SEED MFS GENERATED DURING RECOMBINATION

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[Fenu, Pitrou, Maartens, **to appear on the arXiv TOMORROW!**]

HARRISON MECHANISM

- Intuitively: photons (γ) + protons (p) + electrons (e) tight-coupled before recombination

beyond the tight-coupling regime $v_{\mathrm{p}} - v_{\mathrm{e}} \neq 0 \quad \Rightarrow \quad E \neq 0 \quad \Rightarrow \quad B \neq 0$

[Harrison, '70]

- Thomson cross-section for e $\propto \sigma_{\mathrm{T}} \gg$ Thomson cross-section for p $\propto \left(\frac{m_{\mathrm{e}}}{m_{\mathrm{p}}}\right)^2 \sigma_{\mathrm{T}}$

$\Longrightarrow$ Vorticity of γ $\rightarrow$ vorticity of e

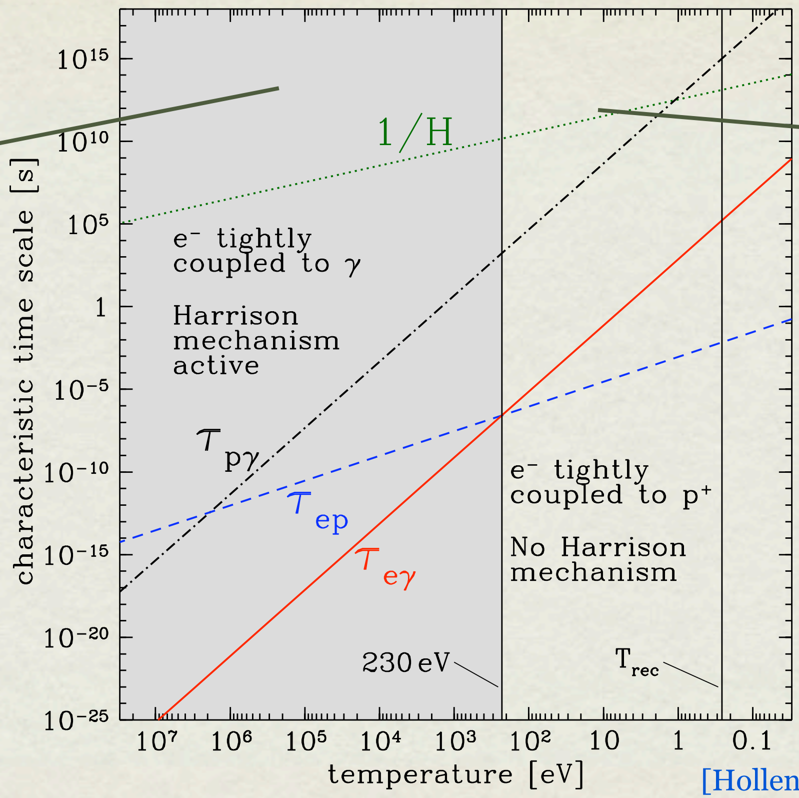
$\Longrightarrow$ Magnetic Field generation

THOMSON VS COULOMB

Period of interest: from $e^{\pm}$ annihilation ($z \lesssim 10^{-9}$) until recombination

Thomson wins

$e - \gamma$ tight-coupled



[Hollenstein et al., '08]

Coulomb wins

$e - p$ tight-coupled

<u>Electric field that couples tightly $e - p$ is generated</u>

<u>Coulomb scattering is not efficient</u>

[Tahahashi et al, '08]

ELECTRIC FIELD GENERATION

Euler eqs. for p and e

$$m_\mathrm{p} n_\mathrm{p} \tilde{\mathcal{D}}(v^\mu_\mathrm{p}) = \tilde{C}^\mu_\mathrm{pe} + \tilde{C}^\mu_{\mathrm{p}\gamma}$$
$$m_\mathrm{e} n_\mathrm{e} \tilde{\mathcal{D}}(v^\mu_\mathrm{e}) = -\tilde{C}^\mu_\mathrm{pe} + \tilde{C}^\mu_{\mathrm{e}\gamma}$$

