Post-inflationary magnetogenesis in axion inflation

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Shin-gakujuku Kick-off Meeting

Kavli IPMU

September 21, 2015

Fujita, RN, Tada, Takeda & Tashiro, JCAP 1505 (2015) 05, 054 [arXiv:1503.05802]

Fujita & RN, *soon to appear*

Outline

1. Introduction – Extragalactic magnetic fields
2. Axion inflation – Helical magnetic fields
3. Post-inflationary evolution
4. Present magnetic field amplitude

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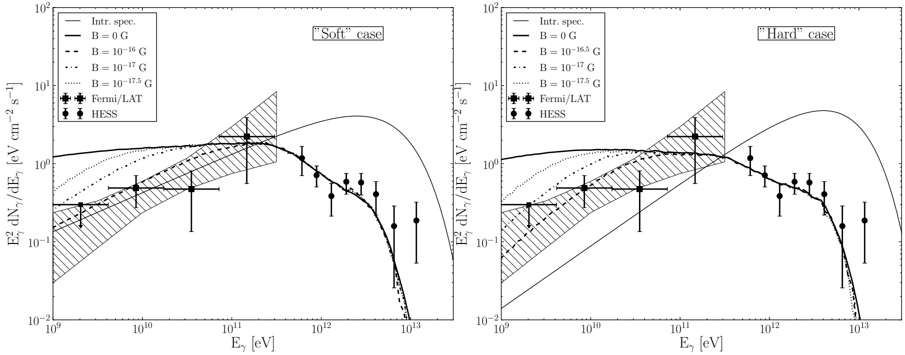
Observed extragalactic magnetic fields

Large-scale magnetic field observed

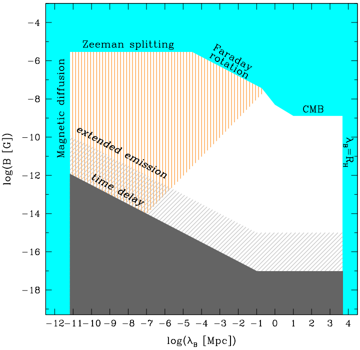
- ◇ **Galactic scale** $\sim$ kpc: $10^{-6} - 10^{-5}$G
- ◇ **Extragalactic scales $\sim$ Mpc:** $B_{\rm eff}^{\rm obs} \gtrsim 10^{-17}$G
  - ▷ Blazar TeV-GeV γ ray observation

Neronov & Vovk '10, Essey et al. '11, Takahashi et al. '13



Vovk et al. '12

Taylor, Vovk & Neronov '11



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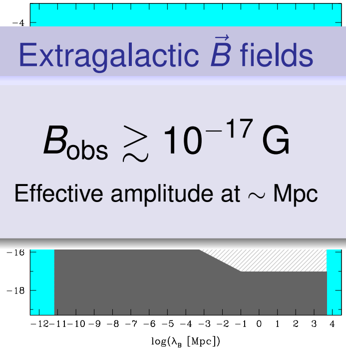


Extragalactic $\vec{B}$ fields

$$B_{\rm obs} \gtrsim 10^{-17}\,{\rm G}$$

Effective amplitude at $\sim$ Mpc

Free EM photon is *conformally* coupled to FRW metric

- EoM: $\left(\partial_\tau^2 + k^2\right) \vec{A} = 0$ – no effects from expansion, **no production**
- Several mechanisms have been proposed
  - Cosmological phase transition — Vachaspati '91 , Enqvist & Olsen '93
  - 2nd-order pert. theory — Ichiki et al. '07, Maeda et al. '09, Fenu et al. '11, Saga et al. '15
- **Inflationary magnetic field production**

  Turner & Widrow '88, Ratra '92, Bamba & Yokoyama '04, Martin & Yokoyama '08, Kunze '10, ...

Difficulties in large-scale magnetogenesis

Most studied model

$$\mathcal{L} = -\frac{I^2(a)}{4} F_{\mu\nu} F^{\mu\nu}$$ Ratra '91

- Time dependence of $I(a)$ breaks conformal inv.

$$\frac{d\langle B^2\rangle}{d\ln k} \sim H^4 \left(\frac{k}{aH}\right)^{5-2|n-\frac{1}{2}|} , \qquad I \propto a^{-n}$$

