Imprints of primordial curvature perturbations on inflationary magnetic fields

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BERNOULLI CENTER
Ascending peaks of knowledge

Generation, evolution, and observations of cosmological magnetic fields
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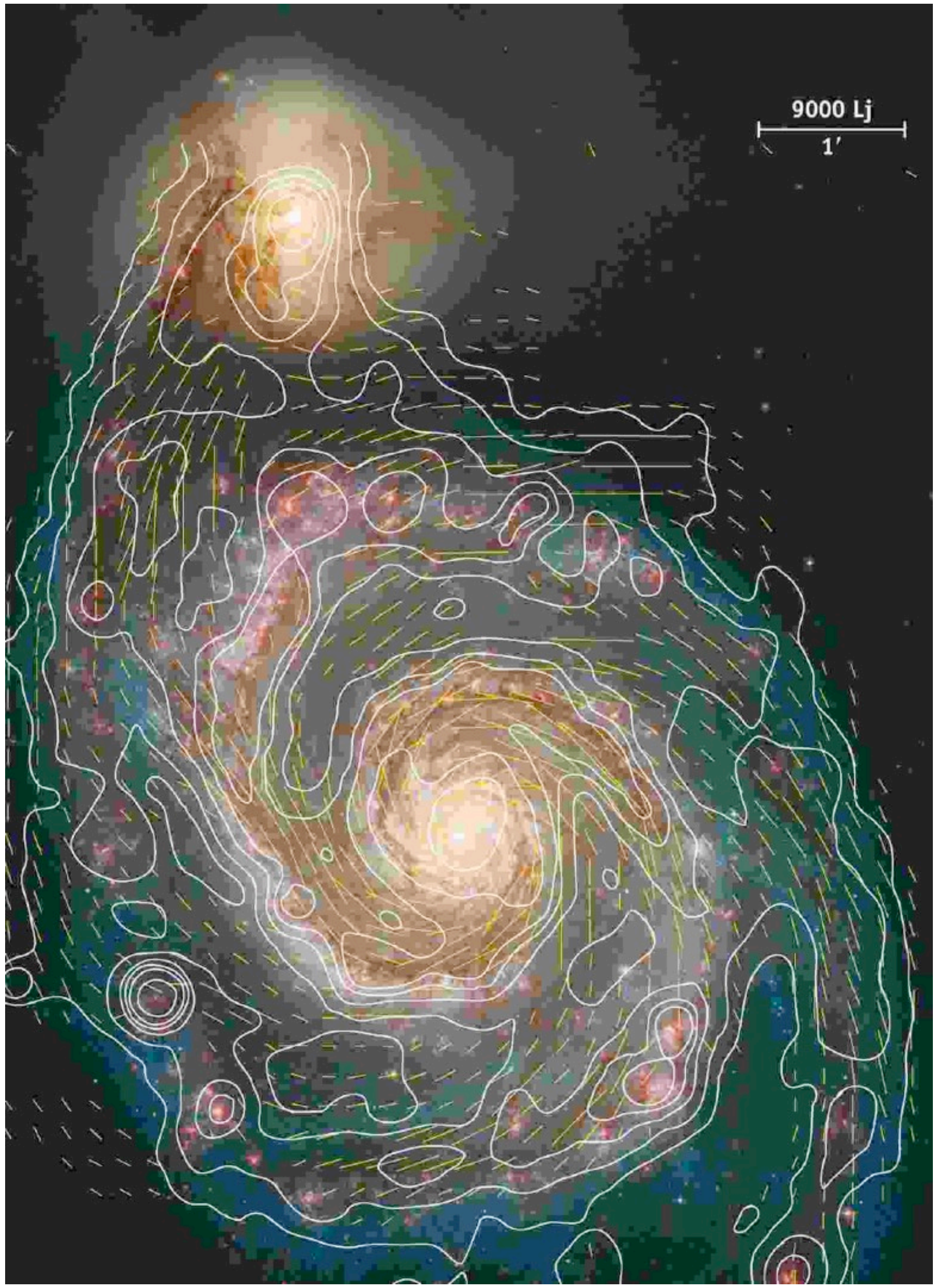
Outline of the talk

- *Observational evidence for magnetic fields*
- *Inflationary magnetogenesis — brief overview*
- *IMF from single field inflationary models*
  - *Mild and strong deviations from slow roll*
  - *Imprints on the magnetic field power spectra*
- *IMF from two field inflationary models*
  - *Imprints of PMF on the CMB anisotropies*
- *Cross-correlation of curvature/tensor perturbations with magnetic fields — soft theorems — full results — observational imprints*
- *Conclusions*

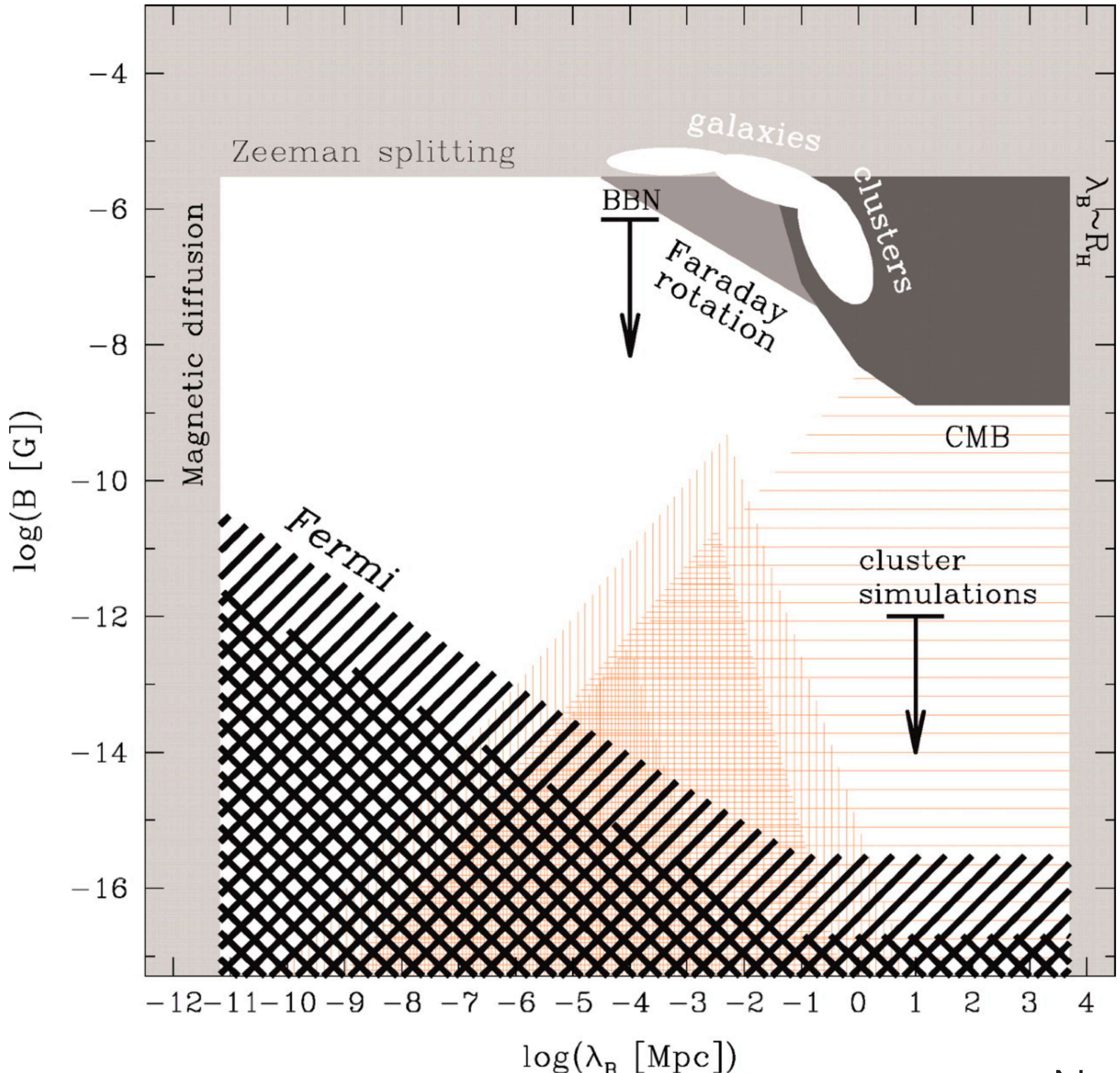
Cosmological magnetic fields

- Our observed universe is magnetized on all scales.
- All the bound structures — stars, galaxies and clusters carry magnetic fields, also present in the intergalactic medium.
- Stars: B ~ 0.1 – few G.
- Galaxies: B ~ 1 – 10 μG with coherence length as large as 10 kpc.
- Clusters: B ~ 0.1 – 1 μG, coherent on scales up to 100 kpc.
- Intergalactic medium: $B \gtrsim 3 \times 10^{-16}\,\mathrm{G}$ on scales of ~ 1 Mpc.