Interaction terms

$$\Rightarrow \cancel{\tilde{\mathcal{D}}(\delta v^\mu_\mathrm{pe})} \sim \cancel{n x_\mathrm{e}^2 \eta_C \delta v^\mu_\mathrm{pe}} + x_\mathrm{e} E^\mu + \sigma_\mathrm{T} \rho_\gamma x_\mathrm{e} \left(\delta v^\mu_{\gamma\mathrm{b}} - \Theta^\mu{}_\nu v^\nu_\mathrm{b} - \delta v^\mu_\mathrm{pe} \right)$$

Initial conditions:

$$E = 0 = B\,, \qquad \delta v_\mathrm{pe} \neq 0 \neq \delta v_{\gamma\mathrm{b}}$$

Maxwell eq.:

$$j^\mu = x_\mathrm{e} n \left(v^\mu_\mathrm{p} - v^\mu_\mathrm{e} \right) = \mathrm{curl} B^\mu - E^{\mu\prime}$$

$$\Rightarrow \quad E^\mu \neq 0, \qquad \delta v_\mathrm{pe} \sim 0$$

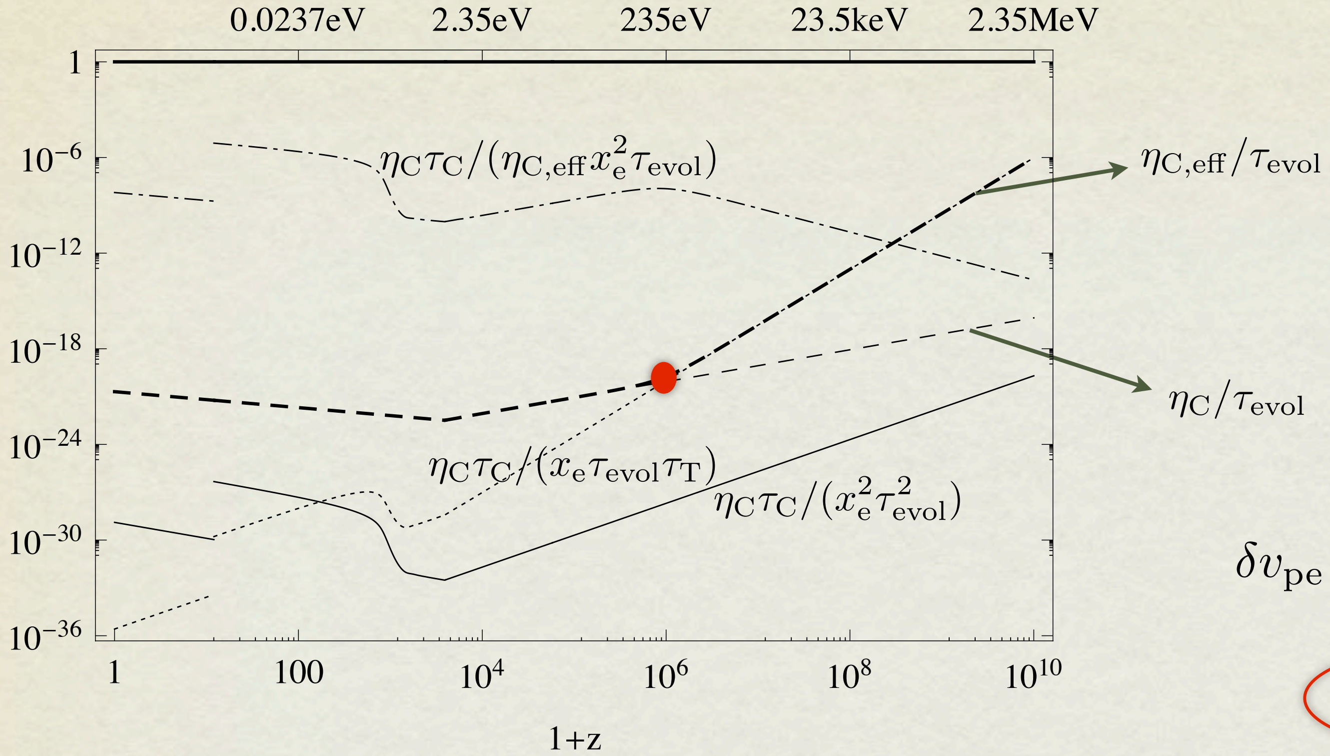
electrons and protons always tightly coupled

