Electroweak cosmology

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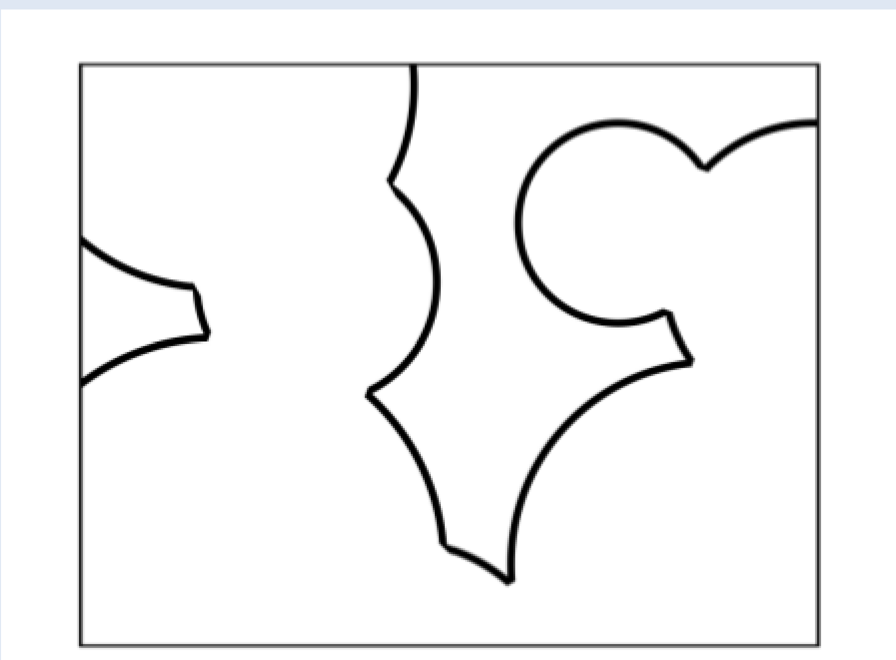
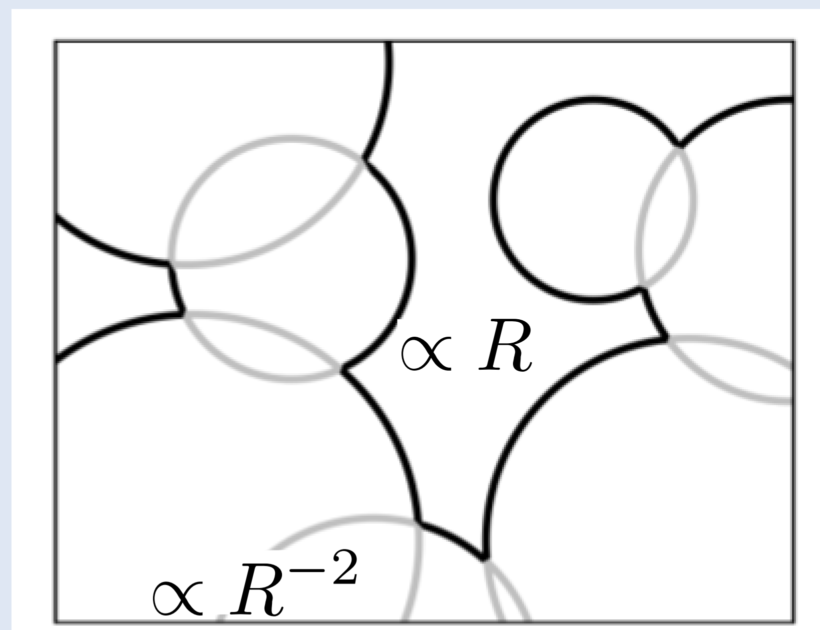
LISA WG, MITP Mainz, Oct 17, 2017

Motivation

Gravitational waves from bubble dynamics: Beyond the Envelope

Ryusuke Jinno[a,b] and Masahiro Takimoto[b,c]





