Title: Spontaneously emitted field fluctuations in the IGM and the generation of magnetic seed fields

Date: Mar 14, 2016 03:30 PM

URL: http://pirsa.org/16030094

Abstract:

SPONTANEOUSLY EMITTED FIELD FLUCTUATIONS
AND THE GENERATION OF MAGNETIC SEED FIELDS

RUB

ULRICH KOLBERG MARCH 14, 2016

Institute for Theoretical Physics IV:
Space and Astrophysics
Ruhr University Bochum, Germany

Origin of cosmological magnetic fields

RUB

Seed fields

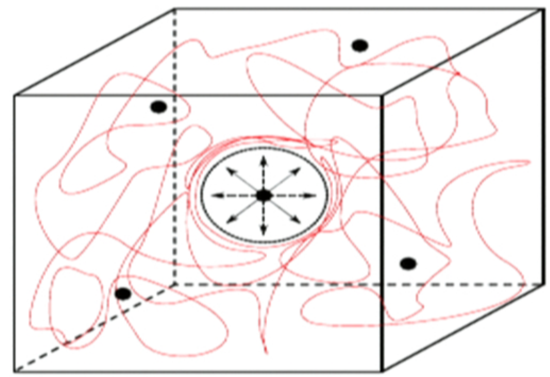
- only $\sim 10^{-20}$ G required
- Biermann battery
- Inflationary fields
- Cosmological phase transitions
- **Spontaneous field fluctuations in the IGM?**

Amplification

- (MHD) dynamo action
- Flux-conserving compression
- plasma instabilities (e. g., Weibel instability)

Ordering, distribution

- e. g., due to shocks

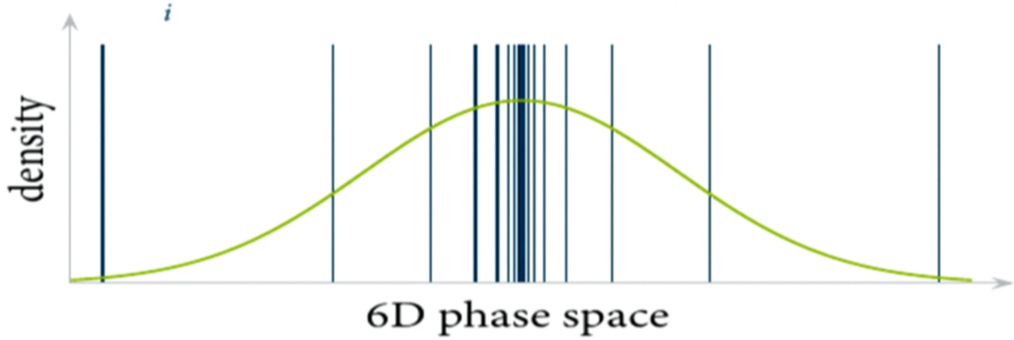


- The IGM might contain seed fields in their initial state $\longrightarrow$ seed field probing?
- No conclusive observational data available yet
- NERONOV & VOVK (2010) derived lower limits on the field strength in the IGM $\longrightarrow$ not compelling [BRODERICK et. al. (2012), MENZLER & SCHLICKEISER (2015)]
- Theoretical calculation of fluctuating field strengths required

Spontaneous and induced fluctuations

RUB

$N = \sum_i \delta(\boldsymbol{r} - \boldsymbol{r}_i(t))\, \delta(\boldsymbol{p} - \boldsymbol{p}_i(t))$ $\langle N \rangle = nf$



Spontaneous fluctuations δN^0

- independent of $\delta \boldsymbol{E}$, $\delta \boldsymbol{B}$
- due to particle discreteness

Induced fluctuations δN^{ind}

- functional of $\delta \boldsymbol{E}$, $\delta \boldsymbol{B}$
- plasma response to $\delta \boldsymbol{E}$, $\delta \boldsymbol{B}$