Neronov & Vovk, 2010



Constraints on cosmic magnetic fields

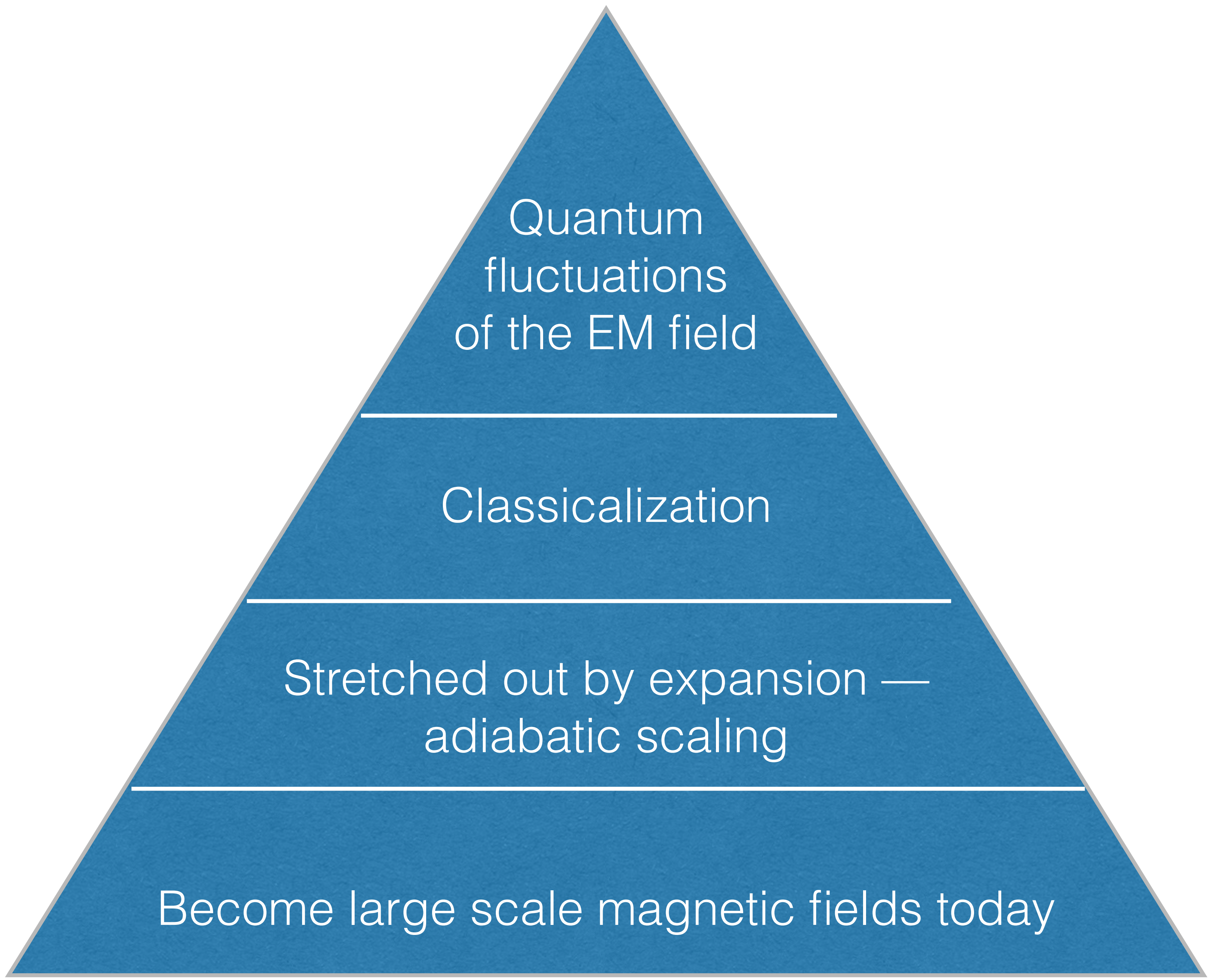


Neronov & Vovk, 2010

Primordial magnetic fields from inflation

- Inflationary mechanisms — most interesting due to the very nature of inflation — large scale correlations
- Standard Maxwell action is conformally invariant — the electromagnetic fluctuations do not grow in any conformally flat background like FRW.
- A necessary condition — break conformal invariance of the Maxwell theory. (Turner & Widrow, 1988, Ratra, 1992)
- Various possible couplings:
  - Kinetic coupling: $\lambda(\phi, \mathcal{R}) F_{\mu\nu} F^{\mu\nu}$
  - Axial coupling: $f(\phi, \mathcal{R}) F_{\mu\nu} \tilde{F}^{\mu\nu}$

Inflationary magnetogenesis



Inflationary magnetogenesis — basic formalism

The parity violating term is introduced to the action as

$$S[A^\mu] \;=\; -\frac{1}{16\,\pi}\int \mathrm{d}^4x\,\sqrt{-g}\left[J^2(\phi)\,F_{\mu\nu}\,F^{\mu\nu} - \frac{\gamma}{2}\,J^2(\phi)\,F_{\mu\nu}\,\widetilde{F}^{\mu\nu}\right],$$

where $\widetilde{F}^{\mu\nu} = (\epsilon^{\mu\nu\alpha\beta}/\sqrt{-g})\,F_{\alpha\beta}$.
The equation of motion has the form

$$\mathcal{A}_k^{\sigma\,\prime\prime} + \left(k^2 + \frac{2\,\sigma\,\gamma\,k\,J'}{J} - \frac{J''}{J}\right)\mathcal{A}_k^\sigma = 0,$$

where $\sigma = \pm 1$ represents positive and negative helicity.
The power spectra of the helical magnetic and electric fields are given by

$$\mathcal{P}_{\mathrm{B}}(k) \;=\; \frac{k^5}{4\,\pi^2\,a^4}\left[\left|\mathcal{A}_k^+\right|^2 + \left|\mathcal{A}_k^-\right|^2\right],$$

$$\mathcal{P}_{\mathrm{E}}(k) \;=\; \frac{k^3}{4\,\pi^2\,a^4}\left[\left|\mathcal{A}_k^{+\prime} - \frac{J'}{J}\mathcal{A}_k^+\right|^2 + \left|\mathcal{A}_k^{-\prime} - \frac{J'}{J}\mathcal{A}_k^-\right|^2\right].$$

Inflationary magnetogenesis with kinetic coupling

Power law coupling
$$J(\eta) = \left[\frac{a(\eta)}{a(\eta_{\rm e})}\right]^n = \left(\frac{\eta}{\eta_{\rm e}}\right)^{-n},$$

$$\mathcal{P}_{\rm B}(k) = \frac{H_{\rm I}^4}{8\pi}\mathcal{F}(m)(-k\eta_{\rm e})^{2m+6},$$

$$m = \begin{cases} n, & \text{for } n < -\frac{1}{2} \\ -n-1, & \text{for } n > -\frac{1}{2} \end{cases}$$

$$\mathcal{P}_{\rm E}(k) = \frac{H_{\rm I}^4}{8\pi}\mathcal{G}(m)(-k\eta_{\rm e})^{2m+4},$$

$$m = \begin{cases} n, & \text{for } n < \frac{1}{2} \\ 1-n, & \text{for } n > \frac{1}{2} \end{cases}$$

$$\mathcal{F}(m) = \frac{1}{2^{2m+1}\cos^2(m\pi)\Gamma^2(m+3/2)},$$

$$n_{\rm B} = \begin{cases} 2n+6, & \text{for } n < -\frac{1}{2} \\ 4-2n, & \text{for } n > -\frac{1}{2} \end{cases}$$

$$\mathcal{G}(m) = \frac{1}{2^{2m-1}\cos^2(m\pi)\Gamma^2(m+1/2)},$$

$$n_{\rm E} = \begin{cases} 2n+4, & \text{for } n < \frac{1}{2} \\ 6-2n, & \text{for } n > \frac{1}{2} \end{cases}.$$

Inflationary magnetogenesis — kinetic + helical

Power law coupling $$J(\eta) = \left[\frac{a(\eta)}{a(\eta_e)}\right]^n = \left(\frac{\eta}{\eta_e}\right)^{-n},$$

$$\mathcal{P}_B(k) = \frac{H_I^4}{8\pi^2} \frac{\Gamma^2(|2n+1|)}{|\Gamma(\frac{1}{2} + in\gamma + |n + \frac{1}{2}|)|^2} \times \frac{\cosh(n\pi\gamma)}{2^{|2n+1|-2}} (-k\eta_e)^{5-|2n+1|}.$$

$$\mathcal{P}_E(k) = \frac{H_I^4}{4\pi^2} \frac{\Gamma^2(2|n|)}{|\Gamma(|n| + in\gamma)|^2} \frac{\gamma^2}{1+\gamma^2} \frac{\cosh(n\pi\gamma)}{2^{2|n|-2}} (-k\eta_e)^{4-2|n|}$$

$$n_B = 5 - |2n+1|, \qquad n_E = 4 - 2|n|.$$

Constraints for successful magnetogenesis

- Background
  - Strong coupling problem
  - Backreaction issue
- Perturbations
  - Power spectrum constraints
  - Induced bispectrum etc..
- Energy scale of inflation (from tensor modes)
- Schwinger effect — strong E field induces charged particle production