$$E^\mu \sim \frac{4 \rho_\gamma \sigma_\mathrm{T}}{3e} \left(\delta v^\mu_{\gamma\mathrm{b}} - \frac{2}{5} \Theta^\mu{}_\nu v^\nu_\mathrm{b} \right)$$

$\boxed{\longrightarrow \ \text{no } x_\mathrm{e} \ !!}$

[Tahahashi et al, '08]

TIME SCALES



$\tau_C, \tau_T =$ relaxation times

$\eta_C \propto \dfrac{1}{\tau_C} =$ electric resistivity

$$\eta_{C,\mathrm{eff}} \sim \eta_C \left(1 + \frac{\tau_C}{\tau_T}\right)$$

$$\tau_{\mathrm{evol}} \sim \min\left[k_{\mathrm{Silk}}^{-1}, k_{1\mathrm{Mpc}}^{-1}\right]$$

$$x_e \neq 0$$

$$\delta v_{pe} \propto \frac{\eta_C \tau_C}{x_e \tau_{\mathrm{evol}} \tau_T} \delta v_{b\gamma}$$

$$\delta v_{pe} \ll \delta v_{b\gamma}$$

$$\widehat{E}^\mu \left[1 - \mathcal{O}\left(\cancel{\frac{\eta_C \tau_C}{x_e^2 \tau_{\mathrm{evol}}^2} + \frac{\eta_C}{\tau_{\mathrm{evol}}} + \frac{\eta_C \tau_C}{x_e \tau_{\mathrm{evol}} \tau_T}}\right)\right]$$

$$= \cancel{\mathrm{curl}\widehat{B}^\mu\, \eta_{C,\mathrm{eff}}} \left[1 - \mathcal{O}\left(\cancel{\frac{\eta_C \tau_C}{\eta_{C,\mathrm{eff}} x_e^2 \tau_{\mathrm{evol}}}}\right)\right] + \frac{4m}{3e\tau_T}\left[\widehat{\delta v}^{\mu}_{\gamma b} - \Theta^\mu{}_\nu \widehat{v_b}^\nu\right],$$

ALWAYS TRUE!

NUMERICAL ANALYSIS

Second order in perturbation theory

- Curl of the generated EF (Maxwell eq.)

$$\left(a^2 B^i\right)' = -a^2 \epsilon^{ijk} \partial_j \left[\left(1 + \Phi - \Psi\right) E_k\right]$$

- Only the first order scalar potentials Ψ and Φ enter in the evolution equation for the MF
- $\delta v_{\rm pe} \ll \delta v_{\rm b\gamma} \Rightarrow$ solve for the dynamics of $\rm b$ and $\gamma \sim$ CMB
- Numerical integration $\Rightarrow$ beyond the tight-coupling regime
- Stop the numerical integration AFTER recombination, since the MF is still produced!

