^4}\int_{k_{\min}}^{k_{\mathrm{c}}} dk\,\frac{k^2}{2\pi^2}\,\frac{d}{d\tau}\left(|A_+|^2 + |A_-|^2\right)$$

$\xi_R = 2.35\times 10^9,\ \xi_H = 10^{-3},\ \Lambda = 2\times 10^{-5} M_{\mathrm{P}}$

Boyarsky-Frohlich-Ruchayskiy (2012)
Akamatsu-Yamamoto (2013)
Kamada-Long (2016)
Domcke-Harling-Morgante-Mukaida (2019)

From helicity to baryon asymmetry

- At EWPT, there is a competition between weak sphaleron washout and B asymmetry from decaying helicity (SM chiral anomaly).

$$\eta_B \simeq 4 \cdot 10^{-12} \, f_{\theta_W} \frac{\mathcal{H}}{H_E^3} \left(\frac{H_E}{10^{13}\,\mathrm{GeV}} \right)^{\frac{3}{2}} \left(\frac{T_{\mathrm{rh}}}{T_{\mathrm{rh}}^{\mathrm{ins}}} \right) \simeq 9 \cdot 10^{-11}$$

$$f_{\theta_W} = -\sin(2\theta_W) \frac{\mathrm{d}\theta_W}{\mathrm{d}\ln T}\bigg|_{T=135\ \mathrm{GeV}}$$

$$5.6 \cdot 10^{-4} \lesssim f_{\theta_W} \lesssim 0.32$$

- Helicity must nevertheless survive from inflaton to EW scale.

$$\mathcal{R}_m^{\mathrm{rh}} \approx 5.9 \cdot 10^{-6} \, \frac{\rho_B \ell_B^2}{H_E^2} \left(\frac{H_E}{10^{13}\,\mathrm{GeV}} \right) \left(\frac{T_{\mathrm{rh}}}{T_{\mathrm{rh}}^{\mathrm{ins}}} \right)^{\frac{2}{3}} > 1$$

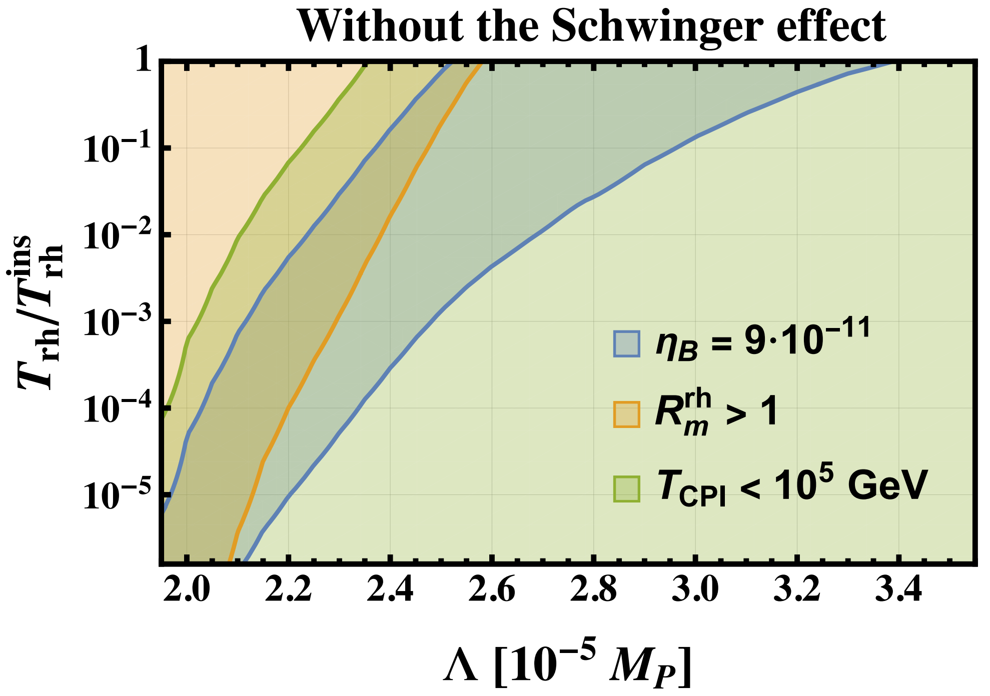
$$\ell_B = \frac{2\pi}{\rho_B \, a^3} \int^{k_c} \mathrm{d}k \, \frac{k^3}{4\pi^2} \left(|A_+|^2 + |A_-|^2 \right)$$

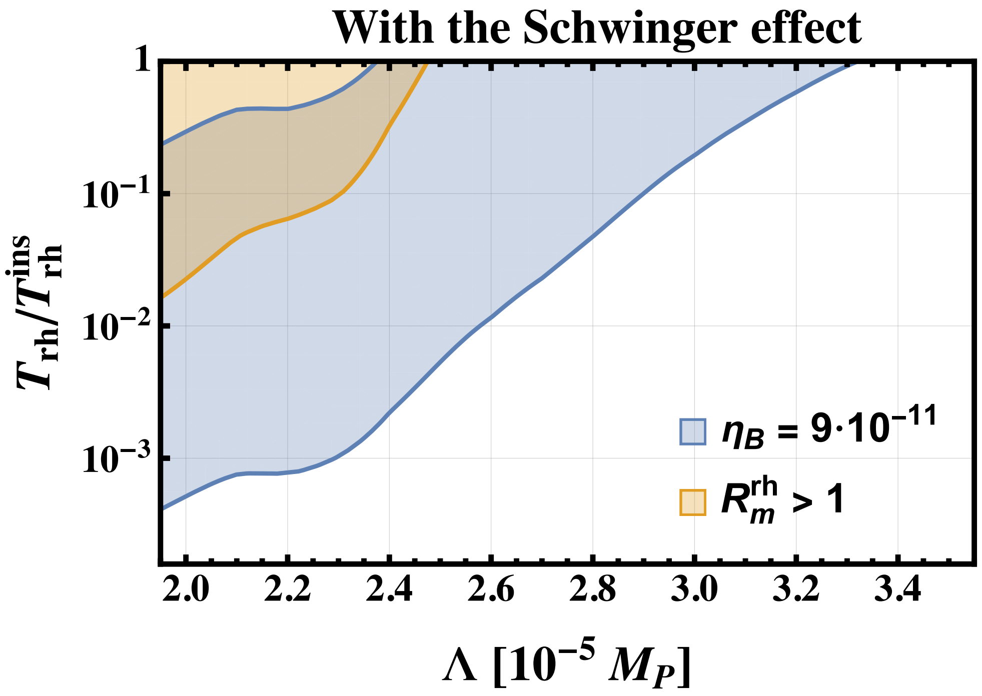
- Chiral plamsa instability (CPI) must be avoided.

$$T_{\mathrm{CPI}}/\mathrm{GeV} \approx 4 \cdot 10^{-7} \, \frac{\mathcal{H}^2}{H_E^6} \left(\frac{H_E}{10^{13}\,\mathrm{GeV}} \right)^3 \left(\frac{T_{\mathrm{rh}}}{T_{\mathrm{rh}}^{\mathrm{ins}}} \right)^2 \lesssim 10^5$$

Baryogenesis parameter space

Higgs Inflation





$$\xi_R = 2.35 \times 10^9,\ \xi_H = 10^{-3}$$

TO CONCLUDE

- R^2-Higgs inflation is one of the best-fit models of Planck data.
- With an additionnal dim-6 coupling $\Lambda^{-2}B_{\mu\nu}\tilde{B}^{\mu\nu}R$, the model predicts the right amount of baryon asymmetry in the present Universe, for $\Lambda \simeq 2.5 \times 10^{-5} M_{\rm pl}$
- The Schwinger effect has been taken into account and is not a problem for the baryogenesis mechanism.
- The Schwinger effect can nevertheless jeopardize non-perturbative gauge reheating.
- (P)reheating must be studied in more details