EM fields power spectra — single field slow roll

In terms of e-folds, the coupling function is expected to be

$$J(N) = \exp\left[n\left(N - N_{\mathrm{e}}\right)\right].$$

The Klein-Gordon equation for inflaton field is

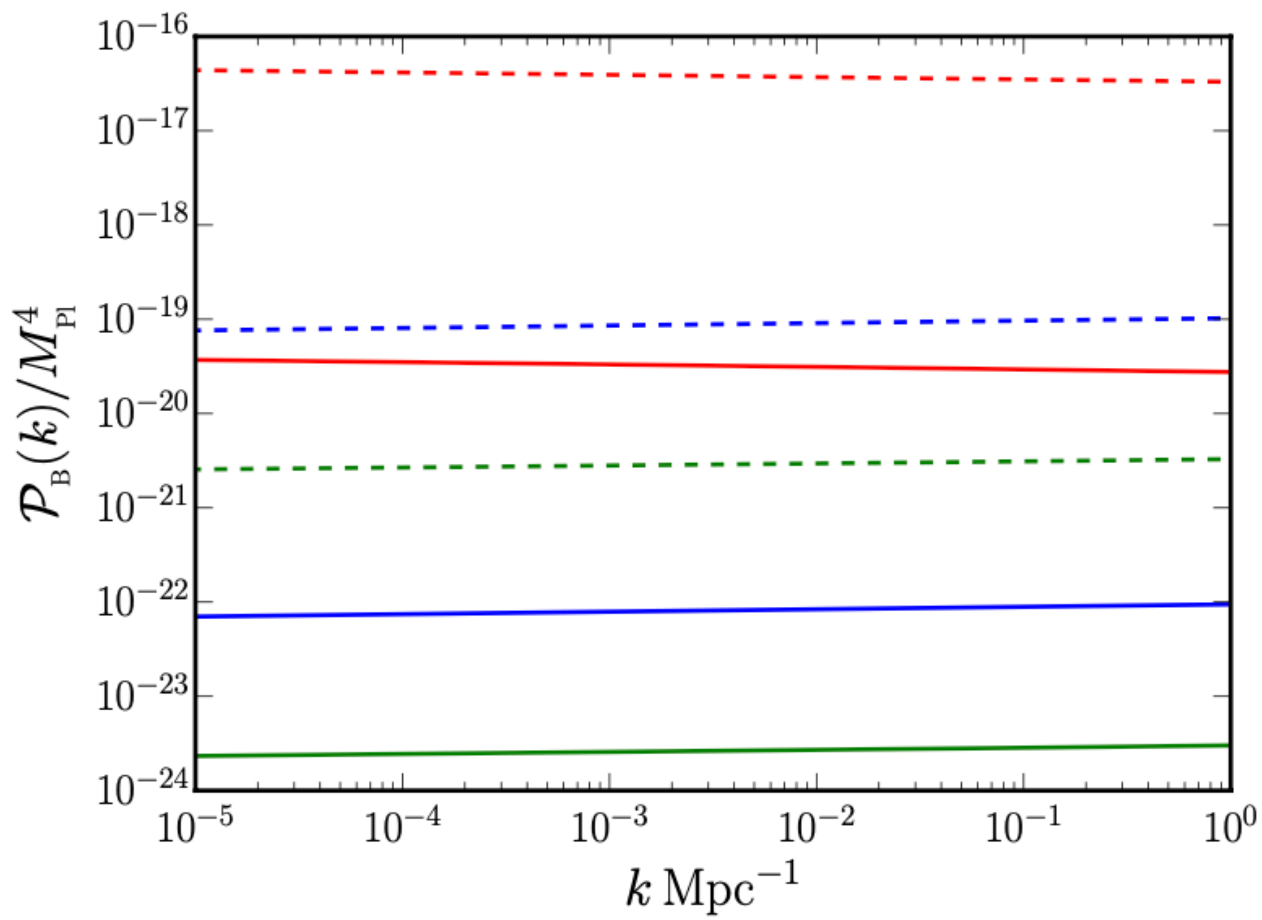
$$\ddot{\phi} + 3H\dot{\phi} + V_{\phi} = 0.$$

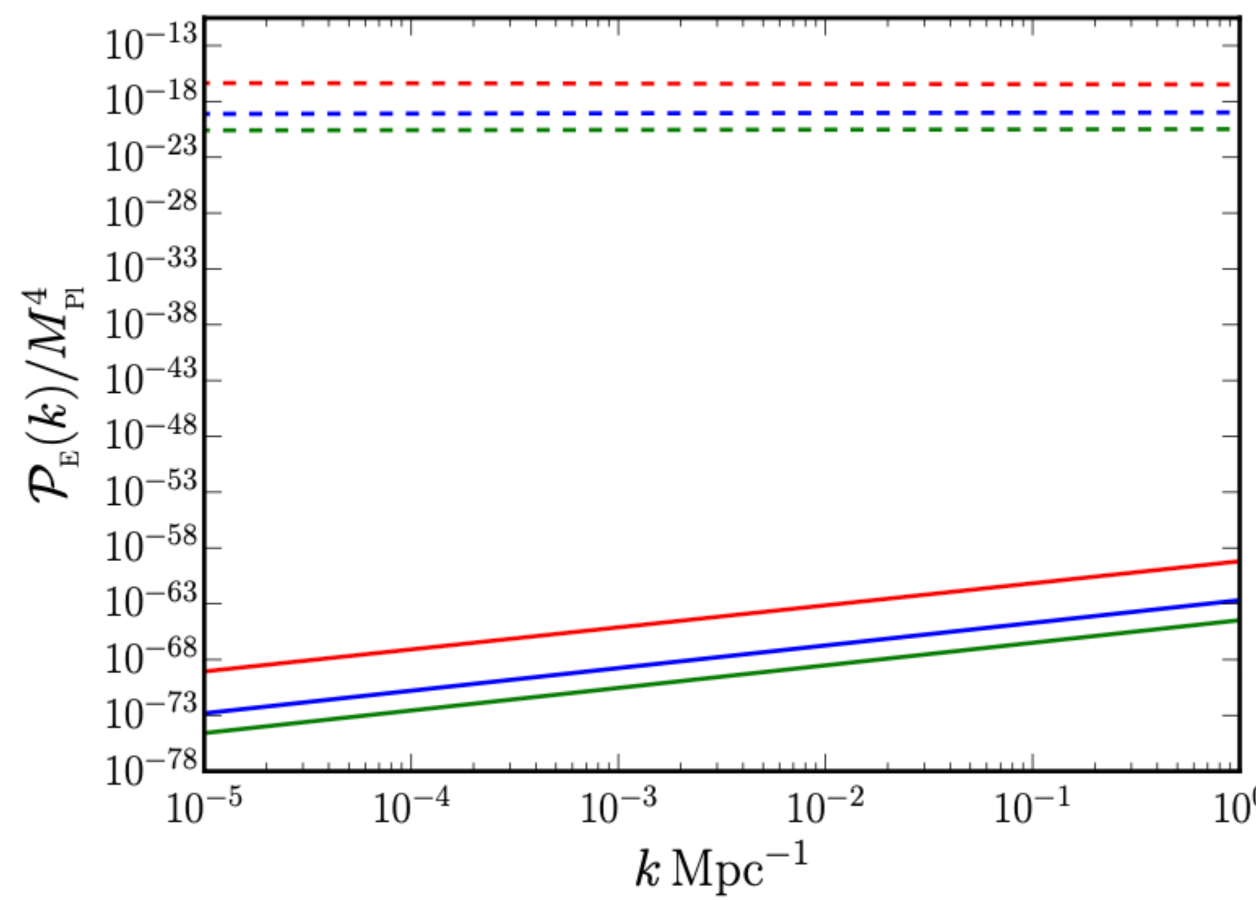
SR Model	**Potential**	**Coupling fuction** $[J(\phi)]$
Quadratic potential (QP)	$\frac{m^2}{2}\phi^2$	$\exp\left[-\frac{n}{4M_{\mathrm{Pl}}^2}\left(\phi^2 - \phi_{\mathrm{e}}^2\right)\right]$
Small field model (SFM)	$V_0\left[1 - \left(\frac{\phi}{\mu}\right)^q\right]$	$\left(\frac{\phi}{\phi_{\mathrm{e}}}\right)^{n\mu^2/2M_{\mathrm{Pl}}^2} \exp\left[-\frac{n}{4M_{\mathrm{Pl}}^2}\left(\phi^2 - \phi_{\mathrm{e}}^2\right)\right]$
First Starobinsky model (FSM)	$V_0\left[1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\mathrm{Pl}}}\right)\right]^2$	$\exp\left\{-\frac{3n}{4}\left[\exp\left(\sqrt{\frac{2}{3}}\frac{\phi}{M_{\mathrm{Pl}}}\right) - \exp\left(\sqrt{\frac{2}{3}}\frac{\phi_{\mathrm{e}}}{M_{\mathrm{Pl}}}\right) - \sqrt{\frac{2}{3}}\left(\frac{\phi}{M_{\mathrm{Pl}}} - \frac{\phi_{\mathrm{e}}}{M_{\mathrm{Pl}}}\right)\right]\right\}$

EM fields power spectra in slow roll

$$\mathcal{P}_{\mathrm{B}}(k) = \frac{k^5}{2\pi^2}\frac{J^2}{a^4}|\bar{A}_k|^2 = \frac{k^5}{2\pi^2 a^4}|\mathcal{A}_k|^2,$$

$$\mathcal{P}_{\mathrm{E}}(k) = \frac{k^3}{2\pi^2}\frac{J^2}{a^4}|\bar{A}'_k|^2 = \frac{k^3}{2\pi^2 a^4}\left|\mathcal{A}'_k - \frac{J'}{J}\mathcal{A}_k\right|^2.$$

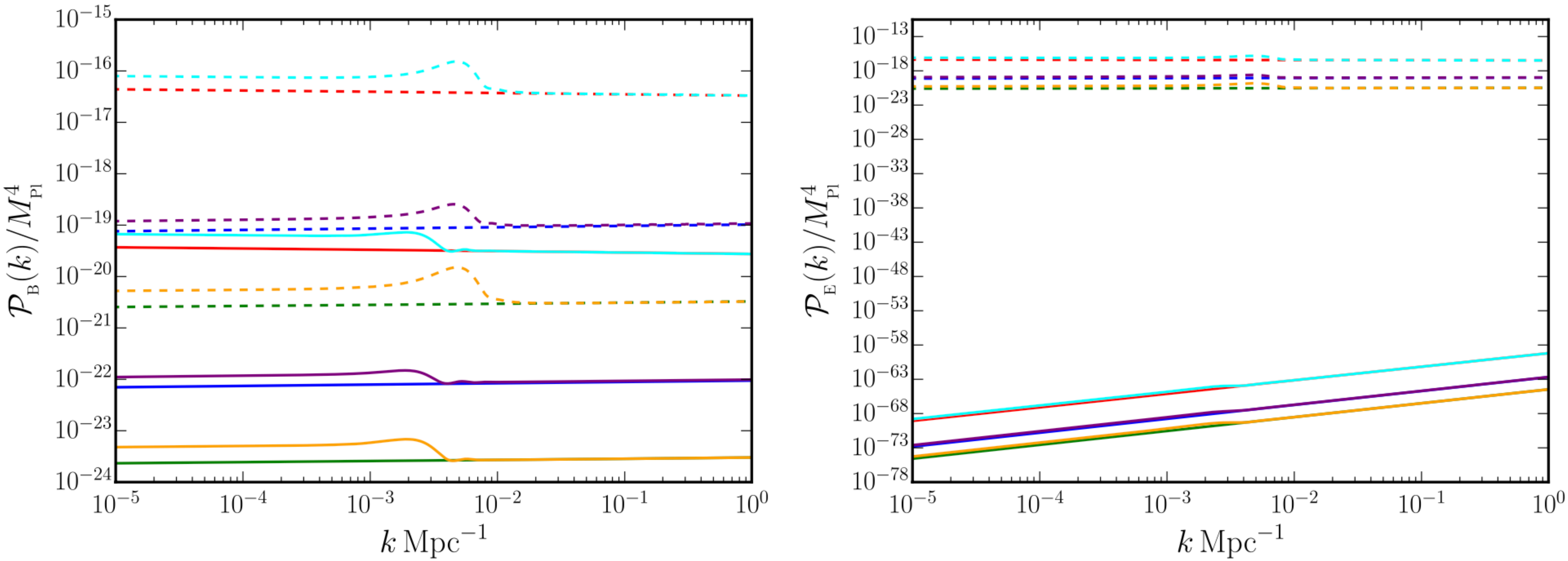




EM spectra — mild deviations from slow roll

Features in the inflaton potential — features in the scalar perturbation spectrum — possible explanation of CMB anomalies

