Magnetic Fields, Baryon Asymmetry, and Gravitational Waves from Pseudoscalar Inflation.

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Based on *arXiv:1707.07943 [hep-ph]*. In collaboration with

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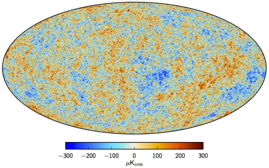
Pseudoscalar inflation coupled to gauge fields



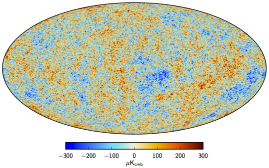
[PLANCK '15]

Inflation: Successful paradigm of early universe cosmology.
[Starobinsky '80] [Guth '81] [Linde '82] [Albrecht & Steinhardt '82]

- Homogeneity, isotropy on cosmological scales
- Seeds for structure formation on galactic scales

Big question: How to embed inflation into particle physics!?

Pseudoscalar inflation coupled to gauge fields



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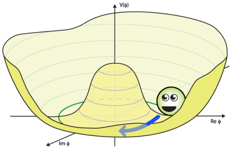
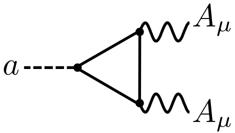
Big question: How to embed inflation into particle physics!?

Promising idea: Inflation driven by pseudoscalar (axion) field a
[Freese, Frieman, Olinto '90] [Adams, Bond, Freese, Frieman, Olinto '93]

- PNGB of spontaneously broken global symmetry $G_{\rm global}$
- Naturally flat potential, protected by shift symmetry
- Anomalies of global symmetry $\rightarrow$ coupling to gauge fields





$$\Rightarrow \qquad \mathscr{L}_{\rm eff} \supset \frac{a}{4\Lambda} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Recent work on the rich phenomenology of axion inflation

- Primordial magnetogenesis (and baryogenesis via decaying magnetic helicity):

  1503.05802 [astro-ph.CO] (Fujita, Namba, Tada, Takeda, Tashiro); 1507.00744 [hep-th] (Anber, Sabancilar);

  1606.08474 [astro-ph.CO] (Adshead, Giblin, Scully, Sfakianakis); 1611.02293 [hep-ph] (Cado, Sabancilar)

- Primordial black holes (as a fraction of dark matter):

  1511.08470 [astro-ph.CO] (Erfani); 1704.03464 [astro-ph.CO] (Domcke, Muia, Pieroni, Witkowski);

  1707.02441 [astro-ph.CO] (Garcia-Bellido, Peloso, Unal)

- Stochastic gravitational waves from inflation:

  1603.01287 [astro-ph.CO] (Binétruy, Domcke, Pieroni); 1608.04216 [astro-ph.CO] (Dimastrogiovanni, Fasiello, Fujita);

  1610.03763 [astro-ph.CO] (Garcia-Bellido, Peloso, Unal)

- Gravitational leptogenesis:

  1604.06520 [hep-ph] (Maleknejad); 1706.03765 [astro-ph.CO] (Caldwell, Devulder); 1708.08007 [astro-ph.CO] (Papageorgiou, Peloso)

- Signatures in the CMB power spectra:

  1612.08817 [astro-ph.CO] (Obata)

- See also recent work on theoretical aspects (perturbativity, thermalization, etc.):

  1512.06116 [astro-ph.CO] (Ferreira, Ganc, Noreña, Sloth); 1606.00459 [astro-ph.CO] (Peloso, Sorbo, Unal); 1706.00373 [astro-ph.CO] (Ferreira, Notari)

This talk: Correlation between magnetic fields, baryon asymmetry, and gravitational waves.

Gauge field production during inflation

Our analysis: Couple inflaton to the gauge field of the standard model hypercharge $U(1)_Y$

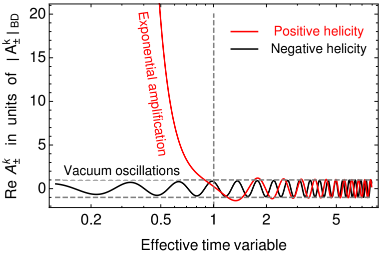
- Minimal scenario: Abelian rather than non-Abelian gauge field; $U(1)_Y$ part of the SM.
- Gauge field production during inflation $\rightarrow$ opportunity for primordial magnetogenesis.