NASA/ESA/CSA James Webb Space Telescope, heart of M74

Back-up slides

ELECTROWEAK BARYOGENESIS

Helicity production

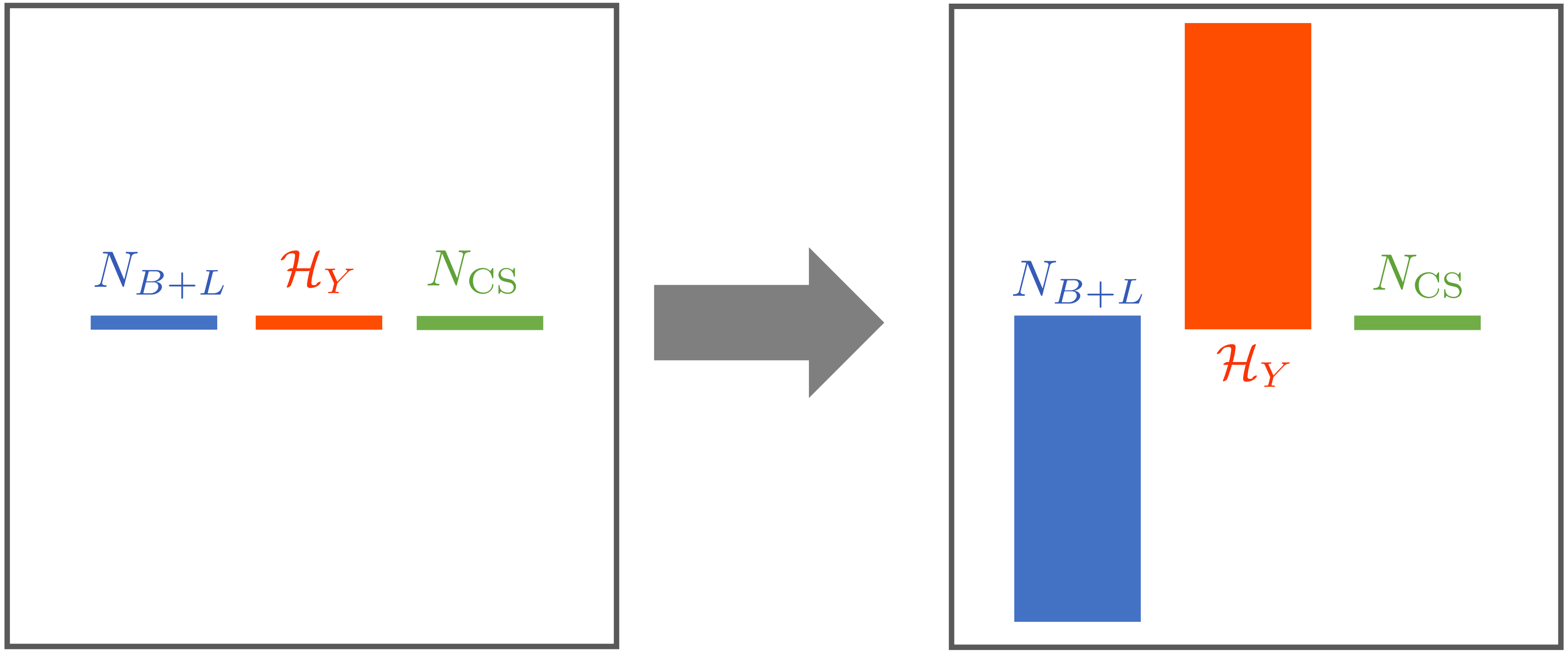
$$T \gtrsim 10^{12}\ \mathrm{GeV}$$

EW sphalerons are not in thermal equilibrium

Chiral anomaly in the SM (schematically)

$$\Delta N_{B+L} + c_1\, \Delta \mathcal{H}_Y = c_2\, \Delta N_{\mathrm{CS}}$$

this term vanishes



ELECTROWEAK BARYOGENESIS

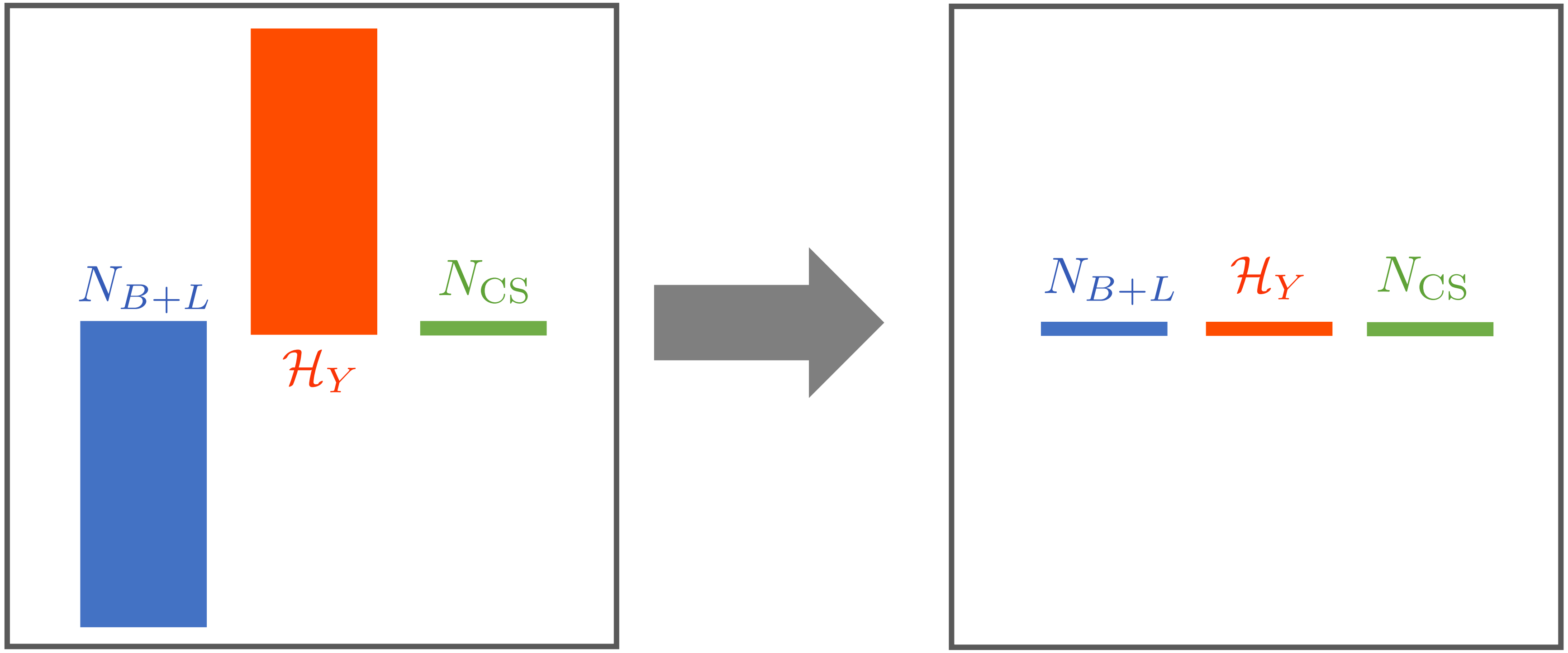
Chiral plasma instability (CPI)

$$T_{\rm CPI} \gtrsim 10^5 \ {\rm GeV}$$

Gauge sector is energytically more favorable

Chiral anomaly in the SM (schematically)