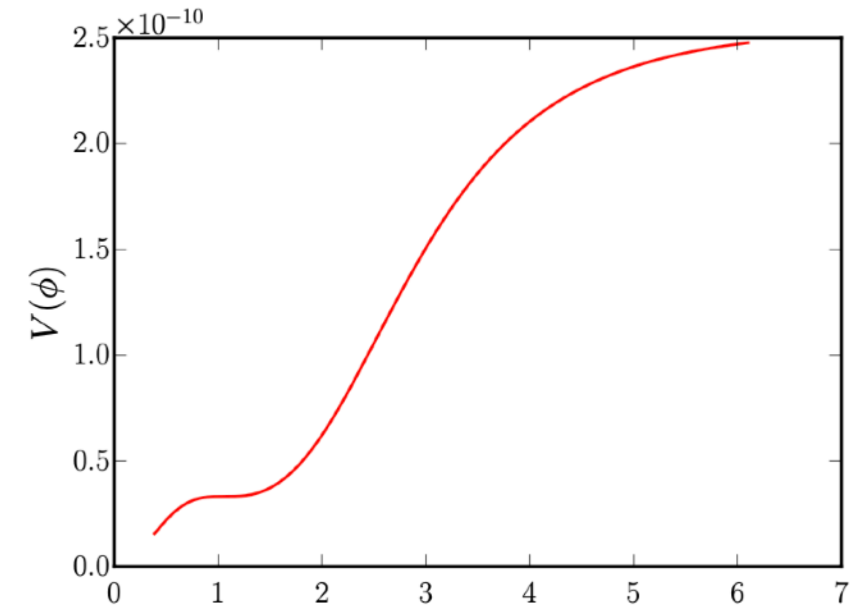
$$V_{\rm step}(\phi) = V(\phi)\left[1 + \alpha \tanh\left(\frac{\phi - \phi_0}{\Delta\phi}\right)\right],$$



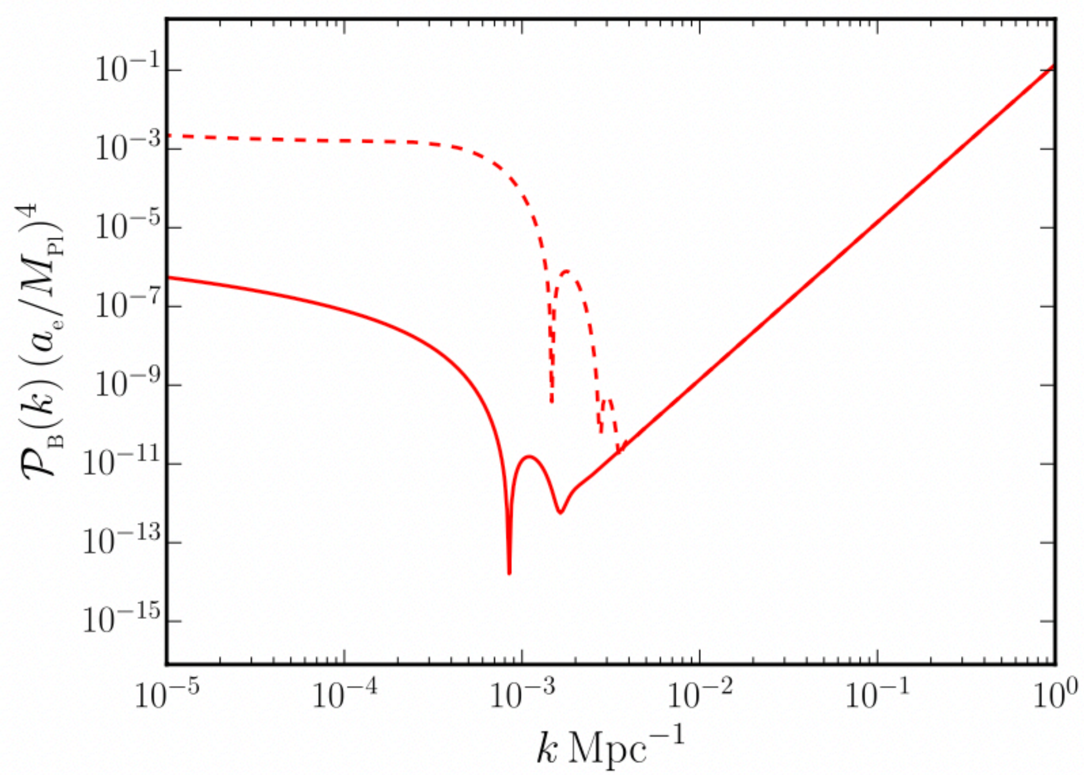
Tripathy, Chowdhury, **RKJ** & Sriramkumar, PRD 105, 063519 (2022)

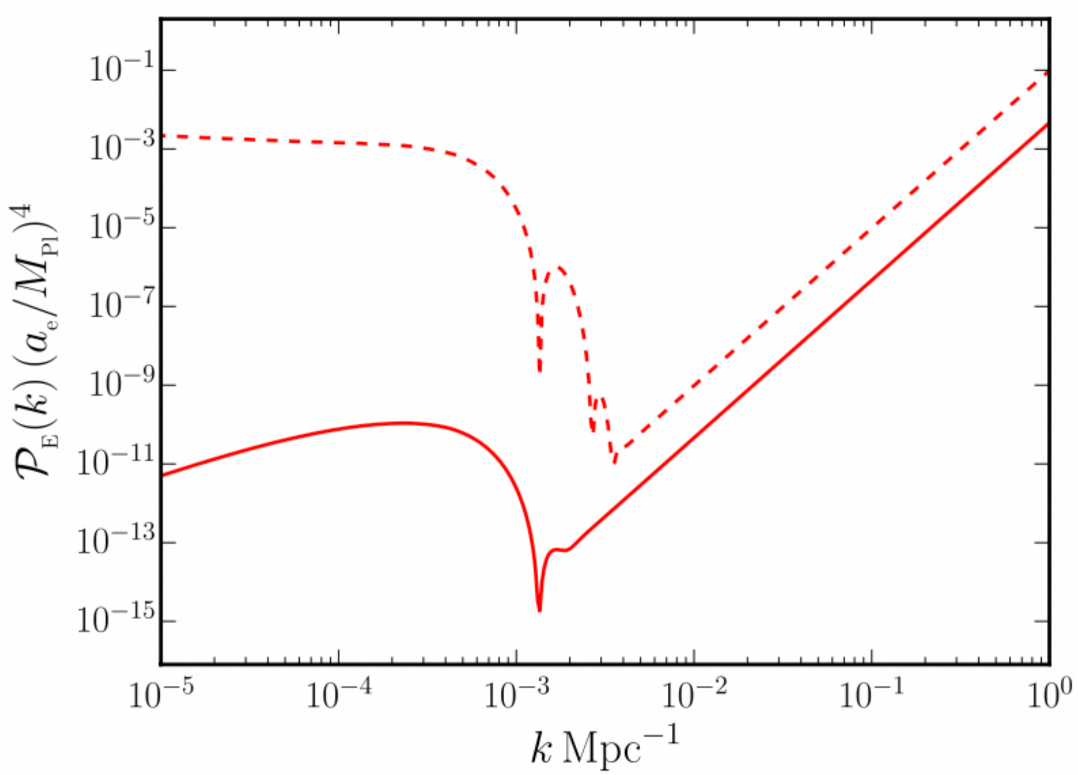
EM spectra — ultra slow roll

$$V(\phi) = \frac{m^2}{2}\phi^2 - \frac{2m^2}{3\phi_0}\phi^3 + \frac{m^2}{4\phi_0^2}\phi^4.$$



Polynomial potential — allows USR



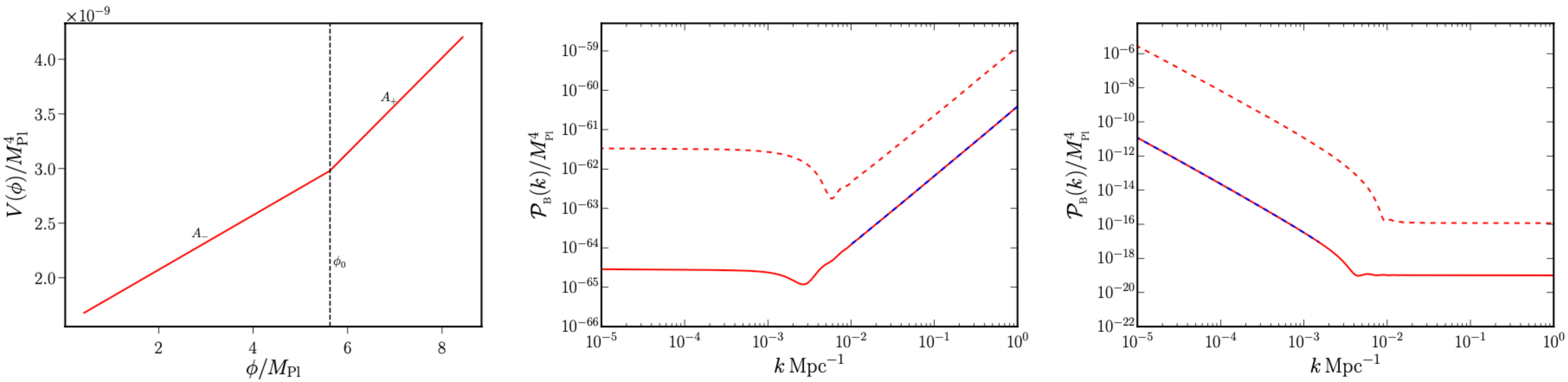


Tripathy, Chowdhury, **RKJ** & Sriramkumar, PRD 105, 063519 (2022)