Motivation

3.2 Analytic expressions

Now we present the analytic expressions for the GW spectrum. After a short calculation (see Appendix A–C), we obtain the single-bubble spectrum

$$\Delta^{(s)} = \int_{-\infty}^{\infty} dt_x \int_{-\infty}^{\infty} dt_y \int_{v|t_{x,y}|}^{\infty} dr \int_{-\infty}^{t_{\max}} dt_n \int_{t_n}^{t_x} dt_{xi} \int_{t_n}^{t_y} dt_{yi}$$

$$\frac{k^3}{3}\left[\begin{array}{l} e^{-I(x_i,y_i)}\, \Gamma(t_n)\, \dfrac{r}{r_{xn}^{(s)} r_{yn}^{(s)}} \\ \times \left[j_0(kr)\mathcal{K}_0(n_{xn\times}, n_{yn\times}) + \dfrac{j_1(kr)}{kr}\mathcal{K}_1(n_{xn\times}, n_{yn\times}) + \dfrac{j_2(kr)}{(kr)^2}\mathcal{K}_2(n_{xn\times}, n_{yn\times}) \right] \\ \times\, \partial_{txi}\left[r_B(t_{xi}, t_n)^3 D(t_x, t_{xi})\right] \partial_{tyi}\left[r_B(t_{yi}, t_n)^3 D(t_y, t_{yi})\right] \cos(kt_{x,y}) \end{array}\right], \tag{3.2}$$

and the double-bubble spectrum

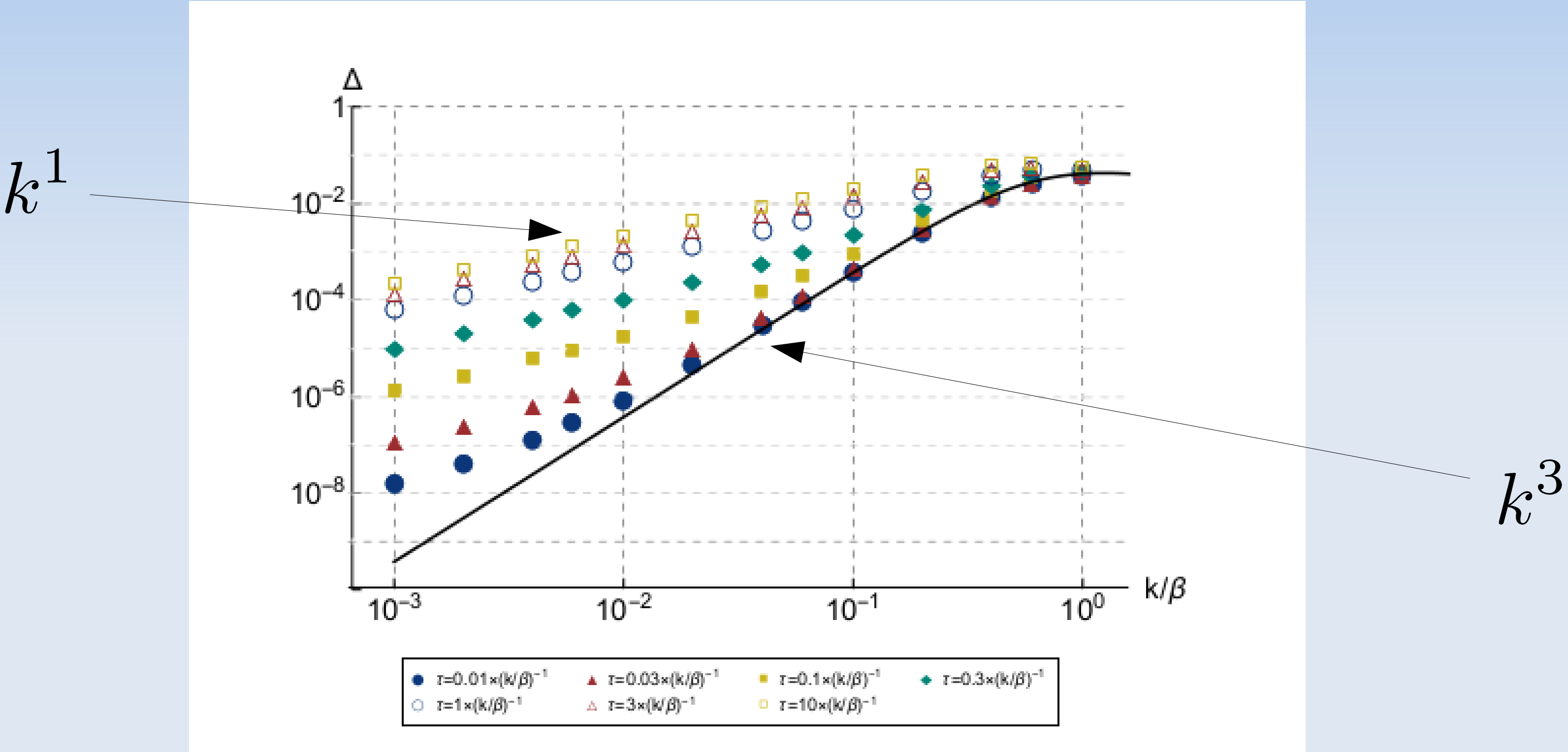
$$\Delta^{(d)} = \int_{-\infty}^{\infty} dt_x \int_{-\infty}^{\infty} dt_y$$