MAGNETIC FIELD GENERATION

$$\left(a^2 B^i\right)' = \Delta v_{\mathrm{b}\gamma}^{(2)} + \left[\delta_\gamma^{(1)} + \Phi^{(1)} - \Psi^{(1)}\right] \Delta v_{\mathrm{b}\gamma}^{(1)} + \left[\Theta_2^{(1)} v_{\mathrm{b}}^{(1)}\right]$$

- Scalar perturbations cannot generate MF, we need vortical perturbations
- We consider all the source terms, like the second order velocity difference between baryons and photons
- The sum is suppressed on large scales $\Rightarrow$ if we do not consider the sum, we overestimate the final MF

[Ichiki et al., '07]

Early time and super-Hubble scales

$$\delta_\gamma \propto \text{const}$$

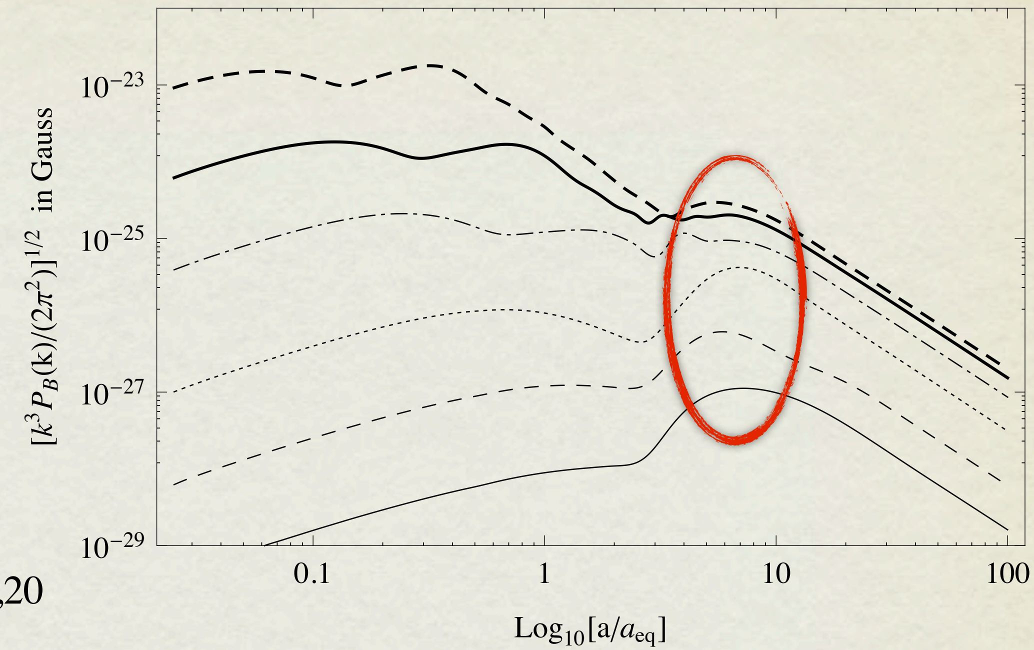
$$v_b - v_\gamma \propto R\frac{k}{\tau'}\left(\frac{\delta_\gamma}{4} - \frac{\mathcal{H}v_b}{k}\right) \propto k^3\eta^5$$

