Post-inflationary magnetogenesis

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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. Model 1: axion inflation
   - Production
   - Post-inflationary evolution
   - Present magnetic field amplitude
3. Model 2: post-inflationary kinetic coupling
   - Post-inflationary production
   - CMB and backreaction constraints
   - Preliminary results

Outline

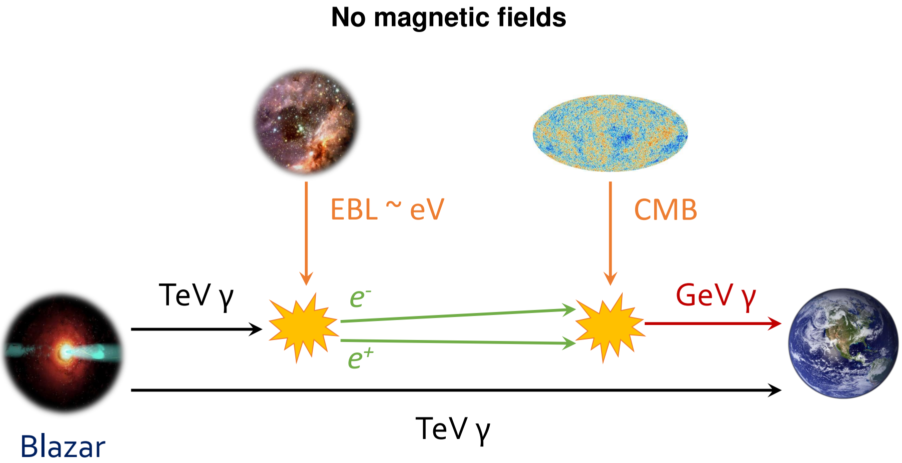
Observed large-scale magnetic fields

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

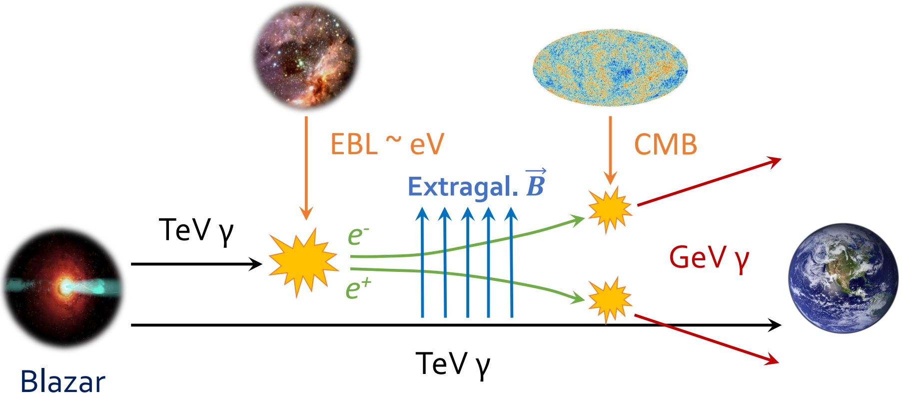
Observational method for extragalactic $\vec{B}$



Observe both TeV + GeV γ rays

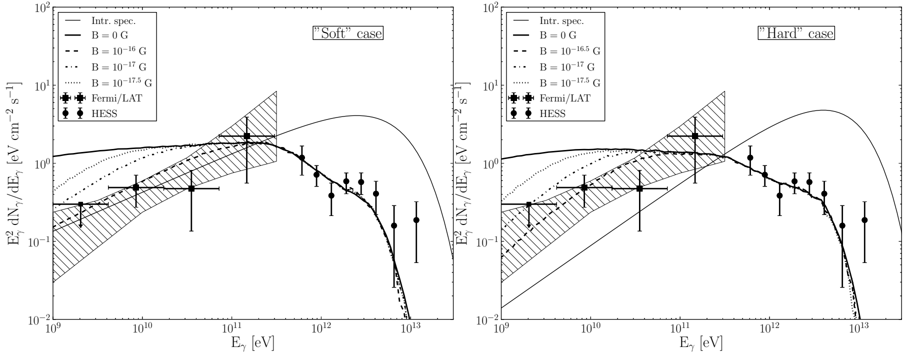
Observational method for extragalactic $\vec{B}$