$$\int_{0}^{\infty} dr \int_{-\infty}^{t_x} dt_{xn} \int_{-\infty}^{t_y} dt_{yn} \int_{t_{xn}}^{t_x} dt_{xi} \int_{t_{yn}}^{t_y} dt_{yi} \int_{-1}^{1} dc_{xn} \int_{-1}^{1} dc_{yn} \int_{0}^{2\pi} d\phi_{xn,yn}$$

$$\frac{k^3}{3}\left[\begin{array}{l} \Theta_{\rm sp}(x_i, y_n)\Theta_{\rm sp}(x_n, y_i) e^{-I(x_i,y_i)}\Gamma(t_{xn})\Gamma(t_{yn}) \\ \times\, r^2 \left[j_0(kr)\mathcal{K}_0(n_{xn}, n_{yn}) + \dfrac{j_1(kr)}{kr}\mathcal{K}_1(n_{xn}, n_{yn}) + \dfrac{j_2(kr)}{(kr)^2}\mathcal{K}_2(n_{xn}, n_{yn}) \right] \\ \times\, \partial_{txi}\left[r_B(t_{xi}, t_{xn})^3 D(t_x, t_{xi})\right] \partial_{tyi}\left[r_B(t_{yi}, t_{yn})^3 D(t_y, t_{yi})\right] \cos(kt_{x,y}) \end{array}\right]. \tag{3.3}$$

10 integrations?

Motivation



k^1
k^3
Δ
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-3}
10^{-2}
10^{-1}
10^{0}
k/β
$\tau=0.01\times(k/\beta)^{-1}$
$\tau=0.03\times(k/\beta)^{-1}$
$\tau=0.1\times(k/\beta)^{-1}$
$\tau=0.3\times(k/\beta)^{-1}$
$\tau=1\times(k/\beta)^{-1}$
$\tau=3\times(k/\beta)^{-1}$
$\tau=10\times(k/\beta)^{-1}$

Motivation

Shape of the acoustic gravitational wave power spectrum from a first order phase transition

Mark Hindmarsh,[1,2,*] Stephan J. Huber,[1,†] Kari Rummukainen,[2,‡] and David J. Weir[2,§]