Friedmann equation:

$$H^2 = \frac{1}{3M_{\rm Pl}^2}\left[\frac{1}{2}\dot{a}^2 + V(a) + \frac{1}{2}\left\langle \boldsymbol{E}^2\right\rangle + \frac{1}{2}\left\langle \boldsymbol{B}^2\right\rangle\right]$$

Equations of motion:

$$\ddot{a} + 3H\dot{a} + \frac{dV}{da} = \frac{1}{\Lambda}\left\langle \boldsymbol{EB}\right\rangle\,, \quad \Box\boldsymbol{A} = -\frac{a'}{\Lambda}\boldsymbol{\nabla}\times\boldsymbol{A}$$



- Axion-gauge-field coupling results in new source terms.
- Gauge field modes of one helicity (+ or −) are exponentially amplified.

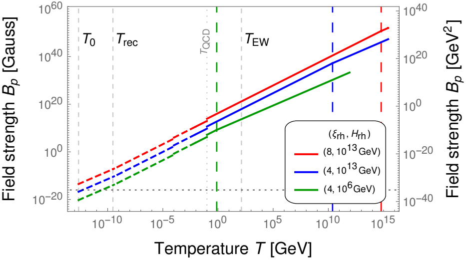
[Turner & Widrow '88] [Garretson, Field, Carroll '92] [Anber & Sorbo '06; '10] [Durrer, Hollenstein, Jain '11] [Barnaby & Peloso '11] [Sorbo '11] [Barnaby, Namba, Peloso '11] [Barnaby, Pajer, Peloso '12] [Meerburg & Pajer '13] [Linde, Mooij, Pajer '13]

Gauge field evolution after inflation

Physical strength and correlation length of the hypermagnetic $\boldsymbol{B}$ field at the end of inflation:

$$B_p = \left\langle \boldsymbol{B}^2 \right\rangle^{1/2} \sim 10^{-2}\,\frac{e^{\pi\xi}}{\xi^{5/2}}\,H^2\,, \qquad \lambda_p = \langle \lambda \rangle \sim \frac{\xi}{H}\,, \qquad \xi = \frac{1}{2H}\left|\frac{\dot a}{\Lambda}\right|$$

Our analysis: Instant reheating approximation + simple scaling laws after inflation. Better treatment would require dedicated numerical magnetohydrodynamics (MHD) simulation.



Adiabatic dilution at high temperature

$$B_p \propto \frac{1}{R^2}\,, \qquad \lambda_p \propto R$$

Inverse cascade below critical $T_{\rm ic}$

$$B_p \propto \frac{1}{R^{7/3}}\,, \qquad \lambda_p \propto R^{5/3}$$

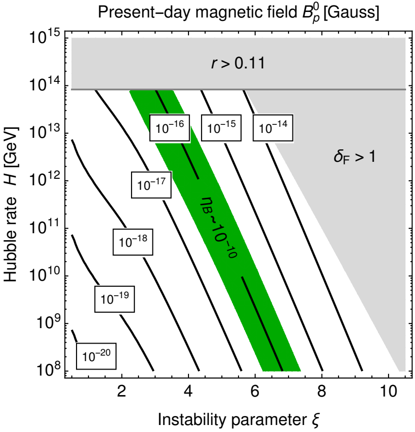
Inverse cascade: Alfvén waves generate plasma turbulence on scales of size $\lambda_T \sim v_A t$. Once $\lambda_T \sim \lambda_p$, λ_p continues to scale like λ_T. Transfer of energy from small to large scales.

[Banerjee & Jedamzik '04] [Brandenburg & Subramanian '05] [Kandus, Kunze, Tsagas '11] [Widrow, Ryu, Schleicher, Subramanian, Tsagas, Treumann '12] [Kahniashvili, Tevzadze, Brandenburg, Neronov '13] [Durrer & Neronov '13]

Present-day magnetic field

Physical strength and correlation length of the hypermagnetic ***B*** field in the present epoch:

$$B_p^0 \simeq 3 \times 10^{-19}\,\mathrm{G} \left(\frac{e^{2\pi\xi}}{\xi^4}\right)^{1/3} \left(\frac{H}{10^{13}\,\mathrm{GeV}}\right)^{1/2}, \qquad \lambda_p^0 \simeq \frac{1.0\,\mathrm{pc}}{(4\pi)^{1/2}} \left(\frac{B_p^0}{10^{-14}\,\mathrm{G}}\right)$$



Our result:

- Simple estimate. But, completely model-independent! No assumptions about $V(a)$, neglect dynamics of RH.

