# Gravitational waves from phase transitions

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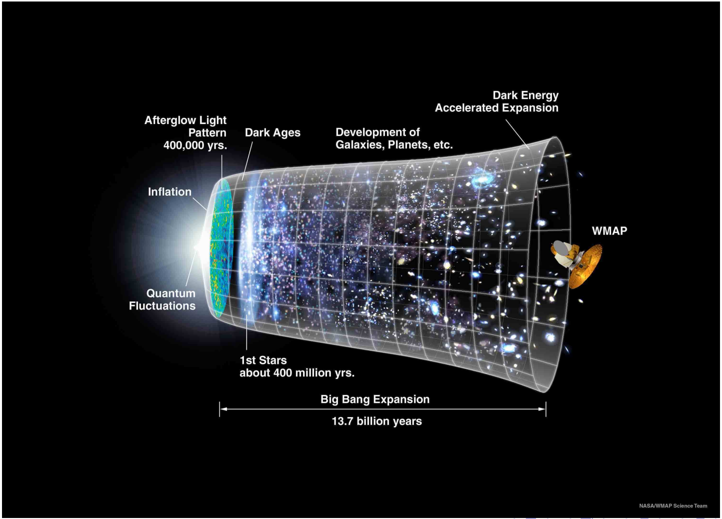
astro-ph/0106244, astro-ph/0304556, astro-ph/0305059, astro-ph/0603476, arXiv:0711.2593, arXiv:0901.1661, arXiv:0906.4772, arXiv:0909.0622, arXiv:1007.1218

Bad Honnef, October 05, 2010

# Outline

# Introduction

The Universe has expanded and cooled down from a very hot initial state to (presently) $2.7^o$K. It seems likely that it underwent several phase transitions during adiabatic expansion.



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In this talk I present a semi-analytical evaluation of the GW signal from a first order phase transition in terms of free parameters.

# Generics

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- On large scales, $k \ll k_*$ the spectrum is blue,

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- The behaviour of the spectrum on small scales, $k \gg k_*$ depends on the details of the source.

# Sources of gravitational waves

Gravitational waves are sourced by fluctuations in the energy momentum tensor which have a non-vanishing spin-2 contribution.

$$ds^2 = a^2\left(d\eta^2 + (\gamma_{ij} + 2h_{ij})dx^i dx^j\right)$$

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Einstein's eqn. to first order in $h_{ij}$ give

$$\left(\partial_\eta^2 + 2\mathcal{H}\partial_\eta + k^2\right) h_{ij} = 8\pi G a^2 \Pi_{ij}$$

Here $\Pi_{ij}(\mathbf{k})$ is the tensors type (spin-2) anisotropic stress and $\mathcal{H} = \frac{a'}{a}$.

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Duration: $\Delta\eta_* < \mathcal{H}_*^{-1}$, bubble size: $R = v_b\Delta\eta_*$, $v_b$ = bubble velocity.
$k_* = (\Delta\eta_*)^{-1}$ or $R^{-1}$.

# Typical frequencies and the spectrum

- Because of causality, the correlator $\langle \Pi_{ij}(\eta_1, \mathbf{x}) \Pi_{lm}(\eta_2, \mathbf{y}) \rangle = \mathcal{M}_{ijlm}(\eta_1, \eta_2, \mathbf{x} - \mathbf{y})$ is a function of compact support. For distances $|\mathbf{x} - \mathbf{y}| > \max(\eta_1, \eta_2)$, $\mathcal{M} \equiv 0$.