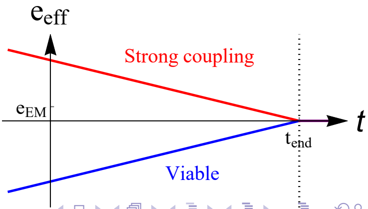
1. Strong coupling problem

   Demozzi, Mukhanov & Rubinstein '09

   ◇ $\vec{A}_c = I\vec{A}$

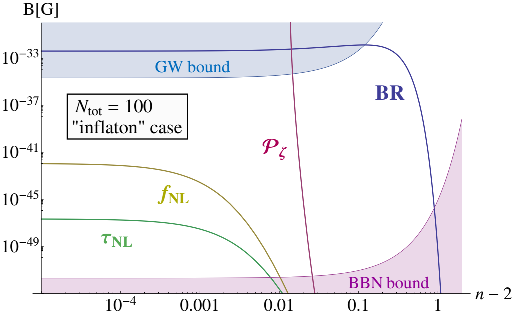
   $$\Longrightarrow \mathcal{L}_{A\psi\psi} = e\bar{\psi}\gamma^\mu A_\mu \psi = \frac{e}{I}\bar{\psi}\gamma^\mu A_{c,\mu}\psi$$

   ◇ needs $I \gtrsim 1$ at all times $\Leftrightarrow n > 0$



1. Strong backreaction problem
   - Large-scale $\vec{B}$ $\Leftrightarrow$ magnetic spectral index $n_B < 0$
   - However, $\rho_E \gg \rho_B$
   - **Iso-curvature mode due to ρ_E back-react to inflationary dynamics and curvature perturbations !**

Fujita & Yokoyama '13



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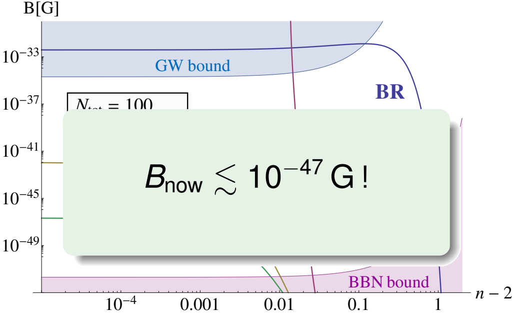

$$B_{\rm now} \lesssim 10^{-47}\,\mathrm{G}\,!$$

Model independent limit

$$\rho_{\rm inf}^{1/4} < 300\,\mathrm{MeV} \left(\frac{1\,\mathrm{Mpc}}{L_B} \right)^{5/4} \left(\frac{10^{-15}\,\mathrm{G}}{B_{\rm obs}} \right) , \quad (L_B \le 1\,\mathrm{Mpc})$$

Fujita & Yokoyama '14

Must break the premises

- **Production only during inflation**
- $\vec{B}$ evolves adiabatically after inflation, $B_{\rm phy} \propto a^{-2}$
- $A_i \propto \tau^n$ is a good approx at the last e-folding of inflation

Must overcome the obstacles

- ◇ **Substantial dilution after inflation**
- ◇ Too large electromagnetic energy spoiling inflation
- ◇ Induced curvature perturbations consistent with CMB

For sufficient production...

Post-inflationary evolution

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Why and what is **axion inflation** ?

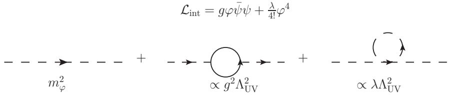
Axion inflation

- Successful inflation
- UV controllable theory

Why and what is **axion inflation** ?

- **Slow roll** of inflaton φ is necessary for a prolonged inflationary stage

- Slow roll in a standard single-field inflation is **UV sensitive**
  - Radiative corrections



  - η problem in supergravity

$$|\eta| \ll 1 \text{ is needed but } V_{\rm SG} \sim V\frac{\varphi^2}{M_p^2} \text{ leads } \eta \sim \mathcal{O}(1)$$

- One solution – to invoke **shift symmetry**
  - Symmetry exact $\Leftrightarrow$ completely flat potential $V(\varphi) = \text{const.}$
  - Mild breaking guarantees flat $V(\varphi)$

- Natural candidate...?

Why and what is **axion inflation** ?