Since $\delta \boldsymbol{J} = \sum_a e_a \int d^3p\, \boldsymbol{v}\, \delta N_a$, spontaneous fluctuations δN_a^0 lead to a quasi-external current density $\delta \boldsymbol{J}^0$:

$$(\partial/\partial t + \boldsymbol{v} \cdot \nabla)(\delta N^a_{t,\boldsymbol{r},\boldsymbol{p}} - \delta N^{a0}_{t,\boldsymbol{r},\boldsymbol{p}}) = -n_a\, \delta \boldsymbol{F}^a_{t,\boldsymbol{r},\boldsymbol{p}} \cdot \nabla_p f^a_{\boldsymbol{p}} \quad \text{Klimontovich equation}$$

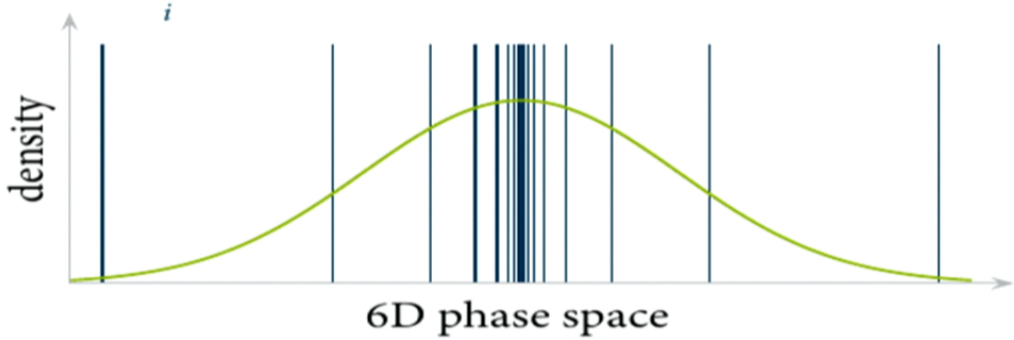
$$\delta N^a_{\omega,\boldsymbol{k},\boldsymbol{p}} - \delta N^{a0}_{\omega,\boldsymbol{k},\boldsymbol{p}} = \mathbf{s}^a_{\omega,\boldsymbol{k},\boldsymbol{p}} \otimes \delta \boldsymbol{E}_{\omega,\boldsymbol{k}} \quad \text{Fourier-Laplace transform}$$

$$\delta \boldsymbol{J}_{\omega,\boldsymbol{k}} - \delta \boldsymbol{J}^0_{\omega,\boldsymbol{k}} = \boldsymbol{\sigma}_{\omega,\boldsymbol{k}} \otimes \delta \boldsymbol{E}_{\omega,\boldsymbol{k}} \quad \text{Ohm's law, linear response}$$

Spontaneous and induced fluctuations

RUB

$$N = \sum_i \delta(\boldsymbol{r} - \boldsymbol{r}_i(t))\, \delta(\boldsymbol{p} - \boldsymbol{p}_i(t)) \qquad \langle N \rangle = nf$$



Spontaneous fluctuations δN^0

- independent of $\delta \boldsymbol{E}$, $\delta \boldsymbol{B}$
- due to particle discreteness

Induced fluctuations δN^{ind}

- functional of $\delta \boldsymbol{E}$, $\delta \boldsymbol{B}$
- plasma response to $\delta \boldsymbol{E}$, $\delta \boldsymbol{B}$

Since $\delta \boldsymbol{J} = \sum_a e_a \int \mathrm{d}^3 p\, \boldsymbol{v}\, \delta N_a$, spontaneous fluctuations δN_a^0 lead to a quasi-external current density $\delta \boldsymbol{J}^0$:

$$(\partial/\partial t + \boldsymbol{v} \cdot \nabla)(\delta N^a_{t,\boldsymbol{r},\boldsymbol{p}} - \delta N^{a0}_{t,\boldsymbol{r},\boldsymbol{p}}) = -n_a\, \delta \boldsymbol{F}^a_{t,\boldsymbol{r},\boldsymbol{p}} \cdot \nabla_p f^a_{\boldsymbol{p}} \qquad \text{Klimontovich equation}$$