EM spectra — strong deviations from slow roll

Starobinsky model is described by the potential

$$V(\phi) = \begin{cases} V_0 + A_+ (\phi - \phi_0), & \text{for } \phi > \phi_0, \\ V_0 + A_- (\phi - \phi_0), & \text{for } \phi < \phi_0. \end{cases}$$

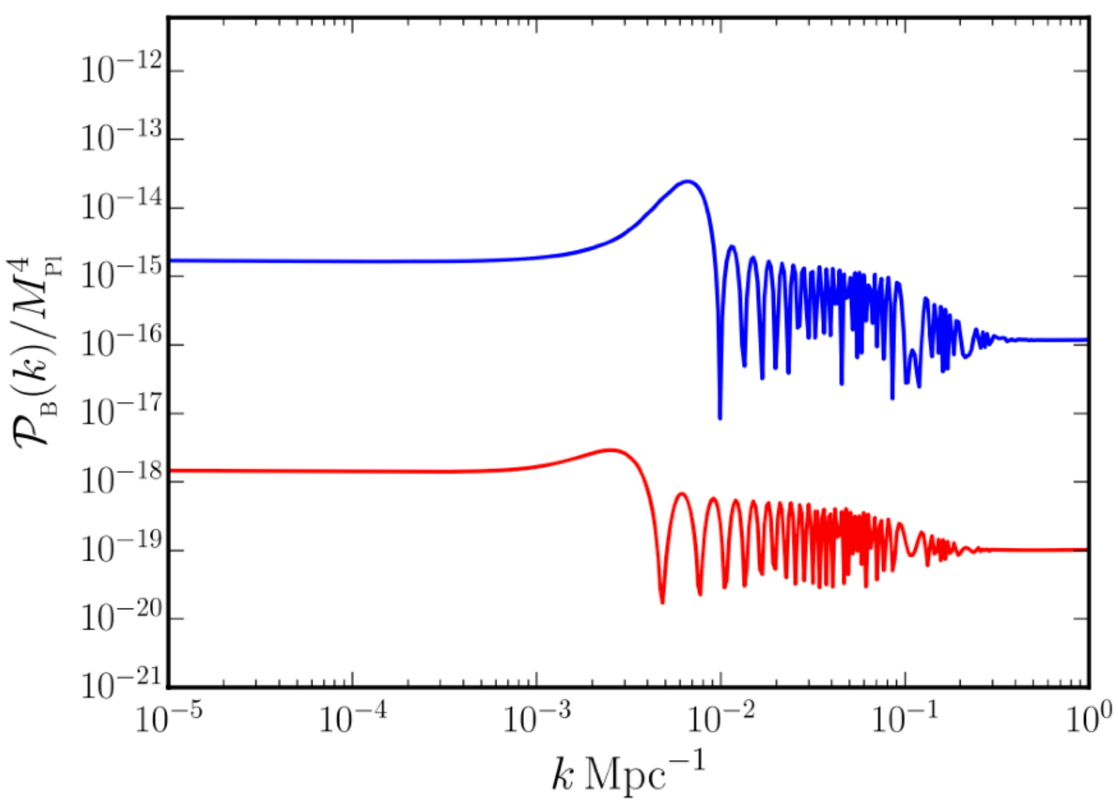


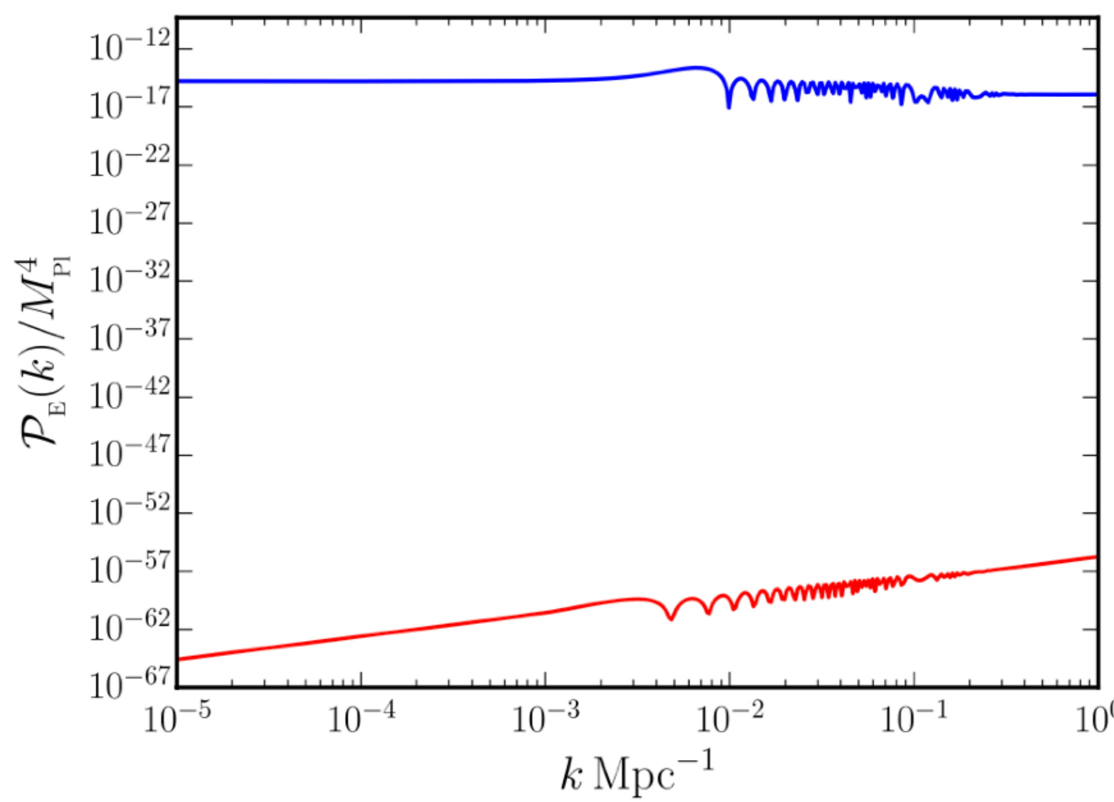
Tripathy, Chowdhury, **RKJ** & Sriramkumar, PRD 105, 063519 (2022)

EM spectra — strong deviations from slow roll

$$V(\phi) = V_0 + \frac{1}{2}(A_+ + A_-)(\phi - \phi_0) + \frac{1}{2}(A_+ - A_-)(\phi - \phi_0)\tanh\left(\frac{\phi - \phi_0}{\Delta\phi}\right),$$

$$J(\phi) = \frac{J_1}{2J_{0+}}\left[1 + \tanh\left(\frac{\phi - \phi_0}{\Delta\phi_1}\right)\right]J_+(\phi) + \frac{J_1}{2J_{0-}}\left[1 - \tanh\left(\frac{\phi - \phi_0}{\Delta\phi_1}\right)\right]J_-(\phi),$$





PMF from two field models

Action for two field models

$$S[\phi,\chi] \;=\; \int \mathrm{d}^4x\,\sqrt{-g}\left[-\frac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi - \frac{f(\phi)}{2}\,\partial_\nu\chi\,\partial^\nu\chi - V(\phi,\chi)\right]$$

$$f(\phi) = \mathrm{e}^{2b(\phi)}.$$

Equations of motion

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = b_\phi \mathrm{e}^{2b}\dot{\chi}^2,$$

$$H^2 = \frac{1}{3M_{\mathrm{Pl}}^2}\left(\frac{\dot{\phi}^2}{2} + \mathrm{e}^{2b}\frac{\dot{\chi}^2}{2} + V\right),$$

$$\ddot{\chi} + (3H + 2b_\phi\dot{\phi})\dot{\chi} + \mathrm{e}^{-2b}V_\chi = 0,$$

$$\dot{H} = -\frac{1}{2M_{\mathrm{Pl}}^2}(\dot{\phi}^2 + \mathrm{e}^{2b}\dot{\chi}^2).$$