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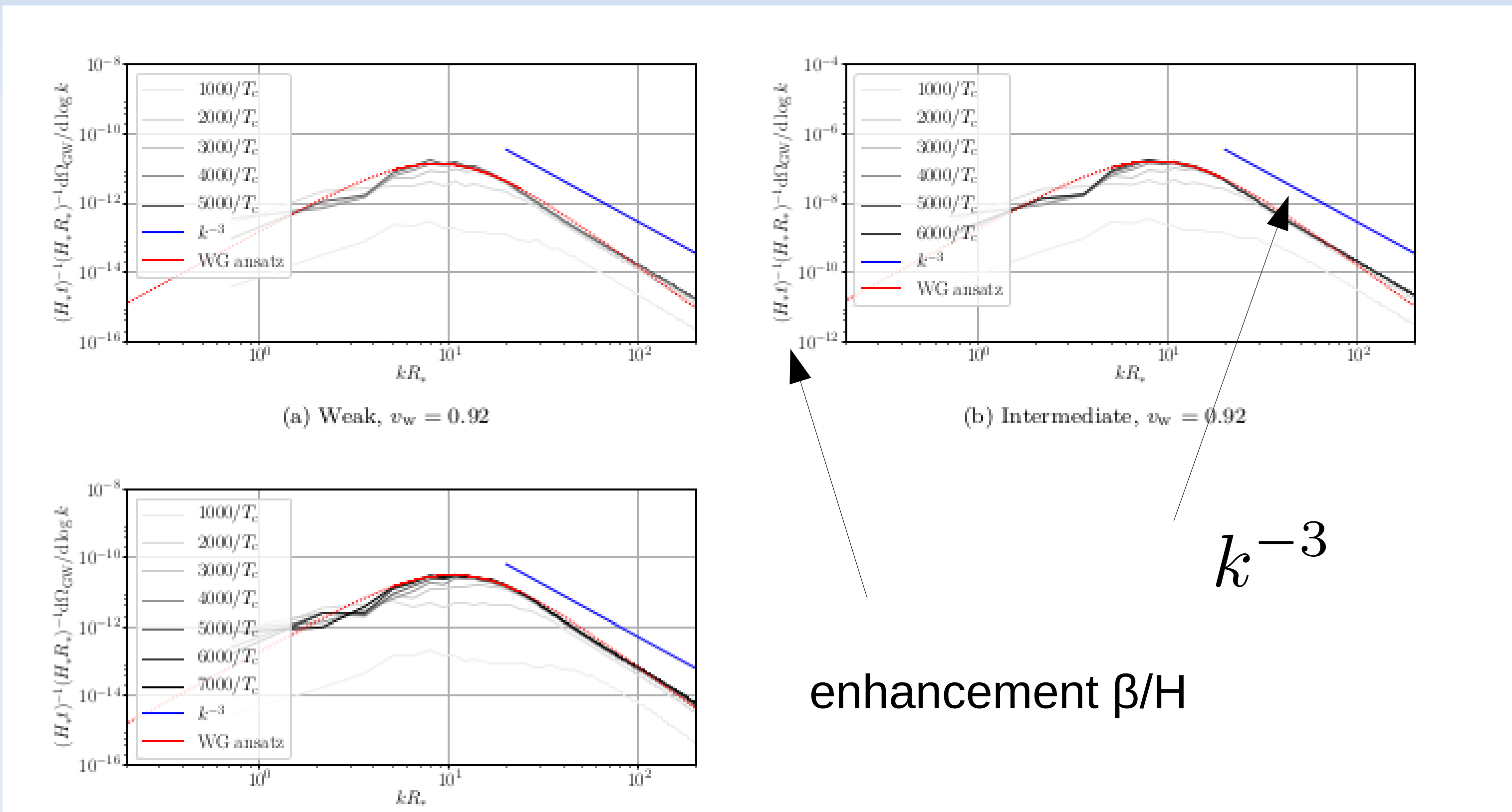
(Dated: April 20, 2017)



(a) Weak, $v_{\mathrm{w}} = 0.92$

(b) Intermediate, $v_{\mathrm{w}} = 0.92$

Envelope redux

Gravitational Wave Production by Collisions: More Bubbles

Stephan J. Huber[(1)] and Thomas Konstandin[(2)*]

$$\frac{dE_{GW}}{d\omega d\Omega} = 2G\omega^2 \Lambda_{ij,lm}(\hat{\mathbf{k}}) T^*_{ij}(\hat{\mathbf{k}},\omega) T_{lm}(\hat{\mathbf{k}},\omega),$$

where $T_{ij}(\hat{\mathbf{k}},\omega)$ denotes the stress-energy tensor in Fourier space

$$T_{ij}(\hat{\mathbf{k}},\omega) = \frac{1}{2\pi}\int dt\, e^{i\omega t}\int d^3x\, e^{-i\omega\hat{\mathbf{k}}\cdot\mathbf{x}}\, T_{ij}(\mathbf{x},t),$$

