

On a new method towards proof of Riemann's Hypothesis

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Abstract

We consider the analytic continuation of Riemann's Zeta Function derived from **Riemann's Xi function** $\xi(s)$ which is evaluated at $s = \frac{1}{2} + \sigma + i\omega$, given by $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$, where σ, ω are real and $-\infty \leq \omega \leq \infty$ and compute its inverse Fourier transform given by $E_p(t)$.

We use a new method and show that the Fourier Transform of $E_p(t)$ given by $E_{p\omega}(\omega) = \xi(\frac{1}{2} + \sigma + i\omega)$ **does not have zeros** for finite and real ω when $0 < |\sigma| < \frac{1}{2}$, corresponding to the critical strip **excluding** the critical line and prove Riemann's hypothesis.

More importantly, the new method **does not** contradict the existence of non-trivial zeros on the critical line with real part of $s = \frac{1}{2}$ and **does not** contradict Riemann Hypothesis. It is shown that the new method is **not** applicable to Hurwitz zeta function and related functions and **does not** contradict the existence of their non-trivial zeros away from the critical line.

If the specific solution presented in this paper is incorrect, it is **hoped** that the new method discussed in this paper will lead to a correct solution by other researchers.

Keywords: Riemann, Hypothesis, Zeta, Xi, exponential functions

1. Introduction

It is well known that Riemann's Zeta function given by $\zeta(s) = \sum_{m=1}^{\infty} \frac{1}{m^s}$ converges in the half-plane where the real part of s is greater than 1. Riemann proved that $\zeta(s)$ has an analytic continuation to the whole s -plane apart from a simple pole at $s = 1$ and that $\zeta(s)$ satisfies a symmetric functional equation given by $\xi(s) = \xi(1-s) = \frac{1}{2}s(s-1)\pi^{-\frac{s}{2}}\Gamma(\frac{s}{2})\zeta(s)$ where $\Gamma(s) = \int_0^{\infty} e^{-u}u^{s-1}du$ is the Gamma function.^{[4] [5]} We can see that if Riemann's Xi function has a zero in the critical strip, then Riemann's Zeta function also has a zero at the same location. Riemann made his conjecture in his 1859 paper, that all of the non-trivial zeros of $\zeta(s)$ lie on the critical line with real part of $s = \frac{1}{2}$, which is called the Riemann Hypothesis.^[1]

Hardy and Littlewood later proved that infinitely many of the zeros of $\zeta(s)$ are on the critical line with real part of $s = \frac{1}{2}$.^[2] It is well known that $\zeta(s)$ does not have non-trivial zeros when real part of $s = \frac{1}{2} + \sigma + i\omega$, given by $\frac{1}{2} + \sigma \geq 1$ and $\frac{1}{2} + \sigma \leq 0$. In this paper, **critical strip** $0 < \text{Re}[s] < 1$ corresponds to $0 \leq |\sigma| < \frac{1}{2}$.

In this paper, a **new method** is discussed and a specific solution is presented to prove Riemann's Hypothesis. If the specific solution presented in this paper is incorrect, it is **hoped** that the new

method discussed in this paper will lead to a correct solution by other researchers.

In Section 2 to Section 6, we prove Riemann's hypothesis by taking the analytic continuation of Riemann's Zeta Function derived from Riemann's Xi function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ and compute inverse Fourier transform of $E_{p\omega}(\omega)$ given by $E_p(t)$ and show that its Fourier transform $E_{p\omega}(\omega)$ does not have zeros for finite and real ω when $0 < |\sigma| < \frac{1}{2}$, corresponding to the critical strip **excluding** the critical line.

In Section 7, it is shown that the new method is **not** applicable to Hurwitz zeta function and related functions and **does not** contradict the existence of their non-trivial zeros away from the critical line with real part of $s = \frac{1}{2}$.

We present an **outline** of the new method below.

1.1. Step 1: Inverse Fourier Transform of $\xi(\frac{1}{2} + i\omega)$

Let us start with Riemann's Xi Function $\xi(s)$ evaluated at $s = \frac{1}{2} + i\omega$ given by $\xi(\frac{1}{2} + i\omega) = \Xi(\omega) = E_{0\omega}(\omega)$, where $-\infty \leq \omega \leq \infty$. Its inverse Fourier Transform is given by $E_0(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{0\omega}(\omega) e^{i\omega t} d\omega$, where ω, t are real, as follows (link).^[3]

$$E_0(t) = \Phi(t) = 2 \sum_{n=1}^{\infty} [2n^4 \pi^2 e^{\frac{9t}{2}} - 3n^2 \pi e^{\frac{5t}{2}}] e^{-\pi n^2 e^{2t}} = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} \quad (1)$$

We see that $E_0(t) = E_0(-t)$ is a real and **even** function of t , given that $E_{0\omega}(\omega) = E_{0\omega}(-\omega)$ because $\xi(s) = \xi(1-s)$ and hence $\xi(\frac{1}{2} + i\omega) = \xi(\frac{1}{2} - i\omega)$ when evaluated at $s = \frac{1}{2} + i\omega$.

The inverse Fourier Transform of $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ is given by the real function $E_p(t)$. We can write $E_p(t)$ as follows for $0 < |\sigma| < \frac{1}{2}$ and this is shown in detail in Appendix A.

$$E_p(t) = E_0(t) e^{-\sigma t} = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{-\sigma t} \quad (2)$$

We can see that $E_p(t)$ is an analytic function in the interval $|t| \leq \infty$, given that the sum and product of exponential functions are analytic in the same interval and hence infinitely differentiable in that interval.

1.2. Step 2: On the zeros of a related function $G(\omega, t_2, t_0)$

Statement 1: Let us assume that Riemann's Xi function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ has a zero at $\omega = \omega_0$ where ω_0 is real and finite and $0 < |\sigma| < \frac{1}{2}$, corresponding to the critical strip excluding the critical line. We will prove that this assumption leads to a **contradiction**.

Let us consider $0 < \sigma < \frac{1}{2}$ at first. Let us consider a new function $g(t, t_2, t_0) = f(t, t_2, t_0) e^{-\sigma t} u(-t) + f(t, t_2, t_0) e^{\sigma t} u(t)$, where $f(t, t_2, t_0) = e^{-2\sigma t_0} f_1(t, t_2, t_0) + e^{2\sigma t_0} f_2(t, t_2, t_0)$ and $f_1(t, t_2, t_0) = e^{\sigma t_0} E'_p(t + t_0, t_2)$ and $f_2(t, t_2, t_0) = e^{-\sigma t_0} E'_p(t - t_0, t_2)$ and $E'_p(t, t_2) = e^{-\sigma t_2} E_p(t - t_2) - e^{\sigma t_2} E_p(t + t_2)$ and t_0, t_2 are real and $g(t, t_2, t_0)$ is a real function of variable t and $u(t)$ is Heaviside unit step function. We can

73 see that $g(t, t_2, t_0)h(t) = f(t, t_2, t_0)$ where $h(t) = [e^{\sigma t}u(-t) + e^{-\sigma t}u(t)]$.

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75 In Section 2.1, we will show that the Fourier transform of the **even function** $g_{even}(t, t_2, t_0) =$
76 $\frac{1}{2}[g(t, t_2, t_0) + g(-t, t_2, t_0)]$ given by $G_R(\omega, t_0, t_2)$ must have **at least one zero** at $\omega = \omega_z(t_2, t_0) \neq 0$,
77 for every value of t_0 , for a given value of t_2 , to satisfy Statement 1, where $\omega_z(t_2, t_0)$ is real and finite.

78 1.3. Step 3: On the zeros of the function $G_R(\omega, t_0, t_2)$

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80 In Section 2.2, we compute the Fourier transform of the function $g(t, t_2, t_0)$ and compute its real
81 part given by $G_R(\omega, t_2, t_0)$ and we can write as follows.

$$\begin{aligned} G_R(\omega, t_2, t_0) = & e^{-2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2)] \cos(\omega\tau) d\tau \\ & + e^{2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2)] \cos(\omega\tau) d\tau \end{aligned}$$

(3)

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83 We require $G_R(\omega, t_2, t_0) = 0$ for $\omega = \omega_z(t_2, t_0)$ for every value of t_0 , for **each fixed value**
84 of t_2 , to satisfy **Statement 1**. In general $\omega_z(t_2, t_0) \neq \omega_0$. Hence we can see that $P(t_2, t_0) =$
85 $G_R(\omega_z(t_2, t_0), t_2, t_0) = 0$.

86 1.4. Step 4: Zero Crossing function $\omega_z(t_2, t_0)$ is an even function of variable t_0

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88 In Section 2.3, we show the result in Eq. 4 and that $\omega_z(t_2, t_0) = \omega_z(t_2, -t_0)$. It is shown that
89 $P(t_2, t_0) = G_R(\omega_z(t_2, t_0), t_2, t_0) = P_{odd}(t_2, t_0) + P_{odd}(t_2, -t_0) = 0$ and that $P_{odd}(t_2, t_0)$ is an **odd**
90 function of t_0 , for a given value of t_2 as follows.

$$\begin{aligned} P_{odd}(t_2, t_0) = & [\cos(\omega_z(t_2, t_0)t_0) \int_{-\infty}^{t_0} E'_0(\tau, t_2)e^{-2\sigma\tau} \cos(\omega_z(t_2, t_0)\tau) d\tau \\ & + \sin(\omega_z(t_2, t_0)t_0) \int_{-\infty}^{t_0} E'_0(\tau, t_2)e^{-2\sigma\tau} \sin(\omega_z(t_2, t_0)\tau) d\tau] \\ & + e^{2\sigma t_0} [\cos(\omega_z(t_2, t_0)t_0) \int_{-\infty}^{t_0} E'_{0n}(\tau, t_2) \cos(\omega_z(t_2, t_0)\tau) d\tau + \sin(\omega_z(t_2, t_0)t_0) \int_{-\infty}^{t_0} E'_{0n}(\tau, t_2) \sin(\omega_z(t_2, t_0)\tau) d\tau] \end{aligned}$$

(4)

92 1.5. Step 5: Final Step

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94 In Section 4, it is shown that $\omega_z(t_2, t_0)$ is a **continuous** function of variable t_0 and t_2 , for all
95 $|t_0| \leq \infty$ and $|t_2| \leq \infty$. In Section 6, it is shown that $E_0(t)$ is **strictly decreasing** for $t > 0$.

96
97 In Section 3, we set $t_0 = t_{0c}$ and $t_2 = t_{2c} = 2t_{0c}$, such that $\omega_z(t_{2c}, t_{0c})t_{0c} = \frac{\pi}{2}$ and substitute
98 in the equation for $P_{odd}(t_2, t_0)$ in Eq. 4 and show that this leads to the result in Eq. 5. We use
99 $E'_0(t, t_2) = E_0(t - t_2) - E_0(t + t_2)$ and $E'_{0n}(t, t_2) = E'_0(-t, t_2)$.

$$\int_0^{t_{0c}} (E_0(\tau - t_{2c}) - E_0(\tau + t_{2c}))(\cosh(2\sigma t_{0c}) - \cosh(2\sigma\tau)) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau = 0$$

(5)

We show that the **each** of the terms in the integrand in Eq. 5 are **greater than zero**, in the interval $0 < \tau < t_{0c}$ and the integrand is zero at $\tau = 0$ and $\tau = t_{0c}$, where $t_{0c} > 0$.

Hence the result in Eq. 5 leads to a **contradiction** for $0 < \sigma < \frac{1}{2}$.

We have shown this result for $0 < \sigma < \frac{1}{2}$ and then use the property $\xi(\frac{1}{2} + \sigma + i\omega) = \xi(\frac{1}{2} - \sigma - i\omega)$ to show the result for $-\frac{1}{2} < \sigma < 0$. Hence we have produced a **contradiction** of **Statement 1** that the Fourier Transform of the function $E_p(t) = E_0(t)e^{-\sigma t}$ has a zero at $\omega = \omega_0$ for $0 < |\sigma| < \frac{1}{2}$.

2. An Approach towards Riemann's Hypothesis

Theorem 1: Riemann's Xi function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ does not have zeros for any real value of $-\infty < \omega < \infty$, for $0 < |\sigma| < \frac{1}{2}$, corresponding to the critical strip excluding the critical line, given that $E_0(t) = E_0(-t)$ is an even function of variable t , where $E_p(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{p\omega}(\omega) e^{i\omega t} d\omega$, $E_p(t) = E_0(t)e^{-\sigma t}$ and $E_0(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$.

Proof: We assume that Riemann Hypothesis is false and prove its truth using proof by contradiction.

Statement 1: Let us assume that Riemann's Xi function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ has a zero at $\omega = \omega_0$ where ω_0 is real and finite and $0 < |\sigma| < \frac{1}{2}$, corresponding to the critical strip excluding the critical line. We will prove that this assumption leads to a **contradiction**.

We will prove it for $0 < \sigma < \frac{1}{2}$ first and then use the property $\xi(\frac{1}{2} + \sigma + i\omega) = \xi(\frac{1}{2} - \sigma - i\omega)$ to show the result for $-\frac{1}{2} < \sigma < 0$ and hence show the result for $0 < |\sigma| < \frac{1}{2}$.

We know that $\omega_0 \neq 0$, because $\zeta(s)$ has no zeros on the real axis between 0 and 1, when $s = \frac{1}{2} + \sigma + i\omega$ is real, $\omega = 0$ and $0 < |\sigma| < \frac{1}{2}$. [3] This is shown in detail in first two paragraphs in Appendix B.1.

2.1. New function $g(t, t_2, t_0)$

Let us consider the function $E_p'(t, t_2) = e^{-\sigma t_2} E_p(t - t_2) - e^{\sigma t_2} E_p(t + t_2) = (E_0(t - t_2) - E_0(t + t_2))e^{-\sigma t} = E_0'(t, t_2)e^{-\sigma t}$, where t_2 is finite and real, and $E_0'(t, t_2) = E_0(t - t_2) - E_0(t + t_2)$. Its Fourier transform is given by $E_{p\omega}'(\omega, t_2) = E_{p\omega}(\omega)(e^{-\sigma t_2} e^{-i\omega t_2} - e^{\sigma t_2} e^{i\omega t_2})$ which has a zero at the **same** $\omega = \omega_0$.

Let us consider the function $f(t, t_2, t_0) = e^{-2\sigma t_0} f_1(t, t_2, t_0) + e^{2\sigma t_0} f_2(t, t_2, t_0)$ where $f_1(t, t_2, t_0) = e^{\sigma t_0} E_p'(t + t_0, t_2)$ and $f_2(t, t_2, t_0) = e^{-\sigma t_0} E_p'(t - t_0, t_2)$ where t_0 is finite and real and we can see that the Fourier Transform of this function $F(\omega, t_2, t_0) = E_{p\omega}'(\omega, t_2)(e^{-\sigma t_0} e^{i\omega t_0} + e^{\sigma t_0} e^{-i\omega t_0})$ also has a zero

at the **same** $\omega = \omega_0$.

