Magnetogenesis from isocurvatures @ second order

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Based on ongoing work with Karim Malik

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Cosmic Magnetism

- Magnetic fields are found at all scales in the Universe
  - Planets, Stars, Galaxies,…
- It is even measured in the large-scale structure,
  - Clusters $B{\sim}10^{-5}G$
  - Filaments $B{\sim}10^{-7}G$

May be **seeded** by $B{\sim}10^{-20\ldots-15}\ G$

Leftover in Voids

  - Voids $B \gtrsim 10^{-17}G$
- **Could the origin of magnetic seeds be cosmological?**

Magnetogenesis

- We study a model based on vortical currents generated by non-linearities:
  - Thomson scattering generates a net electric field

$$\vec{E} \sim (1-\beta^3)\sigma_T \Delta\vec{v}_{b\gamma}$$

  - At 1st order in perturbations, no $\vec{B}$ is generated (no vectors)

$$(a^2\vec{B})' \propto \nabla \times \vec{E} = 0$$

  - But at 2nd order we get

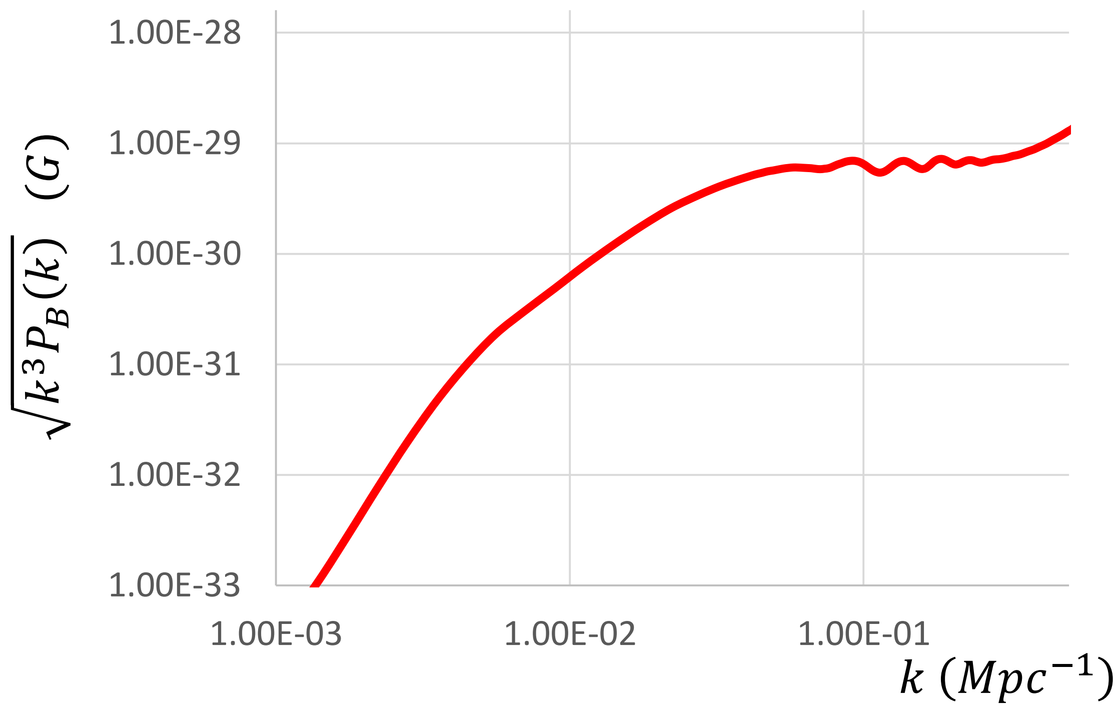
$$(a^2\vec{B})' \sim \nabla \times \Delta\vec{v}_{b\gamma} + \nabla(\delta_\gamma - \Psi + \Phi) \times \Delta\vec{v}_{b\gamma} + \nabla \times (\Pi_\gamma \cdot \vec{v}_b)$$

Magnetogenesis

- Adiabatic case already explored with Boltzmann codes

  [Ichiki et al 2007, Fenu et al 2011, Saga et al 2015, Fidler et al 2016]

  - Result for adiabatic mode $B \sim 10^{-29}\ G\ @\ 1\ \mathrm{Mpc}\ @\ z = 0$



Magnetogenesis from Isocurvatures

- Introducing isocurvatures has several advantages [Maeda et al. 2011]
  - With 2 d.o.f. we can generate vorticity

$$\vec{\omega}' \propto \nabla\delta S \times \Delta\vec{v}_{b\gamma}$$

  - Suppressed only at first order in tight coupling

$$\left(a^2\vec{B}\right)' \propto \vec{\omega} + \nabla\delta S \times \Delta\vec{v}_{b\gamma} \sim O(\alpha^{-1})$$

- Promising analytical results of $B \sim 10^{-20}\ G\ @\ 1\ \mathrm{Mpc}$, but only calculated at M-R equality.