$$\delta N^a_{\omega,\boldsymbol{k},\boldsymbol{p}} - \delta N^{a0}_{\omega,\boldsymbol{k},\boldsymbol{p}} = \mathbf{s}^a_{\omega,\boldsymbol{k},\boldsymbol{p}} \otimes \delta \boldsymbol{E}_{\omega,\boldsymbol{k}} \qquad \text{Fourier-Laplace transform}$$

$$\delta \boldsymbol{J}_{\omega,\boldsymbol{k}} - \delta \boldsymbol{J}^0_{\omega,\boldsymbol{k}} = \boldsymbol{\sigma}_{\omega,\boldsymbol{k}} \otimes \delta \boldsymbol{E}_{\omega,\boldsymbol{k}} \qquad \text{Ohm's law, linear response}$$

The radiation law

RUB

- Maxwell's equations + response model (Ohm's law) $\longrightarrow$ wave equation:

$$\boldsymbol{\Lambda}_{\omega,\boldsymbol{k}} \otimes \delta \boldsymbol{E}_{\omega,\boldsymbol{k}} = -\frac{4\pi\mathrm{i}}{\omega}\,\delta \boldsymbol{J}^{0}_{\omega,\boldsymbol{k}}$$

Maxwell tensor (EM plasma properties) | generated waves | current density (source of waves)

- Emission into the transverse mode $\omega_{\mathrm{M}}(\boldsymbol{k})$: $\langle |\delta \boldsymbol{E}^{\perp}_{\omega,\boldsymbol{k}}|^2 \rangle = I^{\perp}_{\boldsymbol{k}}\, \delta(\omega - \omega_{\mathrm{M}}(\boldsymbol{k}))$

- The generalized Kirchhoff radiation law accounts for the competing effects of spontaneous and induced emission and absorption in the mode $\omega_{\mathrm{M}}(\boldsymbol{k})$:

$$\frac{\partial I^{\perp}_{\boldsymbol{k}}}{\partial t} = \alpha^{\perp}_{\boldsymbol{k}} - \mu^{\perp}_{\boldsymbol{k}} I^{\perp}_{\boldsymbol{k}}\,, \qquad \mu^{\perp}_{\boldsymbol{k}} = -2\gamma^{\perp}_{\boldsymbol{k}} = -2\Im(\omega_{\mathrm{M}}(\boldsymbol{k}))\,, \quad \alpha^{\perp}_{\boldsymbol{k}} = \alpha^{\perp}_{\boldsymbol{k}}\{\delta \boldsymbol{J}^{0}_{\omega,\boldsymbol{k}}\}$$

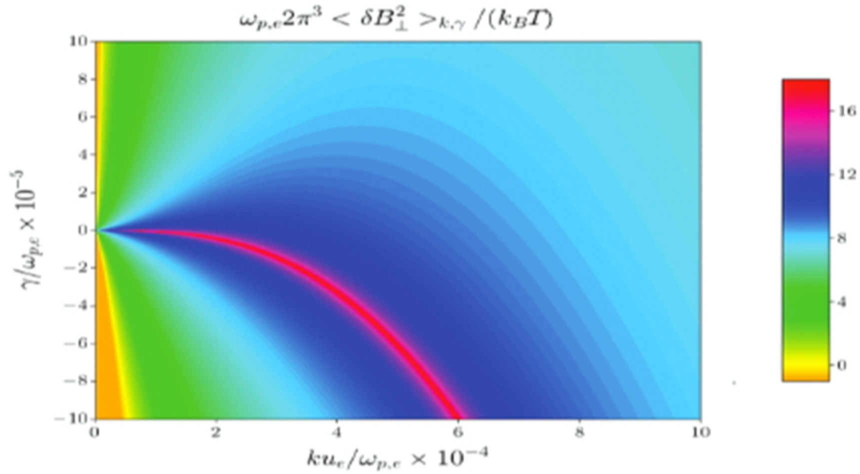
- For damped modes, the stationary solution evolves towards an equilibrium:

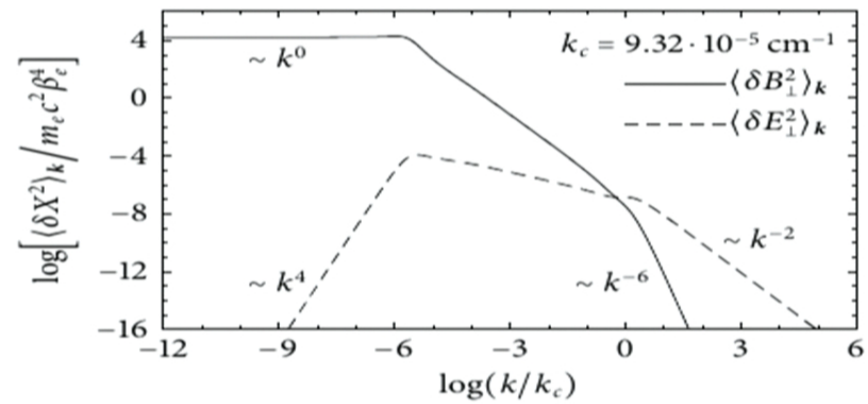
$$I^{\perp}_{\boldsymbol{k}} = \frac{\alpha^{\perp}_{\boldsymbol{k}}}{\mu^{\perp}_{\boldsymbol{k}}}\left[1 - \exp(-\mu^{\perp}_{\boldsymbol{k}} t)\right] \xrightarrow{t\to\infty} \frac{\alpha^{\perp}_{\boldsymbol{k}}}{\mu^{\perp}_{\boldsymbol{k}}}$$

Fluctuating magnetic fields in the IGM

RUB

- Modeling the IGM ($z = 0$): $T_e = T_p = 10^4$ K, $n_e = n_p = 10^{-7}$ cm^{-3}
- dominated by a transverse, damped, aperiodic mode $\omega_M(\boldsymbol{k}) = i\gamma_{\boldsymbol{k}}^{\perp}$ [Felten et. al. (2013), Yoon et. al. (2014)]