Compare with experimental bounds:

- CMB anisotropies, ionisation, etc.: [PLANCK '15]

$$B_p^0 \lesssim 10^{-9}\,\mathrm{G} \quad \checkmark$$

- Indications from blazars / γ rays: [Takahashi et al. '13] [Chen, Buckley, Ferrer '15]

$$B_p^0 \gtrsim 10^{-17} \cdots 10^{-14}\,\mathrm{G} \quad ???$$

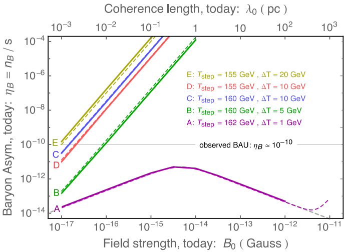
Baryogenesis via decaying hypermagnetic helicity

- Hypermagnetic field generated during inflation is maximally helical

$$\mathcal{H}_Y = \int_V d^3\boldsymbol{x}\, \boldsymbol{A}\cdot\boldsymbol{B} = \frac{1}{R^3}\int_V d^3\boldsymbol{x} \int \frac{d^3\boldsymbol{k}}{(2\pi)^3}\, k\left(\left|A_+^k\right|^2 - \left|A_-^k\right|^2\right), \qquad \left|A_+^k\right| \gg \left|A_-^k\right|$$

- Opportunity for baryogenesis via the chiral triangle anomaly in the standard model

$$\Delta B = \Delta L = N_g\left(\Delta N_{\mathrm{CS}} - \frac{g_Y^2}{16\pi^2}\Delta\mathcal{H}_Y\right)$$



- Slow decay of $\mathcal{H}_Y$ around the time of the EWPT results in nonzero baryon asymmetry.
- Solve complicated system of kinetic equations (incl. Yukawas, chiral magnetic effect, etc.).
- Observed value $\eta_B^{\mathrm{obs}} \sim 10^{-10}$ reproduced for

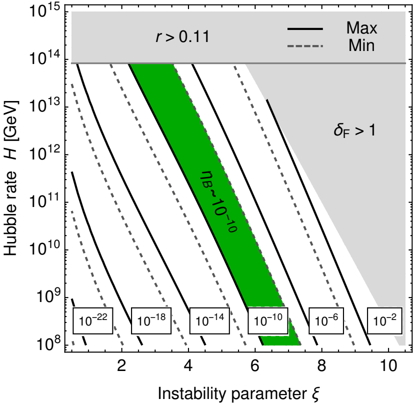
$$\boxed{B_p^0 \sim 10^{-16}\,\mathrm{G}}$$

[Giovannini & Shaposhnikov '98; '98] [Bamba '06] [Anber & Sabancilar '15] [Fujita & Kamada '16] [Kamada & Long '16; '16] [Cado & Sabancilar '16]

Final baryon asymmetry

Our analysis of primordial magnetogenesis + BAU calculation by [Kamada & Long '16]

$$\eta_B \simeq (6.5 \times 10^{-3} \cdots 3.8) \times 10^{-17} \left(\frac{e^{2\pi\xi}}{\xi^4}\right) \left(\frac{H}{10^{13}\,\mathrm{GeV}}\right)^{3/2}$$



Prediction:

- Successful baryogenesis (mostly) based on standard model physics!

$$\eta_B \sim 10^{-10} \quad \Leftrightarrow \quad B_p^0 \sim 10^{-16}\,\mathrm{G}$$

- IGMFs have positive helicity. Testable in future (blazar halo) observations!

Largest uncertainties:

- Effect of reheating on the primordial gauge fields, exact behavior of θ_W.

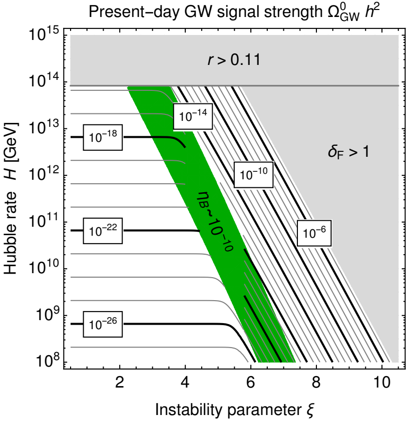
[Fujita et al. '15] [Adshead et al'16]

GW production during inflation

Gauge field perturbations source tensor perturbations in the metric → stochastic GWs