- **Slow roll** of inflaton φ is necessary for a prolonged inflationary stage
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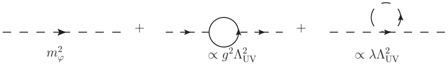
$$\mathcal{L}_{\rm int} = g\varphi\bar{\psi}\psi + \frac{\lambda}{4!}\varphi^4$$



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- Or
- Na

Axions – (pseudo) Nambu-Goldstone bosons

- Arise from global symmetry breaking
- Ubiquitous in particle theory
- Flat $V(\varphi)$ guaranteed – **a good candidate for inflaton!**
  - Natural inflation   Freese, Frieman & Olinto '90

Axion inflation

- Successful inflation
- UV controllable theory

A natural coupling to electromagnetic fields
– fixed by symmetries

Axion-gauge coupling

$$\mathcal{L}_{\rm int} = \frac{\alpha}{f}\,\varphi\,\vec{E}\cdot\vec{B}$$

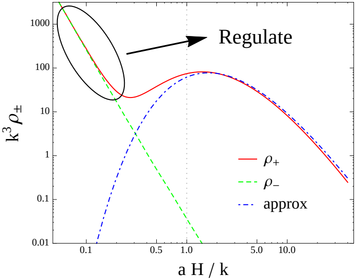
A natural coupling to electromagnetic fields
– fixed by symmetries

Modified dispersion of the EM field

$$\frac{\partial^2}{\partial\tau^2}A_\pm + \left(k^2 \mp a\frac{\alpha}{f}\,k\,\dot{\varphi}\right)A_\pm = 0$$

◇ **Only one helicity** grows exponentially

Anber & Sorbo /09



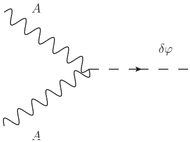
Large production of helical magnetic fields !

Other phenomenological features

- **Bounds from CMB observations**
  - ▷ Produced photons **inverse-decay** to inflaton quanta

    $\Longrightarrow$ contribute to **curvature perturbations**

$$A + A \to \delta\varphi \to \zeta$$



Barnaby, RN & Peloso ’12; Meerburg & Pajer ’12

CMB bounds

$$\frac{\alpha}{f} \leq 35 - 48 M_p^{-1}$$

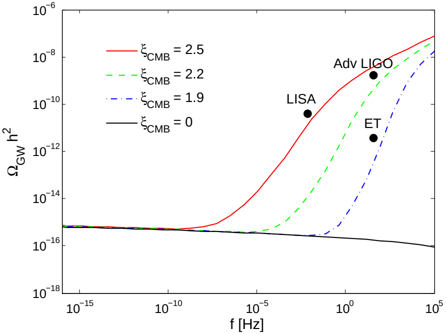
Planck collaboration ’15

Other phenomenological features

- **Prospects at gravitational-wave detectors**
  - ▷ Produced photons contribute to anisotropic shear

    $\Longrightarrow$ source **tensor perturbations (GW)**
  - ▷ No signal at CMB scales $\Leftrightarrow$ Bounds on scalar perturbations are too strong
  - ▷ **Potential signals at GW interferometer scales**

Barnaby, Pajer & Peloso '12



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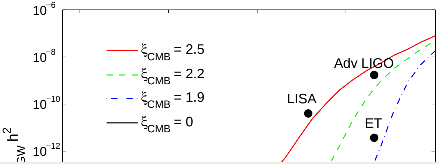

- No constraints from current (1^{st} generation) detectors
- Future (2^{nd} & 3^{rd} gen.) have potential **to detect helical GWs !**

Crowder et al. ’12; c.f. Seto & Taruya ’07

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Evolution of magntic fields

Distinctive post-inflationary evolution

- Coupling to inflaton φ until reheating
- **Slow roll breaks down**
- **Inflaton oscillation** after inflation
- **Helical nature** of the produced $\vec{B}$ fields

Numerical computation during and after inflation until the coupling shuts off:

$$\ddot{A}_\pm + H\dot{A}_\pm + \left(\frac{k^2}{a^2} \mp \frac{\alpha}{f}\frac{k}{a}\dot{\phi}_0\right)A_\pm = 0$$

$$\ddot{\phi}_0 + 3H\dot{\phi}_0 + V_\phi(\phi_0) = \frac{\alpha}{f}\langle\vec{E}\cdot\vec{B}\rangle$$

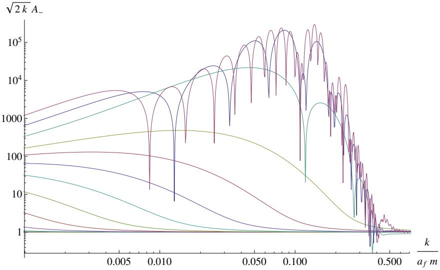
$$3M_p^2H^2 = \frac{1}{2}\dot{\phi}_0^2 + V(\phi_0) + \frac{\langle\vec{E}^2 + \vec{B}^2\rangle}{2}$$