Magnetic fields are present



Observe TeV γ rays, lack of GeV γ rays

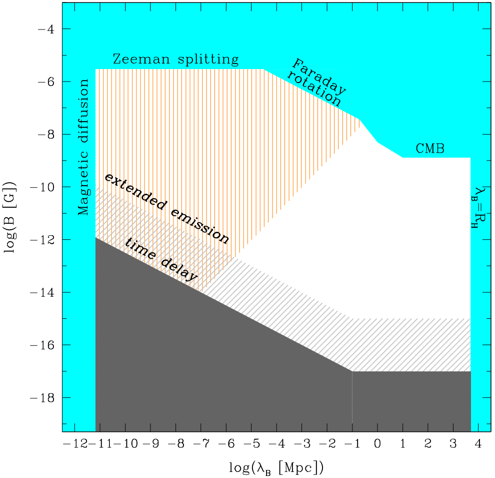
Spectrum of blazar photons



Vovk et al. '12

Observed extragalactic $\vec{B}$

Taylor, Vovk & Neronov '11



Observed extragalactic $\vec{B}$

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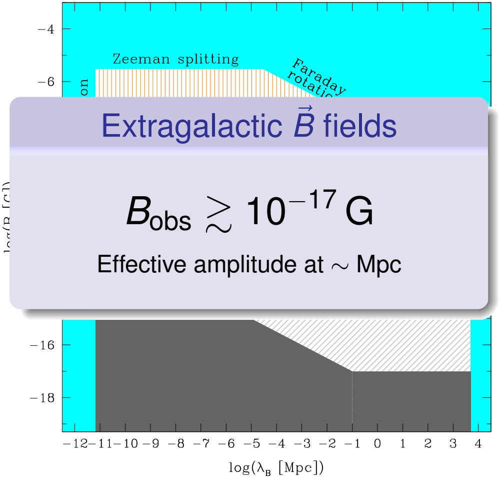


Extragalactic $\vec{B}$ fields

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

Effective amplitude at $\sim$ Mpc

Cosmological origins

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
  - Second-order perturbation theory

    Matarrese et al. '04, 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, . . .

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.

Difficulties in large-scale magnetogenesis

$\vec{B}$ field spectrum in *IFF* model

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

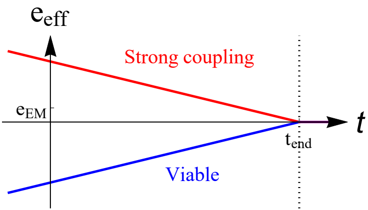
1. Strong coupling problem

   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 $\Leftrightarrow n > 0$

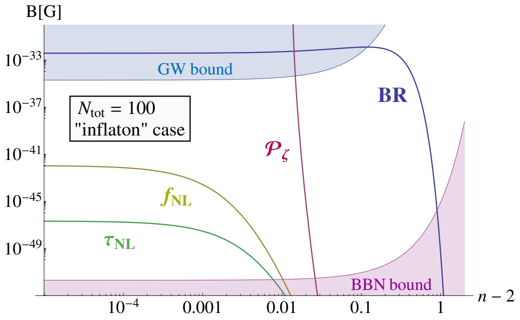


Difficulties in large-scale magnetogenesis

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

Barnaby et al. '12, Fujita & Mukohyama '12, Fujita & Yokoyama '13, Ferreira et al. '14

Fujita & Yokoyama '13



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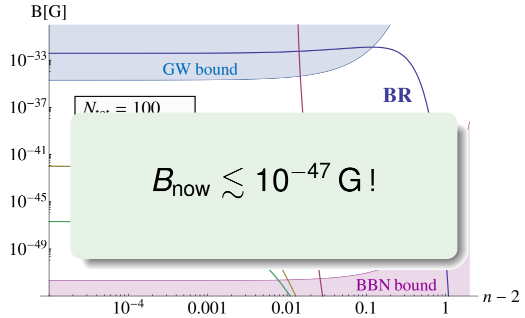


$$B_{\rm now} \lesssim 10^{-47}\,\text{G} \,!$$

Model independent limit

$$\rho_{\rm inf}^{1/4} < 30\,{\rm MeV} \left(\frac{1\,{\rm Mpc}}{L_B}\right)^{5/4} \left(\frac{10^{-15}\,{\rm G}}{B_{\rm obs}}\right) , \quad (L_B \le 1\,{\rm Mpc})$$

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 approximation 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

Outline

Why and what is **axion inflation** ?

