

# 1 Out of Time Order Correlator of $H = xp$ model

The Riemann hypothesis states that non-trivial zeros of the classical zeta function have real part equal to  $1/2$ . The classical zeta function defined by

$$\zeta(s) = \sum_{n=1}^{\infty} n^{-s} \quad (1)$$

for  $\text{Re } s > 1$ . By the fundamental theorem of arithmetic, which is also equivalent to the Euler product over primes

$$\zeta(s) = \prod_p (1 - p^{-s})^{-1} \quad (2)$$

where  $p$  are all the prime numbers.

Zeros of Riemann zeta function are two different types. Trivial zeros of zeta / Riemann zeta function occurs at all negative integers (for  $s = -2, -4, -6, \dots$ ). For complex  $s (= \sigma + it)$  (with real part between zero and one), zeta function becomes nontrivial ones. And the Riemann hypothesis is for  $s = \frac{1}{2} - it$  zeta function becomes zero  $\zeta(\frac{1}{2} - it) = 0$ . Hilbert-Pólya conjecture suggests that the imaginary parts of the nontrivial zeros are the eigenvalues of a self-adjoint hamiltonian operator  $\hat{H}$ . It is also one of the approach to proving the Riemann hypothesis. Berry-Keating conjectured that the hamiltonian operator of the Hilbert-Pólya conjecture should take the form[1]

$$\hat{H}_{BK} = \frac{1}{2}(\hat{x}\hat{p} + \hat{p}\hat{x}) \quad (3)$$

Here  $x$  and  $p$  are position and momentum operators. This 1d classical Hamiltonian ( $H = xp$ ) related to the Riemann zeros.[1] Berry proposed the Quantum Chaos conjecture, according to which the Riemann zeros are the spectrum of a Hamiltonian obtained by quantization of a classical chaotic hamiltonian, whose periodic orbits are labeled by the prime numbers. Connes took the adelic approach to introduce  $H = xp$  [2]. He showed that using different semiclassical regularization, Riemann zeros appear as missing spectral lines in a continuum.

Now we look into the Berry-Keating and Connes semiclassical approaches to  $H = xp$

## 2 Semiclassical approach

The classical Berry-Keating-Connes (BKC) Hamiltonian is [1, 2]

$$H_0^{cl} = xp \quad (4)$$

which has hyperbolic trajectories

$$x(t) = x_0 e^t \quad p(t) = p_0 e^{-t} \quad (5)$$

So the dynamics is unbounded. There is a continuous spectrum as the quantum level. Berry-Keating and Connes introduced two different types of regularizations and counted the semiclassical states. Berry-Keating introduced Plank cell in a phase space:  $|x| > l_x$  and  $|p| > l_p$ , with  $l_x l_p = 2\pi\hbar$ . Connes choosed  $|x| < \Lambda$  and  $|p| < \Lambda$ , where  $\Lambda$  is a cutoff. German Sierra introduced us a third regularization,  $l_x < x < \Lambda$  combines the Berry-Keating and Connes regularization position, not taking assumptions for the momenta p.

Semiclassical states number  $\mathcal{N}(E)$  with an enery between 0 to E is given by

$$\begin{aligned} \mathcal{N}(E) &= \frac{A}{2\pi\hbar} \\ &= \frac{A}{h} \end{aligned} \quad (6)$$

Where A is the area of the allowed phase space region below the curve  $E = xp$ . So the the number of semiclassical states will be for Berry-Keating

regularization

$$\begin{aligned}
\mathcal{N}_{BK}(E) &= \frac{1}{h} \int_{l_x}^{\frac{E}{l_p}} dx \int_{l_p}^{\frac{E}{x}} dp + \dots\dots \\
&= \frac{1}{h} \left[ \int_{l_x}^{\frac{E}{l_p}} dx \left[ \frac{E}{x} - l_p \right] \right] \\
&= \frac{1}{h} \left[ E [\ln x]_{l_x}^{\frac{E}{l_p}} - l_p \left[ \frac{E}{l_p} - l_x \right] \right] \\
&= \frac{1}{h} \left[ E \ln \frac{E}{l_x l_p} - E - l_x l_p \right] \\
&= \frac{1}{h} \left[ E \ln \frac{E}{l_x l_p} - E - h \right] \\
&= \frac{E}{h} \left[ \ln \frac{E}{l_x l_p} - 1 \right] + 1 \\
&= \frac{E}{2\pi\hbar} \left[ \ln \frac{E}{2\pi\hbar} - 1 \right] + 1
\end{aligned} \tag{7}$$

adding Maslov phase  $(-\frac{1}{8})$  and  $\hbar = 1$ , it becomes

$$\mathcal{N}_{BK}(E) = \frac{E}{2\pi} \left[ \ln \frac{E}{2\pi} - 1 \right] + \frac{7}{8} + \dots\dots, \quad E \gg 1 \tag{8}$$

