Baryon Asymmetry and Gravitational Waves from Pseudoscalar Inflation.

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Based on *arXiv:1706.xxxxx [hep-ph]*. In collaboration with

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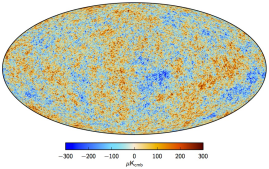
Pseudoscalar inflation coupled to gauge fields



[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!?

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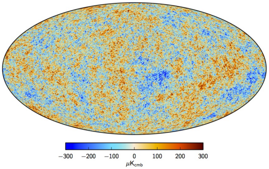

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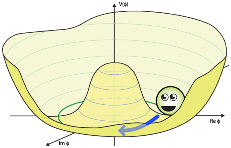
Big question: How to embed inflation into particle physics!?

This talk: Inflation driven by a pseudoscalar axion-like field a
[Freese, Frieman, Olinto '90] [Adams, Bond, Freese, Frieman, Olinto '93]



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

$$\mathcal{A}\left[G_{\text{global}} - G_{\text{local}}^2\right] \neq 0 \quad \Rightarrow \quad \mathscr{L}_{\text{eff}} \supset \frac{a}{4\Lambda} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Rich phenomenology: Primordial magnetic fields, baryon asymmetry, stochastic GWs!

Gauge field production during inflation

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

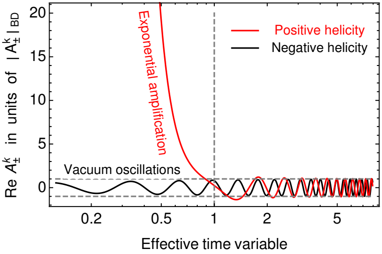
- Minimal scenario: Abelian rather than non-Abelian gauge field; $U(1)_Y$ part of the SM.
- Gauge field production during inflation $\to$ opportunity for primordial magnetogenesis.

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:

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



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

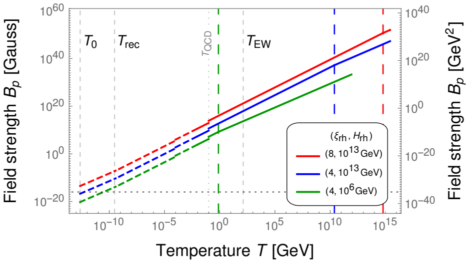
[Turner & Widrow '88] [Garretson, Field, Carroll '92] [Anber & Sorbo '06; '10] [Durrer, Hollenstein, Jain '11] [Barnaby & Peloso '11] [Sorbo '11] [Barnaby, Namba, Peloso '11] [Barnaby, Pajer, Peloso '12] [Meerburg & Pajer '13] [Linde, Mooij, Pajer '13]

Gauge field evolution after inflation

Physical strength and correlation length of the hypermagnetic ***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 $T_{\rm ic}$

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

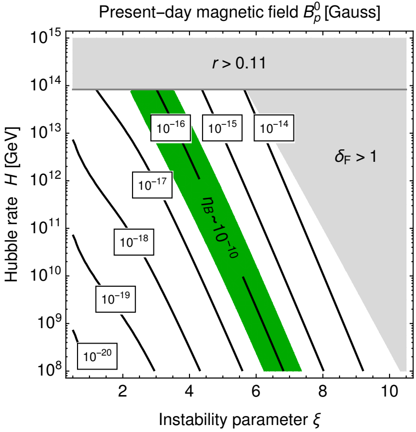
Inverse cascade: Alfvén waves generate plasma turbulence on scales of size $\lambda_T \sim v_A t$. Once $\lambda_T \sim \lambda_p$, λ_p continues to scale like λ_T. Transfer of energy from small to large scales.

[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]

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

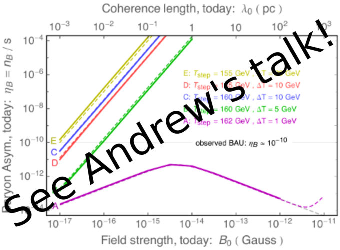
Baryogenesis via decaying hypermagnetic helicity

- 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

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



- 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 $\eta_B^{\rm obs} \sim 10^{-10}$ reproduced for

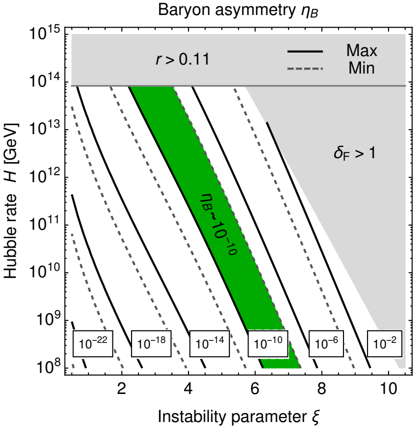
$$\boxed{B_p^0 \sim 10^{-16}\,\mathrm{G}}$$

[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]

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



Update of previous analyses in the literature. New features of our calculation:

- Adiabatic / inverse cascade regime, T-dependent weak mixing angle θ_W, Yukawas, chiral magnetic effect, etc.