Axion inflation

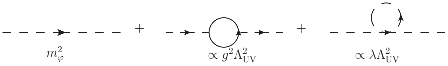
- Successful inflation
- UV controllable theory

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

$$\mathcal{L}_{\rm int} = g\varphi\bar{\psi}\psi + \frac{\lambda}{4!}\varphi^4$$



  - 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...?

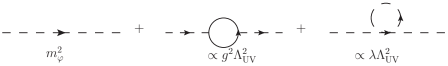
Why and what is **axion inflation** ?

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

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

▷ Radiative corrections

$$\mathcal{L}_{\rm int} = g\varphi\bar{\psi}\psi + \frac{\lambda}{4!}\varphi^4$$



▷ η problem in supergravity

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

◇ 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

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

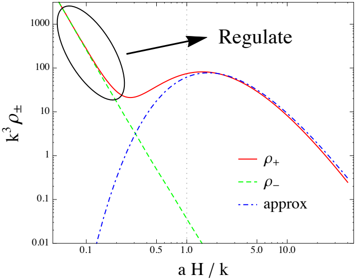
A natural coupling to electromagnetic fields
– fixed by symmetries

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

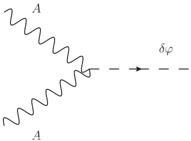


Large production of helical magnetic fields !

Bounds on the coupling constant

- **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

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 decoupling

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

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

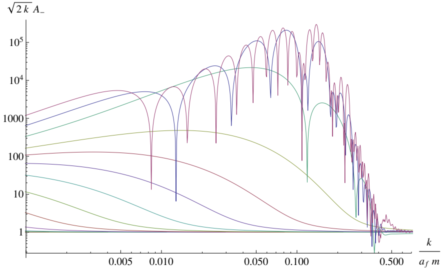
$$3M_p^2 H^2 = \frac{1}{2}\dot{\phi}_0^2 + V(\phi_0) + \frac{\langle \vec{E}^2 + \vec{B}^2\rangle}{2}$$