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- We decompose $\Pi_{ij}$ into two helicity modes which we assume to be statistically equal and uncorrelated (parity),

$$\Pi_{ij}(\eta, \mathbf{k}) = e^+_{ij} \Pi_+(\eta, k) + e^-_{ij} \Pi_-(\eta, k)$$

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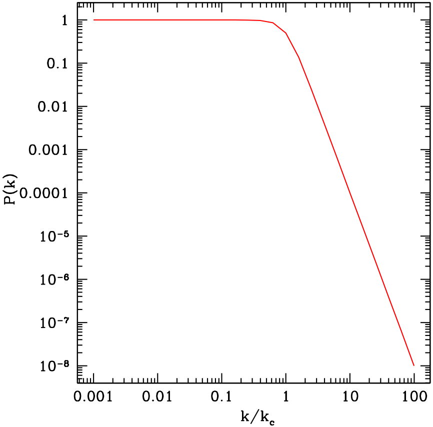
  Here $\rho_X$ is the energy density of the component $X$ with anisotropic stress $\Pi$ which has been factorized in order to keep $k^3 P(\eta, \eta', k)$ dimensionless.
- Causality implies that the function $P(\eta, \eta', k)$ is analytic in $k$. We therefore expect it to start out as white noise and to decay beyond a certain correlation scale $k_*(\eta, \eta') > \min(1/\eta, 1/\eta')$.

# The spectrum




The anisotropic stress power spectrum from Kolmogorov turbulence. On small scales $P \propto k^{-11/3}$.

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$$\begin{aligned} h(\mathbf{k},\eta) &= \frac{8i\pi G a_*^3}{6ak}\left[e^{-ik\eta}\int_{\eta_*}^{\eta_*+\Delta\eta_*} d\eta' e^{ik\eta'}\Pi(\eta',\mathbf{k}) + \right. \\ &\quad \left. e^{ik\eta}\int_{\eta_*}^{\eta_*+\Delta\eta_*} d\eta' e^{-ik\eta'}\Pi(\eta',\mathbf{k})\right] \\ &= \frac{8i\pi G a_*^3}{6ak}\left[e^{-ik\eta}\Pi(k,\mathbf{k}) + e^{ik\eta}\Pi(-k,\mathbf{k})\right] \end{aligned}$$

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- If the Universe is radiation dominated during the phase when the gravitational waves are generated, this gives on large scales, $k < k_*$

$$
\frac{d\Omega_{gw}}{d\ln(k)}(\eta_0) = \frac{12\Omega_{\rm rad}(\eta_0)}{\pi^2}\left(\frac{\Omega_X(\eta_*)}{\Omega_{\rm rad}(\eta_*)}\right)^2 \mathcal{H}_*^2 k^3 \mathrm{Re}[P(k,k,k)]\,.
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- The behavior or the spectrum close to the peak and its decay rate on smaller scales depends on the source characteristics, on its temporal behavior (continuity, differentiability) and its power spectrum.

# Peak position

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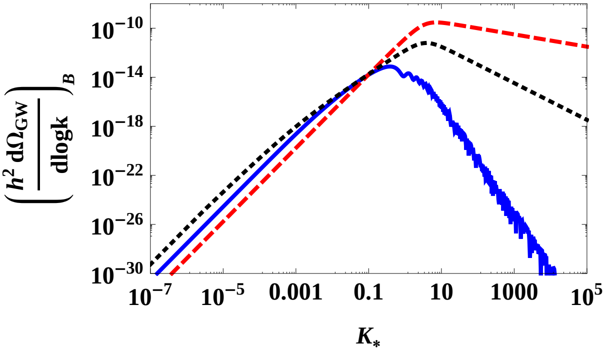
- For a source with finite coherence time, $P(\eta,\eta',k) = \sqrt{P(\eta',\eta',k)P(\eta,\eta,k)}\Theta(x_c - |\eta-\eta'|k), \quad x_c \sim 1$ the GW spectrum is again determined by the peak of the spatial Fourier transform of the source.




The GW energy density spectrum in the incoherent (red), tophat (black) and coherent (blue). The parameters are: $T_* = 100$ GeV, $\Delta\eta_*\mathcal{H}_* = 0.01$, $\Omega_X/\Omega_{\rm rad} = 2/9 \quad (\langle v^2\rangle = 1/3)$

. Caprini, RD and Servant, 2009, arXiv:0909.0622

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  The spectrum is supposed to peak at the correlation scale $k_* = 1/\Delta\eta_* \simeq 100/\eta_* \sim 10^{-3}$Hz, which is close to the frequency of the peak sensitivity for the space born gravitational wave antenna LISA, proposed for launch in 2018, a ESA cosmic vision project.