$$\Delta N_{B+L} + c_1 \, \Delta \mathcal{H}_Y = c_2 \, \Delta N_{\rm CS}$$



ELECTROWEAK BARYOGENESIS

Sphaleron washout

$$10^{12}\ \mathrm{GeV} \gtrsim T \gtrsim 130\ \mathrm{GeV}$$

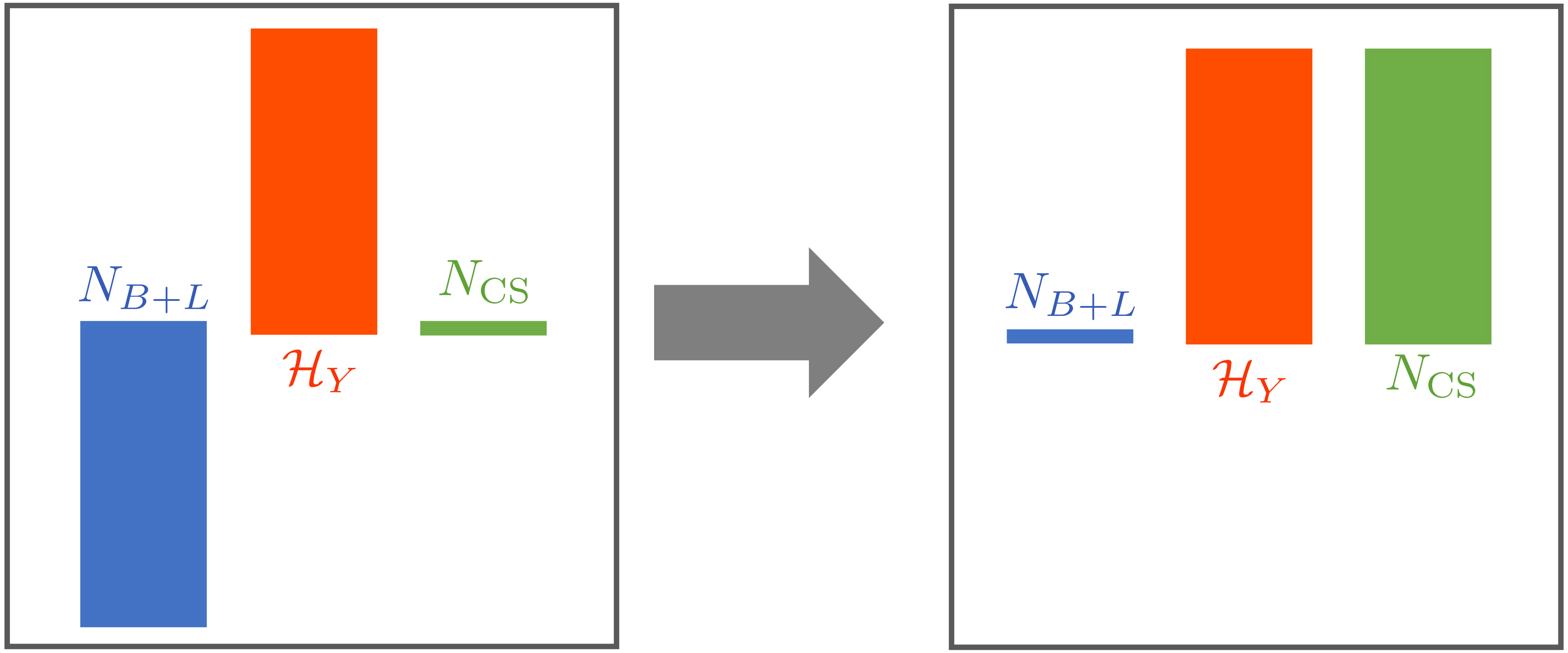
Chiral anomaly in the SM (schematically)

$$\Delta N_{B+L} + c_1\, \Delta \mathcal{H}_Y = c_2\, \Delta N_{\mathrm{CS}}$$

this term vanishes

Assume CPI is avoided, helicity is preserved if:

$$\mathcal{R}_m^{\mathrm{rh}} \gtrsim 1$$



ELECTROWEAK BARYOGENESIS

EW crossover

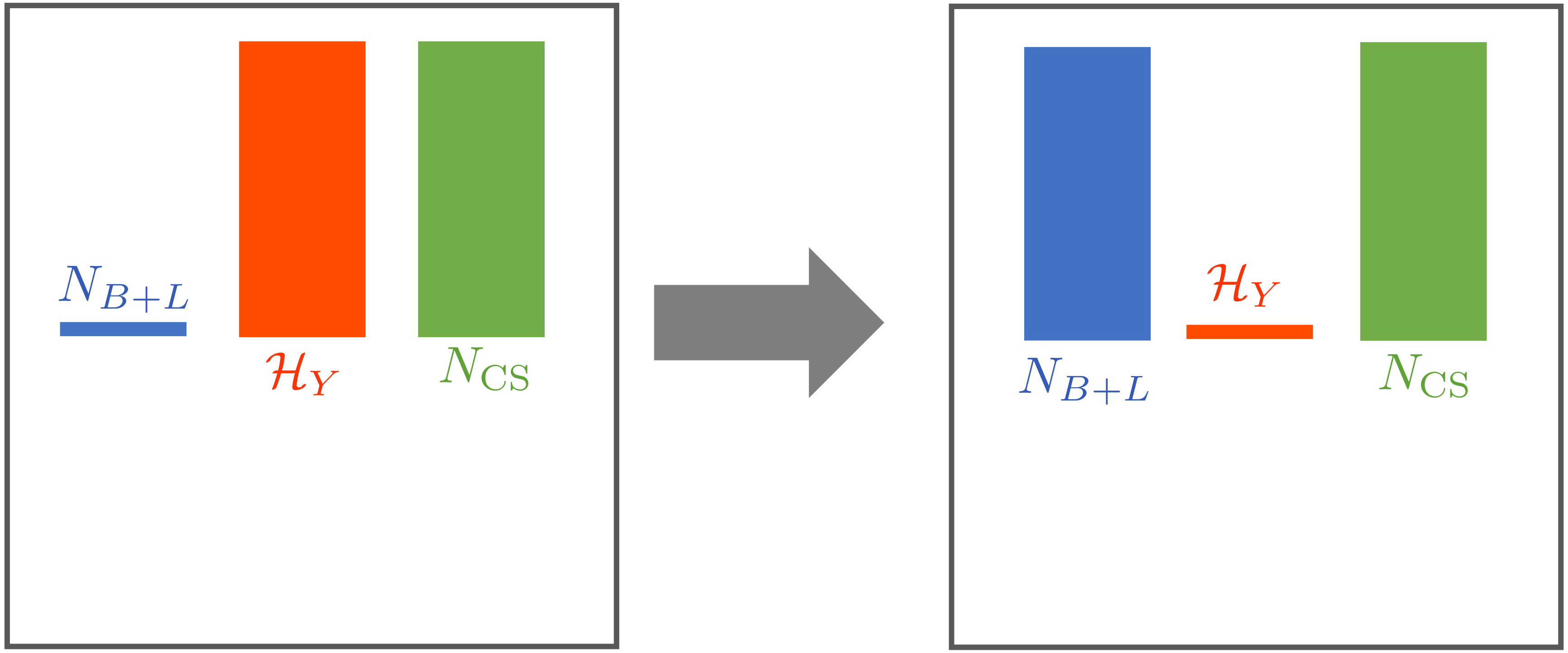
$$T \lesssim 130 \text{ GeV}$$

EW sphalerons are not in thermal equilibrium

Chiral anomaly in the SM (schematically)