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Let us consider a new function $g(t, t_2, t_0) = g_-(t, t_2, t_0)u(-t) + g_+(t, t_2, t_0)u(t)$ where $g(t, t_2, t_0)$ is a real function of variable t and $u(t)$ is Heaviside unit step function and $g_-(t, t_2, t_0) = f(t, t_2, t_0)e^{-\sigma t}$ and $g_+(t, t_2, t_0) = f(t, t_2, t_0)e^{\sigma t}$. We can see that $g(t, t_2, t_0)h(t) = f(t, t_2, t_0)$ where $h(t) = [e^{\sigma t}u(-t) + e^{-\sigma t}u(t)]$.

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We can show that $E_p(t), E'_p(t, t_2), h(t), g(t, t_2, t_0)$ are real absolutely integrable functions and go to zero as $t \rightarrow \pm\infty$. Hence their respective Fourier transforms given by $E_{p\omega}(\omega), E'_{p\omega}(\omega, t_2), H(\omega), G(\omega, t_2, t_0)$ are finite for $|\omega| \leq \infty$ and go to zero as $|\omega| \rightarrow \infty$, as per Riemann Lebesgue Lemma (link). This is shown in detail in Appendix B.1.

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If we take the Fourier transform of the equation $g(t, t_2, t_0)h(t) = f(t, t_2, t_0)$ where $h(t) = [e^{\sigma t}u(-t) + e^{-\sigma t}u(t)]$, we get $\frac{1}{2\pi}[G(\omega, t_2, t_0)*H(\omega)] = F(\omega, t_2, t_0) = E'_{p\omega}(\omega, t_2)(e^{-\sigma t_0}e^{i\omega t_0} + e^{\sigma t_0}e^{-i\omega t_0}) = F_R(\omega, t_2, t_0) + iF_I(\omega, t_2, t_0)$ as per convolution theorem (link), where $*$ denotes convolution operation given by $F(\omega, t_2, t_0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega', t_2, t_0)H(\omega - \omega')d\omega'$ and $H(\omega) = H_R(\omega) = [\frac{1}{\sigma - i\omega} + \frac{1}{\sigma + i\omega}] = \frac{2\sigma}{(\sigma^2 + \omega^2)}$ is real and is the Fourier transform of the function $h(t)$ and $G(\omega, t_2, t_0) = G_R(\omega, t_0, t_2) + iG_I(\omega, t_2, t_0)$ is the Fourier transform of the function $g(t, t_2, t_0)$. We can write $g(t, t_2, t_0) = g_{\text{even}}(t, t_2, t_0) + g_{\text{odd}}(t, t_2, t_0)$ where $g_{\text{even}}(t, t_2, t_0)$ is an even function and $g_{\text{odd}}(t, t_2, t_0)$ is an odd function of variable t .

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If Statement 1 is true, then we require the Fourier transform of the function $f(t, t_2, t_0)$ given by $F(\omega, t_2, t_0)$ to have a zero at $\omega = \omega_0$ for **every value** of t_0 , for a given fixed value of t_2 . This implies that the **real** part of the Fourier transform of the **even function** $g_{\text{even}}(t, t_2, t_0) = \frac{1}{2}[g(t, t_2, t_0) + g(-t, t_2, t_0)]$ given by $G_R(\omega, t_0, t_2)$ must have **at least one zero** at $\omega = \omega_z(t_2, t_0) \neq 0$ where $\omega_z(t_0)$ is real and finite, where $G_R(\omega, t_0, t_2)$ crosses the zero line to the opposite sign, and can be different from ω_0 in general. We call this **Statement 2**.

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Because $H(\omega) = \frac{2\sigma}{(\sigma^2 + \omega^2)}$ is real and does not have zeros for any finite value of ω , **if** $G_R(\omega, t_0, t_2)$ does not have at least one zero for some $\omega = \omega_z(t_2, t_0) \neq 0$, where $G_R(\omega, t_0, t_2)$ crosses the zero line to the opposite sign, **then the real part** of $F(\omega, t_2, t_0)$ given by $F_R(\omega, t_2, t_0) = \frac{1}{2\pi}[G_R(\omega, t_0, t_2) * H(\omega)]$, obtained by the convolution of $H(\omega)$ and $G_R(\omega, t_0, t_2)$, **cannot** possibly have zeros for any non-zero finite value of ω , which goes against **Statement 1**. This is shown in detail in Lemma 1.

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Lemma 1: If Riemann's Xi function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ has a zero at $\omega = \omega_0 \neq 0$ where ω_0 is real and finite, then the **real** part of the Fourier transform of the **even function** $g_{\text{even}}(t, t_2, t_0) = \frac{1}{2}[g(t, t_2, t_0) + g(-t, t_2, t_0)]$ given by $G_R(\omega, t_0, t_2)$ must have **at least one zero** at $\omega = \omega_z(t_2, t_0) \neq 0$ for **every value** of t_0 , for a given fixed value of t_2 , where $G_R(\omega, t_0, t_2)$ crosses the zero line to the opposite sign and $\omega_z(t_2, t_0)$ is real and finite, where $g(t, t_2, t_0)h(t) = f(t, t_2, t_0) = e^{-2\sigma t_0}f_1(t, t_2, t_0) + e^{2\sigma t_0}f_2(t, t_2, t_0)$ where $f_1(t, t_2, t_0) = e^{\sigma t_0}E'_p(t + t_0, t_2)$ and $f_2(t, t_2, t_0) = e^{-\sigma t_0}E'_p(t - t_0, t_2)$, $E'_p(t, t_2) = e^{-\sigma t_2}E_p(t - t_2) - e^{\sigma t_2}E_p(t + t_2)$, and $h(t) = e^{\sigma t}u(-t) + e^{-\sigma t}u(t)$ and $0 < \sigma < \frac{1}{2}$.

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Proof: If $E_{p\omega}(\omega)$ has a zero at finite $\omega = \omega_0 \neq 0$ to satisfy Statement 1, then $F(\omega, t_2, t_0) = E'_{p\omega}(\omega, t_2)(e^{-\sigma t_0}e^{i\omega t_0} + e^{\sigma t_0}e^{-i\omega t_0}) = E_{p\omega}(\omega)(e^{-\sigma t_2}e^{-i\omega t_2} - e^{\sigma t_2}e^{i\omega t_2})(e^{-\sigma t_0}e^{i\omega t_0} + e^{\sigma t_0}e^{-i\omega t_0})$ also has a zero at $\omega = \omega_0$ and its real part given by $F_R(\omega, t_2, t_0)$ also has a zero at the same location $\omega = \omega_0 \neq 0$.

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Let us consider the case where $G_R(\omega, t_0, t_2)$ **does not** have at least one zero for finite $\omega =$

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186 $\omega_z(t_2, t_0) \neq 0$ and show that $F_R(\omega, t_2, t_0)$ does not have at least one zero at finite $\omega \neq 0$ for this case,
 187 which **contradicts** Statement 1. Given that $H(\omega)$ is real, we can write the convolution theorem only
 188 for the real parts as follows.

$$F_R(\omega, t_2, t_0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G_R(\omega', t_2, t_0) H(\omega - \omega') d\omega' \quad (6)$$

189 We can show that the above integral converges for all $|\omega| \leq \infty$, given that $G(\omega, t_2, t_0)$ and $H(\omega)$
 190 have fall-off rate of $\frac{1}{\omega^2}$ as $|\omega| \rightarrow \infty$ because the first derivatives of $g(t, t_2, t_0)$ and $h(t)$ are discontinuous
 191 at $t = 0$.(Appendix B.2)

192 We substitute $H(\omega) = \frac{2\sigma}{(\sigma^2 + \omega^2)}$ in Eq. 6 and we get

$$F_R(\omega, t_2, t_0) = \frac{\sigma}{\pi} \int_{-\infty}^{\infty} G_R(\omega', t_2, t_0) \frac{1}{(\sigma^2 + (\omega - \omega')^2)} d\omega' \quad (7)$$

194 We can split the integral in Eq. 7 as follows.

$$F_R(\omega, t_2, t_0) = \frac{\sigma}{\pi} \left[\int_{-\infty}^0 G_R(\omega', t_2, t_0) \frac{1}{(\sigma^2 + (\omega - \omega')^2)} d\omega' + \int_0^{\infty} G_R(\omega', t_2, t_0) \frac{1}{(\sigma^2 + (\omega - \omega')^2)} d\omega' \right] \quad (8)$$

196 We see that $G_R(-\omega, t_2, t_0) = G_R(\omega, t_2, t_0)$ because $g(t, t_2, t_0)$ is a real function (link). We can
 197 substitute $\omega' = -\omega''$ in the first integral in Eq. 8 and substituting $\omega'' = \omega'$ in the result, we can write
 198 as follows.

$$F_R(\omega, t_2, t_0) = \frac{\sigma}{\pi} \int_0^{\infty} G_R(\omega', t_2, t_0) \left[\frac{1}{(\sigma^2 + (\omega - \omega')^2)} + \frac{1}{(\sigma^2 + (\omega + \omega')^2)} \right] d\omega' \quad (9)$$

200 In Appendix B.1 last paragraph, it is shown that $G(\omega, t_2, t_0)$ is finite for $|\omega| \leq \infty$ and goes to
 201 zero as $|\omega| \rightarrow \infty$. We can see that for $\omega' = 0$ and $\omega' = \infty$, the integrand in Eq. 9 is zero. For
 202 finite $\omega \geq 0$, and $0 < \omega' < \infty$, we can see that the term $\frac{1}{(\sigma^2 + (\omega - \omega')^2)} + \frac{1}{(\sigma^2 + (\omega + \omega')^2)} > 0$. We see that
 203 $G_R(\omega, t_0, t_2)$ is **not** an all zero function and that $G_R(\omega, t_2, t_0)$ is a continuous function of ω , for a fixed
 204 t_0 and t_2 (Section 4.1).

205
 206 • **Case 1:** $G_R(\omega', t_2, t_0) \geq 0$ for all finite $\omega' > 0$

208 We see that $F_R(\omega, t_2, t_0) > 0$ for all finite $\omega \geq 0$. We see that $F_R(-\omega, t_2, t_0) = F_R(\omega, t_2, t_0)$ because
 209 $f(t, t_2, t_0)$ is a real function (link). Hence $F_R(\omega, t_2, t_0) > 0$ for all finite $\omega \leq 0$.

210
 211 This **contradicts** Statement 1 which requires $F_R(\omega, t_2, t_0)$ to have at least one zero at finite $\omega \neq 0$
 212 because we showed that $\omega_0 \neq 0$ in **Section 2** paragraph 5. Therefore $G_R(\omega')$ must have **at least**
 213 **one zero** at $\omega' = \omega_z(t_2, t_0) \neq 0$ where it crosses the zero line and becomes negative, where $\omega_z(t_2, t_0)$
 214 is real and finite.

215
 216 • **Case 2:** $G_R(\omega', t_2, t_0) \leq 0$ for all finite $\omega' > 0$

217

218 We see that $F_R(\omega, t_2, t_0) < 0$ for all finite $\omega \geq 0$. We see that $F_R(-\omega, t_2, t_0) = F_R(\omega, t_2, t_0)$ because
 219 $f(t, t_2, t_0)$ is a real function (link). Hence $F_R(\omega, t_2, t_0) < 0$ for all finite $\omega \leq 0$.

220

221 This **contradicts** Statement 1 which requires $F_R(\omega, t_2, t_0)$ to have at least one zero at finite $\omega \neq 0$.
 222 Therefore $G_R(\omega', t_2, t_0)$ must have **at least one zero** at $\omega' = \omega_z(t_2, t_0) \neq 0$, where it crosses the
 223 zero line and becomes positive, where $\omega_z(t_2, t_0)$ is real and finite.

224

225 We have shown that, $G_R(\omega, t_2, t_0)$ must have **at least one zero** at finite $\omega = \omega_z(t_2, t_0) \neq 0$ where
 226 it crosses the zero line to the opposite sign, to satisfy **Statement 1**. We call this **Statement 2**. In
 227 the rest of the sections, we consider only the **first** zero crossing away from origin, where $G_R(\omega, t_0, t_2)$
 228 crosses the zero line to the opposite sign.

229 2.2. *On the zeros of a related function $G(\omega, t_2, t_0)$*

230

231 We can compute the fourier transform of the function $g_{even}(t, t_2, t_0) = \frac{1}{2}[g(t, t_2, t_0) + g(-t, t_2, t_0)]$
 232 given by $G_R(\omega, t_0, t_2)$. We require $G_R(\omega, t_0, t_2) = 0$ for $\omega = \omega_z(t_2, t_0)$ for **every value** of t_0 , for a
 233 given value of t_2 , to satisfy **Statement 1**. In general, $\omega_z(t_2, t_0) \neq \omega_0$.

234

235 First we compute the Fourier transform of the function $g_1(t, t_2, t_0)$ given by $G_1(\omega, t_2, t_0) = G_{1R}(\omega, t_2, t_0) +$
 236 $iG_{1I}(\omega, t_2, t_0)$. We use $g_1(t, t_2, t_0) = f_1(t, t_2, t_0)e^{-\sigma t}u(-t) + f_1(t, t_2, t_0)e^{\sigma t}u(t) = e^{\sigma t_0}E'_p(t+t_0, t_2)e^{-\sigma t}u(-t) +$
 237 $e^{\sigma t_0}E'_p(t+t_0, t_2)e^{\sigma t}u(t)$.