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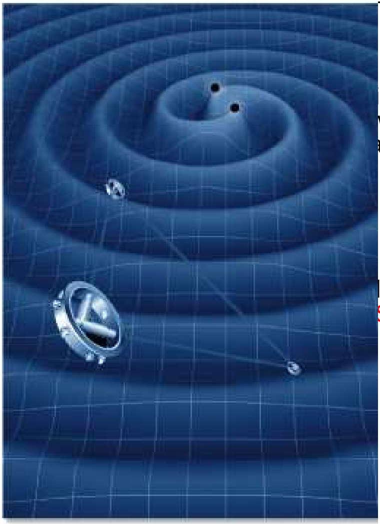

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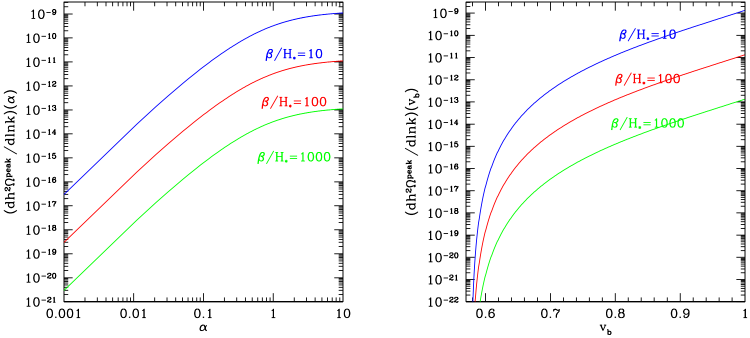


Caprini, RD, Konstandin, Servant, 2009 arXiv:0901.1661 $(\beta = (\Delta\eta_*)^{-1})$

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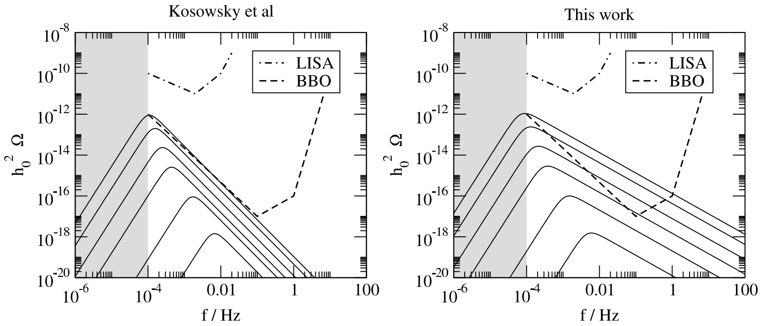


Huber & Konstandin 2008

$\Omega_{GW}$ from colliding bubbles, numerical results, $\Omega_X/\Omega_{\rm rad} = 0.03$.

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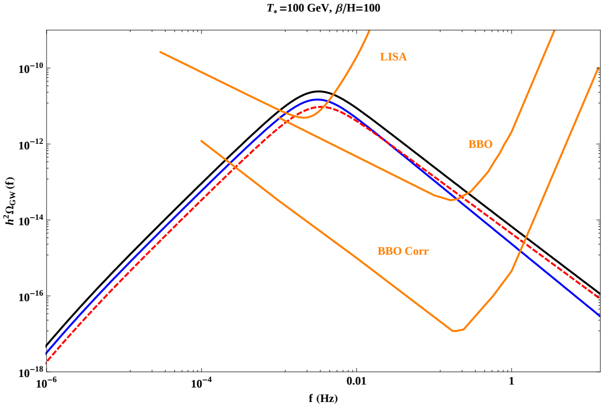
- For the induced GW spectrum this yields

$$\frac{d\Omega_{GW\bullet}(k,\eta_0)}{d\ln(k)} \simeq \epsilon\Omega_{\rm rad}(\eta_0)\left(\frac{\Omega_\bullet(\eta_*)}{\Omega_{\rm rad}(\eta_*)}\right)^2 \times \begin{cases} (k/k_c)^3 & \text{for } k < k_c \\ (k/k_c)^{-\alpha} & \text{for } k > k_c \end{cases}$$