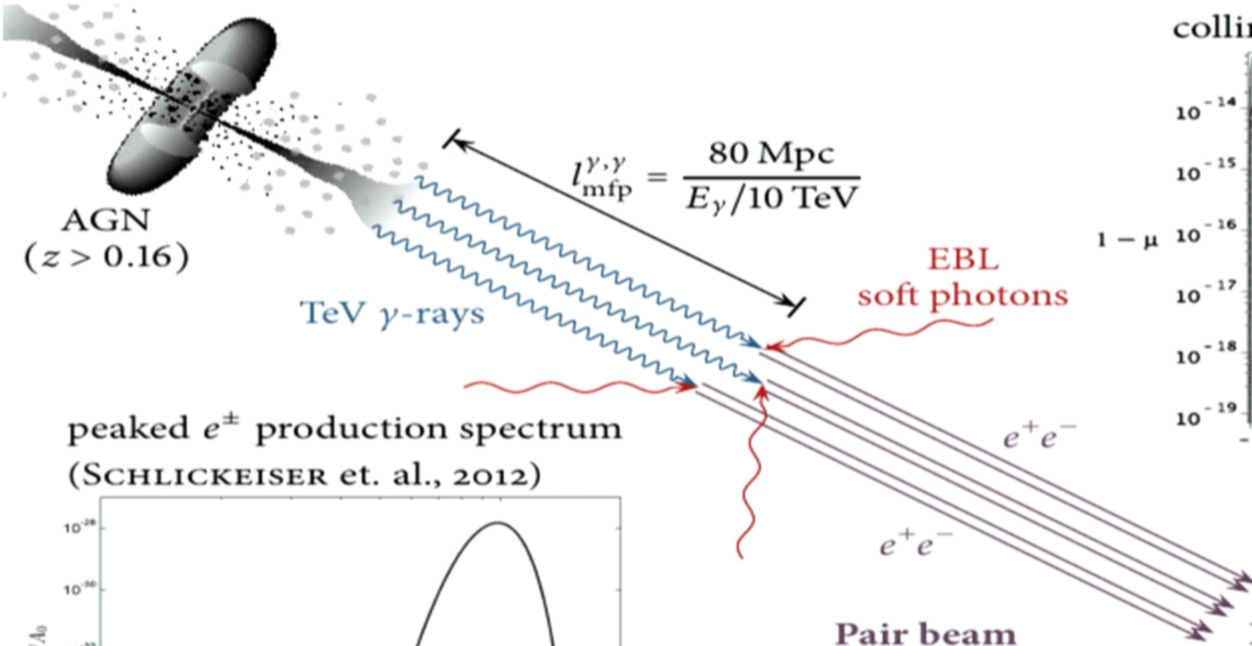


Integrating the spectra over all wave number values yields

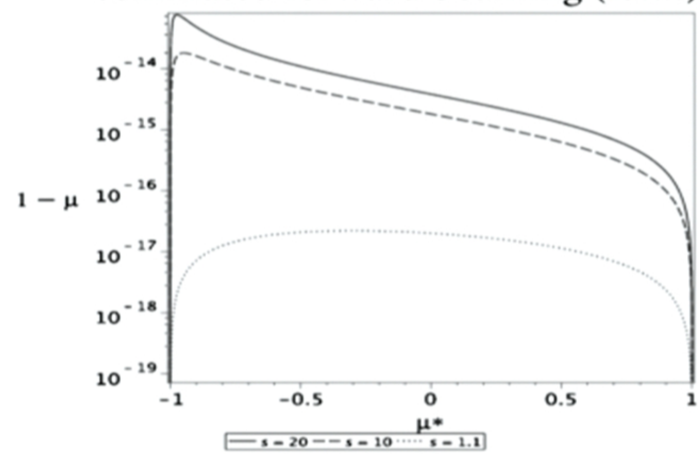
$$|\delta B_\perp| \equiv \sqrt{\langle \delta B_\perp^2 \rangle} = 6.3 \cdot 10^{-18}\ \mathrm{G} \longrightarrow \text{magnetic seed fields}$$

Disturbance by a pair beam traversing the IGM

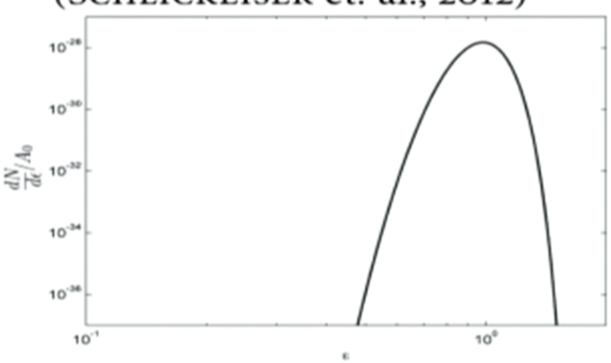
RUB



collimated forward beaming (*Ibid.*)



peaked $e^{\pm}$ production spectrum
(Schlickeiser et. al., 2012)



Pair beam

$f_{\mathrm{b}}(\boldsymbol{p}) = \delta(\boldsymbol{p} - \boldsymbol{P})$

$\Gamma = 10^6$

$n_e^{\mathrm{b}} = \varepsilon n_e^{\mathrm{IGM}}$

$\varepsilon = 10^{-15}$

Intergalactic medium

$f_{\mathrm{IGM}}(\boldsymbol{p})$ = thermal distribution

$T_e = T_p = 10^4\ \mathrm{K}$

$n_e^{\mathrm{IGM}} = n_p^{\mathrm{IGM}} = 10^{-7}\ \mathrm{cm}^{-3}$

$\langle \boldsymbol{E} \rangle = 0, \ \langle \boldsymbol{B} \rangle = 0$

Modified radiation law

RUB

The beam provides free energy and alters the electromagnetic properties of the plasma by altering the Maxwell tensor:

- $\mathbf{\Lambda}_{\omega,\boldsymbol{k}} = \mathbf{\Lambda}^{\text{thermal}}_{\omega,\boldsymbol{k}} + \varepsilon\,\mathbf{\Lambda}^{\text{beam}}_{\omega,\boldsymbol{k}}$, where $\varepsilon = 10^{-15}$ $\longrightarrow$ perturbation theory
- $\mathbf{\Lambda}_{\omega,\boldsymbol{k}}$ is no longer diagonal (the beam breaks the isotropic symmetry)
- The dispersion relation of the mode remains unaffected to first order: $\det \mathbf{\Lambda}[\omega_{\mathrm{M}}(\boldsymbol{k})] = 0 + \mathcal{O}(\varepsilon^2)$