Growth around the end of inflation

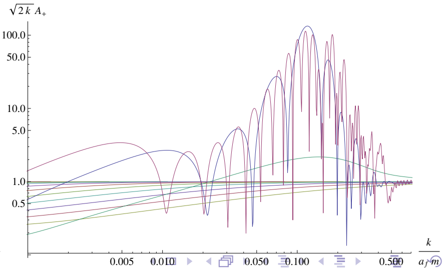
Growth triggered by the coupling

1. **Tachyonic growth**
   - ▷ towards the end of inflation
   - ▷ growth only in one helicity state
2. **Parametric resonance**
   - ▷ lasts a few e-folds after inflation
   - ▷ growth in both helicity states

Spectrum of growing state

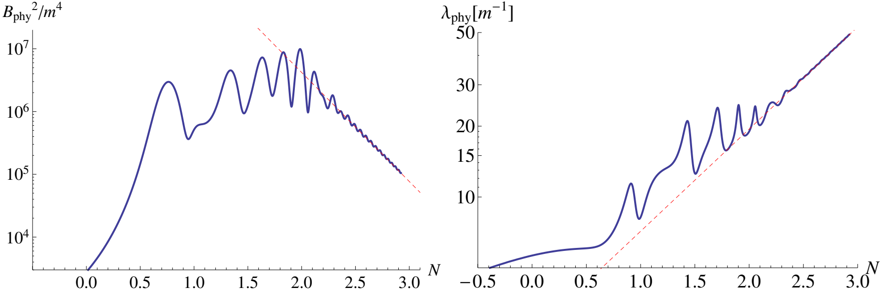


Spectrum of non-growing state



Evolution of amplitude and correlation length

- Non-trivial evolution of $\vec{B}$ fields during and after inflation
- Once parametric resonance ceases, the $\vec{B}$ fields evolve adiabatically

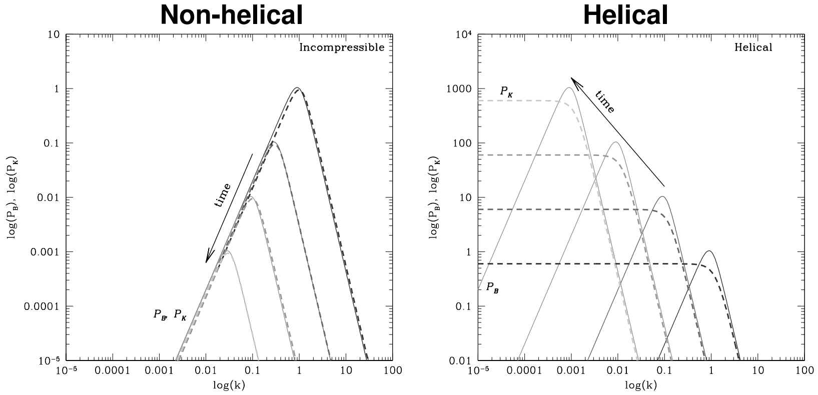


$$B_{\rm phys} \simeq \left(6 \cdot 10^{45}\, a^{-4}\right)\ {\rm G}\,, \quad \lambda_{\rm phys} \simeq \left(9 \cdot 10^{-52}\, a\right)\ {\rm Mpc}\,, \quad \left(\frac{\alpha}{f} = 8\, M_p^{-1}, N \gtrsim 2\right)$$

Inverse cascade in turbulent plasma

Inverse cascade = helicity conservation

- Nonlinearity of MHD dynamics (High Reynolds number)
- Helicity of the magnetized fluid with high conductivity is conserved
- Part of the energy is transferred to larger scales



Durrer & Neronov '13

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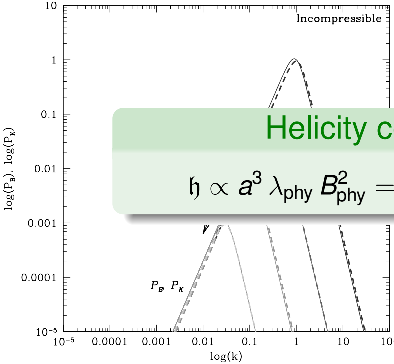
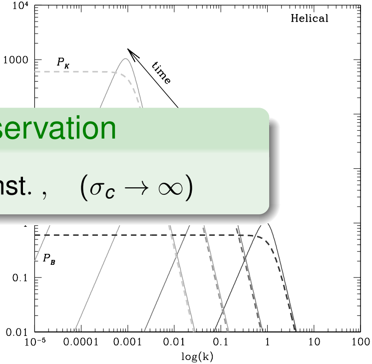
Non-helical / **Helical**