Magnetogenesis from Isocurvatures

- The main question:
  - **Can isocurvatures contribute to magnetogenesis?**

- The Plan:

We calculate the spectrum with 2nd order Boltzmann code SONG: [Pettinari et al 2014]

  - Solve Faraday law and all vector equations
  - Calculate spectrum: $P_B(k) \sim \langle B^i(\vec{k}) B_i(\vec{k}') \rangle$
  - Parametrize input spectrum of isocurvatures with

$$P_{iso}(k) = k^{-3} f_{iso} A_s \left(\frac{k}{k^*}\right)^{n_i - 1}$$

Magnetogenesis

- Before evolution we need initial conditions for mixed modes:
  - Baryon iso x Adiabatic

$$\vec{B}(\tau_0) = \frac{m_p}{\mathrm{e}} \frac{1-\beta^3}{1+\beta^2} \frac{5R_b(4275 + 1320R_\nu + 64R_\nu^2)}{288\,(15+2R_\nu)(15+4R_\nu)^2} \vec{k}_1 \times \vec{k}_2\; \omega\tau_0\; \delta S^0_{b,k_1} \zeta^0_{k_2}$$

  - CDM iso x Adiabatic

$$\vec{B}(\tau_0) = \frac{m_p}{\mathrm{e}} \frac{1-\beta^3}{1+\beta^2} \frac{5R_c(525 + 220R_\nu + 24\,R_\nu^2)}{48\,(15+2R_\nu)(15+4R_\nu)^2} \vec{k}_1 \times \vec{k}_2\; \omega\tau_0\; \delta S^0_{c,k_1} \zeta^0_{k_2}$$

  - Other modes

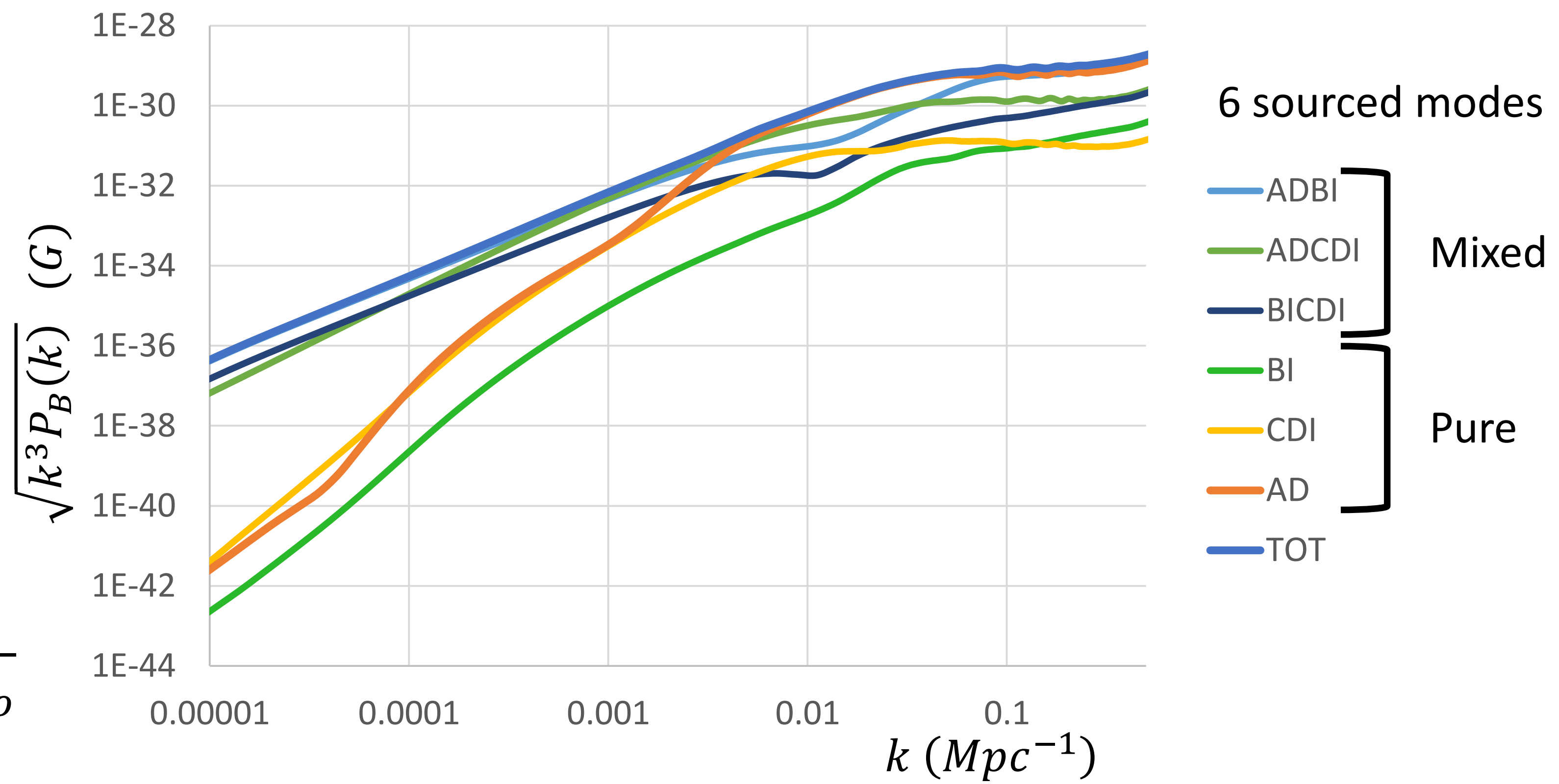
$$\vec{B}(\tau_0) \lesssim \mathrm{O}({\tau_0}^2)$$