238

$$\begin{aligned} G_1(\omega, t_2, t_0) &= \int_{-\infty}^{\infty} g_1(t, t_2, t_0)e^{-i\omega t}dt = \int_{-\infty}^0 g_1(t, t_2, t_0)e^{-i\omega t}dt + \int_0^{\infty} g_1(t, t_2, t_0)e^{-i\omega t}dt \\ G_1(\omega, t_2, t_0) &= \int_{-\infty}^0 e^{\sigma t_0}E'_p(t+t_0, t_2)e^{-\sigma t}e^{-i\omega t}dt + \int_0^{\infty} e^{\sigma t_0}E'_p(t+t_0, t_2)e^{\sigma t}e^{-i\omega t}dt \end{aligned}$$

239

(10)

240 We use $E'_p(t, t_2) = E'_0(t, t_2)e^{-\sigma t}$ where $E'_0(t, t_2) = E_0(t-t_2) - E_0(t+t_2)$ and $E'_p(t+t_0, t_2) =$
 241 $E'_0(t+t_0, t_2)e^{-\sigma t}e^{-\sigma t_0}$. Substituting $t = -t$ in the second integral in Eq. 10, we have

$$\begin{aligned} G_1(\omega, t_2, t_0) &= \int_{-\infty}^0 E'_0(t+t_0, t_2)e^{-2\sigma t}e^{-i\omega t}dt + \int_0^{\infty} E'_0(t+t_0, t_2)e^{-i\omega t}dt \\ G_1(\omega, t_2, t_0) &= \int_{-\infty}^0 E'_0(t+t_0, t_2)e^{-2\sigma t}e^{-i\omega t}dt + \int_{-\infty}^0 E'_0(-t+t_0, t_2)e^{i\omega t}dt \end{aligned}$$

242

(11)

243 We define $E'_{0n}(t, t_2) = E'_0(-t, t_2)$ and get $E'_0(-t+t_0, t_2) = E'_{0n}(t-t_0, t_2)$ and write Eq. 11 as
 244 follows.

$$G_1(\omega, t_2, t_0) = \int_{-\infty}^0 E'_0(t+t_0, t_2)e^{-2\sigma t}e^{-i\omega t}dt + \int_{-\infty}^0 E'_{0n}(t-t_0, t_2)e^{i\omega t}dt = G_{1R}(\omega, t_2, t_0) + iG_{1I}(\omega, t_2, t_0)$$

245

(12)

246 The above equations can be expanded as follows using the identity $e^{i\omega t} = \cos(\omega t) + i \sin(\omega t)$.
 247 Comparing the **real parts** of $G_1(\omega)$, we have

$$G_{1R}(\omega, t_2, t_0) = \int_{-\infty}^0 E'_0(t + t_0, t_2) e^{-2\sigma t} \cos(\omega t) dt + \int_{-\infty}^0 E'_{0n}(t - t_0, t_2) \cos(\omega t) dt$$

(13)

249 **2.3. Zero crossing function $\omega_z(t_2, t_0)$ is an even function of variable t_0 , for a fixed t_2**

250
 251 Now we consider the function $f(t, t_2, t_0) = e^{-2\sigma t_0} f_1(t, t_2, t_0) + e^{2\sigma t_0} f_2(t, t_2, t_0) = e^{-\sigma t_0} E'_p(t + t_0, t_2) +$
 252 $e^{\sigma t_0} E'_p(t - t_0, t_2)$ where $f_1(t, t_2, t_0) = e^{\sigma t_0} E'_p(t + t_0, t_2)$ and $f_2(t, t_2, t_0) = f_1(t, t_2, -t_0) = e^{-\sigma t_0} E'_p(t - t_0, t_2)$
 253 and $g(t, t_2, t_0)h(t) = f(t, t_2, t_0)$ where $g(t, t_2, t_0) = f(t, t_2, t_0)e^{-\sigma t}u(-t) + f(t, t_2, t_0)e^{\sigma t}u(t)$ and $h(t) =$
 254 $[e^{\sigma t}u(-t) + e^{-\sigma t}u(t)]$ and compute the Fourier transform of the function $g(t, t_2, t_0)$ and compute its
 255 real part using the procedure in above section, similar to Eq. 13 and we can write as follows. We
 256 substitute $t = \tau$.

$$\begin{aligned} G_R(\omega, t_2, t_0) &= e^{-2\sigma t_0} G_{1R}(\omega, t_2, t_0) + e^{2\sigma t_0} G_{1R}(\omega, t_2, -t_0) \\ G_{1R}(\omega, t_2, t_0) &= \int_{-\infty}^0 [E'_0(\tau + t_0, t_2) e^{-2\sigma \tau} + E'_{0n}(\tau - t_0, t_2)] \cos(\omega \tau) d\tau \\ G_R(\omega, t_2, t_0) &= e^{-2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau + t_0, t_2) e^{-2\sigma \tau} + E'_{0n}(\tau - t_0, t_2)] \cos(\omega \tau) d\tau \\ &\quad + e^{2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau - t_0, t_2) e^{-2\sigma \tau} + E'_{0n}(\tau + t_0, t_2)] \cos(\omega \tau) d\tau \end{aligned}$$

(14)

258 We require $G_R(\omega, t_2, t_0) = 0$ for $\omega = \omega_z(t_2, t_0)$ for every value of t_0 , for **every given fixed**
 259 **value** of t_2 , to satisfy **Statement 1**. In general $\omega_z(t_2, t_0) \neq \omega_0$. Hence we can see that $P(t_2, t_0) =$
 260 $G_R(\omega_z(t_2, t_0), t_2, t_0) = 0$ and we can rearrange the terms as follows.

$$\begin{aligned} P(t_2, t_0) &= \int_{-\infty}^0 [e^{-2\sigma t_0} E'_0(\tau + t_0, t_2) e^{-2\sigma \tau} + e^{2\sigma t_0} E'_{0n}(\tau + t_0, t_2)] \cos(\omega_z(t_2, t_0) \tau) d\tau \\ &\quad + \int_{-\infty}^0 [e^{2\sigma t_0} E'_0(\tau - t_0, t_2) e^{-2\sigma \tau} + e^{-2\sigma t_0} E'_{0n}(\tau - t_0, t_2)] \cos(\omega_z(t_2, t_0) \tau) d\tau = 0 \end{aligned}$$

(15)

262 We can write as follows, where $P_{odd}(t_2, t_0)$ is an **odd** function of variable t_0 .

$$\begin{aligned} P(t_2, t_0) &= P_{odd}(t_2, t_0) + P_{odd}(t_2, -t_0) = 0 \\ P_{odd}(t_2, t_0) &= \int_{-\infty}^0 [e^{-2\sigma t_0} E'_0(\tau + t_0, t_2) e^{-2\sigma \tau} + e^{2\sigma t_0} E'_{0n}(\tau + t_0, t_2)] \cos(\omega_z(t_2, t_0) \tau) d\tau \end{aligned}$$

(16)

264 We see that $f(t, t_2, t_0) = e^{-\sigma t_0} E'_p(t + t_0, t_2) + e^{\sigma t_0} E'_p(t - t_0, t_2) = f(t, t_2, -t_0)$ is **unchanged** by the
 265 substitution $t_0 = -t_0$ and hence $\omega_z(t_2, t_0)$ is an **even** function of variable t_0 , for **every fixed value**
 266 of t_2 .

268 3. Final Step

269

270 We expand $P_{odd}(t_2, t_0)$ in Eq. 16 as follows, using the substitution $\tau + t_0 = \tau'$ and substituting
 271 back $\tau' = \tau$. We use $E'_{0n}(\tau, t_2) = E'_0(-\tau, t_2)$ and $E'_0(\tau, t_2) = E_0(\tau - t_2) - E_0(\tau + t_2)$.

$$\begin{aligned}
 P_{odd}(t_2, t_0) &= [\cos(\omega_z(t_2, t_0)t_0) \int_{-\infty}^{t_0} E'_0(\tau, t_2) e^{-2\sigma\tau} \cos(\omega_z(t_2, t_0)\tau) d\tau \\
 &\quad + \sin(\omega_z(t_2, t_0)t_0) \int_{-\infty}^{t_0} E'_0(\tau, t_2) e^{-2\sigma\tau} \sin(\omega_z(t_2, t_0)\tau) d\tau] \\
 &+ e^{2\sigma t_0} [\cos(\omega_z(t_2, t_0)t_0) \int_{-\infty}^{t_0} E'_{0n}(\tau, t_2) \cos(\omega_z(t_2, t_0)\tau) d\tau + \sin(\omega_z(t_2, t_0)t_0) \int_{-\infty}^{t_0} E'_{0n}(\tau, t_2) \sin(\omega_z(t_2, t_0)\tau) d\tau]
 \end{aligned}$$

(17)

272

273 In Section 2.1, it is shown that $0 < \omega_z(t_2, t_0) < \infty$, for all $|t_0| < \infty$, for a given value of t_2 .

274

275 In Section 4, it is shown that $\omega_z(t_2, t_0)$ is a **continuous** function of variable t_0 and t_2 , for all
 276 $|t_0| \leq \infty$ and $|t_2| \leq \infty$.

277

278 In Section 6, it is shown that $E_0(t)$ is **strictly decreasing** for $t > 0$.

279

280 Given that $\omega_z(t_2, t_0)$ is a continuous function of both t_0 and t_2 , we can find a suitable value of
 281 $t_0 = t_{0c}$ and $t_2 = t_{2c} = 2t_{0c}$ such that $\omega_z(t_{2c}, t_{0c})t_{0c} = \frac{\pi}{2}$. Given that $\omega_z(t_2, t_0)$ is a continuous function
 282 of t_0 and t_2 and given that t_0 is a continuous function, we see that the **product** of two continuous
 283 functions $\omega_z(t_2, t_0)t_0$ is a **continuous** function and is positive for $t_0 > 0$ because $0 < \omega_z(t_2, t_0) < \infty$.

284

285 We see that $0 < \omega_z(t_2, t_0) < \infty$, as $t_0 \rightarrow \infty$ and that the order of $\omega_z(t_2, t_0)$ is 1 (5) and the
 286 order of $\omega_z(t_2, t_0)t_0$ is given by $O[t_0]$. As t_0 is increased from zero towards ∞ , the continuous function
 287 $\omega_z(t_2, t_0)t_0$ starts from zero and increases towards ∞ with order $O[t_0]$ and will pass through $\frac{\pi}{2}$.

288

289 We use $P_{odd}(t_2, t_0) + P_{odd}(t_2, -t_0) = 0$ as follows. We set $t_0 = t_{0c} > 0$ and $t_2 = t_{2c} = 2t_{0c}$ such
 290 that $\omega_z(t_{2c}, t_{0c})t_{0c} = \frac{\pi}{2}$ in Eq. 17 as follows. We use the fact that $\omega_z(t_{2c}, -t_{0c}) = \omega_z(t_{2c}, t_{0c})$ shown in
 291 Section 2.3.

$$\begin{aligned}
 &\int_{-\infty}^{t_{0c}} E'_0(\tau, t_{2c}) e^{-2\sigma\tau} \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau + e^{2\sigma t_{0c}} \int_{-\infty}^{t_{0c}} E'_{0n}(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\
 &- \int_{-\infty}^{-t_{0c}} E'_0(\tau, t_{2c}) e^{-2\sigma\tau} \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau - e^{-2\sigma t_{0c}} \int_{-\infty}^{-t_{0c}} E'_{0n}(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau = 0
 \end{aligned}$$

292

(18)

293 We split the first two integrals in the left hand side of Eq. 18 and write as follows.

$$\begin{aligned}
& \left[\int_{-\infty}^{-t_{0c}} E'_0(\tau, t_{2c}) e^{-2\sigma\tau} \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau + \int_{-t_{0c}}^{t_{0c}} E'_0(\tau, t_{2c}) e^{-2\sigma\tau} \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \right] \\
& + e^{2\sigma t_{0c}} \left[\int_{-\infty}^{-t_{0c}} E'_{0n}(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau + \int_{-t_{0c}}^{t_{0c}} E'_{0n}(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \right] \\
& - \int_{-\infty}^{-t_{0c}} E'_0(\tau, t_{2c}) e^{-2\sigma\tau} \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau - e^{-2\sigma t_{0c}} \int_{-\infty}^{-t_{0c}} E'_{0n}(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau = 0
\end{aligned} \tag{19}$$

We combine the terms with common integrals and cancel common terms in Eq. 19 as follows.

$$\begin{aligned}
& \int_{-t_{0c}}^{t_{0c}} E'_0(\tau, t_{2c}) e^{-2\sigma\tau} \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau + e^{2\sigma t_{0c}} \int_{-t_{0c}}^{t_{0c}} E'_{0n}(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\
& = -2 \sinh(2\sigma t_{0c}) \int_{-\infty}^{-t_{0c}} E'_{0n}(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau
\end{aligned} \tag{20}$$

We can rearrange the terms in Eq. 20 as follows.

$$\begin{aligned}
& \int_{-t_{0c}}^{t_{0c}} [E'_0(\tau, t_{2c}) e^{-2\sigma\tau} + E'_{0n}(\tau, t_{2c}) e^{2\sigma t_{0c}}] \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\
& = -2 \sinh(2\sigma t_{0c}) \int_{-\infty}^{-t_{0c}} E'_{0n}(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau
\end{aligned} \tag{21}$$

We denote the right hand side of Eq. 21 as RHS . We can split the integral in Eq. 21 using $\int_{-t_{0c}}^{t_{0c}} = \int_{-t_{0c}}^0 + \int_0^{t_{0c}}$ as follows.

$$\begin{aligned}
& \int_{-t_{0c}}^0 [E'_0(\tau, t_{2c}) e^{-2\sigma\tau} + E'_{0n}(\tau, t_{2c}) e^{2\sigma t_{0c}}] \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\
& + \int_0^{t_{0c}} [E'_0(\tau, t_{2c}) e^{-2\sigma\tau} + E'_{0n}(\tau, t_{2c}) e^{2\sigma t_{0c}}] \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau = RHS
\end{aligned} \tag{22}$$

We substitute $\tau = -\tau$ in the first integral in Eq. 22 as follows. We use $E'_0(-\tau) = E'_{0n}(\tau, t_{2c})$ and $E'_{0n}(-\tau) = E'_0(\tau, t_{2c})$.

$$\begin{aligned}
& \int_{t_{0c}}^0 [E'_{0n}(\tau, t_{2c}) e^{2\sigma\tau} + E'_0(\tau, t_{2c}) e^{2\sigma t_{0c}}] \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\
& + \int_0^{t_{0c}} [E'_0(\tau, t_{2c}) e^{-2\sigma\tau} + E'_{0n}(\tau, t_{2c}) e^{2\sigma t_{0c}}] \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau = RHS
\end{aligned} \tag{23}$$

Given that $\int_0^0 = -\int_0^{t_{0c}}$, we can simplify as follows.

$$\int_0^{t_{0c}} [E'_0(\tau, t_{2c})(e^{-2\sigma\tau} - e^{2\sigma t_{0c}}) + E'_{0n}(\tau, t_{2c})(-e^{2\sigma\tau} + e^{2\sigma t_{0c}})] \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau = RHS \quad (24)$$

We substitute $\tau = -\tau$ in the right hand side of Eq. 21 as follows. We use $E'_{0n}(-\tau) = E'_0(\tau, t_{2c})$.

$$RHS = 2 \sinh(2\sigma t_{0c}) \int_{t_{0c}}^{\infty} E'_0(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \quad (25)$$

We split the integral on the right hand side in Eq. 25 as follows.

$$RHS = 2 \sinh(2\sigma t_{0c}) \left[\int_0^{\infty} E'_0(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau - \int_0^{t_{0c}} E'_0(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \right] \quad (26)$$

We consolidate the integrals with the term $\int_0^{t_{0c}} E'_0(\tau, t_{2c})$ in Eq. 24 and Eq. 26 as follows. We use $2 \sinh(2\sigma t_{0c}) = e^{2\sigma t_{0c}} - e^{-2\sigma t_{0c}}$.

$$\begin{aligned} \int_0^{t_{0c}} [E'_0(\tau, t_{2c})(e^{-2\sigma\tau} - e^{2\sigma t_{0c}} + e^{2\sigma t_{0c}} - e^{-2\sigma t_{0c}}) + E'_{0n}(\tau, t_{2c})(-e^{2\sigma\tau} + e^{2\sigma t_{0c}})] \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\ = 2 \sinh(2\sigma t_{0c}) \int_0^{\infty} E'_0(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \end{aligned} \quad (27)$$