[Cook & Sorbo '12] [Anber & Sorbo '12] [Domcke, Pieroni, Bintruy '16] [Garcia-Bellido, Peloso, Unal '16]

$$\Omega^0_{\rm GW} h^2 \simeq \frac{\Omega^0_{\rm rad} h^2}{12} \left(\frac{g_*}{g^0_*}\right) \left(\frac{g^0_{*,s}}{g_{*,s}}\right)^{4/3} \left(\frac{H}{\pi M_{\rm Pl}}\right)^2 \left[1 + \left(\frac{H}{M_{\rm Pl}}\right)^2 (f_L(\xi) + f_R(\xi))\, e^{4\pi\xi}\right]$$



Successful baryogenesis requires

$$\xi \sim 5 \quad \Rightarrow \quad \Lambda \sim 3 \times 10^{17}\,\mathrm{GeV}$$

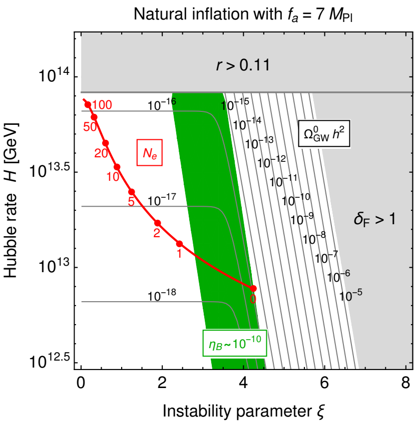
- Inflaton must be weakly coupled. Otherwise, overproduction of BAU.
- Always stay in the weak field regime. Gauge field production never dominates inflationary dynamics.
- Upper bound on GW signal strength

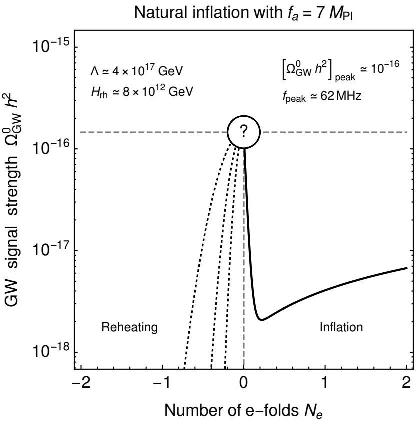
$$\Omega^0_{\rm GW} h^2 \lesssim 10^{-14}$$

Peak in the spectrum of primordial GWs

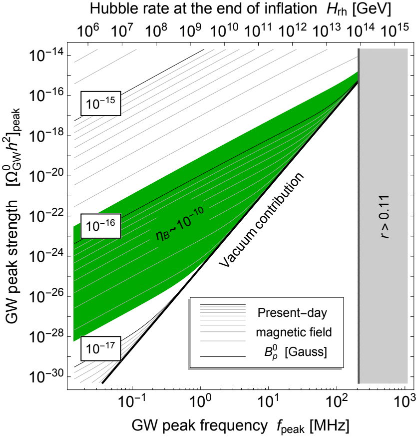
Inflationary trajectories in the ξ–H parameter plane

- $\xi \propto |\dot{a}|/H$ increases towards the end of inflation $\rightarrow$ feature in the GW spectrum!
- Frequency determined by H at the end of inflation: $f_{\rm peak} \simeq 71\,\mathrm{MHz}\,\left(H/10^{13}\,\mathrm{GeV}\right)^{1/2}$





Correlation between GWs and BAU



Our results so far

$$B_p^0(\xi, H)\,, \quad \eta_B(\xi, H)\,, \quad \Omega^0_{\mathrm{GW}} h^2(\xi, H)$$

Trade ξ and H for B_p^0 and f_{peak}

$$\xi = \xi\left(B_p^0, H\right)\,, \quad H = H\left(f_{\mathrm{peak}}\right)$$

Correlation between physical observables

$$B_p^0\left(\Omega^0_{\mathrm{GW}} h^2, f_{\mathrm{peak}}\right)\,, \quad \eta_B\left(\Omega^0_{\mathrm{GW}} h^2, f_{\mathrm{peak}}\right)$$

- Weak signal at high frequencies; but in principle, unique signature of baryogenesis via decaying helicity. Stronger GWs result in the overproduction of baryon number.

Take-Home Messages

Pseudoscalar (axion) inflation coupled to the standard model hypercharge gauge sector

$$\mathscr{L}_{\rm eff} \supset \frac{a}{4\Lambda} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Rich phenomenology:

- Explosive gauge field production during inflation $\rightarrow$ primordial magnetogenesis.
- Maximally helical hypermagnetic field $\rightarrow$ baryogenesis via the chiral anomaly.
- Gauge field production feeds into tensor spectrum $\rightarrow$ source of stochastic GWs.