For $\bullet = v$ we have $\alpha = 11/3 - 1 = 8/3$ and for $\bullet = B$ we have $\alpha = 7/2 - 1 = 5/2$. (See Caprini & RD, 2006, astro-ph/0603476)

# The electroweak phase transition: GW's from turbulence and magnetic fields




Caprini, RD, Servant, arXiv:0909.0622

$\Omega_{GW}$ from magnetic fields (red) and turbulence (blue), total (black). Modelling the time-decorrelation of the source (Kraichnan decorrelation) by a 'top-hat' in Fourier space. Sensitivity curves from A. Buonanno 2003.

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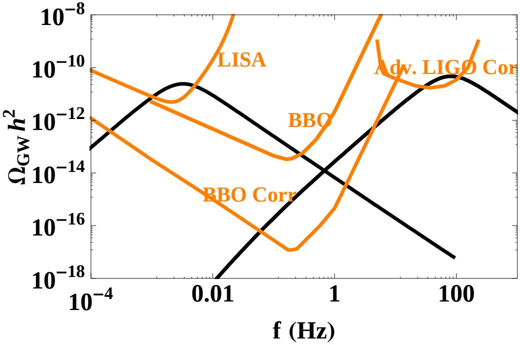


Caprini, RD, Servant, arXiv:0909.0622

We also consider a phase transition at $T = 5 \times 10^6$ GeV with $\Delta\eta_* \mathcal{H}_* = 0.02$.

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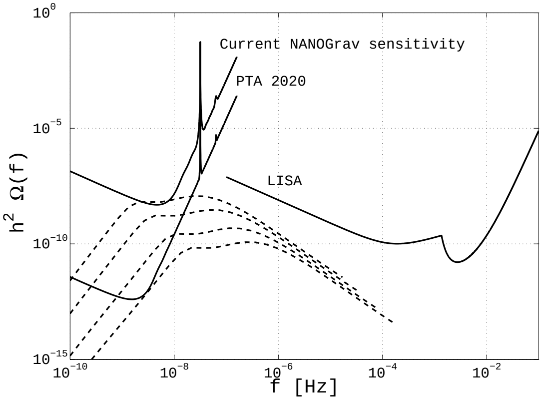
- In this case the QCD phase transition proceeds via bubble nucleation and leads to turbulence and probably the generation of magnetic fields (very large kinetic and magnetic Reynolds numbers).




Caprini, RD, Siemens, arXiv:1007.1218

GW's from the QCD phase transition at $T = 100$ MeV with $\Omega_X = 0.1$ and $\Delta\eta_*\mathcal{H}_* = 1, 0.5, 0.2, 0.1$ (from top to bottom).

# Limits of primordial magnetic fields

It is difficult to estimate $\Omega_B(\eta_*)$ or $\Omega_v(\eta_*)$ accurately, but since causality requires the spectra to be so blue, $\frac{d\Omega_B(k,\eta_*)}{d\ln(k)} \propto k^5$, the limit on gravitational waves (which comes from small scales $k \simeq k_*$) yields very strong limits on primordial magnetic fields on large scales.
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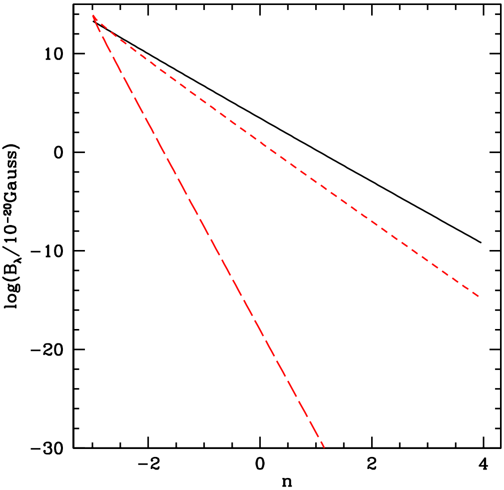
This is purely a consequence of the redness of the magnetic field spectrum. The simple requirement that $\rho_B(t_*) < \rho_c(t_*)$ yields