Helicity conservation

$$\mathfrak{h} \propto a^3 \lambda_{\rm phy} B_{\rm phy}^2 = \text{const.} , \quad (\sigma_c \to \infty)$$

Durrer & Neronov '13

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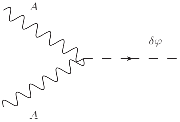
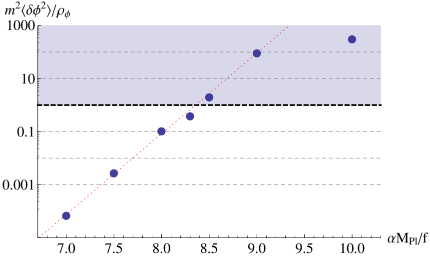
Concerning issues

1. **Low conductivity**
   - ▷ Thermalized charged particles wash away $\vec{E}$ fields and "freeze" $\vec{B}$ fields
   - ▷ Do not thermalize if $\Gamma_\phi \lesssim 10^6$ GeV
2. **Perturbation under control**
   - ▷ We have neglected the effects from inflaton perturbation $\delta\varphi$, e.g.,



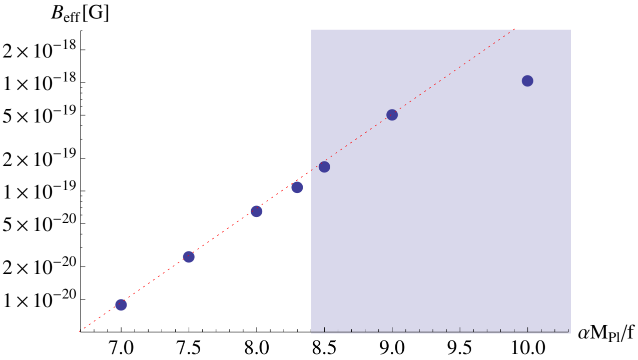
   - ▷ Calculation consistent as long as $\delta\varphi \ll \phi_0$ at all times



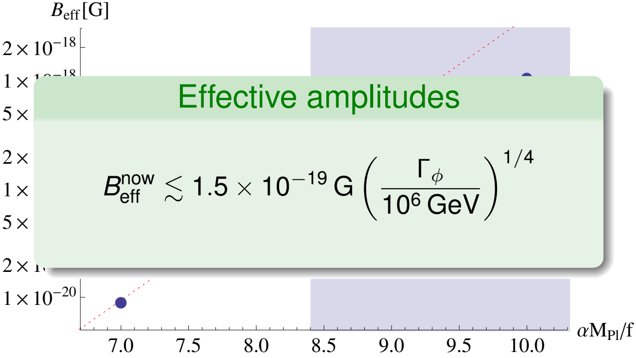
Consistency bound

$$\frac{\alpha}{f} < 8.4\, M_p^{-1}$$

Present magnetic field amplitude



Present magnetic field amplitude



Effective amplitudes

$$B_{\rm eff}^{\rm now} \lesssim 1.5 \times 10^{-19}\,{\rm G} \left(\frac{\Gamma_\phi}{10^6\,{\rm GeV}} \right)^{1/4}$$

- ◇ MUCH bigger than those in inflationary *IFF* models, $\lesssim 10^{-47}$ G !
- ◇ STILL smaller than the observed bound, $B_{\rm obs} \gtrsim 10^{-17}$ G...

Summary and outlook

- Blazars observations $\Rightarrow B_{\rm eff} \gtrsim 10^{-17}$ G at ~ 1 Mpc !
- Challenging to find **inflation-only** origins $\Rightarrow$ **post-inflationary evolution**
- Theoretically motivated **axion inflation** studied
  - Rich phenomenology
    - Non-Gaussian curvature perturbations, gravitational waves at interferometers
  - Generation mechanism of $\vec{B}$ naturally implemented
  - Rich physics
    - Tachyonic enhancement near the end of inflation
    - Parametric resonance
    - Parity violation $\Rightarrow$ helical $\vec{B} \Rightarrow$ Inverse cascade
  - Much larger $\vec{B}$ than previous studies ! ...but not enough for blazars
- More elaborate model that incorporates post-inf. evolution of $\vec{B}$ is needed
  - Work in progress: **post-inflationary kinetic coupling model**
  - Preliminary results: $B_{\rm obf} \gtrsim 10^{-15}$ G is possible with all constraints satisfied
  - ...but not enough time in this talk