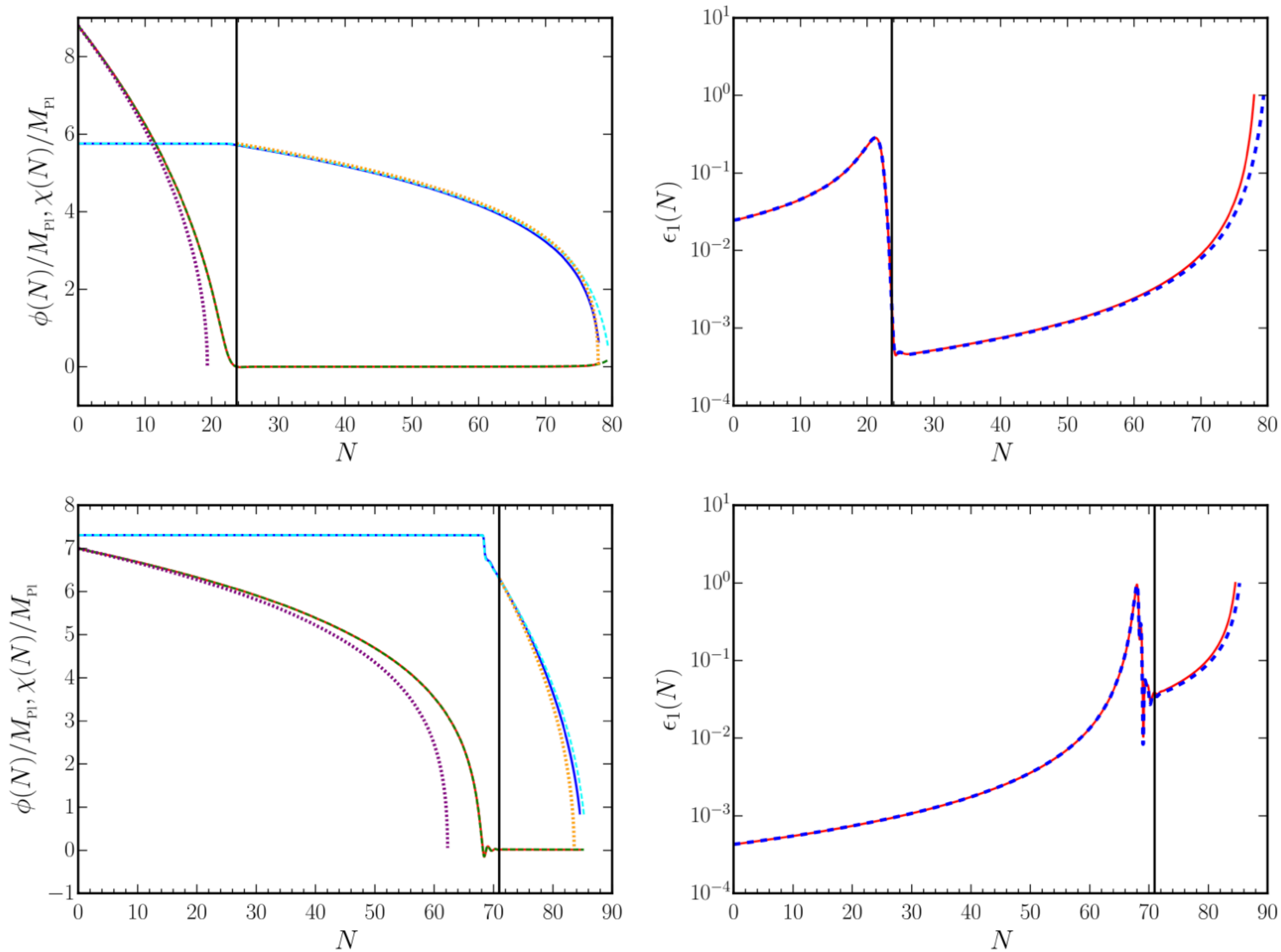
Two different representative potentials

$$V(\phi,\chi) = \frac{m_\phi^2}{2}\,\phi^2 + V_0\,\frac{\chi^2}{\chi_0^2+\chi^2}.$$

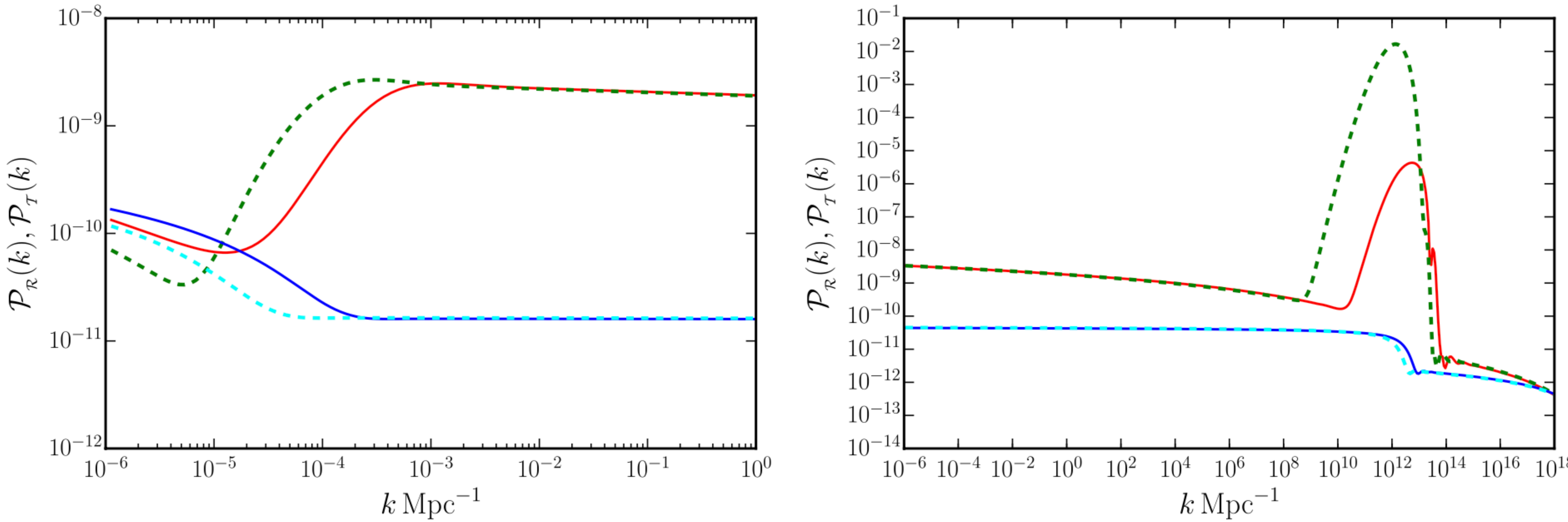
$$V(\phi,\chi) = V_0\,\frac{\phi^2}{\phi_0^2+\phi^2} + \frac{m_\chi^2\,\chi^2}{2}.$$

Tripathy, Chowdhury, Ragavendra, **RKJ** & Sriramkumar, PRD 107, 043501 (2023)

Background dynamics — two field models



Primordial scalar and tensor power spectra



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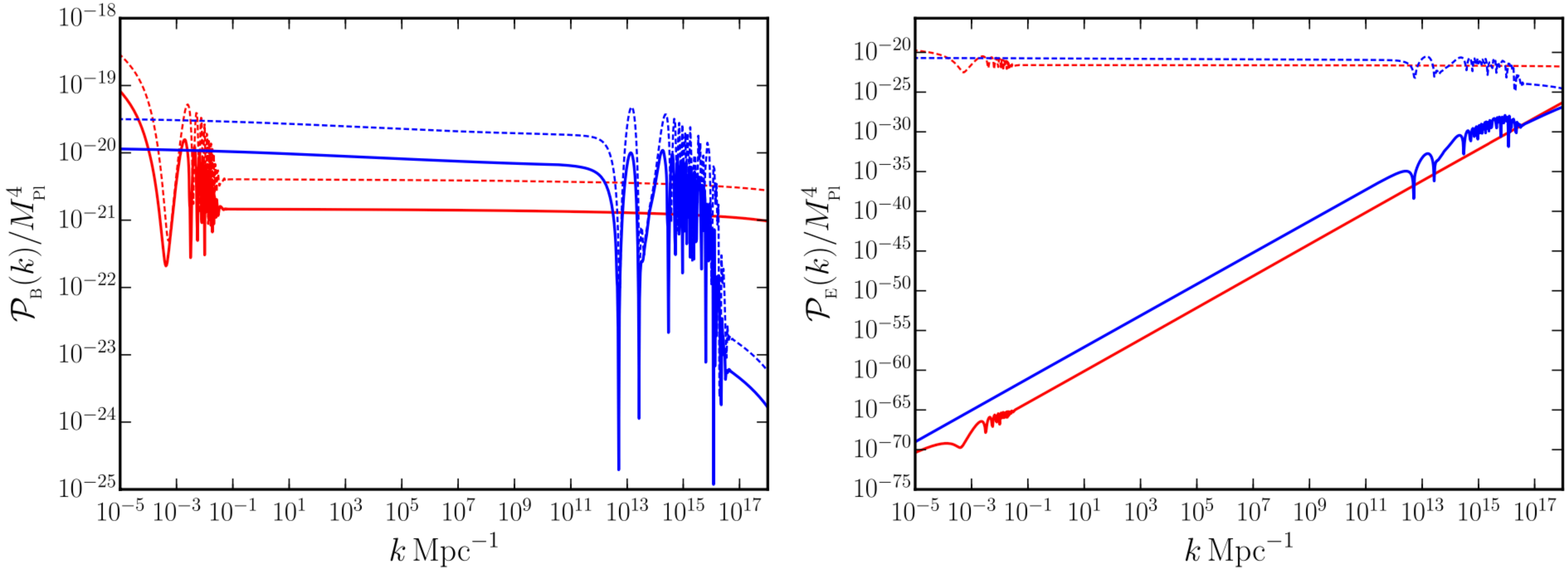
EM power spectra for two field models