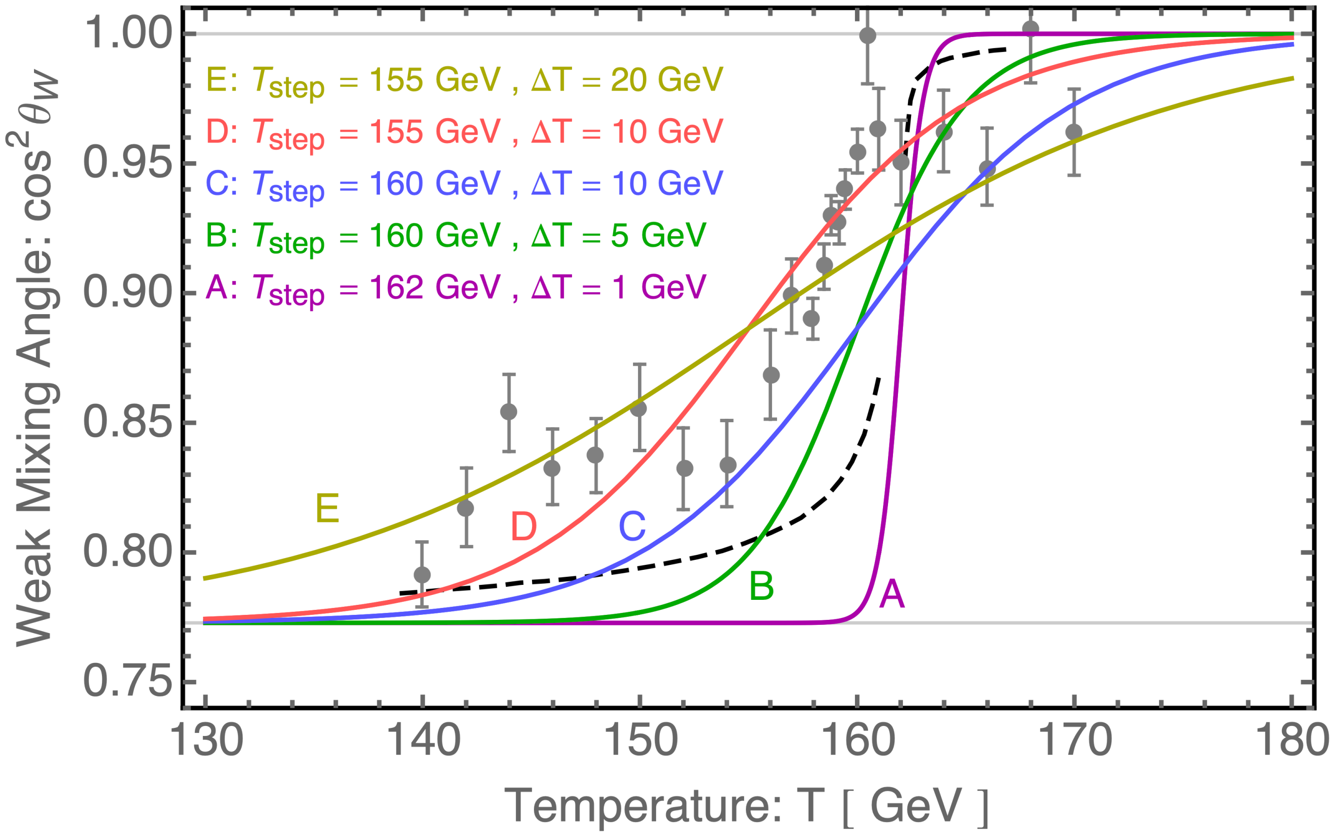
$$\Delta N_{B+L} + c_1\, \Delta \mathcal{H}_Y = c_2\, \Delta N_{\rm CS}$$

this term vanishes



EW crossover

Kajantie-Laine-Rummukainen-Shaposhnikov (1997)
Kamada-Long (2016)



$$\cos^2\theta_W = \frac{g^2}{g'^2+g^2} + \frac{1}{2}\frac{g'^2}{g'^2+g^2}\left(1+\tanh\left[\frac{T-T_{\rm step}}{\Delta T}\right]\right)$$

$$155\,\mathrm{GeV} \lesssim T_{\rm step} \lesssim 160\,\mathrm{GeV}$$

$$5\,\mathrm{GeV} \lesssim \Delta T \lesssim 20\,\mathrm{GeV}$$

EW crossover

D'Onofrio-Rummukainen-Tranberg (2014)
Kamada-Long (2016)

Including all contributions, the Boltzmann equation for the baryon-to-entropy ratio is

$$\frac{d\eta_B}{dx} = -\frac{111}{34}\gamma_{W\mathrm{sph}}\,\eta_B + \frac{3}{16\pi^2}(g'^2+g^2)\sin(2\theta_W)\frac{d\theta_W}{dx}\frac{\mathcal{H}_Y}{s}$$

$$x = \frac{T}{H(T)}$$

Dimensionless transport coefficient for the EW sphaleron (for T < 161 GeV)

$$\gamma_{W\mathrm{sph}} \simeq \exp\left(-147.7 + 107.9\,\frac{T}{130\,\mathrm{GeV}}\right)$$

The baryon-to-entropy ratio was found to become frozen, i.e. $\dot{\eta}_B = 0$, at a temperature $T \simeq 135$ GeV, hence:

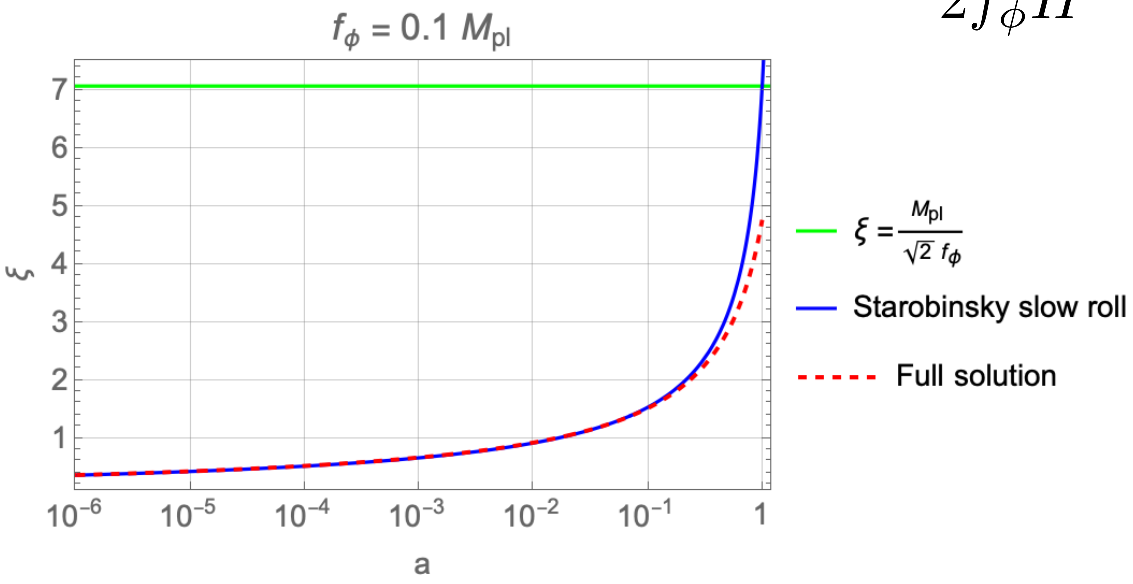
$$\eta_B \simeq 4\cdot 10^{-12}\, f_{\theta_W}\frac{\mathcal{H}_Y}{H_E^3}\left(\frac{H_E}{10^{13}\,\mathrm{GeV}}\right)^{\frac{3}{2}}\left(\frac{T_{\mathrm{rh}}}{T_{\mathrm{rh}}^{\mathrm{ins}}}\right)$$

THE SCHWINGER EFFECT

Instability parameter comparison

$$S \supset -\int d^4x\, \frac{\phi}{4f_\phi}\, Y_{\mu\nu}\tilde{Y}^{\mu\nu}$$

$$\xi = -\frac{\dot{\phi}}{2f_\phi H}$$

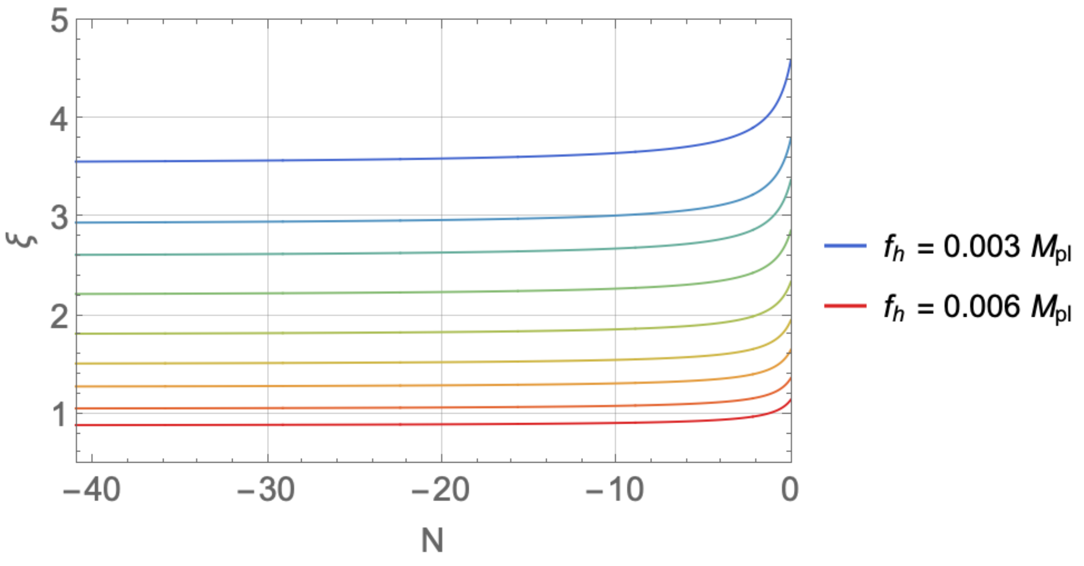


α-ATTRACTOR HILLTOP

$$S \supset -\int d^4x\, \frac{\cos^2\theta_W}{4}\frac{h^2}{f_h^2}\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$h \to \chi(h)$$

$$\xi = -\frac{e\sqrt{\frac{2}{3}}\,\chi}{6^{3/2}\xi_h^2}\,\frac{\dot{\chi}}{2Hf_\chi}$$