The exact formula for the Riemann zeros,  $\mathcal{N}_R(E)$  contains a fluctuation term which depends on the zeta function.[3]

$$\begin{aligned}
\mathcal{N}_R(E) &= \langle \mathcal{N} \rangle + \mathcal{N}_{fl}(E) \\
\langle \mathcal{N}(E) \rangle &= \frac{1}{\pi} \text{Im} \ln \left[ \Gamma \frac{1}{2} \left( \frac{1}{2} - iE \right) \right] - \frac{E}{2\pi} \ln \pi + 1 \\
\mathcal{N}_{fl}(E) &= \frac{1}{\pi} \text{Im} \ln \left[ \zeta \left( \frac{1}{2} - iE \right) \right]
\end{aligned} \tag{9}$$

Bery-Keatin took this result and analogies between formulae in Number Theory and Quantum Chaos, they pointed the quantization of classical chaotic Hamiltonian give rise to the zeros as point like spectra.[1, 4] Whereas Connes found the number of semiclassical states diverges in the limit where the cutoff  $\Lambda$  goes to infinity, and that there is a finite size correction given by minus the average position of the Riemann zeros.

$$\begin{aligned}
\mathcal{N}_c(E) &= \frac{1}{h} \left[ 2E - \left( \frac{E}{\Lambda} \right)^2 + \int_{\frac{E}{\Lambda}}^{\Lambda} dx \int_{\frac{E}{x}}^{\frac{E}{\Lambda}} dp \right] \\
&= \frac{1}{h} \left[ 2E - \left( \frac{E}{\Lambda} \right)^2 + \int_{\frac{E}{\Lambda}}^{\Lambda} dx \left[ \frac{E}{x} - \frac{E}{\Lambda} \right] \right] \\
&= \frac{1}{h} \left[ 2E - \left( \frac{E}{\Lambda} \right)^2 + E [\ln x]_{\frac{E}{\Lambda}}^{\Lambda} - \frac{E}{\Lambda} \left[ \Lambda - \frac{E}{\Lambda} \right] \right] \\
&= \frac{1}{h} \left[ 2E - \left( \frac{E}{\Lambda} \right)^2 + E \left[ \ln \frac{\Lambda^2}{E} \right] - E + \left( \frac{E}{\Lambda} \right)^2 \right] \tag{10} \\
&= \frac{1}{h} \left[ E + E \left[ \ln \frac{\Lambda^2}{E} \right] \right] \\
&= \frac{1}{h} \left[ E + E \left[ \ln \frac{\Lambda^2}{E} \frac{2\pi}{2\pi} \right] \right] \\
&= \frac{E}{h} \ln \frac{\Lambda^2}{2\pi} - \frac{E}{h} \left[ \ln \frac{E}{2\pi} - 1 \right] \\
&= \frac{E}{2\pi} \ln \frac{\Lambda^2}{2\pi} - \frac{E}{2\pi} \left[ \ln \frac{E}{2\pi} - 1 \right] \quad [taking \hbar = 1]
\end{aligned}$$

This result les to the missing spectral interpretation of the Riemann zeros, according to which there is a continuum of eginstates (represented by the term  $\frac{E}{\pi} \ln \Lambda$  in  $\mathcal{N}(E)$ ) where states assoicated with Riemann zeros are missing.

Finally, in the S-regularization the number of semiclassical states diverges as  $\frac{E}{2\pi} \ln \frac{\Lambda}{l_x}$  suggesting a continuum spectrum, ike in Connes's approach. But there is no finite size correction to that formula, and cosequently the possible connection to the Riemann zeros is lost.