We cancel common terms in Eq. 27 as follows.

$$\begin{aligned} \int_0^{t_{0c}} [E'_0(\tau, t_{2c})(e^{-2\sigma\tau} - e^{-2\sigma t_{0c}}) + E'_{0n}(\tau, t_{2c})(-e^{2\sigma\tau} + e^{2\sigma t_{0c}})] \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\ = 2 \sinh(2\sigma t_{0c}) \int_0^{\infty} E'_0(\tau, t_{2c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \end{aligned} \quad (28)$$

We substitute $E'_0(\tau, t_{2c}) = E_0(\tau - t_{2c}) - E_0(\tau + t_{2c})$ and $E'_{0n}(\tau, t_{2c}) = E'_0(-\tau, t_{2c}) = E_0(-\tau - t_{2c}) - E_0(-\tau + t_{2c})$. We see that $E_0(-\tau - t_{2c}) = E_0(\tau + t_{2c})$ and $E_0(-\tau + t_{2c}) = E_0(\tau - t_{2c})$ given that $E_0(\tau) = E_0(-\tau)$. Hence we see that $E'_{0n}(\tau, t_{2c}) = E_0(\tau + t_{2c}) - E_0(\tau - t_{2c}) = -E'_0(\tau, t_{2c})$. We can write Eq. 28 as follows.

$$\begin{aligned} \int_0^{t_{0c}} (E_0(\tau - t_{2c}) - E_0(\tau + t_{2c}))(e^{-2\sigma\tau} - e^{-2\sigma t_{0c}} + e^{2\sigma\tau} - e^{2\sigma t_{0c}}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\ = 2 \sinh(2\sigma t_{0c}) \int_0^{\infty} (E_0(\tau - t_{2c}) - E_0(\tau + t_{2c})) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \end{aligned}$$

(29)

We substitute $2 \cosh(2\sigma\tau) = e^{2\sigma\tau} + e^{-2\sigma\tau}$ and $2 \cosh(2\sigma t_{0c}) = e^{2\sigma t_{0c}} + e^{-2\sigma t_{0c}}$ and cancel the common factor of 2 in Eq. 29 as follows.

$$\begin{aligned} & \int_0^{t_{0c}} (E_0(\tau - t_{2c}) - E_0(\tau + t_{2c})) (\cosh(2\sigma\tau) - \cosh(2\sigma t_{0c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\ &= \sinh(2\sigma t_{0c}) \int_0^\infty (E_0(\tau - t_{2c}) - E_0(\tau + t_{2c})) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \end{aligned}$$

323

(30)

Next Step:

324

325

We denote the right hand side of Eq. 30 as RHS . We substitute $\tau + t_{2c} = \tau'$ in the right hand side of Eq. 30 and then substitute $\tau' = \tau$. Similarly we substitute $\tau - t_{2c} = \tau'$ as follows.

326

327

$$\begin{aligned} RHS = & \sinh(2\sigma t_{0c}) [\cos(\omega_z(t_{2c}, t_{0c})t_{2c}) \int_{-t_{2c}}^\infty E_0(\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\ & + \sin(\omega_z(t_{2c}, t_{0c})t_{2c}) \int_{-t_{2c}}^\infty E_0(\tau) \cos(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\ & - \cos(\omega_z(t_{2c}, t_{0c})t_{2c}) \int_{t_{2c}}^\infty E_0(\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau + \sin(\omega_z(t_{2c}, t_{0c})t_{2c}) \int_{t_{2c}}^\infty E_0(\tau) \cos(\omega_z(t_{2c}, t_{0c})\tau) d\tau] \end{aligned}$$

328

(31)

In Eq. 31, given that $\omega_z(t_{2c}, t_{0c})t_{0c} = \frac{\pi}{2}$ and $t_{2c} = 2t_{0c}$ and hence $\omega_z(t_{2c}, t_{0c})t_{2c} = 2\frac{\pi}{2} = \pi$ and $\sin(\omega_z(t_{2c}, t_{0c})t_{2c}) = 0$ and $\cos(\omega_z(t_{2c}, t_{0c})t_{2c}) = -1$. Hence we cancel common terms and write Eq. 31 and Eq. 30 as follows.

329

330

331

$$\begin{aligned} & \int_0^{t_{0c}} (E_0(\tau - t_{2c}) - E_0(\tau + t_{2c})) (\cosh(2\sigma\tau) - \cosh(2\sigma t_{0c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau \\ &= -\sinh(2\sigma t_{0c}) [\int_{-t_{2c}}^\infty E_0(\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau - \int_{t_{2c}}^\infty E_0(\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau] \end{aligned}$$

332

(32)

We use $\int_{-t_{2c}}^\infty E_0(\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau = \int_{-t_{2c}}^{t_{2c}} E_0(\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau + \int_{t_{2c}}^\infty E_0(\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau$ and cancel the common term $\int_{t_{2c}}^\infty E_0(\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau$ in Eq. 32 as follows. Given that $E_0(\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau)$ is an **odd** function of variable τ , we get $\int_{-t_{2c}}^{t_{2c}} E_0(\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau = 0$.

333

334

335

$$\int_0^{t_{0c}} (E_0(\tau - t_{2c}) - E_0(\tau + t_{2c})) (\cosh(2\sigma\tau) - \cosh(2\sigma t_{0c}) \sin(\omega_z(t_{2c}, t_{0c})\tau) d\tau = 0$$

336

(33)

We can multiply Eq. 33 by a factor of -1 as follows.

337

$$\int_0^{t_{0c}} [E_0(\tau - t_{2c}) - E_0(\tau + t_{2c})](\cosh 2\sigma t_{0c} - \cosh(2\sigma\tau) \sin(\omega_z(t_{2c}, t_{0c})\tau)) d\tau = 0$$

(34)

In Eq. 34, given that $\omega_z(t_{2c}, t_{0c})t_{0c} = \frac{\pi}{2}$, as τ varies over the interval $[0, t_{0c}]$, $\omega_z(t_{2c}, t_{0c})\tau = \frac{\pi\tau}{2t_{0c}}$ varies from $[0, \frac{\pi}{2}]$ where the sinusoidal function varies is > 0 , in the interval $0 < \tau < t_{0c}$, for $t_{0c} > 0$.

In Eq. 34, we see that in the interval $0 < \tau < t_{0c}$, the integral on the left hand side is > 0 for $t_{0c} > 0$, because each of the terms in the integrand are > 0 , in the interval $0 < \tau < t_{0c}$ as follows. Given that $E_0(t)$ is a **strictly decreasing** function for $t > 0$ (Section 6), we see that $E_0(\tau - t_{2c}) - E_0(\tau + t_{2c})$ is > 0 (Section 6.3) in the interval $0 < \tau < t_{0c}$. The term $(\cosh(2\sigma t_{0c}) - \cosh(2\sigma\tau))$ is > 0 in the interval $0 < \tau < t_{0c}$ and the integrand is zero at $\tau = 0$ and $\tau = t_{0c}$ and hence the integral **cannot** equal zero, as required by the right hand side of Eq. 34. Hence this leads to a **contradiction** for $0 < \sigma < \frac{1}{2}$.

For $\sigma = 0$, both sides of Eq. 34 is zero and **does not** lead to a contradiction.

We have shown this result for $0 < \sigma < \frac{1}{2}$ and then use the property $\xi(\frac{1}{2} + \sigma + i\omega) = \xi(\frac{1}{2} - \sigma - i\omega)$ to show the result for $-\frac{1}{2} < \sigma < 0$. Hence we have produced a **contradiction** of **Statement 1** that the Fourier Transform of the function $E_p(t) = E_0(t)e^{-\sigma t}$ has a zero at $\omega = \omega_0$ for $0 < |\sigma| < \frac{1}{2}$.

Therefore, the assumption in **Statement 1** that Riemann's Xi Function given by $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ has a zero at $\omega = \omega_0$, where ω_0 is real and finite, leads to a **contradiction** for the region $0 < |\sigma| < \frac{1}{2}$ which corresponds to the critical strip excluding the critical line. This means $\zeta(s)$ does not have non-trivial zeros in the critical strip excluding the critical line and we have proved Riemann's Hypothesis.

4. $\omega_z(t_2, t_0)$ is a continuous function of t_0 and t_2

We see from Section 2.1 that $\omega_z(t_2, t_0)$ is shown to be **finite and non-zero** for all $|t_0| < \infty$ and that $\omega_z(t_2, t_0)$ is an even function of variable t_0 , for a given value of t_2 . For a given t_2 and t_0 , $\omega_z(t_2, t_0)$ can have more than one value, but we consider only the first zero crossing away from origin in the section below, where $G_R(\omega, t_2, t_0)$ crosses the zero line to the opposite sign, as detailed in **Lemma 1** in Section 2.1 and $\frac{\partial G_R(\omega, t_2, t_0)}{\partial \omega} \neq 0$ at $\omega = \omega_z(t_2, t_0)$. (example plot)

We consider the Fourier transform of $g(t, t_2, t_0)$ given by $G_R(\omega, t_2, t_0)$ in the section below and show that, under this Fourier transformation, as we change t_0 , the zero crossing in $G_R(\omega, t_2, t_0)$ given by $\omega_z(t_2, t_0)$ is a continuous function of t_0 , for all $|t_0| \leq \infty$, for **each** fixed value of t_2 . This is shown in the steps below. For a given **fixed** value of t_2 , $G_R(\omega, t_2, t_0)$ is a function of two variables ω and t_0 , and we use Implicit Function Theorem in R^2 .

- It is shown in Section 4.1 that $G_R(\omega, t_2, t_0)$ is partially differentiable at least twice with respect to ω , as shown in Eq. 35.

- It is shown in Section 4.2 that $G_R(\omega, t_2, t_0)$ is partially differentiable at least twice with respect to t_0 , as shown in Eq. 37 and Eq. 38.

380 • It is shown in Section 4.3 that the zero crossing in $G_R(\omega, t_2, t_0)$ given by $\omega_z(t_2, t_0)$, is a **contin-**
 381 **uous** function of t_0 , for a given t_2 , using **Implicit Function Theorem** in R^2 .

382

383 • It is shown in Section 4.4 that $\omega_z(t_2, t_0)$ is a **continuous** function of t_0 and t_2 , for all $|t_0| \leq \infty$
 384 and $|t_2| \leq \infty$, using **Implicit Function Theorem** in R^3 .

385 *4.1. $G_R(\omega, t_2, t_0)$ is partially differentiable twice as a function of ω*

386

387 $G_R(\omega, t_2, t_0)$ in Eq. 14 is copied below and we can expand $G_R(\omega, t_2, t_0)$ in Eq. 35 by substituting
 388 $\tau + t_0 = t$ and expanding it, similar to Eq. 17.

$$\begin{aligned}
 G_R(\omega, t_2, t_0) &= e^{-2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2)] \cos(\omega\tau) d\tau \\
 &+ e^{2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2)] \cos(\omega\tau) d\tau = G_{1R}(\omega, t_2, t_0) + G_{1R}(\omega, t_2, -t_0) \\
 G_{1R}(\omega, t_2, t_0) &= [\cos(\omega t_0) \int_{-\infty}^{t_0} E'_0(\tau, t_2)e^{-2\sigma\tau} \cos(\omega\tau) d\tau + \sin(\omega t_0) \int_{-\infty}^{t_0} E'_0(\tau, t_2)e^{-2\sigma\tau} \sin(\omega\tau) d\tau] \\
 &+ e^{-2\sigma t_0} [\cos(\omega t_0) \int_{-\infty}^{-t_0} E'_{0n}(\tau, t_2) \cos(\omega\tau) d\tau - \sin(\omega t_0) \int_{-\infty}^{-t_0} E'_{0n}(\tau, t_2) \sin(\omega\tau) d\tau]
 \end{aligned}$$

(35)

390 $G_R(\omega, t_2, t_0)$ is partially differentiable at least twice with respect to ω and the integrals converge
 391 in Eq. 35 for $0 < \sigma < \frac{1}{2}$, because the term $\tau^r E'_0(\tau - t_0, t_2)e^{-2\sigma\tau}$ has exponential asymptotic fall-off
 392 rate as $|\tau| \rightarrow \infty$, for $r = 0, 1, 2$ (Appendix B.4). The integrands are absolutely integrable and
 393 the integrands are analytic functions of variables ω and t_0 . We can interchange the order of partial
 394 differentiation and integration in Eq. 35 using theorem of dominated convergence as follows. (We
 395 could also use theorem 3 in link and link)

$$\begin{aligned}
 \frac{\partial G_R(\omega, t_2, t_0)}{\partial \omega} &= -[e^{-2\sigma t_0} \int_{-\infty}^0 \tau [E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2)] \sin(\omega\tau) d\tau \\
 &+ e^{2\sigma t_0} \int_{-\infty}^0 \tau [E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2)] \sin(\omega\tau) d\tau] \\
 \frac{\partial^2 G_R(\omega, t_2, t_0)}{\partial \omega^2} &= -[e^{-2\sigma t_0} \int_{-\infty}^0 \tau^2 [E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2)] \cos(\omega\tau) d\tau \\
 &+ e^{2\sigma t_0} \int_{-\infty}^0 \tau^2 [E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2)] \cos(\omega\tau) d\tau]
 \end{aligned}$$

(36)

397 *4.2. $G_R(\omega, t_2, t_0)$ is partially differentiable twice as a function of t_0*

398

399 $G_R(\omega, t_2, t_0)$ is partially differentiable at least twice as a function of t_0 and the integrals converge
 400 in Eq. 37 and Eq. 38 shown as follows. The integrands are absolutely integrable because the term
 401 $E'_0(\tau - t_0, t_2)e^{-2\sigma\tau}$ has exponential asymptotic fall-off rate as $|\tau| \rightarrow \infty$ (Appendix B.4). The
 402 integrands are analytic functions of variables ω and t_0 and we can expand $G_R(\omega, t_2, t_0)$ in Eq. 37

by substituting $\tau + t_0 = t$ and expanding it, similar to Eq. 35. We can interchange the order of partial differentiation and integration in Eq. 37 and Eq. 38 using theorem of dominated convergence as follows. (We could also use theorem 3 in link and link)

$$\begin{aligned}
G_R(\omega, t_2, t_0) &= e^{-2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2)] \cos(\omega\tau) d\tau \\
&\quad + e^{2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2)] \cos(\omega\tau) d\tau \\
\frac{\partial G_R(\omega, t_2, t_0)}{\partial t_0} &= -2\sigma e^{-2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2)] \cos(\omega\tau) d\tau \\
&\quad + e^{-2\sigma t_0} \int_{-\infty}^0 \frac{\partial(E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2))}{\partial t_0} \cos(\omega\tau) d\tau \\
&\quad + 2\sigma e^{2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2)] \cos(\omega\tau) d\tau \\
&\quad + e^{2\sigma t_0} \int_{-\infty}^0 \frac{\partial(E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2))}{\partial t_0} \cos(\omega\tau) d\tau
\end{aligned} \tag{37}$$