Growth around the end of inflation

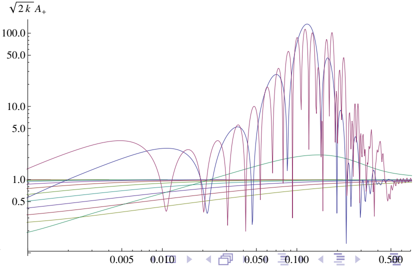
Growth triggered by the coupling

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

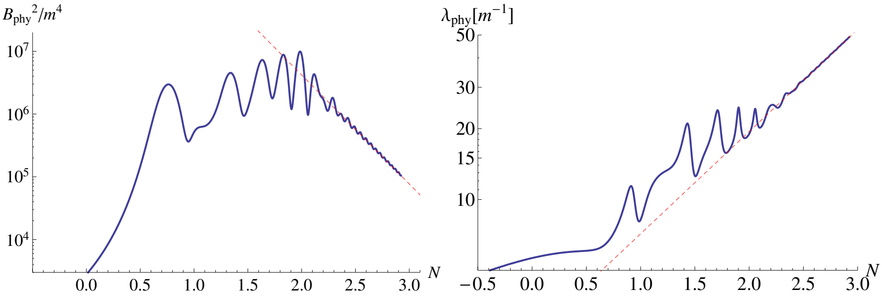


Spectrum of non-growing (+) state



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



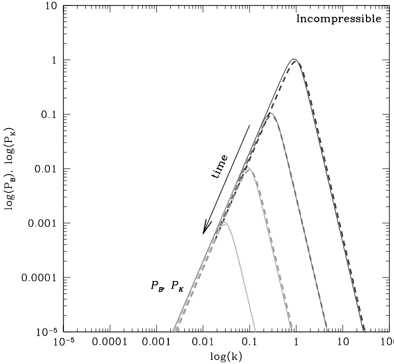
$$B_{\rm phys} \simeq \left(6 \cdot 10^{45}\, a^{-4}\right)\ \mathrm{G}\ , \quad \lambda_{\rm phys} \simeq \left(9 \cdot 10^{-52}\, a\right)\ \mathrm{Mpc}\ , \quad \left(\frac{\alpha}{f} = 8\, M_p^{-1}, N \gtrsim 2\right)$$

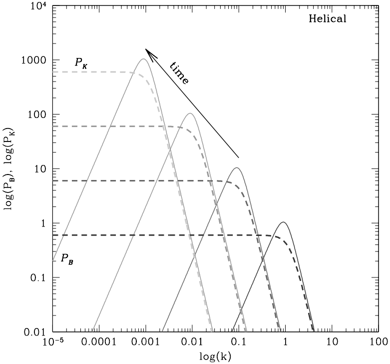
Inverse cascade in turbulent plasma

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

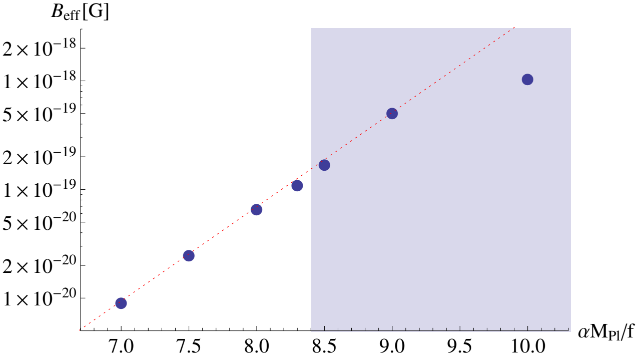
Non-helical **Helical**





Dürre & Neronov '13

Present magnetic field amplitude



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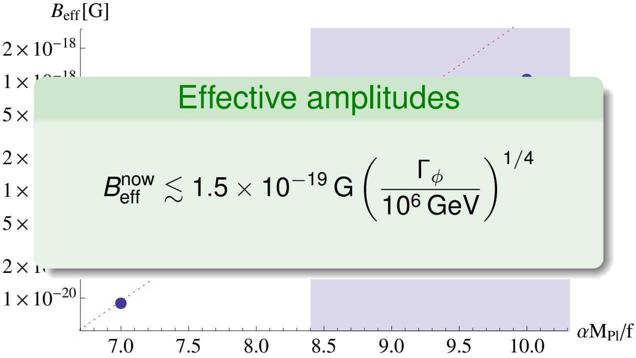


Effective amplitudes

$$B_{\rm eff}^{\rm now} \lesssim 1.5\times10^{-19}\,{\rm G}\left(\frac{\Gamma_\phi}{10^6\,{\rm GeV}}\right)^{1/4}$$

- ◇ MUCH bigger than those in previous studies !
- ◇ STILL smaller than the observed bound, $B_{\rm obs} \gtrsim 10^{-17}\,$G...
- ◇ Search for helical extragalactic $\vec{B}$ fields ? Tashiro et al. '13, '14; Chen et al. '14

Outline

Attempts with kinetic coupling model

Recall...