Radiation law for the transverse field fluctuations ($i, j \in \{x, y\}$ for $\boldsymbol{k} \parallel \hat{\boldsymbol{z}}$):

$$\frac{\partial I^{ij}_{\boldsymbol{k}}}{\partial t} = \alpha^{ij}_{\boldsymbol{k}} - \mu_{\boldsymbol{k}} I^{ij}_{\boldsymbol{k}}\,, \qquad \mu_{\boldsymbol{k}} = -2\gamma^{\text{eff}}_{\boldsymbol{k}}\,, \qquad \gamma^{\text{eff}}_{\boldsymbol{k}} = \gamma^{\perp}_{\boldsymbol{k}} + \varepsilon\gamma^{\text{beam}}_{\boldsymbol{k}}$$

CASE	ABSORPTION COEFF.	GROWTH RATE
without beam	$\mu^{\perp}_{\boldsymbol{k}} > 0$	$\gamma^{\perp}_{\boldsymbol{k}} < 0$
with beam	$\mu_{\boldsymbol{k}} > 0$ & $\mu_{\boldsymbol{k}} < 0$	$\gamma^{\text{eff}}_{\boldsymbol{k}} < 0$ & $\gamma^{\text{eff}}_{\boldsymbol{k}} > 0$

Conditions for amplification

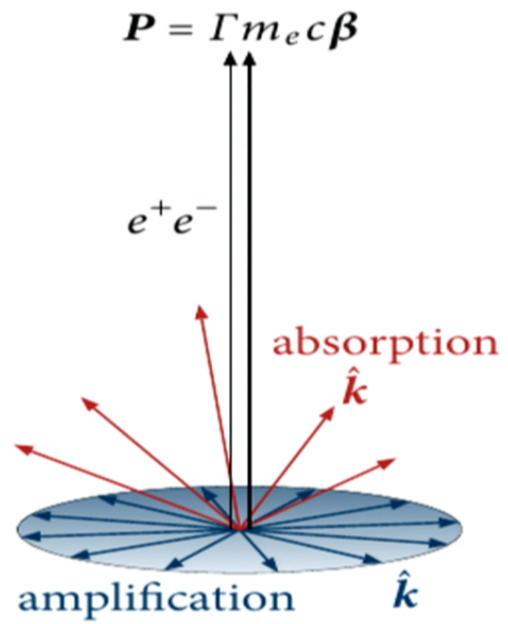
RUB

Positive effective growth rates and amplification occur in certain spectral bands

- if beam velocity $\boldsymbol{\beta} = \boldsymbol{P}/\Gamma m_e c$ and wavevector $\boldsymbol{k}$ are almost perpendicular to each other ($\beta_\parallel \equiv \boldsymbol{\beta} \cdot \hat{\boldsymbol{k}} \ll 1$),
- and if, additionally, the ratio Γ/ε is sufficiently small:

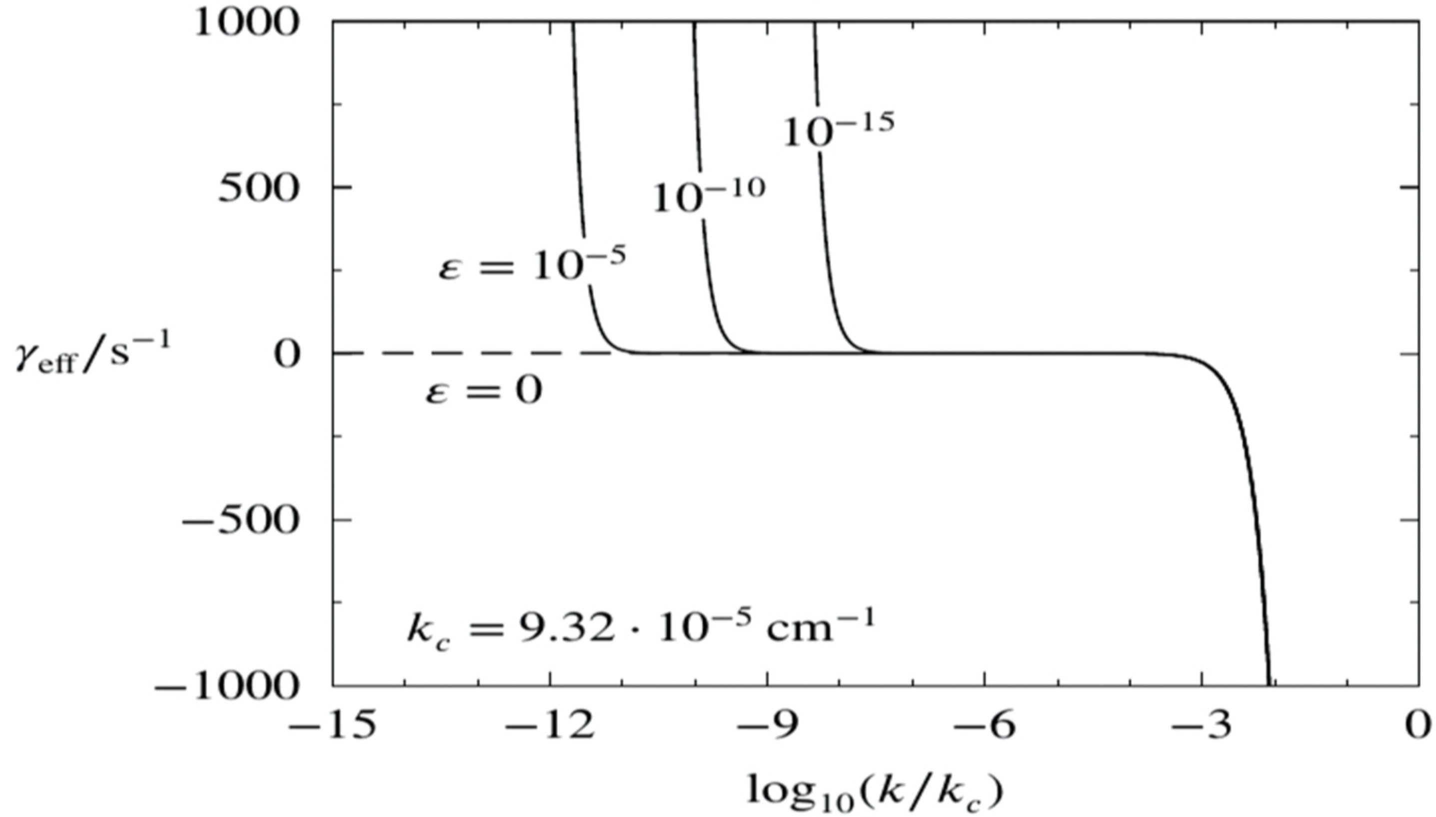
$$\frac{\Gamma}{\varepsilon}\beta_\parallel^3\left(4\beta_\parallel^2 + 1.32 \cdot 10^{-8}\right) < 1.64 \cdot 10^{-12} \,.$$

- They *always* occur, if beam and wavevector are *exactly* perpendicular to each other ($\beta_\parallel = 0$).