The second partial derivative of $G_R(\omega, t_2, t_0)$ with respect to t_0 is given by

$$\begin{aligned}
\frac{\partial^2 G_R(\omega, t_2, t_0)}{\partial t_0^2} &= 4\sigma^2 e^{-2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2)] \cos(\omega\tau) d\tau \\
&\quad - 4\sigma e^{-2\sigma t_0} \int_{-\infty}^0 \frac{\partial(E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2))}{\partial t_0} \cos(\omega\tau) d\tau \\
&\quad + e^{-2\sigma t_0} \int_{-\infty}^0 \frac{\partial^2(E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2))}{\partial t_0^2} \cos(\omega\tau) d\tau \\
&\quad + 4\sigma^2 e^{2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2)] \cos(\omega\tau) d\tau \\
&\quad + 4\sigma e^{2\sigma t_0} \int_{-\infty}^0 \frac{\partial(E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2))}{\partial t_0} \cos(\omega\tau) d\tau \\
&\quad + e^{2\sigma t_0} \int_{-\infty}^0 \frac{\partial^2(E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2))}{\partial t_0^2} \cos(\omega\tau) d\tau
\end{aligned} \tag{38}$$

We can show that the integrals in Eq. 37 and Eq. 38 converge, as follows. We see that $E'_0(\tau + t_0, t_2) = E_0(\tau + t_0 - t_2) - E_0(\tau + t_0 + t_2)$. Given that $E'_{0n}(\tau, t_2) = E'_0(-\tau, t_2)$, we get $E'_{0n}(\tau - t_0, t_2) = E'_0(-\tau + t_0, -t_2) = E_0(-\tau + t_0 + t_2) - E_0(-\tau + t_0 - t_2) = E_0(\tau - t_0 - t_2) - E_0(\tau - t_0 + t_2)$ given that $E_0(\tau) = E_0(-\tau)$. We see that the first integral in Eq. 38 converges because the term $E'_0(\tau - t_0, t_2)e^{-2\sigma\tau}$ has exponential asymptotic fall-off rate as $|\tau| \rightarrow \infty$ (Appendix B.4).

We consider the integrand in the second integral in Eq. 38 first and use the results in the above paragraph.

$$\frac{\partial(E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2))}{\partial t_0} = \frac{\partial(E_0(\tau + t_0 - t_2)e^{-2\sigma\tau} - E_0(\tau + t_0 + t_2)e^{-2\sigma\tau})}{\partial t_0} + \frac{\partial(E_0(\tau - t_0 - t_2) - E_0(\tau - t_0 + t_2))}{\partial t_0}$$

(39)

We consider the term $E_0(\tau + t_0 + t_2)$ first in Eq. 39 and can show that the integrals converge in Eq. 37 and Eq. 38, as follows.

$$E_0(\tau) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4\tau} - 3\pi n^2 e^{2\tau}] e^{-\pi n^2 e^{2\tau}} e^{\frac{\tau}{2}}$$

$$E_0(\tau + t_2 + t_0) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4\tau} e^{4(t_2+t_0)} - 3\pi n^2 e^{2\tau} e^{2(t_2+t_0)}] e^{-\pi n^2 e^{2\tau} e^{2(t_2+t_0)}} e^{\frac{\tau}{2}} e^{\frac{(t_2+t_0)}{2}}$$

(40)

We can show that $\frac{\partial}{\partial t_0} E_0(\tau + t_2 + t_0) = \frac{\partial}{\partial \tau} E_0(\tau + t_2 + t_0)$ as follows. **(Result A)**

$$\begin{aligned} \frac{\partial}{\partial t_0} E_0(\tau + t_2 + t_0) &= 2 \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2\tau} e^{2(t_2+t_0)}} e^{\frac{\tau}{2}} e^{\frac{(t_2+t_0)}{2}} [8\pi^2 n^4 e^{4\tau} e^{4(t_2+t_0)} - 6\pi n^2 e^{2\tau} e^{2(t_2+t_0)}] \\ &\quad + \left(\frac{1}{2} - 2\pi n^2 e^{2\tau} e^{2(t_2+t_0)}\right) (2\pi^2 n^4 e^{4\tau} e^{4(t_2+t_0)} - 3\pi n^2 e^{2\tau} e^{2(t_2+t_0)})] \\ \frac{\partial}{\partial \tau} E_0(\tau + t_2 + t_0) &= 2 \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2\tau} e^{2(t_2+t_0)}} e^{\frac{\tau}{2}} e^{\frac{(t_2+t_0)}{2}} [8\pi^2 n^4 e^{4\tau} e^{4(t_2+t_0)} - 6\pi n^2 e^{2\tau} e^{2(t_2+t_0)}] \\ &\quad + \left(\frac{1}{2} - 2\pi n^2 e^{2\tau} e^{2(t_2+t_0)}\right) (2\pi^2 n^4 e^{4\tau} e^{4(t_2+t_0)} - 3\pi n^2 e^{2\tau} e^{2(t_2+t_0)})] \end{aligned}$$

(41)

We can replace t_0 by $-t_0$ in Eq. 40 and show that $\frac{\partial}{\partial t_0} E_0(\tau + t_2 - t_0) = -\frac{\partial}{\partial \tau} E_0(\tau + t_2 - t_0)$. **(Result B)**

We can write the term $E_0(\tau + t_0 + t_2)e^{-2\sigma\tau}$ in Eq. 39, corresponding to the term in the second integral in Eq. 38, using Result A, as follows.

$$\begin{aligned} &\int_{-\infty}^0 \frac{\partial(E_0(\tau + t_2 + t_0)e^{-2\sigma\tau})}{\partial t_0} \cos(\omega\tau) d\tau = \int_{-\infty}^0 \frac{\partial(E_0(\tau + t_2 + t_0))}{\partial \tau} e^{-2\sigma\tau} \cos(\omega\tau) d\tau \\ &= \int_{-\infty}^0 \frac{\partial(E_0(\tau + t_2 + t_0)e^{-2\sigma\tau} \cos(\omega\tau))}{\partial \tau} d\tau - \int_{-\infty}^0 E_0(\tau + t_2 + t_0) \frac{\partial(e^{-2\sigma\tau} \cos(\omega\tau))}{\partial \tau} d\tau \\ &= [E_0(\tau + t_2 + t_0)e^{-2\sigma\tau} \cos(\omega\tau)]_{-\infty}^0 + \omega \int_{-\infty}^0 E_0(\tau + t_2 + t_0) e^{-2\sigma\tau} \sin(\omega\tau) d\tau \\ &\quad + 2\sigma \int_{-\infty}^0 E_0(\tau + t_2 + t_0) e^{-2\sigma\tau} \cos(\omega\tau) d\tau \end{aligned}$$

(42)

We see that the integrals in Eq. 42 converge and hence the integral $\int_{-\infty}^0 \frac{\partial(E_0(\tau+t_2+t_0)e^{-2\sigma\tau})}{\partial t_0} \cos(\omega\tau) d\tau$ in Eq. 42 also converges. We set $\sigma = 0$ and see that the integral $\int_{-\infty}^0 \frac{\partial(E_0(\tau+t_2-t_0))}{\partial t_0} \cos(\omega\tau) d\tau$ in Eq. 39 also converges, using Result B.

We set $t_2 = -t_2$ in Eq. 40 to Eq. 42 and see that the integral $\int_{-\infty}^0 \frac{\partial(E_0(\tau+t_0-t_2)e^{-2\sigma\tau})}{\partial t_0} \cos(\omega\tau) d\tau$ in Eq. 39 also converges. We set $\sigma = 0$ and see that the integral $\int_{-\infty}^0 \frac{\partial(E_0(\tau-t_0-t_2))}{\partial t_2} \cos(\omega\tau) d\tau$ in Eq. 39 also converges, using Result D. Hence the second integral in Eq. 38 corresponding to the terms in Eq. 39, also converges.

We can use the above procedure in Eq. 40 to Eq. 42 for the term $\frac{\partial^2(E'_0(\tau+t_0,t_2)e^{-2\sigma\tau} + E'_{0n}(\tau-t_0,t_2))}{\partial t_0^2} = \frac{\partial I(\tau, t_0, t_2)}{\partial t_0}$ where $I(\tau, t_0, t_2) = \frac{\partial(E'_0(\tau+t_0,t_2)e^{-2\sigma\tau} + E'_{0n}(\tau-t_0,t_2))}{\partial t_0}$ in the third integral in Eq. 38 and we can show that it converges, using the procedure used in Eq. 42 twice.

We can see that the last three integrals in Eq. 38 converge, by setting $t_0 = -t_0$ and using Result B. Hence all the integrals in Eq. 37 and Eq. 38 converge.

4.3. *Zero Crossings in $G_R(\omega, t_2, t_0)$ move continuously as a function of t_0 , for a given t_2 .*

We use **Implicit Function Theorem** for the two dimensional case (link and link). Given that $G_R(\omega, t_2, t_0)$ is partially differentiable with respect to ω and t_0 , for a given fixed value of t_2 , with continuous partial derivatives (Section 4.1 and Section 4.2) and given that $G_R(\omega, t_2, t_0) = 0$ at $\omega = \omega_z(t_2, t_0)$ and $\frac{\partial G_R(\omega, t_2, t_0)}{\partial \omega} \neq 0$ at $\omega = \omega_z(t_2, t_0)$ (using Lemma 1), we see that $\omega_z(t_2, t_0)$ is differentiable function of t_0 , for all $|t_0| \leq \infty$.

Hence $\omega_z(t_2, t_0)$ is a **continuous** function of t_0 for all $|t_0| \leq \infty$, for each fixed value of t_2 .

- It is shown in Section 4.5 that $G_R(\omega, t_2, t_0)$ is partially differentiable at least twice with respect to t_2 . We can use the procedure in previous subsections and Implicit Function Theorem and show that $\omega_z(t_2, t_0)$ is a **continuous** function of t_2 , for all $|t_2| \leq \infty$, for **each** fixed value of t_0 .

4.4. *Zero Crossings in $G_R(\omega, t_2, t_0)$ move continuously as a function of t_0 and t_2*

We can use the procedure in previous subsections and show that $\omega_z(t_2, t_0)$ is a **continuous** function of t_2 and t_0 , for all $|t_0| \leq \infty$ and $|t_2| \leq \infty$, using Implicit Function Theorem in R^3 .

We use **Implicit Function Theorem** for the three dimensional case (link). Given that $G_R(\omega, t_2, t_0)$ is partially differentiable with respect to ω and t_0 and t_2 , with continuous partial derivatives (Section 4.1, Section 4.2 and Section 4.5) and given that $G_R(\omega, t_2, t_0) = 0$ at $\omega = \omega_z(t_2, t_0)$ and $\frac{\partial G_R(\omega, t_2, t_0)}{\partial \omega} \neq 0$ at $\omega = \omega_z(t_2, t_0)$ (using Lemma 1), we see that $\omega_z(t_2, t_0)$ is differentiable function of t_0 and t_2 , for all $|t_0| \leq \infty$ and $|t_2| \leq \infty$.

Hence $\omega_z(t_2, t_0)$ is a **continuous** function of t_0 and t_2 , for all $|t_0| \leq \infty$ and $|t_2| \leq \infty$.

469 4.5. $G_R(\omega, t_2, t_0)$ is partially differentiable twice as a function of t_2

470

471 $G_R(\omega, t_2, t_0)$ is partially differentiable at least twice as a function of t_2 and the integrals converge
 472 in Eq. 43 and Eq. 44 shown as follows. The integrands are continuous functions of variables t_2 and
 473 we can interchange the order of partial differentiation and integration in Eq. 43 and Eq. 44.

$$\begin{aligned}
 G_R(\omega, t_2, t_0) &= e^{-2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2)] \cos(\omega\tau) d\tau \\
 &\quad + e^{2\sigma t_0} \int_{-\infty}^0 [E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2)] \cos(\omega\tau) d\tau \\
 \frac{\partial G_R(\omega, t_2, t_0)}{\partial t_2} &= e^{-2\sigma t_0} \int_{-\infty}^0 \frac{\partial(E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2))}{\partial t_2} \cos(\omega\tau) d\tau \\
 &\quad + e^{2\sigma t_0} \int_{-\infty}^0 \frac{\partial(E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2))}{\partial t_2} \cos(\omega\tau) d\tau
 \end{aligned}$$

474 (43)

475 The second partial derivative of $G_R(\omega, t_2, t_0)$ with respect to t_2 is given by

$$\begin{aligned}
 \frac{\partial^2 G_R(\omega, t_2, t_0)}{\partial t_2^2} &= e^{-2\sigma t_0} \int_{-\infty}^0 \frac{\partial^2(E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2))}{\partial t_2^2} \cos(\omega\tau) d\tau \\
 &\quad + e^{2\sigma t_0} \int_{-\infty}^0 \frac{\partial^2(E'_0(\tau - t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau + t_0, t_2))}{\partial t_2^2} \cos(\omega\tau) d\tau
 \end{aligned}$$

476 (44)

477 We use the procedure outlined in Eq. 39 to Eq. 42, with t_0 replaced by t_2 and show that all the
 478 integrals in Eq. 43 and Eq. 44 converge, as follows.