Kinetic coupling model

$$\mathcal{L}_{\rm int} = -\frac{I^2(a)}{4} F_{\mu\nu} F^{\mu\nu}$$

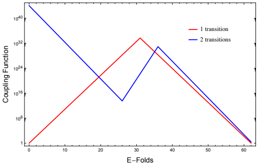
◇ Strongest bounds from the CMB constraints on curvature perturbations

◇ One attempt to evade this

– **sudden onset of magnetic field production**

Ferreira et al. '13

▷ Still too large non-Gaussianity Ferreira et al. '14



◇ **Post-inflationary kinetic coupling** Kobayashi '14

▷ STILL too large $f_{\rm NL}$

Our model

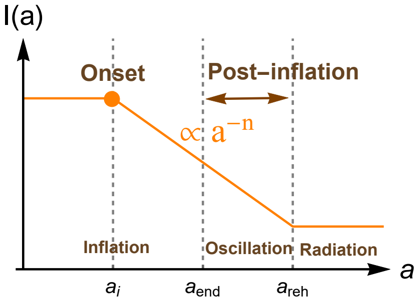
Kinetic coupling model

$$\mathcal{L}_{\rm int} = -\frac{I^2(\chi)}{4} F_{\mu\nu} F^{\mu\nu}$$

- I is a function of spectator $\chi \neq$ inflaton φ
- Motion of χ induces time dependence of I

◇ Sudden onset of χ rolling

◇ Post-inflationary coupling

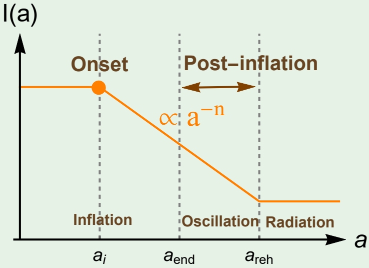


◇ **Impose: Consistency with the CMB observations**

Evolution of EM field

$$\left(\frac{\partial^2}{\partial\tau^2} + k^2 - \frac{\partial_\tau^2 I}{I}\right)\left(I\vec{A}\right) = 0$$

$$I \propto a^{-n}\,, \quad n > 0$$



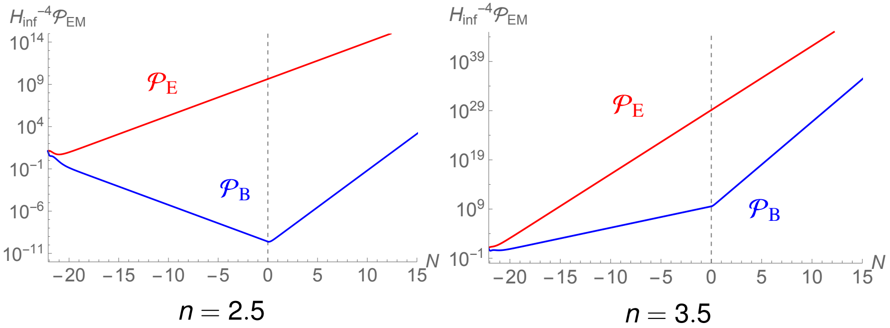
$$\left(\frac{\partial^2}{\partial\tau^2} + k^2\right)\left(I\vec{A}\right) = 0\,, \qquad a < a_i\,,\ a_{\rm reh} < a$$

$$\left(\frac{\partial^2}{\partial\tau^2} + k^2 - \frac{n(n-1)}{\tau^2}\right)\left(I\vec{A}\right) = 0\,, \qquad a_i < a < a_{\rm end}$$

$$\left(\frac{\partial^2}{\partial\tau^2} + k^2 - \frac{2n(2n+1)}{\tau^2}\right)\left(I\vec{A}\right) = 0\,, \qquad a_{\rm end} < a < a_{\rm reh}$$

With BD initial condition, we can solve the E.o.M. exactly

Time evolution of EM power



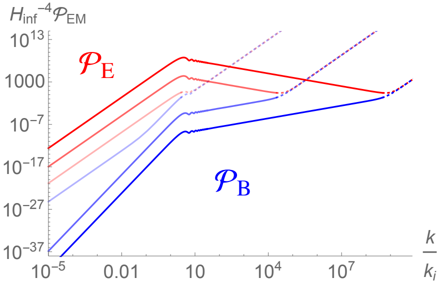
- ▷ During inflation, $\vec{E}$ grows faster than $\vec{B}$
- ▷ After inflation, $\vec{B}$ grows faster than $\vec{E}$

$$\frac{E_k}{B_k} = \frac{\partial_\tau A_k}{k\,A_k} \propto \frac{1}{|k\tau|} \propto \begin{cases} a\,, & \text{inflation} \\ a^{-1/2}\,, & \text{MD} \end{cases}$$