↓

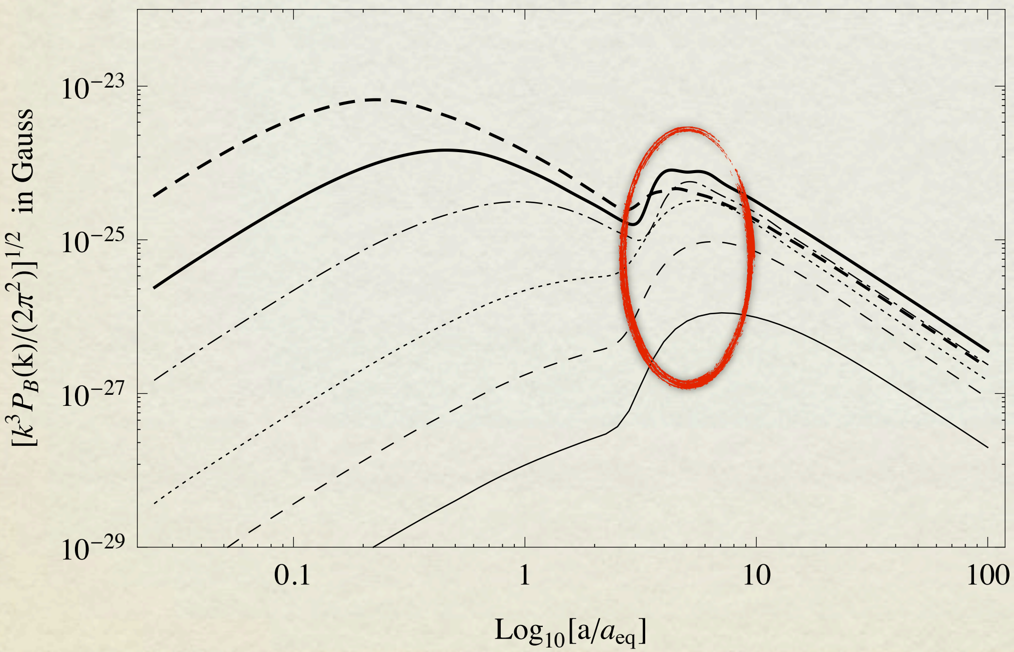
suppressed in tight-coupling limit

$$\sqrt{k^3 P_B(k,\eta)} \propto k^4\eta^2$$

$\Theta_2 . v_b$ contribution for k/k_{eq}=.5,1,2,5,10,20



$\delta_\gamma . \Delta$v contribution for k/k_{eq}=.5,1,2,5,10,20



$$\Theta_\gamma^{(1)} \propto \frac{k}{\tau'}v_\gamma \propto k^2\eta^3$$