479

480 We see that $E'_0(\tau + t_0, t_2) = E_0(\tau + t_0 - t_2) - E_0(\tau + t_0 + t_2)$ and $E'_{0n}(\tau - t_0, t_2) = E_0(\tau - t_0 -$
 481 $t_2) - E_0(\tau - t_0 + t_2)$. We consider the integrand in the third integral in Eq. 43 first.

$$\begin{aligned}
 \frac{\partial(E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2))}{\partial t_2} &= \frac{\partial(E_0(\tau + t_0 - t_2)e^{-2\sigma\tau} - E_0(\tau + t_0 + t_2)e^{-2\sigma\tau})}{\partial t_2} \\
 &\quad + \frac{\partial(E_0(\tau - t_0 - t_2) - E_0(\tau - t_0 + t_2))}{\partial t_2}
 \end{aligned}$$

482 (45)

483 We consider the term $E_0(\tau + t_0 + t_2)$ first and can show that the integrals converge in Eq. 43
 484 and Eq. 44, as follows. We consider Eq. 40 and show that $\frac{\partial}{\partial t_2} E_0(\tau + t_2 + t_0) = \frac{\partial}{\partial \tau} E_0(\tau + t_2 + t_0)$ as
 485 follows. (**Result C**)

$$\begin{aligned}
\frac{\partial}{\partial t_2} E_0(\tau + t_2 + t_0) &= 2 \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2\tau} e^{2(t_2+t_0)}} e^{\frac{\tau}{2}} e^{\frac{(t_2+t_0)}{2}} [8\pi^2 n^4 e^{4\tau} e^{4(t_2+t_0)} - 6\pi n^2 e^{2\tau} e^{2(t_2+t_0)}] \\
&\quad + \left(\frac{1}{2} - 2\pi n^2 e^{2\tau} e^{2(t_2+t_0)}\right) (2\pi^2 n^4 e^{4\tau} e^{4(t_2+t_0)} - 3\pi n^2 e^{2\tau} e^{2(t_2+t_0)})] \\
\frac{\partial}{\partial \tau} E_0(\tau + t_2 + t_0) &= 2 \sum_{n=1}^{\infty} e^{-\pi n^2 e^{2\tau} e^{2(t_2+t_0)}} e^{\frac{\tau}{2}} e^{\frac{(t_2+t_0)}{2}} [8\pi^2 n^4 e^{4\tau} e^{4(t_2+t_0)} - 6\pi n^2 e^{2\tau} e^{2(t_2+t_0)}] \\
&\quad + \left(\frac{1}{2} - 2\pi n^2 e^{2\tau} e^{2(t_2+t_0)}\right) (2\pi^2 n^4 e^{4\tau} e^{4(t_2+t_0)} - 3\pi n^2 e^{2\tau} e^{2(t_2+t_0)})]
\end{aligned}$$

486

(46)

487 We can replace t_2 by $-t_2$ in Eq. 46 and show that $\frac{\partial}{\partial t_2} E_0(\tau + t_0 - t_2) = -\frac{\partial}{\partial \tau} E_0(\tau + t_0 - t_2)$ (**Result**
488 **D**). We can write the term $E_0(\tau + t_0 + t_2)e^{-2\sigma\tau}$ in Eq. 45, corresponding to the term in the third
489 integral in Eq. 43 as follows.

$$\begin{aligned}
&\int_{-\infty}^0 \frac{\partial(E_0(\tau + t_2 + t_0)e^{-2\sigma\tau})}{\partial t_2} \cos(\omega\tau) d\tau = \int_{-\infty}^0 \frac{\partial(E_0(\tau + t_2 + t_0))}{\partial \tau} e^{-2\sigma\tau} \cos(\omega\tau) d\tau \\
&= \int_{-\infty}^0 \frac{\partial(E_0(\tau + t_2 + t_0)e^{-2\sigma\tau} \cos(\omega\tau))}{\partial \tau} d\tau - \int_{-\infty}^0 E_0(\tau + t_2 + t_0) \frac{\partial(e^{-2\sigma\tau} \cos(\omega\tau))}{\partial \tau} d\tau \\
&= [E_0(\tau + t_2 + t_0)e^{-2\sigma\tau} \cos(\omega\tau)]_{-\infty}^0 + \omega \int_{-\infty}^0 E_0(\tau + t_2 + t_0) e^{-2\sigma\tau} \sin(\omega\tau) d\tau \\
&\quad + 2\sigma \int_{-\infty}^0 E_0(\tau + t_2 + t_0) e^{-2\sigma\tau} \cos(\omega\tau) d\tau
\end{aligned}$$

490

(47)

491 We see that the integrals in Eq. 47 converge and hence the integral $\int_{-\infty}^0 \frac{\partial(E_0(\tau + t_2 + t_0)e^{-2\sigma\tau})}{\partial t_2} \cos(\omega\tau) d\tau$
492 in Eq. 47 also converges. We set $\sigma = 0$ and see that the integral $\int_{-\infty}^0 \frac{\partial(E_0(\tau + t_2 - t_0))}{\partial t_2} \cos(\omega\tau) d\tau$ in Eq. 45
493 also converges, using Result D.

494

495 We set $t_2 = -t_2$ in Eq. 46 to Eq. 47 and see that the integral $\int_{-\infty}^0 \frac{\partial(E_0(\tau + t_0 - t_2)e^{-2\sigma\tau})}{\partial t_2} \cos(\omega\tau) d\tau$ in
496 Eq. 45 also converges. We set $\sigma = 0$ and see that the integral $\int_{-\infty}^0 \frac{\partial(E_0(\tau - t_2 - t_0))}{\partial t_2} \cos(\omega\tau) d\tau$ in Eq. 45
497 also converges, using Result D. Hence the third integral in Eq. 43 corresponding to the terms in
498 Eq. 45, also converges.

499

500 We can use the above procedure in Eq. 46 to Eq. 47 for the term $\frac{\partial^2(E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2))}{\partial t_2^2} =$
501 $\frac{\partial I(\tau, t_0, t_2)}{\partial t_2}$ where $I(\tau, t_0, t_2) = \frac{\partial(E'_0(\tau + t_0, t_2)e^{-2\sigma\tau} + E'_{0n}(\tau - t_0, t_2))}{\partial t_2}$ in the first integral in Eq. 44 and we can
502 show that it converges, using the procedure used in Eq. 47 twice.

503

504 We can see that the second integral in Eq. 44 converge, by setting $t_0 = -t_0$ and using Result D.
505 Hence all the integrals in Eq. 43 and Eq. 44 converge.

506

507 **5. $\omega_z(t_2, t_0)$ is non-zero and finite as $t_0 \rightarrow \infty$**

508

509 In Section 2.1, $\omega_z(t_2, t_0)$ is shown to be **finite** for all $|t_0| < \infty$, for a given value of t_2 . In this
510 section, it is shown that $\omega_z(t_2, t_0)$ remains finite and non-zero, as $t_0 \rightarrow \infty$.

511

512 We note that $g(t, t_2, t_0) = f(t, t_2, t_0)e^{-\sigma t}u(-t) + f(t, t_2, t_0)e^{\sigma t}u(t)$ and $h(t) = [e^{\sigma t}u(-t) + e^{-\sigma t}u(t)]$
513 and $f(t, t_2, t_0) = e^{-2\sigma t_0}f_1(t, t_2, t_0) + e^{2\sigma t_0}f_2(t, t_2, t_0) = e^{-\sigma t_0}E'_p(t + t_0, t_2) + e^{\sigma t_0}E'_p(t - t_0, t_2)$ where
514 $f_1(t, t_2, t_0) = e^{\sigma t_0}E'_p(t + t_0, t_2)$ and $f_2(t, t_2, t_0) = f_1(t, t_2, -t_0) = e^{-\sigma t_0}E'_p(t - t_0, t_2)$, $E'_p(t, t_2) =$
515 $e^{-\sigma t_2}E_p(t - t_2) - e^{\sigma t_2}E_p(t + t_2)$, $E'_0(t, t_2) = E_0(t - t_2) - E_0(t + t_2)$ and $g(t, t_2, t_0)h(t) = f(t, t_2, t_0)$.

$$\begin{aligned} g(t, t_2, t_0) &= u(-t)[e^{-\sigma t_0}E'_p(t + t_0, t_2) + e^{\sigma t_0}E'_p(t - t_0, t_2)]e^{-\sigma t} + u(t)[e^{-\sigma t_0}E'_p(t + t_0, t_2) + e^{\sigma t_0}E'_p(t - t_0, t_2)]e^{\sigma t} \\ &= u(-t)[E'_p(t + t_0, t_2)e^{-\sigma(t+t_0)} + E'_p(t - t_0, t_2)e^{-\sigma(t-t_0)}] \\ &\quad + u(t)[e^{-2\sigma t_0}E'_p(t + t_0, t_2)e^{\sigma(t+t_0)} + e^{2\sigma t_0}E'_p(t - t_0, t_2)e^{\sigma(t-t_0)}] \end{aligned}$$

516

(48)

517 We define $t_0 = Nt_{00}$ where t_{00} is finite and N is a positive integer and as $N \rightarrow \infty$, we see that
518 $t_0 \rightarrow \infty$. We define $g'(t, t_2, t_0) = e^{-2\sigma Nt_{00}}g(t, t_2, t_0)$ whose Fourier transform is given by $G'(\omega, t_2, t_0)$.
519 The scaling factor $e^{-2\sigma Nt_{00}}$ does not affect the location of zeros in $G'(\omega, t_2, t_0)$ whose **zeros** are the
520 **same** as that of $G(\omega, t_2, t_0)$ given by $\omega_z(t_2, t_0)$, for every value of t_0 .

$$\begin{aligned} g'(t, t_2, t_0) &= u(-t)e^{-2\sigma Nt_{00}}[E'_p(t + Nt_{00}, t_2)e^{-\sigma(t+Nt_{00})} + E'_p(t - Nt_{00}, t_2)e^{-\sigma(t-Nt_{00})}] \\ &\quad + u(t)[e^{-4\sigma Nt_{00}}E'_p(t + Nt_{00}, t_2)e^{\sigma(t+Nt_{00})} + E'_p(t - Nt_{00}, t_2)e^{\sigma(t-Nt_{00})}] \end{aligned}$$

521

(49)

522 As we increase N towards ∞ , the first 3 terms in Eq. 49 go to zero, due to the terms $e^{-2\sigma Nt_{00}}$ and
523 $e^{-4\sigma Nt_{00}}$, given that $E'_p(t, t_2)e^{-\sigma t}$ and its t-shifted versions are finite. We use $E'_p(t, t_2) = e^{-\sigma t_2}E_p(t -$
524 $t_2) - e^{\sigma t_2}E_p(t + t_2) = (E_0(t - t_2) - E_0(t + t_2))e^{-\sigma t} = E'_0(t, t_2)e^{-\sigma t}$, where $E'_0(t, t_2) = (E_0(t - t_2) - E_0(t + t_2))$.
525 For the choice of $t_2 = 2t_0 = 2Nt_{00}$, we can write $\lim_{t_0 \rightarrow \infty} g'(t, t_2, t_0)$ as follows.

$$\begin{aligned} \lim_{t_0 \rightarrow \infty} g'(t, t_2, t_0) &= \lim_{N \rightarrow \infty} u(t)[E'_p(t - Nt_{00}, t_2)e^{\sigma(t-Nt_{00})}] = \lim_{N \rightarrow \infty} u(t)[E'_0(t - Nt_{00}, t_2)] \\ &= \lim_{N \rightarrow \infty} u(t)[E_0(t - t_2 - Nt_{00}) - E_0(t + t_2 - Nt_{00})] = \lim_{N \rightarrow \infty} u(t)[E_0(t - 3Nt_{00}) - E_0(t + Nt_{00})] \end{aligned}$$

526

(50)

527 We see that the discontinuity at $t = 0$ represented by $u(t)$ in Eq. 50, has a value given by
528 $\lim_{N \rightarrow \infty} [E_0(-3Nt_{00}) - E_0(Nt_{00})]$ goes to zero, as N towards ∞ and the term $E_0(t + Nt_{00})$ goes to
529 zero and we can write as follows.

$$\lim_{t_0 \rightarrow \infty} g'(t, t_2, t_0) = \lim_{N \rightarrow \infty} E_0(t - 3Nt_{00})$$

530

(51)

We want to find out the location of zeros in the Fourier transform of $\lim_{t_0 \rightarrow \infty} g'(t, t_2, t_0)$ in Eq. 51, given by $\lim_{t_0 \rightarrow \infty} \omega_z(t_2, t_0)$.

We know that the Fourier transform of $E_0(t) = \Phi(t)$ given by $\xi(\frac{1}{2} + i\omega)$ has an infinity of zeros on the critical line.^[2] We consider the first zero to the right of origin given by $\omega = \omega_c$ which is finite. We use the **principle of mathematical induction** and show that the Fourier transform of $\lim_{t_0 \rightarrow \infty} g'(t, t_2, t_0)$ has a zero at the **same** location $\omega = \omega_c$ as follows.

We set $t_1 = 3Nt_{00}$. For $N = 1$, the Fourier transform of $f_1(t) = E_0(t - t_1)$ is given by $F_1(\omega) = E_{0\omega}(\omega)e^{-i\omega t_1}$ which has a zero at the **same** location $\omega = \omega_c$. For $N = 2$, the Fourier transform of $f_2(t) = f_1(t - t_1) = E_0(t - 2t_1)$ is given by $F_2(\omega) = F_1(\omega)e^{-i\omega t_1} = E_{0\omega}(\omega)e^{-i2\omega t_1}$ which has a zero at the **same** location $\omega = \omega_c$.

Inductive Hypothesis: Let $f_N(t) = f_{N-1}(t - t_1) = E_0(t - Nt_1)$. Its Fourier transform is given by $F_N(\omega) = F_{N-1}(\omega)e^{-i\omega t_1} = E_{0\omega}(\omega)e^{-iN\omega t_1}$ which has a zero at the **same** location $\omega = \omega_c$.

Inductive Result: Set $N = N + 1$. We get $f_{N+1}(t) = f_N(t - t_1) = E_0(t - (N + 1)t_1)$. Its Fourier transform is given by $F_{N+1}(\omega) = F_N(\omega)e^{-i\omega t_1} = E_{0\omega}(\omega)e^{-i(N+1)\omega t_1}$ which has a zero at the **same** location $\omega = \omega_c$.

Hence we can use the principle of mathematical induction and get the inductive result that the Fourier transform of $\lim_{t_0 \rightarrow \infty} g'(t, t_2, t_0)$ in Eq. 51 has a zero at the **same** location $\omega = \omega_c$ and hence $\lim_{t_0 \rightarrow \infty} \omega_z(t_2, t_0) = \omega_c$ which is non-zero and finite.

We see that $\omega_z(t_2, t_0)$ is non-zero and finite, as $t_0 \rightarrow \infty$ and hence the order of $\omega_z(t_2, t_0)$ is 1.

6. Strictly decreasing $E_0(t)$ for $t > 0$

Let us consider $E_0(t) = \Phi(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$ whose Fourier Transform is given by the entire function $E_{0\omega}(\omega) = \xi(\frac{1}{2} + i\omega)$. It is known that $\Phi(t)$ is positive for $|t| < \infty$ and its first derivative is negative for $t > 0$ and hence $\Phi(t)$ is a **strictly decreasing** function for $t > 0$. (link). This is shown below.

$$E_0(t) = \Phi(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} = \sum_{n=1}^{\infty} [4\pi^2 n^4 e^{4t} - 6\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$$

$$E_0(t) = \sum_{n=1}^{\infty} 2\pi n^2 e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} [2\pi n^2 e^{4t} - 3e^{2t}]$$

(52)

We show that $X(t) = \frac{E_0(t)}{2}$ is a **strictly decreasing** function for $t > 0$ as follows.

- In Section 6.1, it is shown that the first derivative of $X(t)$, given by $\frac{dX(t)}{dt} < 0$ for $t > t_z$ where $t_z = \frac{1}{2} \log \frac{y_z}{\pi}$ and $y_z = 3.16$.

• In Section 6.2, it is shown that, $\frac{dX(t)}{dt} < 0$ for $0 < t \leq t_z$.

Hence $\frac{dX(t)}{dt} < 0$ for all $t > 0$ and hence $X(t)$ is strictly decreasing for all $t > 0$ and $E_0(t) = 2X(t)$ is **strictly decreasing** for all $t > 0$.