Our main results:

- Baryogenesis is feasible for a weakly coupled pseudoscalar inflaton field

$$\eta_B \sim 10^{-10} \quad \leftrightarrow \quad B_p^0 \sim 10^{-16}\,\mathrm{G} \quad \leftrightarrow \quad \Lambda \sim 3 \times 10^{17}\,\mathrm{GeV}$$

- Peak in GW spectrum at MHz frequencies. Out of reach of present-day technology; but in principle, smoking-gun signal for baryogenesis via decaying helicity.

Thank you for your attention!

Supplementary Material

Gauge field production during inflation

Equations of motion for the vector field modes:

$$\left[\frac{\partial^2}{\partial\tau^2} + \omega_k^2(\tau,\xi)\right] A_\pm^k(\tau) = 0\,, \quad \omega_k^2(\tau,\xi) = k^2\left[1 - \frac{(\pm 2\xi)}{(-k\tau)}\right]$$

Tachyonic instability, $\omega_k^2 < 0$, depending on the value of the instability parameter ξ:

$$\xi = \frac{1}{2H}\frac{\dot{a}}{\Lambda}$$

For constant ξ, the modes equations are solved exactly by Whittaker W functions:

$$A_\pm^k(\tau) = \frac{1}{\sqrt{2k}}\exp\left[\pm\frac{\pi\xi}{2}\right] W_{\mp i\xi,1/2}(2ik\tau)$$

Physical strength and correlation length of the hypermagnetic $\boldsymbol{B}$ field at the end of inflation:

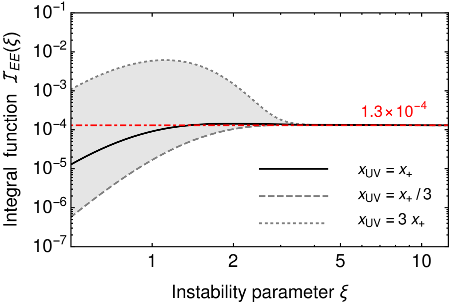
$$\boldsymbol{B} = \frac{1}{R^2}\boldsymbol{\nabla}\times\boldsymbol{A}\,, \qquad B_p = \left\langle \boldsymbol{B}^2\right\rangle^{1/2} \sim 10^{-2}\,\frac{e^{\pi\xi}}{\xi^{5/2}}\,H^2\,, \qquad \lambda_p = \langle\lambda\rangle \sim \frac{\xi}{H}$$

[Turner & Widrow '88] [Garretson, Field, Carroll '92] [Anber & Sorbo '06; '10] [Durrer, Hollenstein, Jain '11] [Barnaby & Peloso '11] [Sorbo '11] [Barnaby, Namba, Peloso '11] [Barnaby, Pajer, Peloso '12] [Meerburg & Pajer '13] [Linde, Mooij, Pajer '13]

Whittaker integral function $\mathcal{I}_{EE}$

Energy density stored in the hyperelectric ***E*** field:

$$\rho_{EE} = \frac{1}{2}\left\langle \boldsymbol{E}^2 \right\rangle = \frac{1}{2R^4}\int \frac{d^3\boldsymbol{k}}{(2\pi)^3}\left|\frac{\partial}{\partial\tau}A_+^k\right|^2 = \mathcal{I}_{EE}(\xi)\,\frac{e^{2\pi\xi}}{\xi^3}\,H^4$$

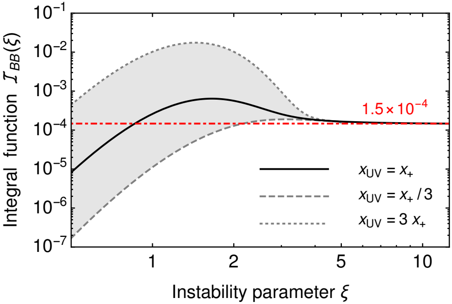


$$\mathcal{I}_{EE}(\xi) = \frac{\xi^3}{8\pi^2}\,e^{-\pi\xi}\int_0^{x_{\rm UV}} dx\, x^3\left|\frac{\partial}{\partial x}W_{\kappa_+,1/2}(-2ix)\right|^2$$

Whittaker integral function $\mathcal{I}_{BB}$

Energy density stored in the hypermagnetic ***B*** field:

$$\rho_{BB} = \frac{1}{2}\left\langle \boldsymbol{B}^2 \right\rangle = \frac{1}{2R^4}\int \frac{d^3\boldsymbol{k}}{(2\pi)^3}\, k^2 \left| A_+^k \right|^2 = \mathcal{I}_{BB}(\xi)\, \frac{e^{2\pi\xi}}{\xi^5}\, H^4$$