HIGGS INFLATION

THE SCHWINGER EFFECT
Effective conductivity

Domcke-Mukaida (2018)
Gorbar-Schmitz-Sobol-Vilchinskii (2021)

In the case of one Dirac fermion *f* with mass m_f and charge Q_f under a *U*(1) group with coupling *g*

$$\sigma_f = \frac{|g\,Q_f|^3}{6\pi^2}\,\frac{a}{H}\,\sqrt{2\rho_B}\,\coth\left(\pi\sqrt{\frac{\rho_B}{\rho_E}}\right)\exp\left(-\frac{\pi m_f^2}{\sqrt{2\rho_E}\,|g\,Q_f|}\right)$$

A fermion contributes if $\pi m_f^2 < \sqrt{2\rho_E}\,|gQ_f|$

When all SM fermions contribute: $\sigma \simeq Z\,\frac{a}{H}\,\sqrt{2\rho_B}\,\coth\left(\pi\sqrt{\frac{\rho_B}{\rho_E}}\right)$

$$Z_Y = \frac{41\,g'^3}{72\,\pi^2}$$

symmetric phase

α-ATTRACTOR
HILLTOP

$$Z_{\rm EM} = \frac{e^3}{\pi^2}$$

broken phase

HIGGS INFLATION

SCHWINGER EFFECT

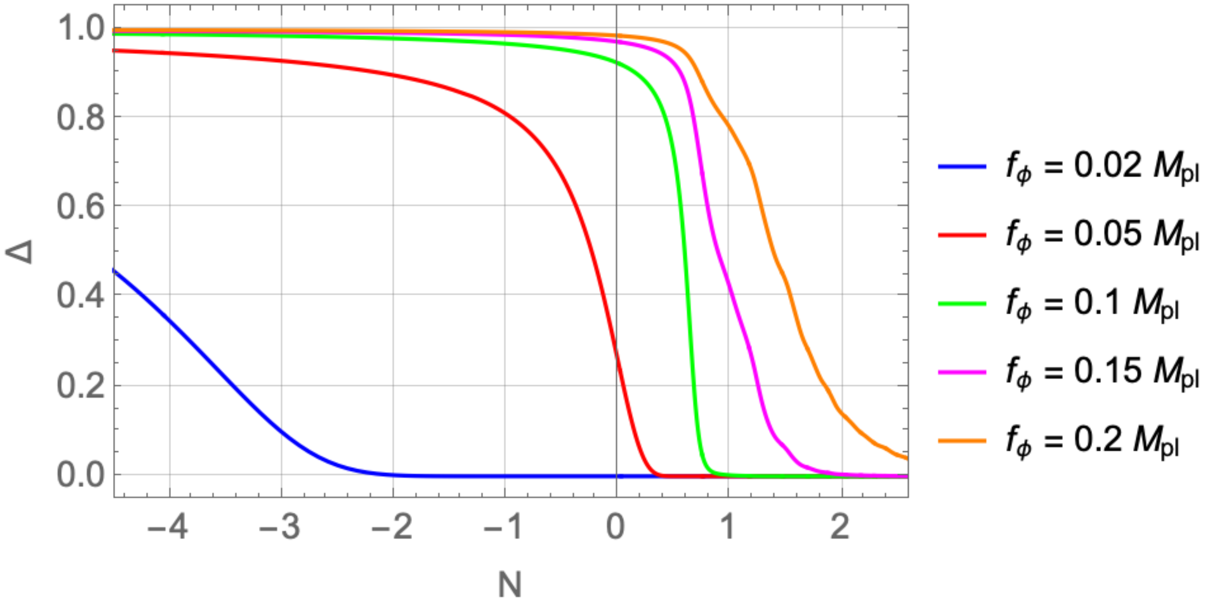
Bunch-Davies vacuum

Gorbar-Schmitz-Sobol-Vilchinskii (2021)

The BD vacuum amplitude of the modes that are still in the vacuum get damped by the ones that left it.

→ In the presence of the Schwinger effect, the BD vacuum is modified

$$A_\lambda(\tau, k) = \sqrt{\frac{\Delta(t)}{2k}} e^{-ik\tau} \qquad (\tau \to -\infty)$$



$$\Delta(t) = \exp\left(-\int_{-\infty}^{t} \hat{\sigma}(t')\, dt'\right)$$

$$\hat{\sigma} = \sigma/a$$

SCHWINGER EFFECT

Bunch-Davies vacuum

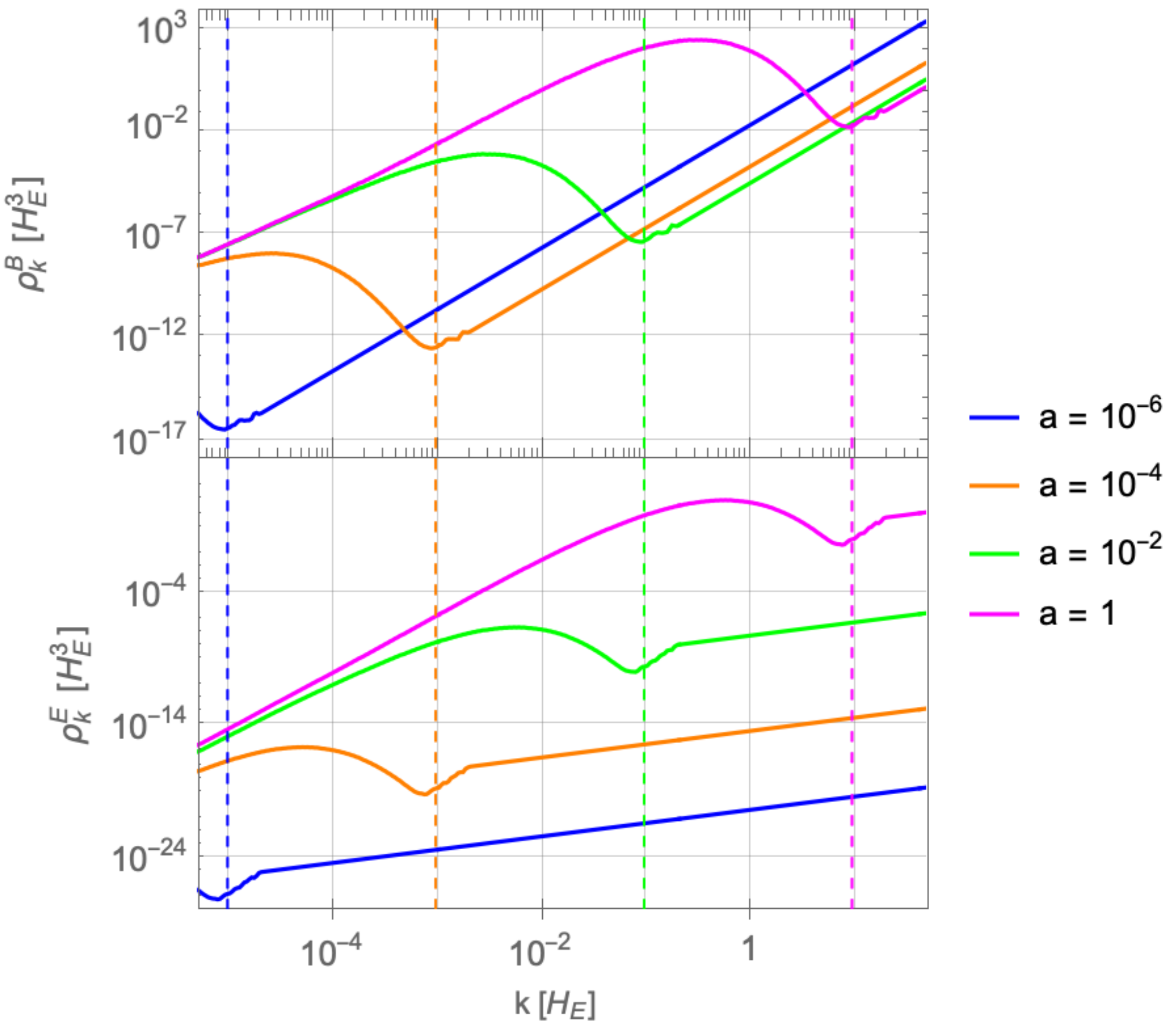
Gorbar-Schmitz-Sobol-Vilchinskii (2021)