and Λ is the projection tensor for the transverse-traceless part

$$\Lambda_{ij,lm}(\hat{\mathbf{k}}) = \delta_{il}\delta_{jm} - 2\hat{\mathbf{k}}_j\hat{\mathbf{k}}_m\delta_{il} + \frac{1}{2}\hat{\mathbf{k}}_i\hat{\mathbf{k}}_j\hat{\mathbf{k}}_l\hat{\mathbf{k}}_m - \frac{1}{2}\delta_{ij}\delta_{lm} + \frac{1}{2}\delta_{ij}\hat{\mathbf{k}}_l\hat{\mathbf{k}}_m + \frac{1}{2}\delta_{lm}\hat{\mathbf{k}}_i\hat{\mathbf{k}}_j.$$

$$\Omega_{GW*} = \omega\frac{dE_{GW}}{d\omega}\frac{1}{E_{tot}} = \kappa^2\left(\frac{H}{\beta}\right)^2\left(\frac{\alpha}{\alpha+1}\right)^2\Delta(\omega/\beta, v_b), \qquad (13)$$

where we used the definition of the Hubble constant

$$H^2 = \frac{8\pi G\rho_{tot}}{3} = \frac{8\pi G(\rho_{vac}+\rho_{rad})}{3}, \qquad (14)$$

and defined the dimensionless function Δ as

No dependence on H!

$$\Delta(\omega/\beta, v_b) = \frac{\omega^3}{\beta^3}\frac{3v_b^6\beta^5}{2\pi V}\int d\hat{\mathbf{k}}\,\Lambda_{ij,lm}C^*_{ij}C_{lm}. \qquad (15)$$

Integrations

$$\frac{dE_{GW}}{d\omega d\Omega} = 4G\rho_{vac}^2\kappa^2 v_b^6\omega^2(|C_+|^2 + |C_-|^2), \tag{A2}$$

$$C_\pm(\omega) = \frac{1}{6\pi}\sum_n \int dt\, e^{i\omega(t-z_n)}(t-t_n)^3 A_{n,\pm}(\omega,t), \tag{A3}$$

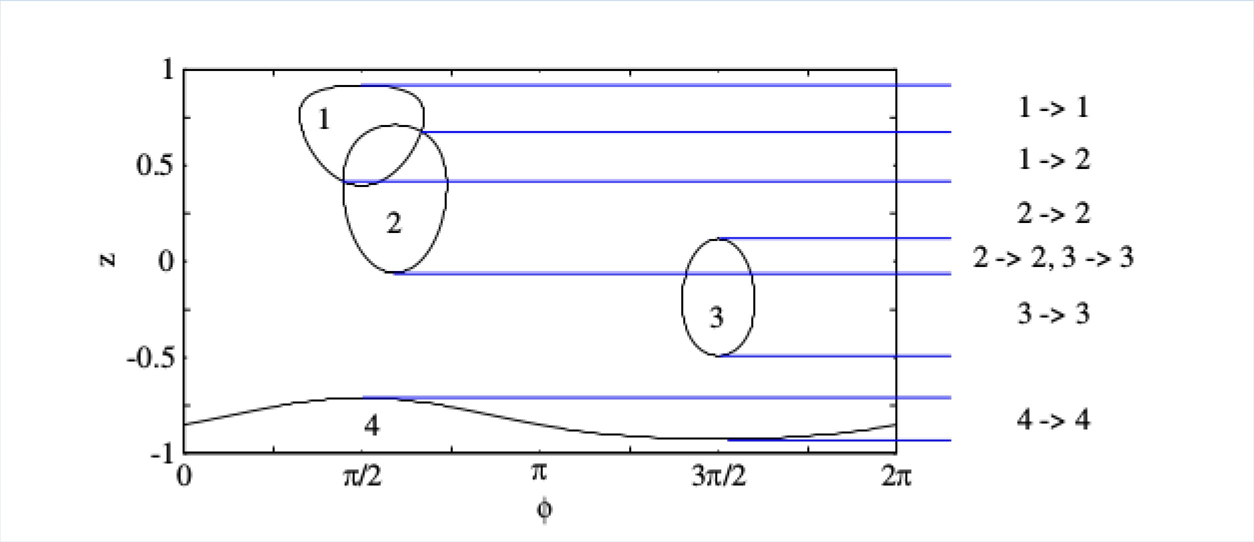
$$A_{n,\pm}(\omega,t) = \int_{-1}^{1} dz\, e^{-iv_b\omega(t-t_n)z} B_{n,\pm}(z,t), \tag{A4}$$

$$B_{n,+}(z,t) = \frac{(1-z^2)}{2}\int_{S_n'} d\phi \cos(2\phi), \quad B_{n,-}(z,t) = \frac{(1-z^2)}{2}\int_{S_n'} d\phi \sin(2\phi). \tag{A5}$$