- Indication: at early times, mixed modes produce larger B.

Magnetogenesis

- Result spectra for isocurvature cases with SONG
  - Scale-invariant isocurvature spectrum ($n_i = 1$)

$$@ \quad z = 0$$
$$f_{iso} = 1$$



$$B_{\mathrm{Ad\times iso}} \propto \sqrt{f_{iso}}$$

Magnetogenesis

- Result spectra for isocurvature cases with SONG
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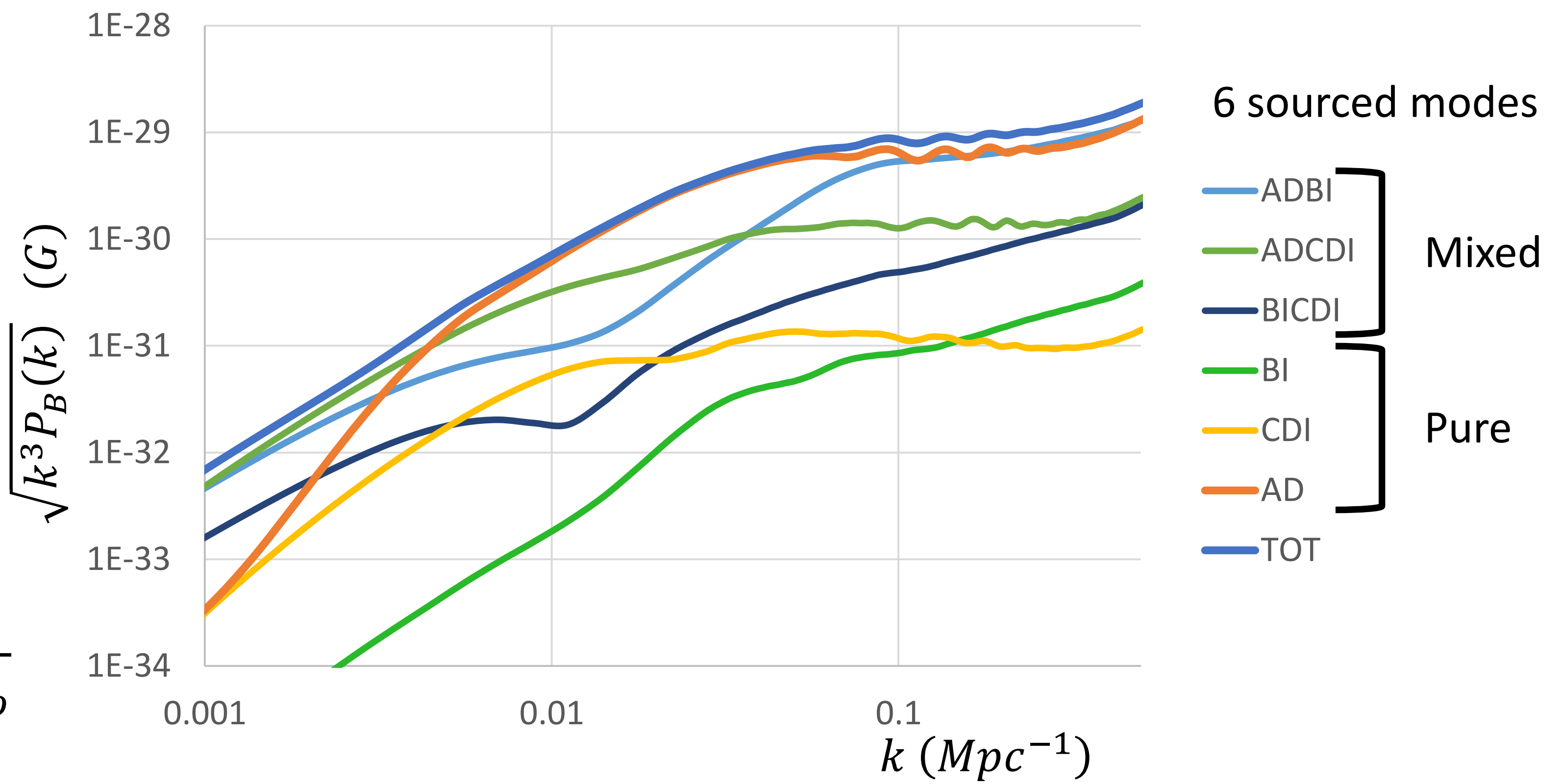
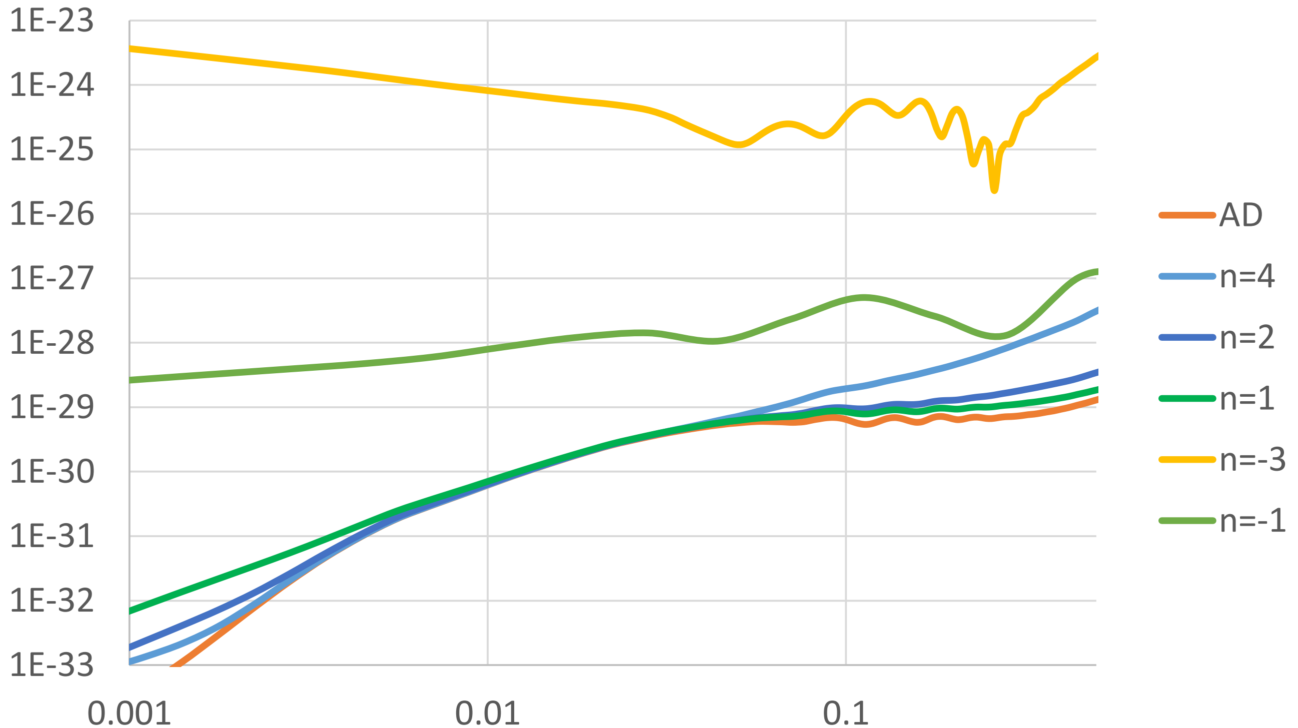


$B_{\mathrm{Ad}\times\mathrm{iso}} \propto \sqrt{f_{iso}}$

Magnetogenesis

- New spectra for isocurvature cases with SONG
  - Dependence on spectral index

$@ \quad z = 0$
$f_{iso} = 1$



$\sqrt{k^3 P_B(k)} \quad (G)$

$k \ (Mpc^{-1})$

$B_{\mathrm{Ad}\times\mathrm{iso}} \propto \sqrt{f_{iso}}$

Conclusions

- Isocurvatures can enhance magnetogenesis:
- Large scales: $k < 10^{-3}\ \mathrm{Mpc}^{-1}$:
  - Large enhancement of several orders of magnitude
- Small scales $k > 10^{-3}\ \mathrm{Mpc}^{-1}$:
  - Small enhancement of order 10—30 depending on $n_i > 1$
  - Large enhancement for $n_i \leq -1$, but depends on IR cut-off.
- Even in the best case scenario $B \ll 10^{-17}\ G$ in this model
- Future: Correlated isocurvatures and compensated isocurvature mode.

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Thank you!

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