Table 1:

Three different regularizations of  $H = xp$  and the corresponding number of semiclassical states in units  $\hbar = 1$ [5]

Type	Regularization	$\mathcal{N}(E)$
BK	$ x  > l_x,  p  > l_p$	$\frac{E}{2\pi} \left( \ln \frac{E}{2\pi} - 1 \right) + 1$
C	$ x  < \Lambda,  p  < \Lambda$	$\frac{E}{2\pi} \ln \frac{\Lambda^2}{2\pi} - \frac{E}{2\pi} \left( \ln \frac{E}{2\pi} - 1 \right)$
S	$l_x < x < \Lambda$	$\frac{E}{2\pi} \ln \frac{\Lambda}{l_x}$

### 3 Quantization of $xp$ and $\frac{1}{xp}$

#### 3.1 The Hamiltonian $H_0 = xp$

Here we construst a self adjoint operator  $H_0$  which acts on a Hilbert space  $L^2(a, b)$  of square integrable function in the interval  $(a, b)$ . Taking  $x \geq 0$ , there are four possible intervals:  $a = 0, l_x$  and  $b = \Lambda, \infty$  where  $l_x$  and  $\Lambda$  were introduced (we shall take  $l_x$  and  $\Lambda = N > 1$ ). Berry-Keating defined the quantum Hamiltonian  $H_0$  as the normal ordered expresion

$$H_0 = \frac{1}{2}(xp + px) \quad (11)$$

where  $p = -i\hbar \frac{d}{dx}$ . If  $x \geq 0$ , Eq. (11) is equivalent to

$$\begin{aligned} H_0 &= \sqrt{x}p\sqrt{x} = -i\hbar\sqrt{x}\frac{d}{dx}\sqrt{x} \\ &= -i\hbar \left( x\frac{d}{dx} + \frac{d}{dx}x \right) \end{aligned} \quad (12)$$

We know that the canonical commutation relation is

$$[\hat{x}, \hat{p}] = i\hbar \quad (13)$$

or, (dropping hat cause we're dealing with quantum system and opera-

tors)

$$\begin{aligned}
[x, p] &= i\hbar \\
\Rightarrow \left[ x, -i\hbar \frac{d}{dx} \right] &= i\hbar \\
\Rightarrow -i\hbar \left[ x, \frac{d}{dx} \right] &= i\hbar \\
\Rightarrow \left[ x, \frac{d}{dx} \right] &= -1 \\
\Rightarrow x \frac{d}{dx} - \frac{d}{dx} x &= -1 \\
\Rightarrow \frac{d}{dx} x &= x \frac{d}{dx} + 1
\end{aligned} \tag{14}$$

Taking this value to R.H.S of Eq(12)

$$\begin{aligned}
-i\hbar \left( x \frac{d}{dx} + \frac{d}{dx} \right) f &= -i\hbar \left[ 2x \frac{d}{dx} + 1 \right] \\
&= -i\hbar 2x \left[ \frac{d}{dx} + \frac{1}{x} \frac{1}{2} \right] f \\
&= -i\hbar \frac{1}{\sqrt{x}} \frac{d}{dx} (\sqrt{x} f) \\
&= -i\hbar \frac{1}{\sqrt{x}} \frac{d}{dx} (\sqrt{x} f) \\
&= \frac{1}{\sqrt{x}} \left( -i\hbar \frac{d}{dx} \right) \sqrt{x} f
\end{aligned} \tag{15}$$

so

$$H_0 = \frac{1}{2} (xp + px) = -i\hbar \sqrt{x} \frac{d}{dx} \sqrt{x} \tag{16}$$

This is a symmetric operator acting on a certain domain of the Hilbert space  $L^2(a, b)$ , By definition, if an operator is symmetric (or Hermitian)[6]

$$\langle \psi | H_0 \phi \rangle = \langle \psi H_0 | \phi \rangle \tag{17}$$

or with limit,

$$\langle \psi | H_0 \phi \rangle - \langle \psi H_0 | \phi \rangle = i\hbar [a\psi^*(a)\phi(a) - b\phi^*(b)\psi(b)] = 0 \tag{18}$$

which is satisfied if both  $\psi(x)$  and  $\phi(x)$  vanish at the points a, b. von Neumann Theorem of deficiency indices states that, an operator is symmetric if its deficiency indices  $n_{\pm}$  are equal.[7]. Deficiency indices (or the defect numbers) of a closable symmetric operator T are cardinal number S

$$\begin{aligned} n_+ &:= d_{\lambda} = \dim \mathcal{R}(T - \bar{\lambda}\mathbb{1})^{\perp} & \text{Im } \lambda > 0 \\ n_- &:= d_{\lambda} = \dim \mathcal{R}(T - \bar{\lambda}\mathbb{1})^{\perp} & \text{Im } \lambda < 0 \end{aligned} \quad (19)$$