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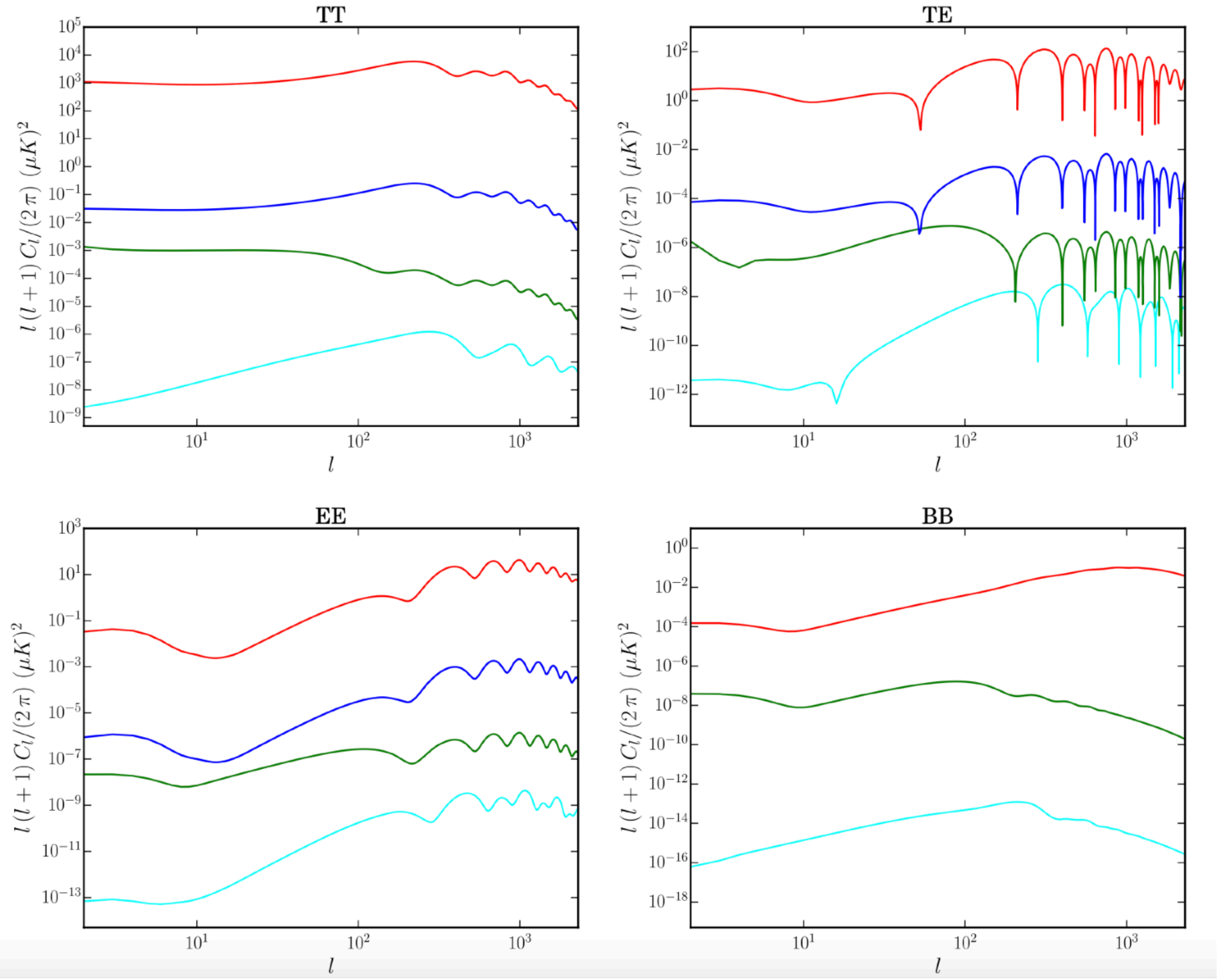
Imprints of PMF on CMB



Tripathy, Chowdhury, Ragavendra, **RKJ** & Sriramkumar, PRD 107, 043501 (2023)

Non-Gaussian imprints of inflationary magnetic fields

Non-Gaussian imprints of inflationary magnetic fields

- Inflationary magnetogenesis — excitation of gauge fields during inflation — a non-trivial cross-correlation of primordial curvature perturbation with magnetic fields.

- Cross-correlations are non-Gaussian in nature — important to understand their strength in a specific scenario.

- A model-independent calculation can not be done as these correlations depend on the coupling function.

$$\langle \zeta(k_1)\mathbf{B}(k_2).\mathbf{B}(k_3)\rangle$$

Primordial non-Gaussianities from inflation

- The primordial perturbations are encoded in the two-point function or the power spectrum

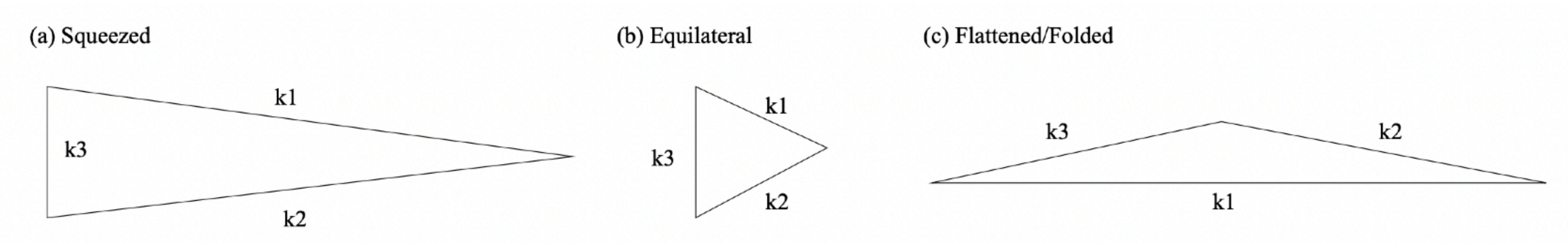
$$\langle \zeta_{k_1} \zeta_{k_2} \rangle = (2\pi)^3 \delta(\vec{k_1} + \vec{k_2}) P_\zeta(k_1)$$

- A non-vanishing three-point function is a signal of primordial non-Gaussianities

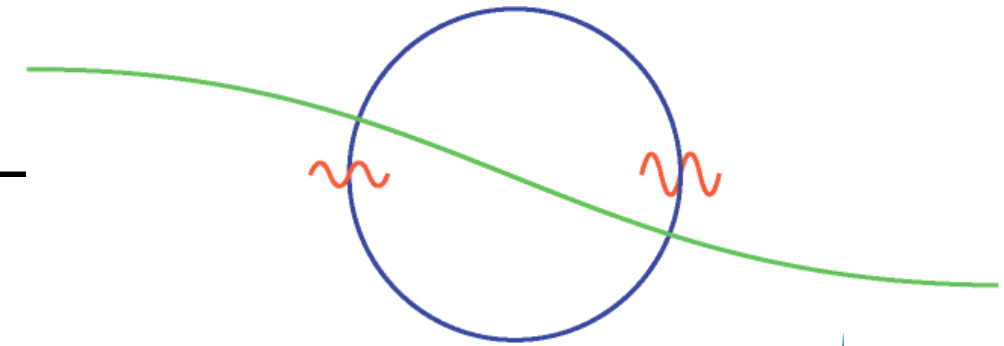
$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle \qquad f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$$

- Introduce $f_{\rm NL}$ as a measure of primordial non-Gaussianities

$$f_{\rm NL} \sim \langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle / P_\zeta(k_1) P_\zeta(k_2) + \text{perm.}$$



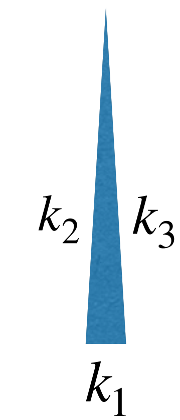
Semi-classical estimate in the squeezed limit



- Squeezed limit: $k_1 \ll k_2 \sim k_3$
- Consider $\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle$ in the squeezed limit i.e. $k_1 \to 0$
  - The long wavelength mode rescales the background for short wavelength modes

$$ds^2 = -dt^2 + a^2(t)\, e^{2\zeta(t,\mathbf{x})} d\mathbf{x}^2$$

  - Taylor expand in the rescaled background



$$\langle \zeta_{k_2} \zeta_{k_3} \rangle_{\zeta_1} = \langle \zeta_{k_2} \zeta_{k_3} \rangle + \zeta_1 \frac{\partial}{\partial \zeta_1} \langle \zeta_{k_2} \zeta_{k_3} \rangle + \ldots$$

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle_{\zeta_1} \approx \left\langle \zeta_{k_1} \langle \zeta_{k_2} \zeta_{k_3} \rangle_{\zeta_1} \right\rangle \sim \langle \zeta_{k_1} \zeta_{k_1} \rangle\, k \frac{d}{dk} \langle \zeta_{k_2} \zeta_{k_3} \rangle$$

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle \sim -(n_s - 1) \langle \zeta_{k_1} \zeta_{k_1} \rangle \langle \zeta_{k_2} \zeta_{k_3} \rangle$$

$$f_{NL}^{\text{local}} = -(n_s - 1)$$

Maldacena, JHEP 0305, 013 (2002)

Non-Gaussian cross-correlation with magnetic fields

- Define the cross-correlation bispectrum of the curvature perturbation with magnetic fields as

$$\langle\zeta(\mathbf{k}_1)\mathbf{B}(\mathbf{k}_2)\cdot\mathbf{B}(\mathbf{k}_3)\rangle \equiv (2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_{\zeta BB}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

$$B_{\zeta BB}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) \equiv b_{NL}P_\zeta(k_1)P_B(k_2)$$

- *Local* resemblance between f_{NL} and b_{NL}

$$\zeta = \zeta^{(G)} + \frac{3}{5}f_{NL}^{local}\left(\zeta^{(G)}\right)^2$$

$$\mathbf{B} = \mathbf{B}^{(G)} + \frac{1}{2}b_{NL}^{local}\zeta^{(G)}\mathbf{B}^{(G)}$$

RKJ & Sloth, Phys. Rev. D 86, 123528 (2012)

A novel magnetic consistency relation

- For a kinetic coupling $\lambda(\phi)F_{\mu\nu}F^{\mu\nu}$, using our semi-classical approach, the cross-correlation becomes

$$\langle\zeta(\tau_I,\mathbf{k}_1)\mathbf{B}(\tau_I,\mathbf{k}_2)\cdot\mathbf{B}(\tau_I,\mathbf{k}_3)\rangle$$
$$= -\frac{1}{H}\frac{\dot{\lambda}}{\lambda}(2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)P_\zeta(k_1)P_B(k_2)$$

- With $\lambda(\phi(\tau)) = \lambda_I(\tau/\tau_I)^{-2n}$, we obtain $\boxed{b_{NL} = n_B - 4}$

In the squeezed limit $k_1 \ll k_2, k_3 = k$

$$\boxed{\langle\zeta(k_1)\mathbf{B}(k_2)\cdot\mathbf{B}(\mathbf{k_3})\rangle = (n_B-4)(2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)P_\zeta(k_1)P_B(k)}$$

$$\boxed{\langle\zeta(k_1)\zeta(k_2)\zeta(k_3)\rangle = -(n_s-1)(2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)P_\zeta(k_1)P_\zeta(k)}$$

RKJ & Sloth, Phys. Rev. D 86, 123528 (2012)

Full in-in calculation

- One has to cross-check the consistency relation by doing a complete in-in calculation.