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

Largest uncertainties:

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

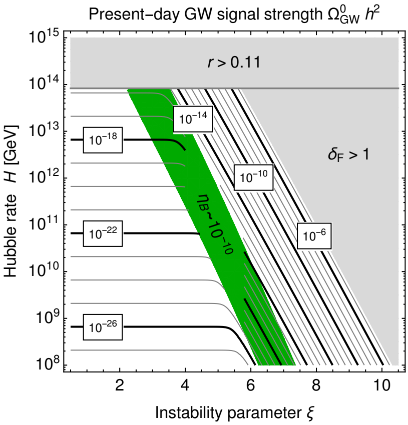
[Fujita et al. '15] [Adshead et al '16]

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]

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



Successful baryogenesis requires

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

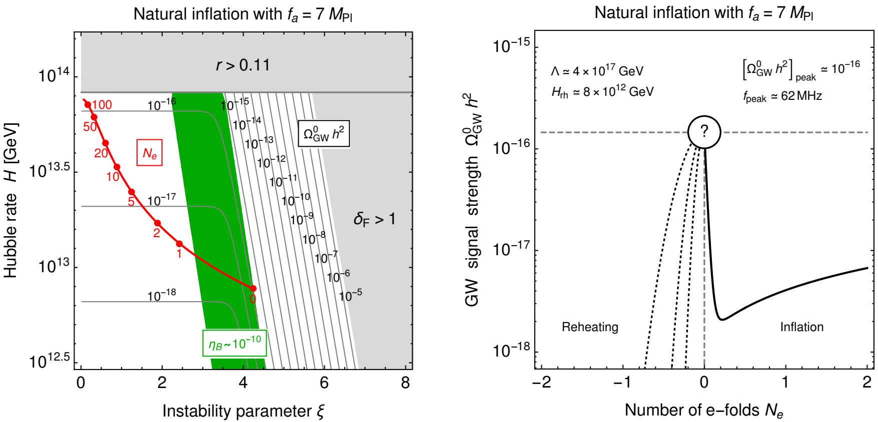
- Inflaton must be weakly coupled. Otherwise, overproduction of BAU.
- Always stay in the weak field regime. Gauge field production never dominates inflationary dynamics.
- Upper bound on GW signal strength

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

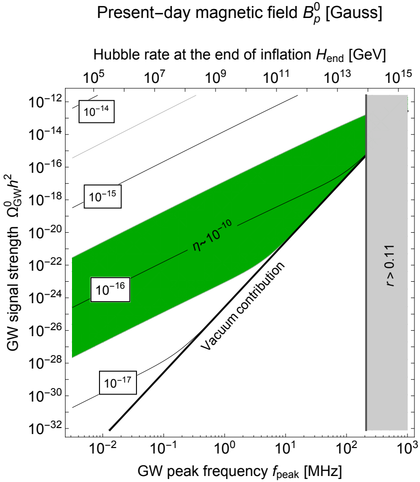
Peak in the spectrum of primordial GWs

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: $f_\text{peak} \simeq 71\,\text{MHz}\,\left(H/10^{13}\,\text{GeV}\right)^{1/2}$



Correlation between GWs and BAU



Our results so far

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

Trade ξ and H for B_p^0 and f_{peak}

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

Correlation between physical observables

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

- 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

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

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.

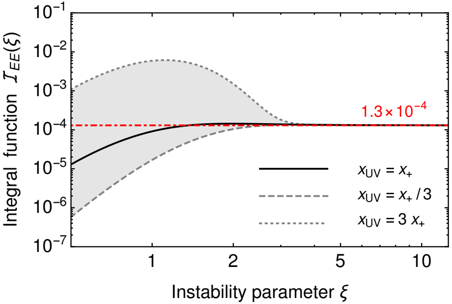
Thank you for your attention!