If T is densely defined and symmetric, then T is closable, and by formula  $\mathcal{N}(T^*) = \mathcal{R}(T)^{\perp}$

$$\begin{aligned} n_+ &:= \dim \mathcal{N}(T^* - i\mathbb{1}) = \dim \mathcal{N}(T^* - \lambda\mathbb{1}) & \text{Im } \lambda > 0 \\ n_- &:= \dim \mathcal{N}(T^* + i\mathbb{1}) = \dim \mathcal{N}(T^* + \lambda\mathbb{1}) & \text{Im } \lambda < 0 \end{aligned} \quad (20)$$

By definition  $n_{\pm}(T) = \dim \mathcal{N}(T^* \mp iT)$

Again if T is a symmetric operator, then

$$\begin{aligned} K_+ &= \ker (i\mathbb{1} - T^*) = \text{Ran } (i\mathbb{1} - T)^{\perp} \\ K_- &= \ker (i\mathbb{1} + T^*) = \text{Ran } (-i\mathbb{1} + T)^{\perp} \end{aligned} \quad (21)$$

$K_+$  and  $K_-$  are called the deficiency subspaces of T, The pair of numbers  $n_+, n_-$  given by  $n_+(T) = \dim[K_+], n_-(T) = \dim[K_-]$  are called deficiency indices of T.

von Neumann Theorem for deficiency indices states that if T an closed operator with deficiency indices  $n_+$  and  $n_-$ . Then

(1) T is symmetric if and only if  $n_+ = n_- = 0$  and self adjoint if  $\mathcal{D}(T) = \mathcal{D}(T^*)$

(2) T is symmetric and self adjoint and also has many self adjoint extensions if and only if  $n_+ = n_- \neq 0$  and  $\mathcal{D}(T) = \mathcal{D}(T^*)$ . There is one-one correspondence between self adjoint extensions of T and unitary maps from  $K_+$  onto  $K_-$

(3) If either  $n_+ = 0 \neq n_-$  or  $n_- = 0 \neq n_+$  then T is not symmetric and has no nontrivial self adjoint extension (such operators are called maximal symmetric operator).

So this indices counts the number of solutions of the equation, which comes from the deficiency spaces for subsystem T

$$K_{\pm} = \ker \left( -H_0^{\dagger} - \mp i\mathbb{1} \right) \quad (22)$$

which leads to find the solution of the equation.

$$H_0^{\dagger} \psi_{\pm} = \pm i\hbar\lambda \psi_{\pm} \quad (23)$$

belonging to the domain of  $H_0^{\dagger}(\lambda > 0)$ . If  $n = n_+ = n_- > 0$ , there are infinitely many self-adjoint extensions of  $H_0$  parameterized by a unitary  $n \times n$  matrix. Stone's theorem states that if  $U(t)$  be a strongly continuous one parameter unitary group on a Hilbert space  $\mathcal{H}$ . Then, there is a self-adjoint operator  $A$  on  $\mathcal{H}$  so that  $U(t) = e^{itA}$ . The solution of the equation ( ) is

$$\begin{aligned} H_0^{\dagger} \psi_{\pm} &= \pm i\hbar\lambda \psi_{\pm} \\ \implies H_0 \psi_{\pm} &= \pm i\hbar\lambda \psi_{\pm} \quad [\text{because } H_0 \text{ is self-adjoint}] \\ \implies \left( -i\hbar\sqrt{x} \frac{d}{dx} \sqrt{x} \right) \psi_{\pm} &= \pm i\hbar\lambda \psi_{\pm} \\ \implies -i\hbar\sqrt{x} \frac{d}{dx} (\sqrt{x} \psi_{\pm}) &= \pm i\hbar\lambda \psi_{\pm} \\ \implies -\sqrt{x} \frac{d}{dx} (\sqrt{x} \psi_{\pm}) &= \pm \lambda \psi_{\pm} \\ \implies -x \frac{d}{dx} \psi_{\pm} - \sqrt{x} \frac{1}{2\sqrt{x}} \frac{d}{dx} \psi_{\pm} &= \pm \lambda \psi_{\pm} \\ \implies -x \frac{d}{dx} \psi_{\pm} &= \left( \pm \lambda + \frac{1}{2} \right) \psi_{\pm} \\ \implies \frac{d}{dx} \psi_{\pm} &= -\frac{1}{x} \left( \pm \lambda + \frac{1}{2} \right) \psi_{\pm} \\ \implies \frac{d\psi_{\pm}}{\psi_{\pm}} &= -\frac{dx}{x} \left( \pm \lambda + \frac{1}{2} \right) \\ \implies \ln \psi_{\pm} &= -(\ln x) \left( \pm \lambda + \frac{1}{2} \right) + \ln C \\ \implies \psi_{\pm} &= Cx^{-\frac{1}{2} \mp \lambda} \end{aligned}$$