This affects the cutoff scale

$$k_c = \left|\frac{a\dot{\phi}}{2f_\phi}\right| + \sqrt{\left(\frac{a\dot{\phi}}{2f_\phi}\right)^2 + \frac{a^2}{2}\left[\dot{\hat{\sigma}} + \hat{\sigma}\left(\frac{\hat{\sigma}}{2} + H\right)\right]}$$

instead of

$$k_c = |2\xi a H| = \left|\frac{a\dot{\phi}}{f_\phi}\right|$$



Numerical solving

Anber-Sabancilar (2015)
Domcke-Mukaida (2018)

$$A''_\lambda + \sigma A'_\lambda + k\left(k - \lambda \frac{a\,\dot\phi}{f_\phi}\right) A_\lambda = 0$$

$$\ddot\phi + 3H\dot\phi + V'(\phi) = \frac{\mathcal{G}}{f_\phi}$$

$$\rho_E = \frac{1}{a^4}\int_0^{k_c} dk\, \frac{k^2}{4\pi^2}\left(|A'_+|^2 + |A'_-|^2\right)$$

$$\rho_B = \frac{1}{a^4}\int_0^{k_c} dk\, \frac{k^4}{4\pi^2}\left(|A_+|^2 + |A_-|^2\right)$$

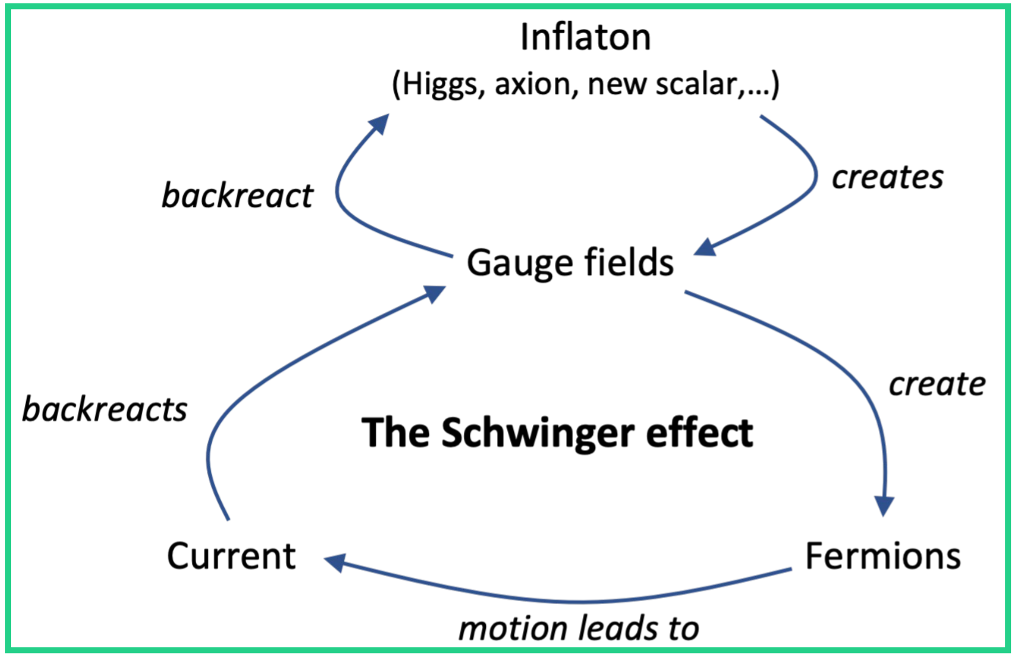
$$\mathcal{G} = \frac{1}{a^4}\int_0^{k_c} dk\, \frac{k^3}{2\pi^2}\left(|A_+A'_+| - |A_-A'_-|\right)$$

$$\sigma = \frac{|eQ|^3}{6\pi^2}\frac{a}{H}\sqrt{2\rho_B}\,\coth\left(\pi\sqrt{\frac{\rho_B}{\rho_E}}\right)\exp\left\{-\frac{\pi m^2}{\sqrt{2\rho_E}\,|eQ|}\right\}$$

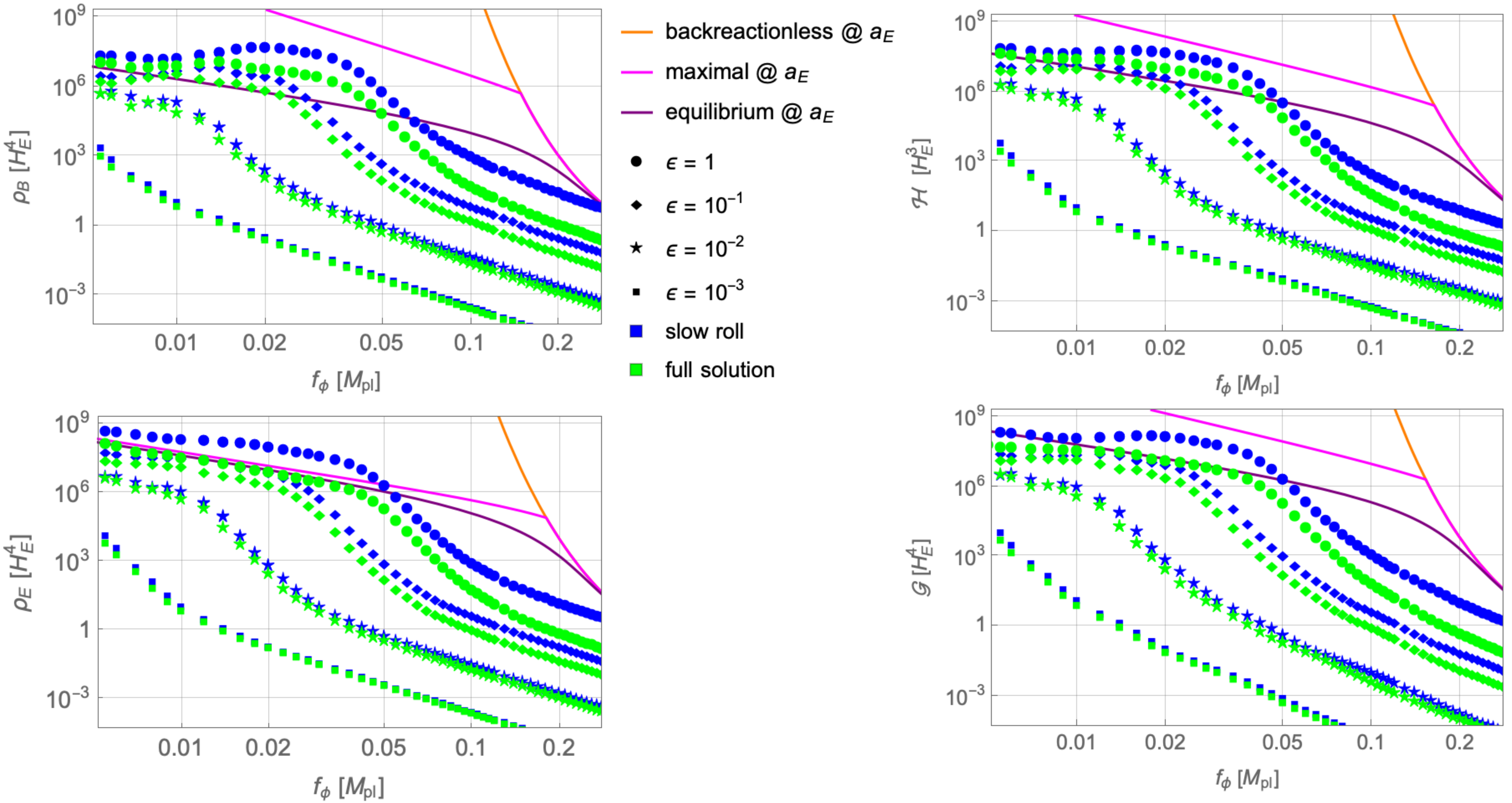
$$\rho_\psi = \lim_{V\to\infty}\frac{\sigma}{V}\int_V d^3x\,\frac{\langle \mathbf{A}\cdot\mathbf{E}\rangle}{a^4} = \frac{\sigma}{a^4}\int_{k_{\rm min}}^{k_c} dk\,\frac{k^2}{2\pi^2}\frac{d}{d\tau}\left(|A_+|^2 + |A_-|^2\right)$$