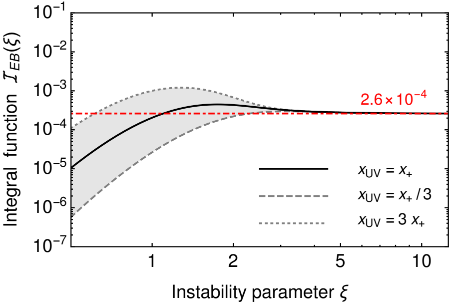


$$\mathcal{I}_{BB}(\xi) = \frac{\xi^5}{8\pi^2}\, e^{-\pi\xi} \int_0^{x_{\rm UV}} dx\, x^3 \left| W_{\kappa_+,1/2}(-2ix) \right|^2$$

Whittaker integral function $\mathcal{I}_{EB}$

Chern-Simons density $\langle \boldsymbol{EB} \rangle = -\frac{1}{4} \langle F\tilde{F} \rangle$ of the hyper-EM field:

$$\rho_{EB} = \frac{1}{2}\langle \boldsymbol{EB} \rangle + \frac{1}{2}\langle \boldsymbol{BE} \rangle = -\frac{1}{2R^4}\int \frac{d^3\boldsymbol{k}}{(2\pi)^3}\, k\, \frac{\partial}{\partial \tau}\left|A_+^k\right|^2 = -\mathcal{I}_{EB}(\xi)\,\frac{e^{2\pi\xi}}{\xi^4}\,H^4$$

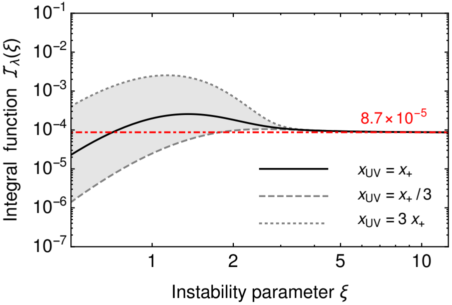


$$\mathcal{I}_{EB}(\xi) = \frac{-\xi^4}{8\pi^2}\, e^{-\pi\xi}\int_0^{x_{\rm UV}} dx\, x^3\, \frac{\partial}{\partial x}\left|W_{\kappa_+,1/2}(-2ix)\right|^2$$

Whittaker integral function $\mathcal{I}_\lambda$

Physical correlation length of the hypermagnetic ***B*** field:

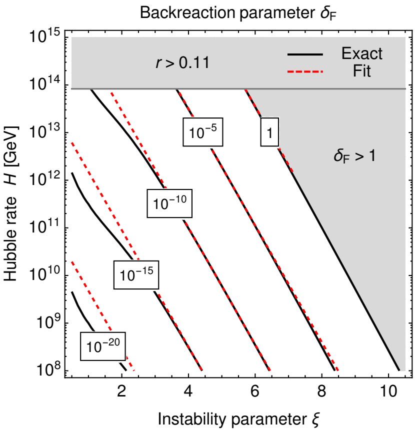
$$\lambda_p = \frac{1}{\rho_{BB}} \frac{1}{2R^4} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{2\pi R}{k} k^2 \left|A_+^k\right|^2 = \xi \, \frac{\mathcal{I}_\lambda(\xi)}{\mathcal{I}_{BB}(\xi)} \frac{2\pi}{H}$$



$$\mathcal{I}_\lambda(\xi) = \frac{\xi^4}{8\pi^2} e^{-\pi\xi} \int_0^{x_{\rm UV}} dx\, x^2 \left| W_{\kappa_+,1/2}(-2ix) \right|^2$$