whose norm in the interval (a,b) is

$$\begin{aligned}
\langle \psi_{\pm} | \psi_{\pm} \rangle &= \int_a^b C^2 x^{-1 \mp \lambda} dx \\
&= \mp \frac{C^2}{2\lambda} (b^{\mp 2\lambda} - a^{\mp 2\lambda}) \\
&= \pm \frac{C^2}{2\lambda} (a^{\mp 2\lambda} - b^{\mp 2\lambda})
\end{aligned} \tag{24}$$

The deficiency indices corresponding to the four intervals considered above are collected in Table[8]. We find the deficiency indices by observing different intervals. For BK intervals  $(1, \infty)$  only  $\psi_+$  belongs to Hilbert space ( $\psi_-$  blows out. or putting intervals in Eq. (20) and testing whether it belongs to the Hilbert space)[5]. And the rest are given below

Table 2: Deficiency indices of  $H_0$ . The corresponding intervals are associated to the semiclassical regularizations of section 2 (BK, C, S). The last one T, describes the case with no constraints on  $x$  except positivity (i.e.  $x > 0$ )

Type	(a,b)	$(n_+, n_-)$	Self-adjoint
BK	$(1, \infty)$	$(1, 0)$	-
C	$(0, N)$	$(0, 1)$	-
S	$(1, N)$	$(1, 1)$	$\checkmark$
T	$(0, \infty)$	$(0, 0)$	$\checkmark$

From the von Neumann theorem we see that  $H_0$  is essentially self-adjoint on the half line  $\mathbb{R}_+ = (0, \infty)$ . This was studied by Twamley and Milbrn, who defined quantum Mellin transform using the eigenstates of  $H_0$ [9]. On the other hand, in the interval  $(1, N)$  the operator  $H_0$  admits infinitely many self-adjoint extensions parameterized by a phase  $e^{i\theta}$ . This phase defines the boundary condition of the functions belonging to the self-adjoint domain.[5]

$$\mathcal{D}(H_{0,\theta}) = \left\{ \psi, H_0 \psi \in L^2(1, N), e^{i\theta} \psi(1) = \sqrt{N} \psi(N) \right\} \tag{25}$$

The eigenfunction of  $H_0$

$$H_0 \psi_E = E \psi_E, \tag{26}$$

are given by [1]

$$\psi_E(x) = \frac{C}{x^{\frac{1}{2}-iE\hbar}}, \quad E \in \mathbb{R} \quad (27)$$

where  $C$  is a normalization constant. In the half line  $\mathbb{R}_+$  there are no further restriction on  $E$ , hence the spectrum of  $H_0$  is continuous and covers the whole real line  $\mathbb{R}$ . In this case the normalization constant is chosen as  $C = \frac{1}{\sqrt{2\pi\hbar}}$  which gurantees the standard normalization

$$\langle \psi_E | \psi_{E'} \rangle = C^2 \int_0^\infty \frac{dx}{x} x^{-i(E-E')/\hbar} = \delta(E - E') \quad (28)$$

In the case where  $H_0$  is defined in ther interval, the boundary condition (21) yeilds the quantization condition for  $E$ , namely

$$\begin{aligned} e^{i\theta} \psi(1) &= \sqrt{N} \psi(N) \\ \implies e^{i\theta} \frac{C}{1^{\frac{1}{2}-iE\hbar}} &= \sqrt{N} \frac{C}{N^{\frac{1}{2}-iE\hbar}} \\ \implies e^{i\theta} &= N^{-iE\hbar} \\ \implies i\theta &= \left(\frac{-iE}{\hbar}\right) \ln N \\ \implies E &= \frac{\hbar\theta}{\ln N} \\ \implies E &= \frac{2\pi\hbar}{\ln N} \left(\frac{\theta}{2\pi}\right) \\ \implies E_n &= \frac{2\pi\hbar}{\ln N} \left(n + \frac{\theta}{2\pi}\right) \quad n \in \mathbb{N} \end{aligned} \quad (29)$$