$$H^2 = \frac{\frac{1}{2}\dot\phi^2 + V + \rho_E + \rho_B + \rho_\psi}{3M_{\rm pl}^2}$$

← We do not assume any peculiar geometry of the Universe



Plasma observables



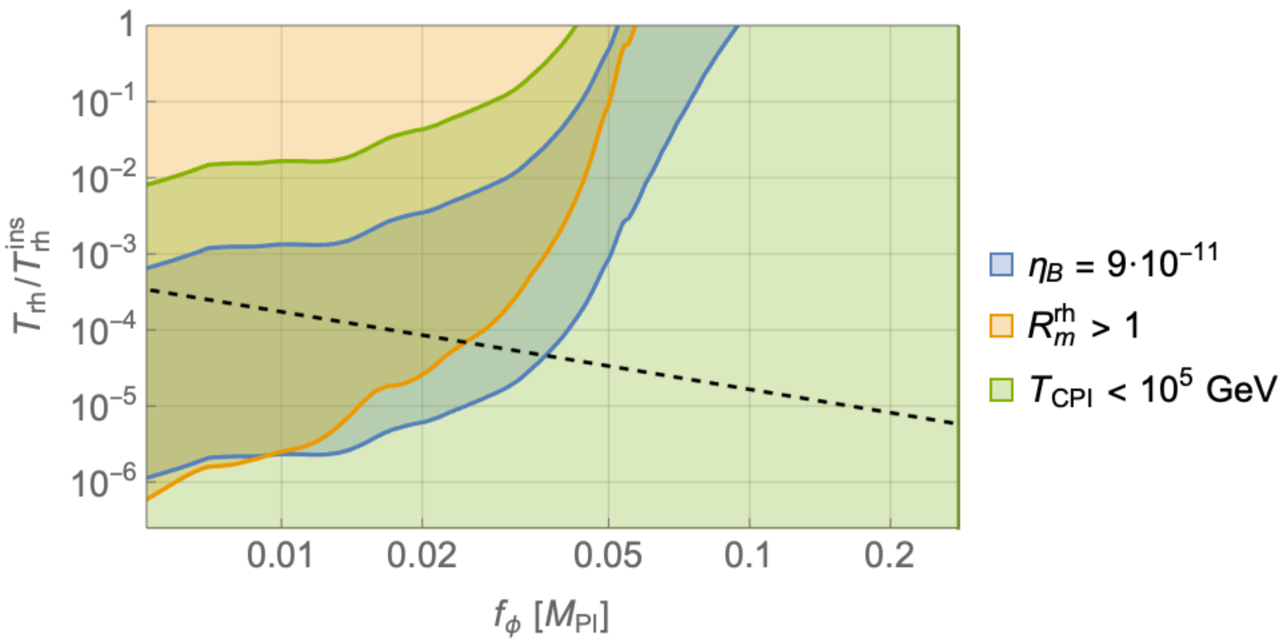
Baryogenesis parameter space

Starobinsky potential

$$V_\alpha(\phi) = \Lambda_\alpha^4 \left[1 - \exp\left(-\sqrt{\frac{2}{3\alpha}}\frac{|\phi|}{M_{\text{pl}}}\right)\right]^2$$

$$\frac{T_{\text{rh}}}{T_{\text{rh}}^{\text{ins}}} \simeq \sqrt{\frac{\Gamma_\phi}{H_E}} \simeq 1.9\ (0.8) \cdot 10^{-4} \left(\frac{0.01}{f_\phi/M_{\text{pl}}}\right)$$