Supplementary Material

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

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

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

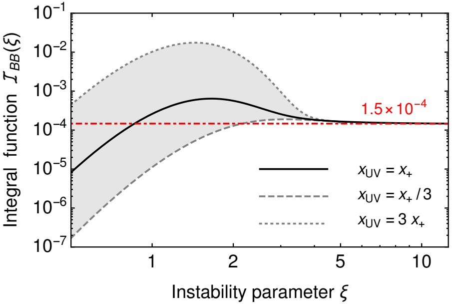


$$\mathcal{I}_{EE}(\xi) = \frac{\xi^3}{8\pi^2}\,e^{-\pi\xi}\int_0^{x_{\rm UV}} dx\,x^3\left|\frac{\partial}{\partial x}W_{\kappa_+,1/2}(-2ix)\right|^2$$

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

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

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

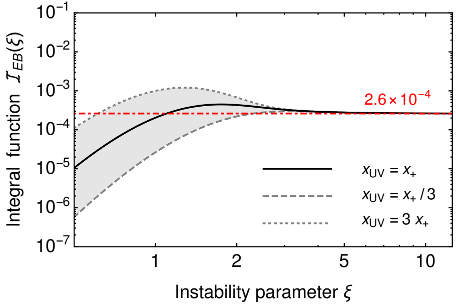


$$\mathcal{I}_{BB}(\xi) = \frac{\xi^5}{8\pi^2}\, e^{-\pi\xi} \int_0^{x_{\rm UV}} dx\, x^3 \left| W_{\kappa_+,1/2}(-2ix) \right|^2$$

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

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

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

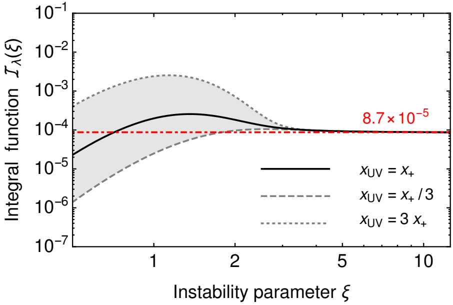


$$\mathcal{I}_{EB}(\xi) = \frac{-\xi^4}{8\pi^2}\,e^{-\pi\xi}\int_0^{x_{\rm UV}} dx\,x^3\,\frac{\partial}{\partial x}\left|W_{\kappa_+,1/2}(-2ix)\right|^2$$

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

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

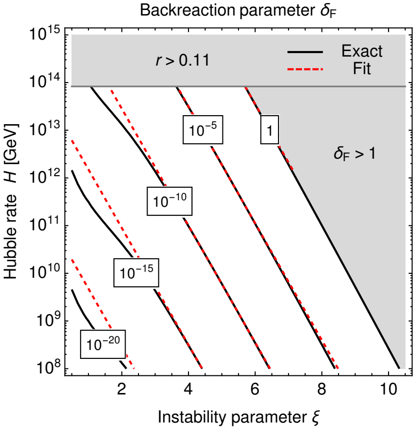
$$\lambda_p = \frac{1}{\rho_{BB}} \frac{1}{2R^4} \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \frac{2\pi R}{k} k^2 \left|A_+^k\right|^2 = \xi \frac{\mathcal{I}_\lambda(\xi)}{\mathcal{I}_{BB}(\xi)} \frac{2\pi}{H}$$



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

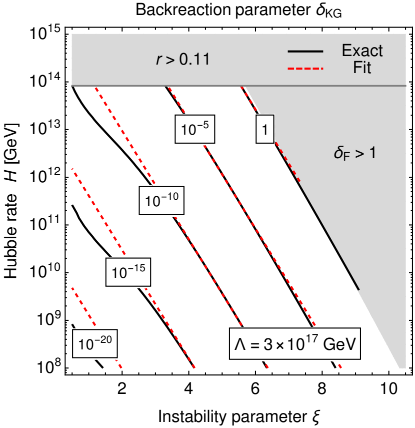
Backreaction parameters

Correction to the Friedmann equation



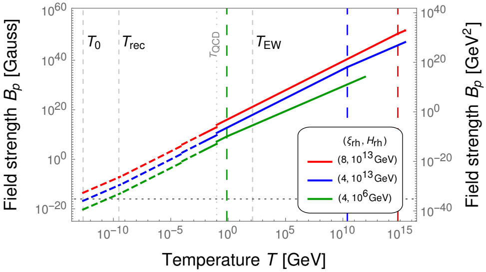
$$\delta_F = \frac{\rho_{EE} + \rho_{BB}}{3H^2 M_{Pl}^2}$$

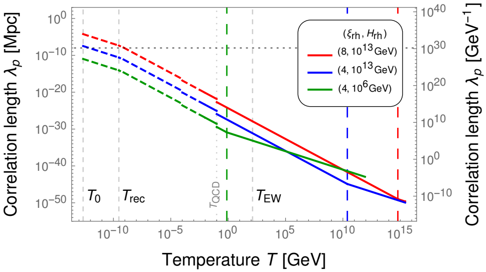
Correction to the Klein-Gordon equation



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

Temperature dependence of B_p and λ_p





Inflationary trajectories of different models