6.1. $\frac{dX(t)}{dt} < 0$ **for** $t > t_z$

We consider $X(t) = \frac{E_0(t)}{2} = \sum_{n=1}^{\infty} \pi n^2 e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} [2\pi n^2 e^{4t} - 3e^{2t}]$ and take the first derivative of $X(t)$ as follows. We note that $E_0(t)$ is an analytic function for $|t| \leq \infty$ and is infinitely differentiable in that interval.

$$\begin{aligned} \frac{dX(t)}{dt} &= \sum_{n=1}^{\infty} \pi n^2 e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} [8\pi n^2 e^{4t} - 6e^{2t} + (2\pi n^2 e^{4t} - 3e^{2t}) (\frac{1}{2} - 2\pi n^2 e^{2t})] \\ \frac{dX(t)}{dt} &= \sum_{n=1}^{\infty} \pi n^2 e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} [8\pi n^2 e^{4t} - 6e^{2t} + (\pi n^2 e^{4t} - \frac{3}{2}e^{2t} - 4\pi^2 n^4 e^{6t} + 6\pi n^2 e^{4t})] \\ \frac{dX(t)}{dt} &= \sum_{n=1}^{\infty} \pi n^2 e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} [-4\pi^2 n^4 e^{6t} + 15\pi n^2 e^{4t} - \frac{15}{2}e^{2t}] \\ \frac{dX(t)}{dt} &= \sum_{n=1}^{\infty} \pi n^2 e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{2t} [-4\pi^2 n^4 e^{4t} + 15\pi n^2 e^{2t} - \frac{15}{2}] \end{aligned}$$

(53)

We substitute $y = \pi e^{2t}$ in Eq. 53 and define $A(y)$ such that $\frac{dX(t)}{dt} = \pi e^{\frac{5t}{2}} A(y)$. [8]

$$A(y) = \sum_{n=1}^{\infty} n^2 e^{-n^2 y} [-4n^4 y^2 + 15n^2 y - \frac{15}{2}]$$

(54)

We see that $A(y) = 0$ at $y = \pi$, given that $\frac{dX(t)}{dt} = 0$ at $t = 0$, because $X(t)$ is an even function of variable t . The quadratic expression $B(y, n) = (-4n^4 y^2 + 15n^2 y - \frac{15}{2})$ in Eq. 54 has roots at $y = \frac{-15n^2 \pm \sqrt{225n^4 - 120n^4}}{-8n^4} = \frac{(15 \pm \sqrt{105})}{8n^2}$. We see that the second derivative of $B(y, n)$ is negative for all y and n and hence $B(y, n)$ is a concave down function for each n , which reaches a maximum at $y = \frac{15}{8n^2}$ and given the dominant term $-4n^4 y^2$ in Eq. 54, we see that $B(y, n) < 0$, for $y > \frac{(15 + \sqrt{105})}{8} > 3.16 = y_z$, for $n \geq 1$ and hence $A(y) < 0$ for $y > y_z$. Hence $\frac{dX(t)}{dt} < 0$ for $t > \frac{1}{2} \log \frac{y_z}{\pi} = t_z$ (**Result 1**).

We want to show that $\frac{dX(t)}{dt} < 0$ for $0 < t \leq t_z$. It suffices to show that $\frac{dA(y)}{dy} < 0$ for $\pi \leq y \leq 3.16$ and hence $A(y) < 0$ for $\pi < y \leq 3.16$.

6.2. $\frac{dX(t)}{dt} < 0$ **for** $0 < t \leq t_z$

It is shown in this section that $\frac{dA(y)}{dy} < 0$ for $\pi \leq y \leq 3.16$ and hence $A(y) < 0$ for $\pi < y \leq 3.16$ [8]. We take the derivative of $A(y)$ in Eq. 54 and take the factor n^2 out of the brackets, as follows.

$$\begin{aligned}\frac{dA(y)}{dy} &= \sum_{n=1}^{\infty} n^2 e^{-n^2 y} [-8n^4 y + 15n^2 + (-4n^4 y^2 + 15n^2 y - \frac{15}{2})(-n^2)] \\ \frac{dA(y)}{dy} &= \sum_{n=1}^{\infty} n^4 e^{-n^2 y} [-8n^2 y + 15 + 4n^4 y^2 - 15n^2 y + \frac{15}{2}] = \sum_{n=1}^{\infty} n^4 e^{-n^2 y} [4n^4 y^2 - 23n^2 y + \frac{45}{2}]\end{aligned}$$

(55)

We examine the term $C(y, n) = n^4 e^{-n^2 y} (4n^4 y^2 - 23n^2 y + \frac{45}{2})$ in Eq. 55 in the interval $\pi \leq y \leq 3.16$ and show that $\frac{dA(y)}{dy} = C(y, 1) + \sum_{n=2}^{\infty} C(y, n) < 0$, as follows.

For $n = 1$, we see that $C(y, 1) = e^{-y} (4y^2 - 23y + \frac{45}{2}) < 0$ in the interval $\pi \leq y \leq 3.16$. Given that $3.16 < 4$ and $3.16^2 < 10$ and $\pi > 3$ and $(4y^2 - 23y + \frac{45}{2}) < 0$ in the interval $\pi \leq y \leq 3.16$, we see that $C(y, 1) < e^{-4} (4 * 10 - 23 * 3 + \frac{45}{2}) < e^{-4} (40 - 69 + 23) = -6e^{-4} = C_{max}(1)$ where $C_{max}(1)$ is the maximum value of $C(y, 1)$ in the interval $\pi \leq y \leq 3.16$.

$$C(y, 1) = e^{-y} (4y^2 - 23y + \frac{45}{2}) < -6e^{-4}, \quad \pi \leq y \leq 3.16$$

(56)

For $n > 1$, in the interval $\pi \leq y \leq 3.16$, we can write $C(y, n)$ as follows, given that $-23n^2 y + \frac{45}{2} < 0$ and $\pi > 3$ and $3.16^2 < 10$.

$$C(y, n) = n^4 e^{-n^2 y} (4n^4 y^2 - 23n^2 y + \frac{45}{2}) < n^4 e^{-\pi n^2} (4n^4 (3.16)^2) < 40n^8 e^{-\pi n^2} < 40n^8 e^{-3n^2}$$

(57)

We want to show that $\frac{dA(y)}{dy} = C(y, 1) + \sum_{n=2}^{\infty} C(y, n) < 0$ in the interval $\pi \leq y \leq 3.16$. Using Eq. 56 and Eq. 57, we write

$$\begin{aligned}\frac{dA(y)}{dy} &= C(y, 1) + \sum_{n=2}^{\infty} C(y, n) < -6e^{-4} + \sum_{n=2}^{\infty} 40n^8 e^{-3n^2} \\ e^4 \frac{dA(y)}{dy} &< -6 + \sum_{n=2}^{\infty} 40n^8 e^{4-3n^2}\end{aligned}$$

(58)

We want to show that $e^4 \frac{dA(y)}{dy} < 0$ in the interval $\pi \leq y \leq 3.16$. We compute $\log(n^8 e^{4-3n^2})$ as follows. We note that $f(x) = \log x$ is a concave down function whose second derivative given by $-\frac{1}{x^2} < 0$ for $|x| < \infty$ and we can write $f(x) = \log x \leq f(x_0) + f'(x_0)(x - x_0)$ using its tangent line at $x = x_0$. We set $x = n$ and $x_0 = 2$ below.

$$\log(n^8 e^{4-3n^2}) = 8 \log n + (4 - 3n^2) \leq 8(\log 2 + \frac{1}{2}(n - 2)) + (4 - 3n^2)$$

$$\log(n^8 e^{4-3n^2}) \leq 8 \log 2 + 4n - 4 - 3n^2$$

(59)

614 We note that $g(x) = 4x - 4 - 3x^2$ in Eq. 59 is a concave down function whose second derivative
 615 given by $-6 < 0$ for all x and we can write $g(x) \leq g(x_0) + g'(x_0)(x - x_0)$ using its tangent line at
 616 $x = x_0$. We set $x = n$ and $x_0 = 2$ and write Eq. 59 as follows.

$$\log(n^8 e^{4-3n^2}) \leq 8 \log 2 - 8 - 8(n-2) \leq 8 \log 2 + 8(1-n)$$

$$n^8 e^{4-3n^2} \leq 2^8 e^{8(1-n)}$$

(60)

618 We substitute the result in Eq. 60 in Eq. 58 as follows.

$$e^4 \frac{dA(y)}{dy} < -6 + 40 * 2^8 \sum_{n=2}^{\infty} e^{8(1-n)}$$

$$e^4 \frac{dA(y)}{dy} < -6 + 40 * 2^8 * e^8 \sum_{n=2}^{\infty} e^{-8n}$$

$$e^4 \frac{dA(y)}{dy} < -6 + 40 * 2^8 * e^8 \frac{e^{-8*2}}{1 - e^{-8}}$$

$$e^4 \frac{dA(y)}{dy} < -6 + 40 * 2^8 * \frac{e^{-8}}{1 - e^{-8}}$$

$$e^4 \frac{dA(y)}{dy} < -6 + 40 * 2^8 * \frac{1}{e^8 - 1}$$

(61)

620 We multiply Eq. 61 by $\frac{(e^8-1)}{6}$ and write as follows.

$$e^4 \frac{dA(y)}{dy} \frac{(e^8 - 1)}{6} < -e^8 + 1 + 40 * \frac{256}{6} = -1273.3$$

(62)

622 We see that $e^4 \frac{dA(y)}{dy} \frac{(e^8-1)}{6} < 0$ in Eq. 62 and hence $\frac{dA(y)}{dy} < 0$, in the interval $\pi \leq y \leq 3.16$. Given
 623 that $A(y) = 0$ at $y = \pi$, we see that $A(y) < 0$ in Eq. 54, for $\pi < y \leq 3.16$ and $\frac{dX(t)}{dt} = \pi e^{\frac{5t}{2}} A(y) < 0$
 624 in the interval $0 < t \leq t_z$. (**Result 2**)

626 In Section 6.1, it is shown that $\frac{dX(t)}{dt} < 0$ for $t > t_z$ (from Result 1). In this section, we have shown
 627 that $\frac{dX(t)}{dt} < 0$ for $0 < t \leq t_z$. Hence $\frac{dX(t)}{dt} < 0$ for all $t > 0$.

629 Hence $E_0(t) = 2X(t)$ is a **strictly decreasing function** for $t > 0$.

630 **6.3. Result** $E_0(t - t_{2c}) - E_0(t + t_{2c}) > 0$

631

632 It is shown in Section 6 that $E_0(t)$ is **strictly decreasing** for $t > 0$. In this section, it is shown
633 that $E_0(t - t_{2c}) - E_0(t + t_{2c}) > 0$, for $0 < t < t_{0c}$ and $t_{2c} = 2t_{0c}$ in Eq. 34 .

634

635 Given that $E_0(t)$ is a **strictly decreasing** function for $t > 0$ and $E_0(t)$ is an **even** function of
636 variable t , and $t_{2c} = 2t_{0c}$, we see that, in the interval $0 < t < t_{0c}$, $E_0(t + t_{2c}) = E_0(t + 2t_{0c})$ ranges
637 from $E_0(2t_{0c})$ to $E_0(3t_{0c})$, which is **less than** $E_0(t - t_{2c}) = E_0(t - 2t_{0c})$ which ranges from $E_0(-2t_{0c})$
638 to $E_0(-t_{0c})$ respectively. Hence we see that $E_0(t - t_{2c}) > E_0(t + t_{2c})$, in the interval $0 < t < t_{0c}$. At
639 $t = 0$, $E_0(t - t_{2c}) = E_0(t + t_{2c})$. At $t = t_{0c}$, $E_0(t - t_{2c}) > E_0(t + t_{2c})$ because $E_0(-t_{0c}) > E_0(3t_{0c})$.

640

641 Hence $E_0(t - t_{2c}) - E_0(t + t_{2c}) > 0$ for $0 < t < t_{0c}$ in Eq. 34 , for $t_{0c} > 0$.

642 7. Hurwitz Zeta Function and related functions

643

644 We can show that the new method is **not** applicable to Hurwitz zeta function and related zeta
645 functions and **does not** contradict the existence of their non-trivial zeros away from the critical line
646 with real part of $s = \frac{1}{2}$. The new method requires the **symmetry** relation $\xi(s) = \xi(1 - s)$ and hence
647 $\xi(\frac{1}{2} + i\omega) = \xi(\frac{1}{2} - i\omega)$ when evaluated at the critical line $s = \frac{1}{2} + i\omega$. This means $\xi(\frac{1}{2} + i\omega) = E_{0\omega}(\omega) =$
648 $E_{0\omega}(-\omega)$ and $E_0(t) = E_0(-t)$ where $E_0(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$ and this condition
649 is satisfied for Riemann's Zeta function.

650

651 It is **not** known that Hurwitz Zeta Function given by $\zeta(s, a) = \sum_{m=0}^{\infty} \frac{1}{(m+a)^s}$ satisfies a symmetry
652 relation similar to $\xi(s) = \xi(1 - s)$ where $\xi(s)$ is an entire function, for $a \neq 1$ and hence the condition
653 $E_0(t) = E_0(-t)$ is **not** known to be satisfied^[6]. Hence the new method is **not** applicable to Hurwitz
654 zeta function and **does not** contradict the existence of their non-trivial zeros away from the critical
655 line.

656

657 Dirichlet L-functions satisfy a symmetry relation $\xi(s, \chi) = \epsilon(\chi) \xi(1 - s, \bar{\chi})$ ^[7] which does **not**
658 translate to $E_0(t) = E_0(-t)$ required by the new method and hence this proof is **not** applicable to
659 them.

660

661 We know that $\zeta(s) = \sum_{m=1}^{\infty} \frac{1}{m^s}$ diverges for real part of $s \leq 1$. Hence we derive a convergent and

662 entire function $\xi(s)$ using the well known theorem $F(x) = 1 + 2 \sum_{n=1}^{\infty} e^{-\pi n^2 x} = \frac{1}{\sqrt{x}} (1 + 2 \sum_{n=1}^{\infty} e^{-\pi \frac{n^2}{x}})$,

663 where $x > 0$ is real ^[4] and then derive $E_0(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$ (link). In the case
664 of **Hurwitz zeta** function and **other zeta functions** with non-trivial zeros away from the critical
665 line, it is **not** known if a corresponding relation similar to $F(x)$ exists, which enables derivation of
666 a convergent and entire function $\xi(s)$ and results in $E_0(t)$ as a Fourier transformable, real, even and
667 analytic function. Hence the new method presented in this paper is **not** applicable to Hurwitz zeta
668 function and related zeta functions.