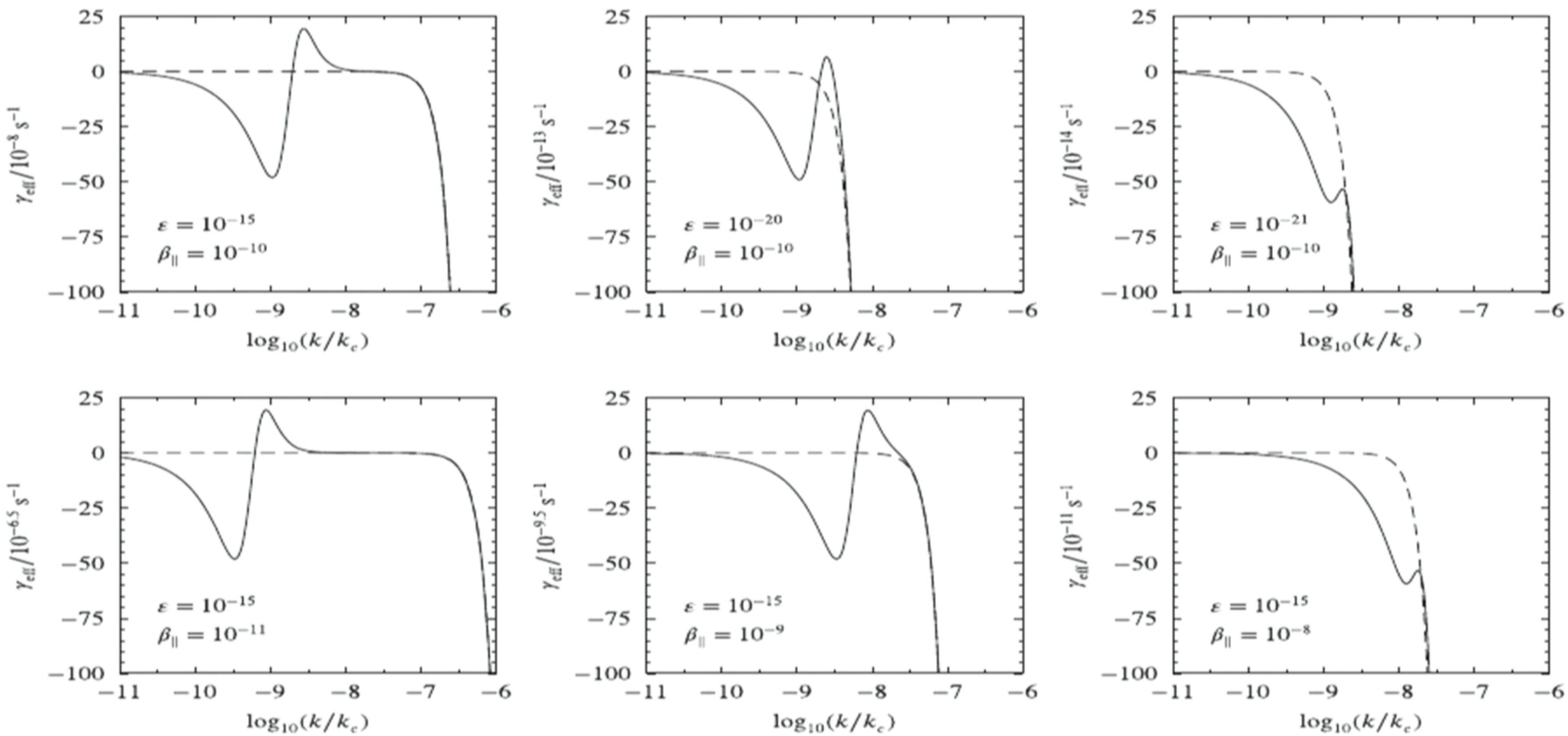
Effective growth rates ($\beta_{\parallel} = 0$, $\Gamma = 10^6$, $T = 10^4$ K)

RUB



Effective growth rates ($\beta_{\parallel} \neq 0$, $\Gamma = 10^6$, $T = 10^4$ K)

RUB



Summary and conclusions

RUB

- Spontaneously emitted field fluctuations in the IGM generate turbulent magnetic seed fields of $6.3 \cdot 10^{-18}$ G.
- A pair beam traversing the IGM (a) provides free energy, (b) breaks the isotropic symmetry, and (c) alters the electromagnetic properties of the IGM.
- The radiation law accounting for the competing effects of spontaneous and induced emission and absorption becomes a tensor equation with modified coefficients.
- The transverse, damped, aperiodic mode dominating the fluctuations displays amplification and hence positive effective growth rates in a spectral band if beam velocity and wavevector are (almost) perpendicular to each other.
- *Outlook on future work:* The fluctuation level of $6.3 \cdot 10^{-18}$ G in the undisturbed IGM is expected to become significantly higher due to the presence of a beam.