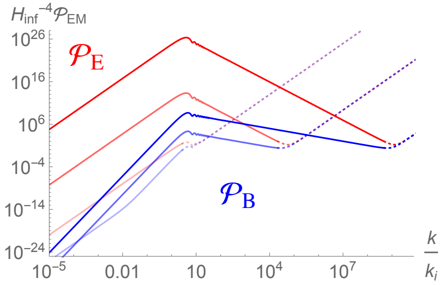
- The hierarchy b/w $\vec{E}$ and $\vec{B}$ is alleviated during MD !

EM power spectra

During inflation



$n = 2.5$



$n = 3.5$

1. Suppression of large-scale power $k < k_i$

$$\mathcal{P}_E \propto k^4 \,, \quad \mathcal{P}_B \propto k^6 \,, \qquad k \ll k_i$$

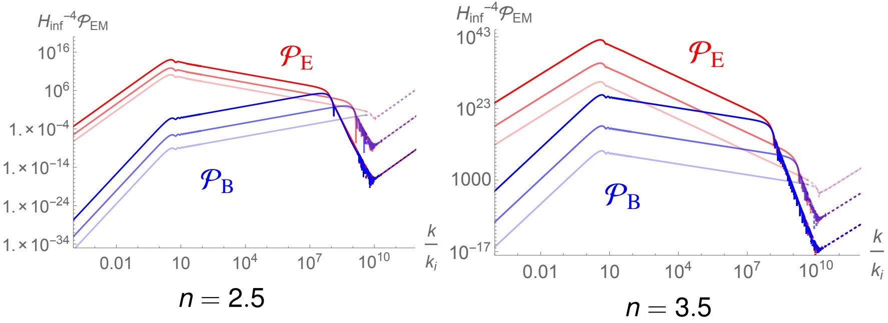
2. $\vec{B}$ spectrum is blue for $n < 3$, red for $n > 3$

$$\mathcal{P}_B \propto k^{6-2n} \,, \qquad k \gg k_i$$

Note: $I \propto a^{-n}$

EM power spectra

During inflaton oscillation



1. Spectral tilt unchanged
2. Higher modes enter horizon, oscillate and damp
3. Lower modes continue growing

Note: $I \propto a^{-n}$

Constraints from curvature perturbations

Several contributions to ζ from produced $\vec{E}$ directly and indirectly

$$\zeta = -\frac{H}{\dot{\rho}^{(0)}}\,\delta\rho$$

$$\delta\rho\,[\vec{E}] = \delta\rho_{\rm E} + \delta\rho_{\chi}^{\rm sourced} + \delta\rho_{\varphi}^{\rm sourced} + \delta\rho_{\varphi}^{\rm mix}$$

$$\left(\frac{\partial^2}{\partial\tau^2} + k^2 + M_{\phi\phi}^2\right)(a\,\delta\varphi) + M_{\phi\chi}^2\,(a\,\delta\chi) = \frac{-a^3\dot{\phi}}{4M_p^2 H}\int\frac{d^3x}{(2\pi)^{3/2}}\,e^{-i\vec{k}\cdot\vec{x}}\,\vec{E}\cdot\vec{E}$$

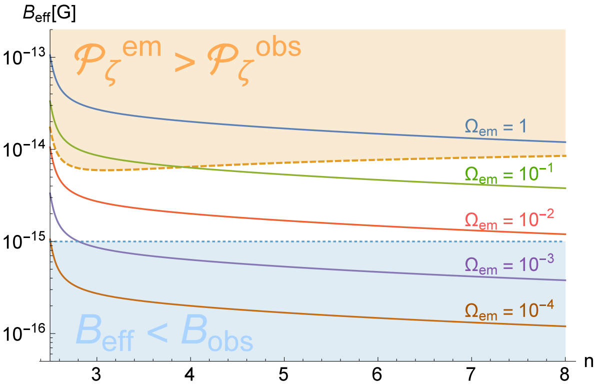
$$\left(\frac{\partial^2}{\partial\tau^2} + k^2 + M_{\sigma\sigma}^2\right)(a\,\delta\chi) + M_{\chi\phi}^2\,(a\,\delta\varphi) = a^3\,\frac{\partial_\chi I}{I}\int\frac{d^3x}{(2\pi)^{3/2}}\,e^{-i\vec{k}\cdot\vec{x}}\,\vec{E}\cdot\vec{E}$$