for $\alpha = 1\ (100)$

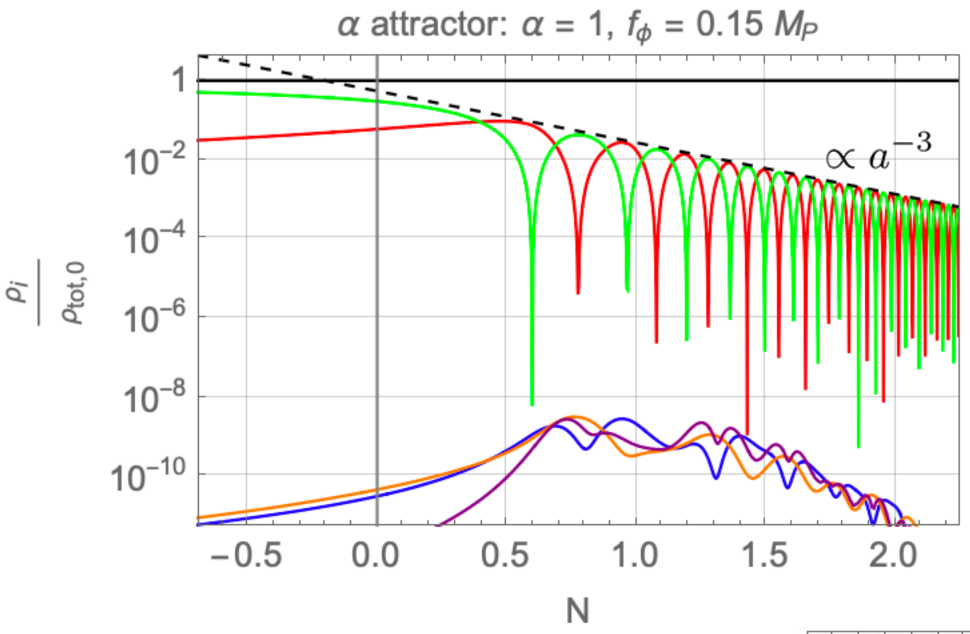


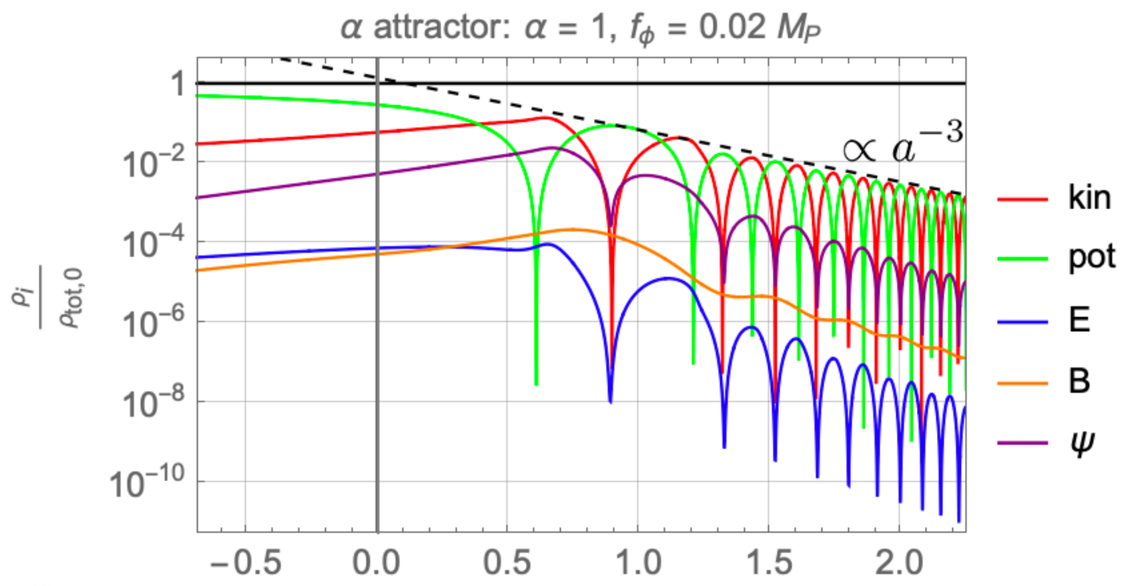
$$\Gamma_\phi \simeq \Gamma(\phi \to AA) \simeq \frac{m_\phi^3}{64\pi f_\phi^2}$$

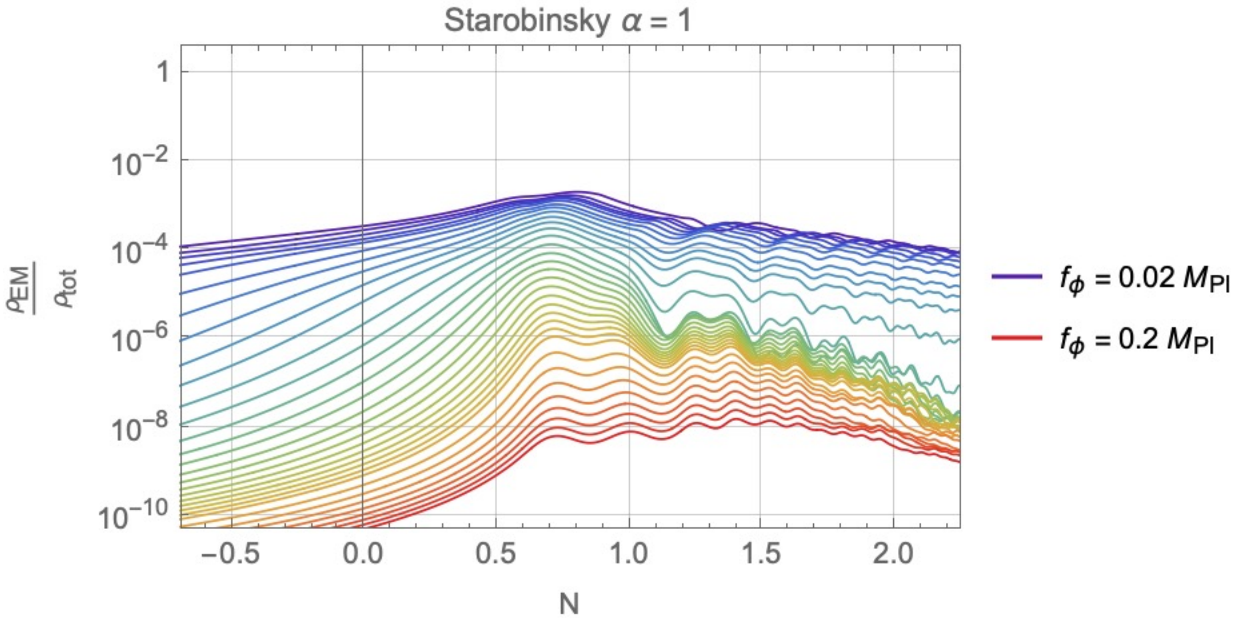
Adshead-Giblin-Scully-Sfakianakis (2015)

$$m_\phi^2 = \left.\frac{\partial^2 V_\alpha}{\partial \phi^2}\right|_{\phi=\phi_{\min}} = \frac{4\Lambda_\alpha^4}{3\alpha M_{\text{pl}}^2}$$

Solution beyond inflation

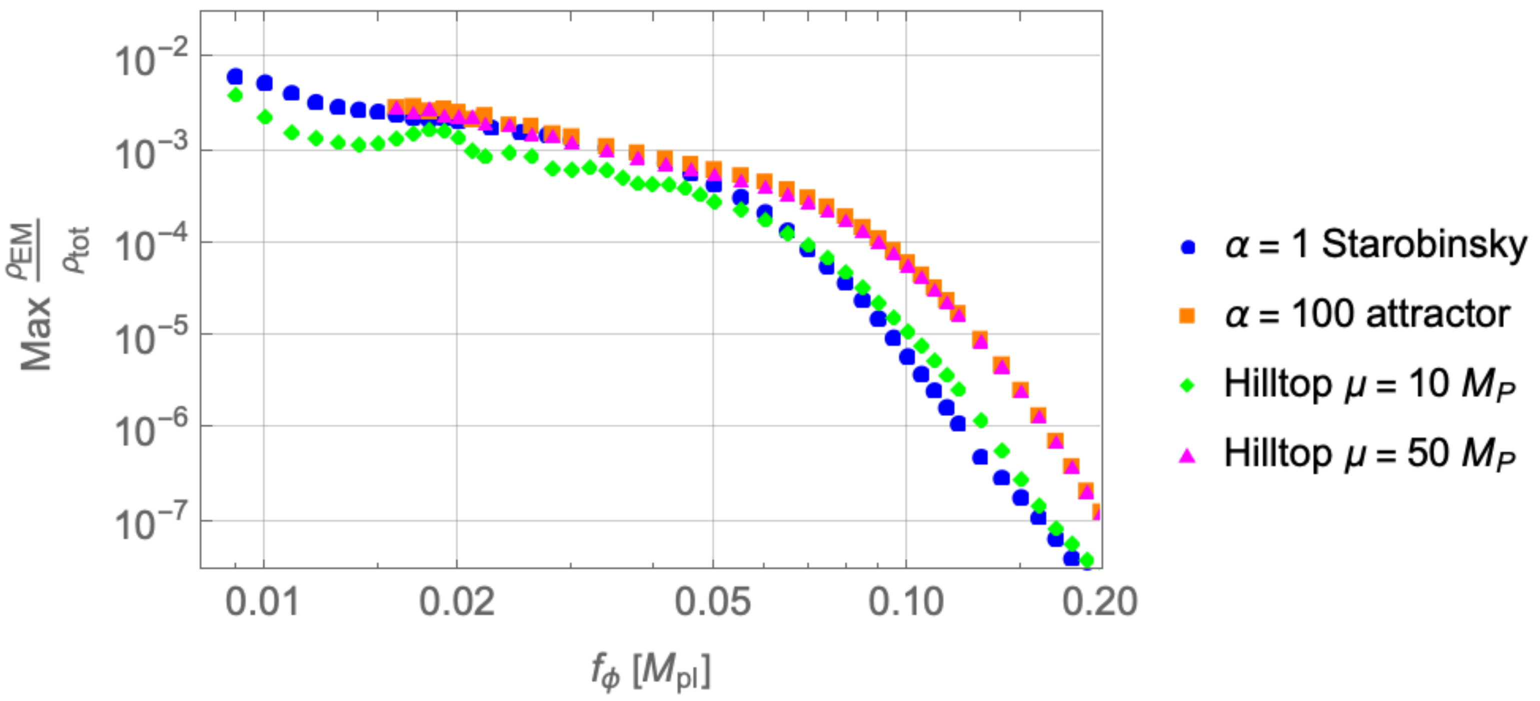






Preheating

Criterion : $$\frac{\rho_E + \rho_B}{\rho_{\rm tot}} \gtrsim 80\%$$ **Cuissa-Figueroa (2019)**



It is much harder to preheat the Universe when taking into account the Schwinger effect.