3 integrations, done 10^11 times, 1 CPU hour

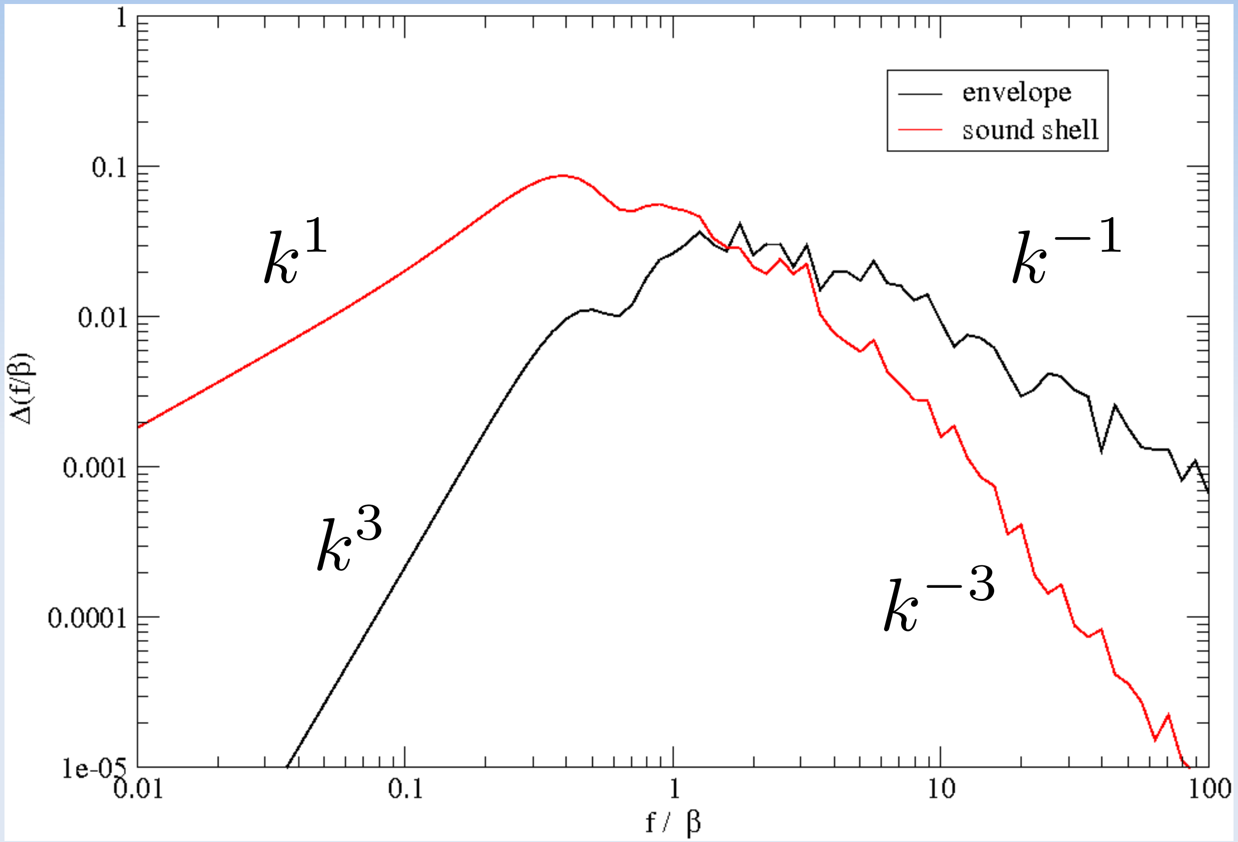
do the first integration analytically!

Integrations



Results

preliminary



all integrals are finite

peak a little lower

amplitude a bit higher