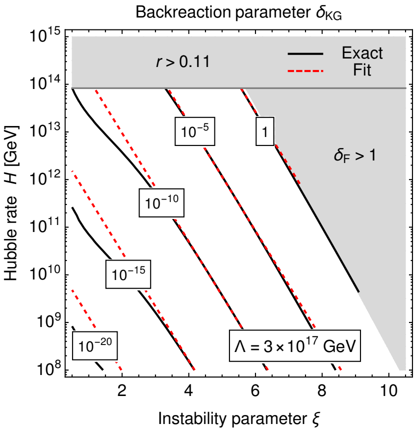
Backreaction parameters

Correction to the Friedmann equation



$$\delta_F = \frac{\rho_{EE} + \rho_{BB}}{3H^2 M_{Pl}^2}$$

Correction to the Klein-Gordon equation



$$\delta_{KG} = \left| \frac{\rho_{EB}/\Lambda}{3H\dot{a}} \right|$$

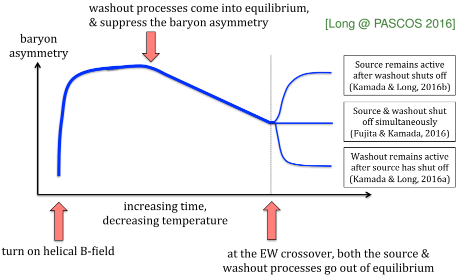
Baryogenesis via decaying hypermagnetic helicity

- Hypermagnetic field generated during inflation is maximally helical

$$\mathcal{H}_Y = \int_V d^3\boldsymbol{x}\, \boldsymbol{A}\cdot\boldsymbol{B} = \frac{1}{R^3}\int_V d^3\boldsymbol{x}\int\frac{d^3\boldsymbol{k}}{(2\pi)^3}\, k\left(\left|A_+^k\right|^2 - \left|A_-^k\right|^2\right)\,, \qquad \left|A_+^k\right| \gg \left|A_-^k\right|$$

- Opportunity for baryogenesis via the chiral triangle anomaly in the standard model

$$\Delta B = \Delta L = N_g\left(\Delta N_W^{\mathrm{CS}} - \frac{g_Y^2}{16\pi^2}\Delta\mathcal{H}_Y\right)$$



Competition between

- $B{+}L$ production from $\Delta\mathcal{H}_Y \neq 0$

$$\frac{d}{dt}\frac{\mathcal{H}_Y}{V} \simeq -\frac{2}{\sigma}\left\langle \boldsymbol{B}\cdot\boldsymbol{\nabla}\times\boldsymbol{B}\right\rangle$$

- $B{+}L$ washout by EW sphalerons

$$\Gamma_{\mathrm{sph}} \simeq 18\,\alpha_W^5\, T^4$$

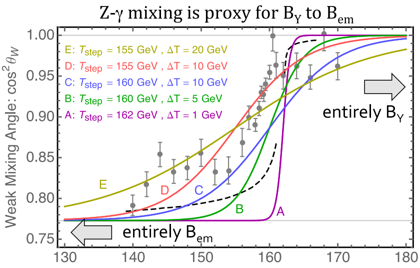
[Giovannini & Shaposhnikov '98; '98] [Bamba '06] [Anber & Sabancilar '15] [Fujita & Kamada '16] [Kamada & Long '16; '16] [Cado & Sabancilar '16]

Evolution during the electroweak crossover

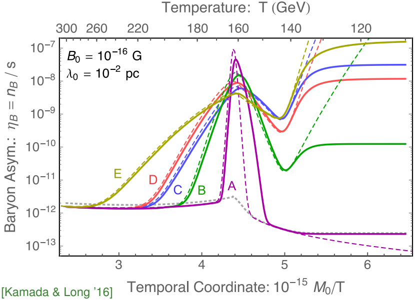
Source term during the electroweak crossover:

$$S = \frac{H}{8\pi^2 s}\frac{\mathcal{H}_Y}{V}\left[-\partial_T\,\theta_W(T)\right]\sin\left[2\theta_W(T)\right]$$

Efficiency controlled by temperature dependence of the weak mixing angle:



[Kamada & Long '16]



[Kamada & Long '16]

- Discrepancy between analytical calculation and lattice simulation.
  [Kajantie, Laine, Rummukainen, Shaposhnikov '96]
  [D'Onofrio & Rummukainen '15]

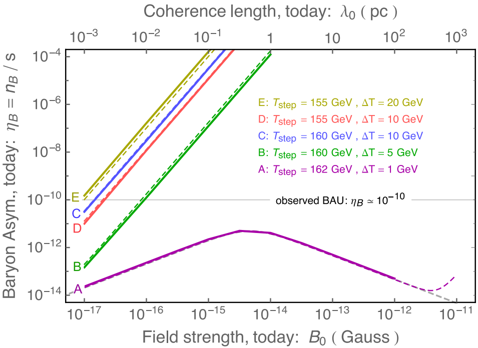
- Use phenomenological ansatz:

$$\cos^2\theta_W = c_0^2 + \frac{1-c_0^2}{2}\left[1+\tanh\left(\frac{T-T_{step}}{\Delta T}\right)\right]$$