- The final result is

$$\langle\zeta(\tau_I,\mathbf{k}_1)\mathbf{B}(\tau_I,\mathbf{k}_2)\cdot\mathbf{B}(\tau_I,\mathbf{k}_3)\rangle = -\frac{1}{H}\frac{\dot{\lambda}_I}{\lambda_I}(2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)|\zeta^{(0)}_{k_1}(\tau_I)|^2|A^{(0)}_{k_2}(\tau_I)||A^{(0)}_{k_3}(\tau_I)| \times\left[\left(\mathbf{k}_2\cdot\mathbf{k}_3+\frac{(\mathbf{k}_2\cdot\mathbf{k}_3)^3}{k_2^2k_3^2}\right)k_2k_3\tilde{\mathcal{I}}^{(1)}_n+2(\mathbf{k}_2\cdot\mathbf{k}_3)^2\tilde{\mathcal{I}}^{(2)}_n\right] .$$

- The two integrals can be solved exactly for different values of n.

RKJ & Sloth, JCAP 1302, 003 (2013)

Full in-in calculation

- **The flattened shape:** In this limit, $k_1 = 2k_2 = 2k_3$, the cross-correlation becomes

$$\langle\zeta(\tau_I, \mathbf{k}_1)\mathbf{B}(\tau_I, \mathbf{k}_2)\cdot\mathbf{B}(\tau_I, \mathbf{k}_3)\rangle \simeq 96\ln(-k_t\tau_I)P_\zeta(k_1)P_B(k_2)$$

  - For the largest observable scale today, $\ln(-k_t\tau_I) \sim -60,$

$$\left|b_{NL}^{flat}\right| \sim 5760$$

- **The squeezed limit:** In this limit, $k_1 \to 0$ and

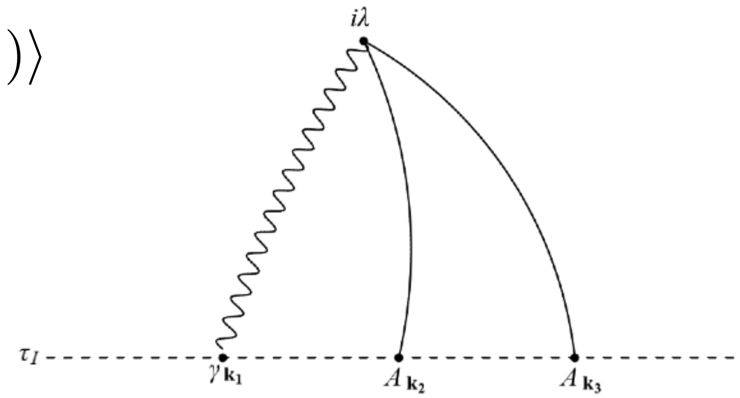
$$\langle\zeta(\tau_I, \mathbf{k}_1)\mathbf{B}(\tau_I, \mathbf{k}_2)\cdot\mathbf{B}(\tau_I, \mathbf{k}_3)\rangle = -\frac{1}{H}\frac{\dot{\lambda}_I}{\lambda_I}(2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)P_\zeta(k_1)P_B(k_2)$$

with $b_{NL} = -\frac{1}{H}\frac{\dot{\lambda}_I}{\lambda_I} = n_B - 4$ in agreement with the consistency relation.

RKJ & Sloth, JCAP 1302, 003 (2013)

Cross-correlations with gravitons

$$\langle\gamma(\mathbf{k_1})\mathbf{A}(\mathbf{k_2})\cdot\mathbf{A}(\mathbf{k_3})\rangle\ , \qquad \langle\gamma(\mathbf{k_1})\mathbf{B}(\mathbf{k_2})\cdot\mathbf{B}(\mathbf{k_3})\rangle\ , \qquad \langle\gamma(\mathbf{k_1})\mathbf{E}(\mathbf{k_2})\cdot\mathbf{E}(\mathbf{k_3})\rangle$$



$$ds^2 = -dt^2 + a^2(t)\left[e^{\gamma}\right]_{ij}dx^i dx^j \approx -dt^2 + a^2(t)\left[\delta_{ij}+\gamma_{ij}\right]dx^i dx^j$$

In the squeezed (soft) limit

$$\lim_{k_1\to 0}\langle\gamma(\tau_I,\mathbf{k}_1)B_\mu(\tau_I,\mathbf{k}_2)B^\mu(\tau_I,\mathbf{k}_3)\rangle = (2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)\left(n-\frac{1}{2}\right)\epsilon_{ij}\frac{k_{2i}k_{2j}}{k_2^2}P_\gamma(k_1)P_B(k_2)$$

$$\lim_{k_1\to 0}\langle\gamma(\tau_I,\mathbf{k}_1)E_\mu(\tau_I,\mathbf{k}_2)E^\mu(\tau_I,\mathbf{k}_3)\rangle = -(2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)\left(n+\frac{1}{2}\right)\epsilon_{ij}\frac{k_{2i}k_{2j}}{k_2^2}P_\gamma(k_1)P_E(k_2)$$

$$\begin{aligned} b_{NL}^{\gamma} &= \left(n-\frac{1}{2}\right)\epsilon_{ij}\frac{k_{2i}k_{2j}}{k_2^2}, \quad n > -1/2 \\ e_{NL}^{\gamma} &= -\left(n+\frac{1}{2}\right)\epsilon_{ij}\frac{k_{2i}k_{2j}}{k_2^2}, \quad n < 1/2 \end{aligned}$$

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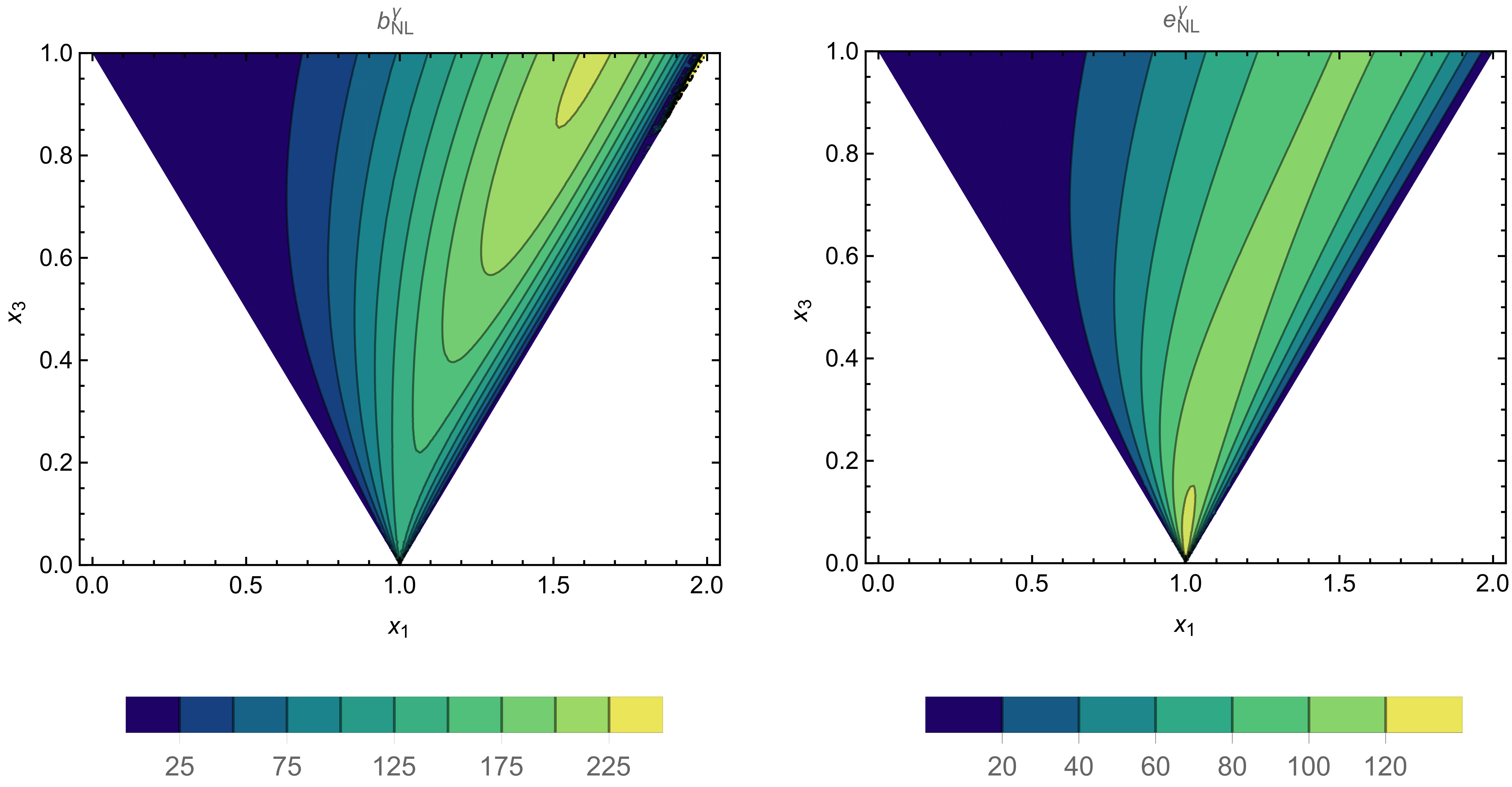
Cross-correlations with gravitons



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Conclusions

- Inflationary magnetogenesis is promising — problems to get strong enough fields — strong constraints
- Non-trivial imprints of slow roll violations on inflationary magnetic fields — a generic feature in both single and two field models
- CMB imprints are still much smaller — than the CMB TT anisotropies
- Novel cross-correlations of curvature perturbations with magnetic fields — soft theorems — imprints on CMB bispectrum — non-trivial $\langle \mu T \rangle$ correlations — constraints from observations.

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Thank you for your attention!