669

670 The proof of Riemann Hypothesis presented in this paper is **only** for the specific case of Rie-
671 mann's Zeta function and **only** for the **critical strip** $0 \leq |\sigma| < \frac{1}{2}$. This proof requires both $E_p(t)$
672 and $E_{p\omega}(\omega)$ to be Fourier transformable where $E_p(t) = E_0(t) e^{-\sigma t}$ is a real analytic function and uses

the fact that $E_0(t)$ is an **even** function which is **strictly decreasing** function for $t > 0$ (Section 6). These conditions may **not** be satisfied for many other functions including those which have non-trivial zeros away from the critical line and hence the new method may **not** be applicable to such functions.

If the proof presented in this paper is internally consistent and does not have mistakes and gaps, then it should be considered correct, **regardless** of whether it contradicts any previously known external theorems, because it is possible that those previously known external theorems may be incorrect.

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Appendix A. Derivation of $E_p(t)$

Let us start with Riemann's Xi Function $\xi(s)$ evaluated at $s = \frac{1}{2} + i\omega$ given by $\xi(\frac{1}{2} + i\omega) = E_{0\omega}(\omega)$. Its inverse Fourier Transform is given by $E_0(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{0\omega}(\omega) e^{i\omega t} d\omega = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}}$ (link). This is re-derived in link.

We will show in this section that the inverse Fourier Transform of the function $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$, is given by $E_p(t) = E_0(t) e^{-\sigma t}$ where $0 \leq |\sigma| < \frac{1}{2}$ is real.

$$\begin{aligned} \xi(\frac{1}{2} + \sigma + i\omega) &= \xi(\frac{1}{2} + i(\omega - i\sigma)) = E_{p\omega}(\omega) = E_{0\omega}(\omega - i\sigma) \\ E_p(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{p\omega}(\omega) e^{i\omega t} d\omega = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{0\omega}(\omega - i\sigma) e^{i\omega t} d\omega \end{aligned}$$

(A.1)

We substitute $\omega' = \omega - i\sigma$ in Eq. A.1 as follows.

$$E_p(t) = e^{-\sigma t} \frac{1}{2\pi} \int_{-\infty - i\sigma}^{\infty - i\sigma} E_{0\omega}(\omega') e^{i\omega' t} d\omega'$$

(A.2)

We can evaluate the above integral in the complex plane using contour integration, substituting $\omega' = z = x + iy$ and we use a rectangular contour comprised of C_1 along the line $x = [-\infty, \infty]$, C_2 along the line $y = [\infty, \infty - i\sigma]$, C_3 along the line $x = [\infty - i\sigma, -\infty - i\sigma]$ and then C_4 along the line $y = [-\infty - i\sigma, -\infty]$. We can see that $E_{0\omega}(z) = \xi(\frac{1}{2} + iz)$ has no singularities in the region bounded by the contour because $\xi(\frac{1}{2} + iz)$ is an entire function in the Z -plane.

In **Appendix B.1**, we show that $\int_{-\infty}^{\infty} |E_p(t)| dt$ is finite and $E_p(t) = E_0(t)e^{-\sigma t}$ is an absolutely integrable function, for $0 \leq |\sigma| < \frac{1}{2}$.

We use the fact that $E_{0\omega}(z) = \xi(\frac{1}{2} + iz) = \xi(\frac{1}{2} - y + ix) = \int_{-\infty}^{\infty} E_0(t)e^{-izt} dt = \int_{-\infty}^{\infty} E_0(t)e^{yt}e^{-ixt} dt$, **goes to zero** as $x \rightarrow \pm\infty$ when $-\sigma \leq y \leq 0$, as per Riemann-Lebesgue Lemma (link), because $E_0(t)e^{yt}$ is a absolutely integrable function in the interval $-\infty \leq t \leq \infty$. Hence the integral in Eq. A.2 **vanishes** along the contours C_2 and C_4 . Using Cauchy's Integral theroem, we can write Eq. A.2 as follows.

$$E_p(t) = e^{-\sigma t} \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{0\omega}(\omega') e^{i\omega' t} d\omega'$$

$$E_p(t) = E_0(t)e^{-\sigma t} = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} e^{-\sigma t}$$

718

(A.3)

Thus we have arrived at the desired result $E_p(t) = E_0(t)e^{-\sigma t}$.

Appendix B. Properties of Fourier Transforms

721

Appendix B.1. $E_p(t), h(t), g(t, t_2, t_0)$ are absolutely integrable functions and their Fourier Transforms are finite.

724

The inverse Fourier Transform of the function $E_{p\omega}(\omega) = \xi(\frac{1}{2} + \sigma + i\omega)$ is given by $E_p(t) = E_0(t)e^{-\sigma t} = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_{p\omega}(\omega) e^{i\omega t} d\omega$. We see that $E_0(t) = 2 \sum_{n=1}^{\infty} [2\pi^2 n^4 e^{4t} - 3\pi n^2 e^{2t}] e^{-\pi n^2 e^{2t}} e^{\frac{t}{2}} > 0$ for all $0 \leq t < \infty$. Given that $E_0(t) = E_0(-t)$, we see that $E_0(t) > 0$ and $E_p(t) = E_0(t)e^{-\sigma t} > 0$ for all $-\infty < t < \infty$.

729

As $t \rightarrow \infty$, $E_p(t)$ goes to zero, due to the term $e^{-\pi n^2 e^{2t}}$. As $t \rightarrow -\infty$, $E_p(t)$ goes to zero, because for every value of n , the term $e^{-\pi n^2 e^{2t}} e^{\frac{5t}{2}} e^{-\sigma t}$ goes to zero, for $0 \leq |\sigma| < \frac{1}{2}$. Hence $E_p(t) = E_0(t)e^{-\sigma t}$ goes to zero, at $t \rightarrow \pm\infty$ and we showed that $E_p(t) > 0$ for all $-\infty < t < \infty$. Hence $E_{p\omega}(\omega) = \int_{-\infty}^{\infty} E_p(t) e^{-i\omega t} dt$, evaluated at $\omega = 0$ **cannot** be zero. Hence $E_{p\omega}(\omega)$ **does not have a zero** at $\omega = 0$ and hence $\omega_0 \neq 0$.

735

Given that $\xi(\frac{1}{2} + \sigma + i\omega) = E_{p\omega}(\omega)$ is an entire function in the whole of s -plane, it is finite for $|\omega| \leq \infty$ and also for $\omega = 0$. Hence $\int_{-\infty}^{\infty} E_p(t) dt$ is finite. We see that $E_p(t) \geq 0$ for all $|t| \leq \infty$. Hence we can write $\int_{-\infty}^{\infty} |E_p(t)| dt$ is finite and $E_p(t)$ is an absolutely **integrable function** and its

739 Fourier transform $E_{p\omega}(\omega)$ goes to zero as $\omega \rightarrow \pm\infty$, as per Riemann Lebesgue Lemma (link).

740

741 Let us consider a new function $g(t, t_2, t_0) = f(t, t_2, t_0)e^{-\sigma t}u(-t) + f(t, t_2, t_0)e^{\sigma t}u(t)$ where $g(t, t_2, t_0)$
 742 is a real function of variable t and $u(t)$ is Heaviside unit step function and $0 < \sigma < \frac{1}{2}$ and
 743 $f(t, t_2, t_0) = e^{-2\sigma t_0}f_1(t, t_2, t_0) + e^{2\sigma t_0}f_2(t, t_2, t_0)$ where $f_1(t, t_2, t_0) = e^{\sigma t_0}E'_p(t + t_0, t_2)$ and $f_2(t, t_2, t_0) =$
 744 $e^{-\sigma t_0}E'_p(t - t_0, t_2)$ and $E'_p(t, t_2) = e^{-\sigma t_2}E_p(t - t_2) - e^{\sigma t_2}E_p(t + t_2)$. We can see that $g(t, t_2, t_0)h(t) =$
 745 $f(t, t_2, t_0)$ where $h(t) = e^{\sigma t}u(-t) + e^{-\sigma t}u(t)$.

746

747 We can see that $h(t) = e^{\sigma t}u(-t) + e^{-\sigma t}u(t)$ is an absolutely **integrable function** because
 748 $\int_{-\infty}^{\infty} |h(t)|dt = \int_{-\infty}^{\infty} h(t)dt = [\int_{-\infty}^{\infty} h(t)e^{-i\omega t}dt]_{\omega=0} = [\frac{1}{\sigma - i\omega} + \frac{1}{\sigma + i\omega}]_{\omega=0} = \frac{2}{\sigma}$, is finite for $0 < \sigma < \frac{1}{2}$
 749 and its Fourier transform $H(\omega)$ goes to zero as $\omega \rightarrow \pm\infty$, as per Riemann Lebesgue Lemma (link).

750

751 It is shown in Appendix B.4 that $E_0(t)$ and $E_0(t)e^{-2\sigma t}$ have fall-off rates **at least** $\frac{1}{t^3}$ as
 752 $|t| \rightarrow \infty$ and hence are absolutely **integrable** functions and the integrals $\int_{-\infty}^{\infty} |E_0(t)|dt < \infty$ and
 753 $\int_{-\infty}^{\infty} |E_0(t)e^{-2\sigma t}|dt < \infty$. Hence $g(t, t_2, t_0) = f(t, t_2, t_0)e^{-\sigma t}u(-t) + f(t, t_2, t_0)e^{\sigma t}u(t)$ is an absolutely
 754 **integrable function** and $\int_{-\infty}^{\infty} |g(t, t_2, t_0)|dt = \int_{-\infty}^{\infty} g(t, t_2, t_0)dt$ is finite and its Fourier transform
 755 $G(\omega, t_2, t_0)$ goes to zero as $\omega \rightarrow \pm\infty$, as per Riemann Lebesgue Lemma (link).

756 Appendix B.2. Convolution integral convergence

757

758 Let us consider $h(t) = e^{\sigma t}u(-t) + e^{-\sigma t}u(t)$ whose **first derivative is discontinuous** at $t = 0$.
 759 The second derivative of $h(t)$ given by $h_2(t)$ has a Dirac delta function $A_0\delta(t)$ where $A_0 = -2\sigma$ and
 760 its Fourier transform $H_2(\omega)$ has a constant term A_0 , corresponding to the Dirac delta function.

761

762 This means $h(t)$ is obtained by integrating $h_2(t)$ twice and its Fourier transform $H(\omega)$ has a term
 763 $-\frac{A_0}{\omega^2}$ (link) and has a **fall off rate** of $\frac{1}{\omega^2}$ as $|\omega| \rightarrow \infty$ and $\int_{-\infty}^{\infty} H(\omega)d\omega$ converges.

764

765 Let us consider the function $g(t, t_2, t_0) = f(t, t_2, t_0)e^{-\sigma t}u(-t) + f(t, t_2, t_0)e^{\sigma t}u(t)$. We can see that
 766 $G(\omega, t_2, t_0), H(\omega)$ have **fall-off rate** of $\frac{1}{\omega^2}$ as $|\omega| \rightarrow \infty$ because the **first derivatives** of $g(t, t_2, t_0), h(t)$
 767 are **discontinuous** at $t = 0$. Also, $h(t), g(t, t_2, t_0)$ are absolutely integrable functions and their Fourier
 768 Transforms are finite. Hence the convolution integral below converges to a finite value for $|\omega| \leq \infty$.

$$F(\omega, t_2, t_0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega', t_2, t_0)H(\omega - \omega')d\omega' = \frac{1}{2\pi} [G(\omega, t_2, t_0) * H(\omega)] \quad (\text{B.1})$$

769 Appendix B.3. Fall off rate of Fourier Transform of functions

770

771 Let us consider a real Fourier transformable function $P(t) = P_+(t)u(t) + P_-(t)u(-t)$ whose
 772 $(N - 1)^{th}$ **derivative is discontinuous** at $t = 0$. The $(N)^{th}$ derivative of $P(t)$ given by $P_N(t)$
 773 has a Dirac delta function $A_0\delta(t)$ where $A_0 = [\frac{d^{N-1}P_+(t)}{dt^{N-1}} - \frac{d^{N-1}P_-(t)}{dt^{N-1}}]_{t=0}$ and its Fourier transform
 774 $P_N(\omega)$ has a constant term A_0 , corresponding to the Dirac delta function.

775

776 This means $P(t)$ is obtained by integrating $P_N(t)$, N times and its Fourier transform $P(\omega)$ has a
 777 term $\frac{A_0}{(i\omega)^N}$ (link) and has a **fall off rate** of $\frac{1}{\omega^N}$ as $|\omega| \rightarrow \infty$.

778

779 We have shown that if the $(N - 1)^{th}$ **derivative** of the function $P(t)$ is **discontinuous** at $t = 0$
 780 then its Fourier transform $P(\omega)$ has a **fall-off rate** of $\frac{1}{\omega^N}$ as $|\omega| \rightarrow \infty$.

781 *Appendix B.4. Payley-Weiner theorem and Exponential Fall off rate of analytic func-*
782 *tions.*

784 We know that Payley-Weiner theorem relates analytic functions and exponential decay rate of
785 their Fourier transforms (link). Using similar arguments, we will show that the functions $E_0(t)$, $E_p(t)$
786 and $x(t) = E_0(t)e^{-2\sigma t}$ have fall-off rates **at least** $\frac{1}{t^3}$ as $|t| \rightarrow \infty$ for $0 < \sigma < \frac{1}{2}$.

787
788 We know that the order of Riemann's Xi function $\xi(\frac{1}{2} + i\omega) = E_{0\omega}(\omega) = \Xi(\omega)$ is given by
789 $O(\omega^A e^{-\frac{|\omega|\pi}{4}})$ where A is a constant^[3] (link). Hence both $E_{0\omega}(\omega)$ and $E_{p\omega}(\omega) = \xi(\frac{1}{2} + \sigma + i\omega) =$
790 $E_{0\omega}(\omega - i\sigma)$ have **exponential fall-off** rate $O(\omega^A e^{-\frac{|\omega|\pi}{4}})$ as $|\omega| \rightarrow \infty$ and they are absolutely inte-
791 grable and Fourier transformable, given that they are derived from an entire function $\xi(s)$.

792
793 Given that $\xi(s)$ is an entire function in the s-plane, we see that $E_{0\omega}(\omega)$ and $E_{p\omega}(\omega)$ are **analytic**
794 functions which are infinitely differentiable which produce no discontinuities for all $|\omega| \leq \infty$ and
795 $0 < \sigma < \frac{1}{2}$. Hence their respective **inverse Fourier transforms** $E_0(t)$, $E_p(t)$ have fall-off rates faster
796 than $\frac{1}{t^M}$ as $M \rightarrow \infty$, as $|t| \rightarrow \infty$ (Appendix B.3) and hence it should have **exponential fall-off**
797 rates as $|t| \rightarrow \infty$.

798
799 We can use similar arguments to show that $x(t) = E_0(t)e^{-2\sigma t}$ has a fall-off rate of **at least** $\frac{1}{t^3}$ as
800 $|t| \rightarrow \infty$, because its Fourier transform is an **analytic** function for all $|\omega| \leq \infty$ with **exponential**
801 **fall-off** rate $O(\omega^A e^{-\frac{|\omega|\pi}{4}})$ as $|\omega| \rightarrow \infty$.