Final baryon asymmetry

- Solve complicated system of kinetic equations (incl. SM Yukawa interactions, etc.).
- Numerical result well reproduced by approximate fit formula:

$$\eta_B \simeq \frac{17}{37}\left[\left(g_W^2+g_Y^2\right)\frac{S}{\gamma_{\rm w,sph}}\right], \quad \gamma_{\rm w,sph} \simeq \exp\left[-147.7+107.9\left(\frac{T}{130\,\mathrm{GeV}}\right)\right]$$



- Observed baryon asymmetry, $\eta_B^{\rm obs} \sim 10^{-10}$, reproduced for

$$B_p^{\rm ew} \sim (0.1\,\mathrm{GeV})^2$$

or equivalently

$$B_p^0 \sim 10^{-16}\,\mathrm{G}$$

- How to obtain such a field strength from magnetogenesis?

GW production during inflation

[Cook & Sorbo '12] [Anber & Sorbo '12] [Domcke, Pieroni, Bintruy '16] [Garcia-Bellido, Peloso, Unal '16; '17]

Gauge field perturbations source tensor perturbations in the metric:

$$\left[\frac{\partial^2}{\partial\tau^2} - \frac{2}{\tau}\frac{\partial}{\partial\tau} + k^2\right] h_\pm(\tau,\boldsymbol{k}) = \frac{2}{M_{\mathrm{Pl}}^2}\Pi_\pm^{ij}(\boldsymbol{k})\, T_{ij}(\tau,\boldsymbol{k})$$

$$T_{ij}(\tau,\boldsymbol{k}) = -R^2(\tau)\int\frac{d^3\boldsymbol{q}}{(2\pi)^{3/2}}\left[E_i(\tau,\boldsymbol{q})\,E_j(\tau,\boldsymbol{k}-\boldsymbol{q}) + B_i(\tau,\boldsymbol{q})\,B_j(\tau,\boldsymbol{k}-\boldsymbol{q})\right]$$

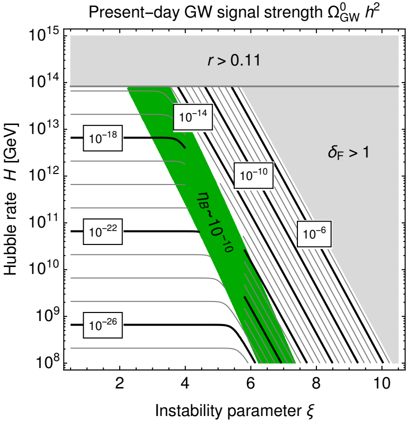
- $h_\pm$: Polarization eigenstates of the transverse-traceless tensor perturbations
- $\Pi_\pm^{ij}$: Polarization tensor; T_{ij}: energy-momentum tensor induced by the gauge fields:

Stochastic spectrum of chiral gravitational waves: $\mathcal{O}\left(H^4\right)$ term amplified by $e^{4\pi\xi}$.

$$\Omega_{\mathrm{GW}}^0 h^2 \simeq \frac{\Omega_{\mathrm{rad}}^0 h^2}{12\pi^2}\left(\frac{g_*}{g_*^0}\right)\left(\frac{g_{*,s}^0}{g_{*,s}}\right)^{4/3}\left(\frac{H}{M_{\mathrm{Pl}}}\right)^2\left[1 + \left(\frac{H}{M_{\mathrm{Pl}}}\right)^2 \left(f_L(\xi) + f_R(\xi)\right) e^{4\pi\xi}\right]$$

- Numerical fit functions: $f_L(\xi) \sim 10^{-7}/\xi^6$ and $f_R(\xi) \sim 10^{-9}/\xi^6$.

Expected GW signal strength



Successful baryogenesis requires

$$\xi = \frac{1}{2H}\frac{\dot{a}}{\Lambda} \sim 5$$

Slow-roll inflation ends once

$$\varepsilon \simeq \frac{\dot{a}^2}{2H^2 M_{\rm Pl}^2} \simeq \frac{2\xi^2\Lambda^2}{M_{\rm Pl}^2} \sim 1$$

This fixes the suppression scale Λ

$$\Lambda \simeq \frac{M_{\rm Pl}}{\sqrt{2}\xi} \sim 3 \times 10^{17}\,\mathrm{GeV}$$

- Inflaton must be weakly coupled. Otherwise, overproduction of BAU.
- Weak field regime: Gauge field production never dominates inflationary dynamics.
- Upper bound on GW signal strength: $\Omega^0_{\rm GW} h^2 \lesssim 10^{-14}$