$$k_1^{3/2}B(k_1) < 10^{-29}\text{Gauss}\left(\frac{k_1 \cdot 0.1\text{Mpc}}{k_* \cdot 10^3\text{sec}}\right)^{5/2} .$$

($10^3\text{sec} = 10^{-11}\text{Mpc}$)




($\lambda = 0.1$Mpc) Caprini & RD., 2001, astro-ph/0106244

# The electroweak phase transition: helical magnetic fields and parity violation

- The most optimistic dynamo models for the generation of the magnetic fields of about $10^{-6}$Gauss observed in galaxies and clusters, need seed fields of the order of at least $10^{-21}$Gauss, which are excluded by this limit.

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- Such helical magnetic fields lead to T-B and E-B correlations in the CMB, and they also generate gravitational waves with non-vanishing helicity (Caprini, Kahniashvili, RD. 2004, astro-ph/0304556).

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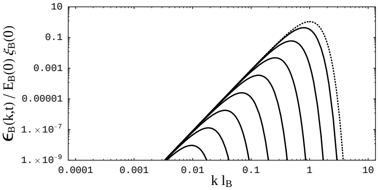
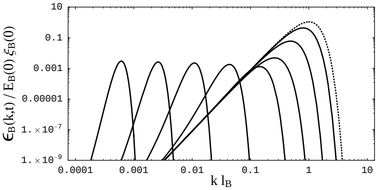
- Contrary to a non-helical magnetic field, helicity conservation for a helical field does lead to an inverse cascade in the evolution of the magnetic field:




Campanelli, 2007

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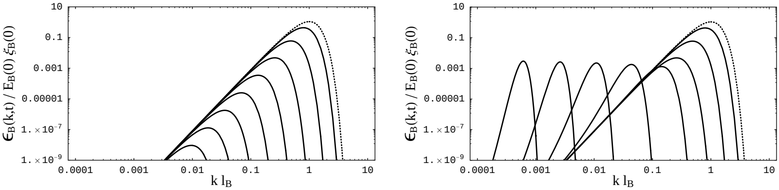


Campanelli, 2007

- This can move power from small to larger scales. However, this is not quite sufficient to present a way out for the electroweak phase transition, but it can work for the QCD phase transition (Caprini, RD, Fenu 2009, arXiv:0906.4772).

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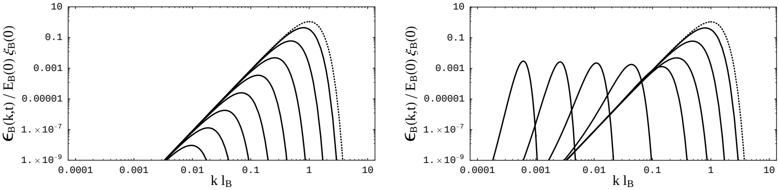


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- In this case, the GW background would not be parity symmetric. There would be more GW's of one helicity than of the other.

# Conclusions

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- Generically, the density parameter of the GW background is of the order of

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- The spectrum grows like $\frac{d\Omega_{GW}(k,t_0)}{d\ln(k)} \propto k^3$ on large scales and decays on scales smaller than the correlations scale $k_* \gtrsim 1/\eta_*$. The decay law depends of the physics of the source.

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- In this case we also expect a parity violating gravitational wave background, $|h_+(k)|^2 \neq |h_-(k)|^2$.