1. Energy density of $\vec{E}$
2. $\vec{E}$ energy density sources $\delta\chi$ through direct coupling, suppressed by $\dot{\chi}/\dot{\phi}$
3. $\vec{E}$ energy density sources $\delta\varphi$ through gravitational interaction
4. Sourced $\delta\chi$ gravitationally mixes with $\delta\varphi$

Results (*preliminary*)

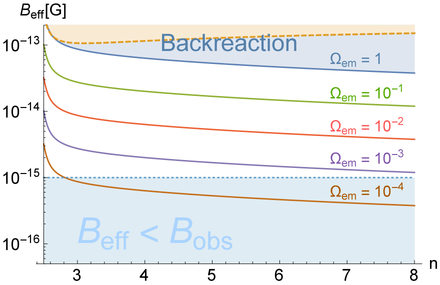
◇ So far we have only included ① & ②

◇ Preliminary results indicate $\delta\rho_\varphi^{\text{sourced}} \sim \delta\rho_\varphi^{\text{mix}} \sim \delta\rho_\chi^{\text{sourced}} \sim \delta\rho_E$

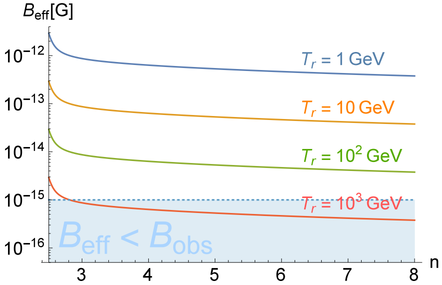


$$T_{\text{reh}} = 1\,\text{GeV}, \;\; k_i = 1\,\text{Mpc}^{-1}, \;\; \Omega_{\text{em}} \equiv \frac{\rho_E}{\rho_{\text{tot}}}(t_{\text{reh}})$$

Results (*preliminary*)



$T_{\rm reh} = 1\,\text{GeV}, \;\; k_i = 10\,\text{Mpc}^{-1}$



$k_i = 1\,\text{kpc}^{-1}, \;\; \Omega_{\rm em}\,(t_{\rm reh}) = 1$

- Increasing k_i ⇔ smaller peak scales ⇔ away from CMB scales
- Backreaction to $\rho_{\rm tot}$ more relevant for larger k_i
- Larger $T_{\rm reh}$ ⇔ $\vec{E}$ vs. $\vec{B}$ hierarchy remains wide ⇔ tighter bounds

$$T_{\rm reh} \lesssim 10^3\,\text{GeV}\,, \qquad \text{for } k_i < 1\,\text{kpc}^{-1} \text{ and } B_{\rm obs} \gtrsim 10^{-15}\,\text{GeV}$$

Message

$$B_{\text{obs}} \gtrsim 10^{-15}\,\text{G}$$

can be realized **without**

- **strong coupling problem**
- **backreaction problem**
- **curvature perturbation problem**

...but preliminary

Summary and outlook

- Blazars observations $\Rightarrow B_{\rm eff} \gtrsim 10^{-17}\,$G at $\sim 1\,$Mpc !
- Challenging to find an **inflation-only** origin
- Post-inflationary evolution is necessary to save the situation
- Theoretically motivated **axion inflation** studied
  - ◇ Generation mechanism of $\vec{B}$ naturally implemented
  - ◇ Rich physics
    - ▷ Tachyonic enhancement at 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
- **Post-inflationary kinetic coupling model** studied
  - ◇ Sudden onset of kinetic fnc $I(a)$, evolution until reheating
  - ◇ $B_{\rm obs} \gtrsim 10^{-15}\,$G **with all constraints satisfied !**
  - ◇ Any natural model ?