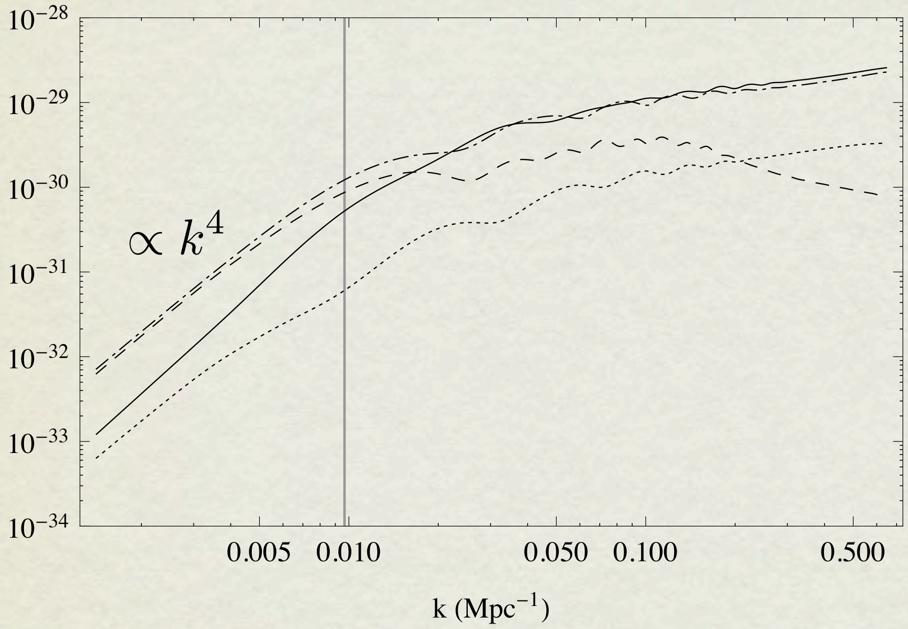
$$v_b \propto k\eta$$

$$\sqrt{k^3 P_B(k,\eta)} \propto k^4\eta$$

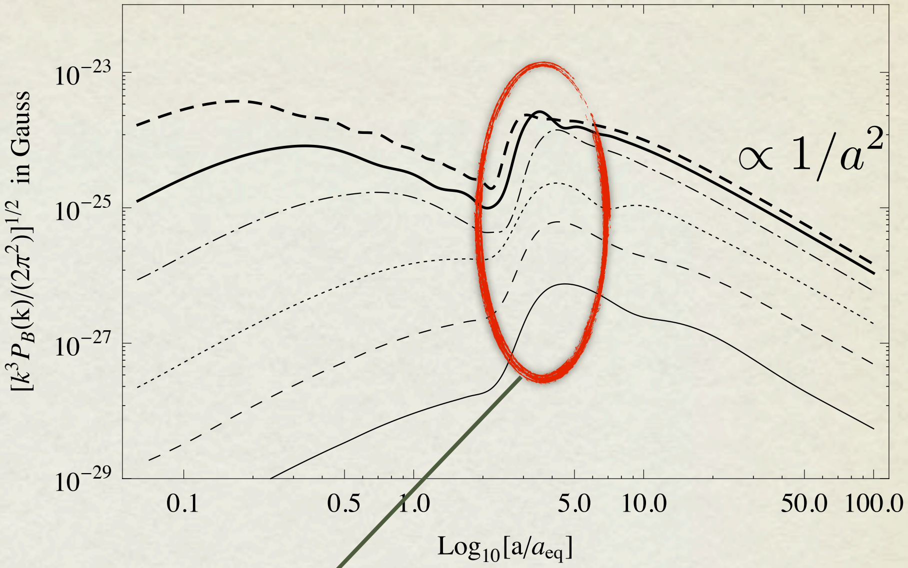
FINAL MF

Final MF power spectrum:

$[k^3 P_B(\mathrm{k})/(2\pi^2)]^{1/2}$ Gauss. Vertical bar: $k_{\mathrm{eq}}=H_{\mathrm{eq}}$.



All contributions for $\mathrm{k}/k_{\mathrm{eq}}$=.5,1,2,5,10,20

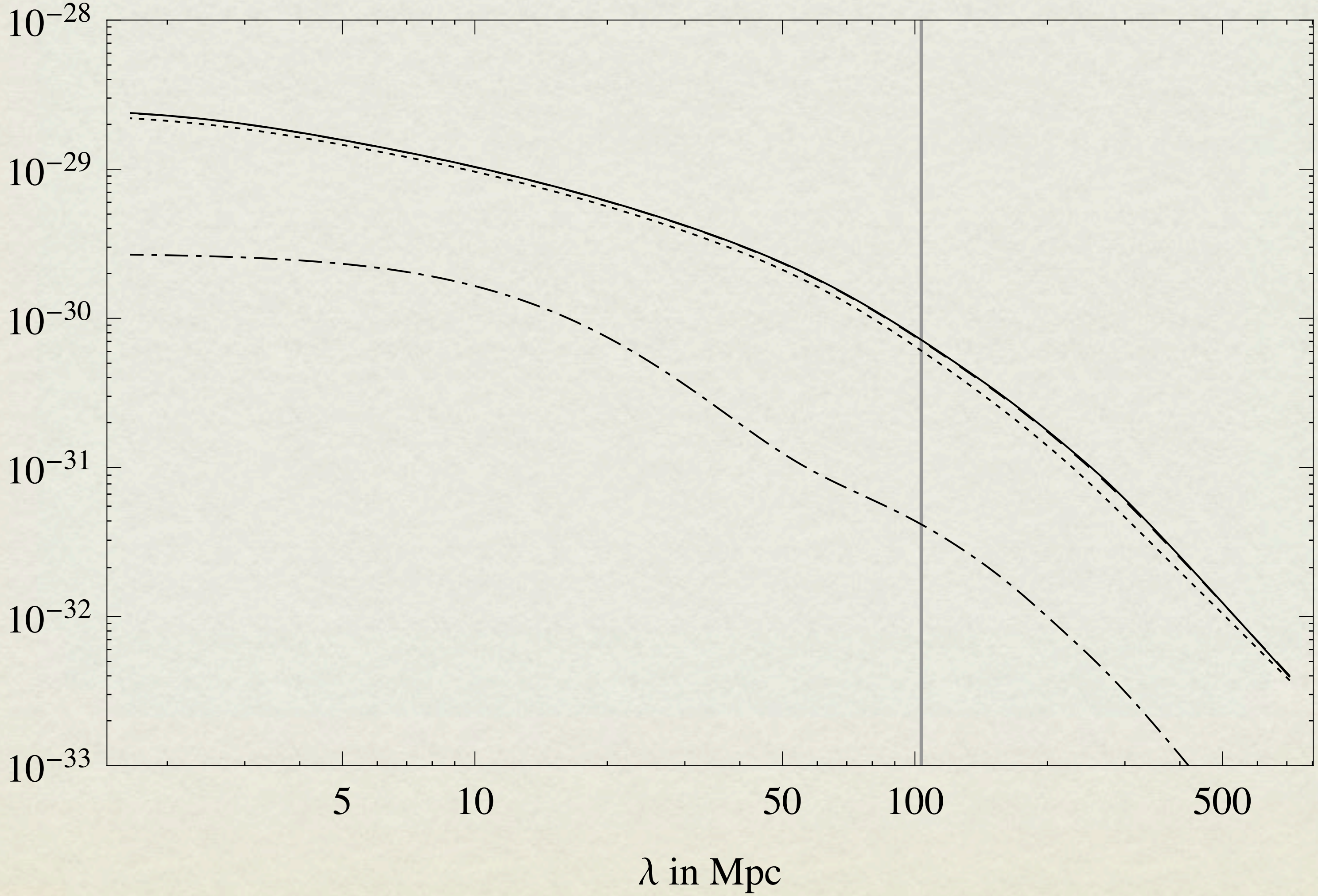


no $x_{\mathrm{e}} \Rightarrow$ recombination bump

$$en x_{\mathrm{e}} E^{\mu} = C^{\mu}_{\mathrm{b}\gamma} = \nabla_{\nu} T^{\mu\nu}_{\mathrm{b}} \quad \Rightarrow \quad B'_i \propto \rho_{\gamma} \frac{\epsilon^{ijk}\partial_j C^{\gamma\mathrm{b}}_k}{x_{\mathrm{e}}} \propto \rho_{\gamma} \frac{\epsilon^{ijk}\partial_j \nabla_{\mu} T^{\mu}_{\mathrm{b}\ k}}{x_{\mathrm{e}}}$$

$$B_\lambda^2 \propto \int_0^\infty \mathrm{d}k\, k^2 P_B(k) e^{-\frac{k^2\lambda^2}{2}} \quad \sim 10^{-29}\mathrm{Gauss}, \quad \lambda \sim 1\mathrm{Mpc}$$

$(a_0/a)^2 B_\lambda$ (G) at $a=a_0/X$ with X=1,10,100,1000



KEY-POINTS AND PHYSICAL INSIGHT

Tight-coupling limit

$$\boxed{(a^2 B_1)' \sim \omega_i^{\mathrm{b}} + \mathcal{O}(\text{quadratic})}$$

vorticity of baryons

quadratic terms present even in the tight-coupling limit

$$\left[\omega_{ij}^{\mathrm{pl}\,\prime} + \mathcal{H}(2 - 3c^2_{\mathrm{pl,\,s}})\omega_{ij}^{\mathrm{pl}}\right] \simeq 0$$

$$\omega^i_{\mathrm{pl}} \simeq \omega^i_{\mathrm{b}} \simeq \omega^i_{\gamma}$$

No vorticity generation at 2nd order in the tight-coupling regime

[Hollenstein et al., '08]

Vorticity exchange between photons and baryons which sources the MF, present only at 2nd order

[Ichiki et al., '07]

Suppression on large scales $\propto (k\eta)^2$

It's the same mechanism!

- Bump after recombination when tight- coupling breaks down $\Rightarrow$ need of numerical integration