Hence the spectrum of  $H_0$  is dscrete, with a level spacing decreasing for largerm values of  $N$ . The normalization constant of the wave function is now  $C = \frac{1}{\sqrt{\ln N}}$  which gives,

$$\langle \psi_{E_n} | \psi_{E_{n'}} \rangle = C^2 \int_1^N \frac{dx}{x} x^{-i(E_n-E_{n'})/\hbar} = \delta_{n,n'} \quad (30)$$

The spectrum (16) agrees with the semiclassical result given in Table 1 for the S-regularization(recall that  $l_x = 1, \Lambda = N, \hbar = 1$ ) For the particular case where  $\theta = \pi$ , one observes that the energy spectrum is symmetric around zero, i.e, if  $E_n$  is an eigenenergy so is  $-E_n$ . This result is obtained in working[10] with the inverse Hamiltonian  $\frac{1}{H_0}$ . We are reviewing that construction in next section.

### 3.2 The inverse Hamiltonian $\frac{1}{H_0}$

First, we take the expression at Eq(16) and take the formal inverse, i.e.,  $H_0^{-1} = x^{1/2}p^{-1}x^{-1/2}$ . The operator  $p_{-1}$  is the one-dimensional Green's function with matrix elements (definition of Green's function: Green's function is the kernel of an integral operator that represents the inverse of a differential operator. Let

$$Lu = f \quad (31)$$

Here  $u$  and  $f$  are vectors and  $L$  is a square, invertible matrix. The inverse matrix exists if  $\lambda = 0$  is not an eigenvalue of  $L$ , or when  $\det L \neq 0$ . Now

$$u = L^{-1}f \quad (32)$$

where  $L^{-1}$  is the inverse operator of  $L$ . The inverse operator to be an integral operator of the form.

$$(L^{-1}f)(x) = \int_a^b g(x, \xi) f(\xi) d\xi \quad (33)$$

with kernel  $G$ . If  $L$  exists, then the kernel function  $g(x, \xi)$  is called the Green's function associated with  $L$ .

So  $p_{-1}$  operator will be

$$\begin{aligned} \langle x | p^{-1} | x' \rangle &= \left\langle x \left| \frac{1}{-i\hbar \frac{d}{dx}} \right| x' \right\rangle \\ &= -i\hbar \left\langle x \left| \frac{1}{\frac{d}{dx}} \right| x' \right\rangle \\ &= \frac{\hbar}{i} G(x, x') \\ &= \frac{\hbar}{2i} \text{sign}(x - x') \end{aligned} \quad (34)$$

Here  $\text{sign}(x - x')$  is the sign function.[10]. The operator  $H_0^{-1}$  is defined in the interval  $(1, N)$  by the continuous matrix,

$$H_0^{-1}(x, x') = \frac{i}{2\hbar} \frac{\text{sign}(x - x')}{\sqrt{xx'}}, \quad 1 \leq x, x' \leq N. \quad (35)$$

It's spectrum is found solving the Schrödinger equation.

$$\begin{aligned}
H_0(x, x')\psi(x') &= E\psi(x) \\
\implies H_0^{-1}(x, x')\psi(x') &= E^{-1}\psi(x) \\
\implies \frac{i}{2\hbar} \int_1^N dx' \frac{\text{sign}(x - x')}{\sqrt{xx'}} \psi(x') &= E^{-1}\psi(x)
\end{aligned} \tag{36}$$

for the eigenvalue  $E^{-1}$ , which must not be singular for  $H_0^{-1}$  to be invertible. Define a new wave function

$$\phi(x) = \frac{\psi(x)}{\sqrt{x}} \tag{37}$$

which satisfies

$$\frac{iE}{2\hbar} \int_1^N dx' \text{sign}(x - x')\phi(x') = x\phi(x) \tag{38}$$

Taking derivative with respect to x

$$\begin{aligned}
\frac{d}{dx} \left( \frac{iE}{2\hbar} \int_1^N dx' \text{sign}(x - x')\phi(x') \right) &= \frac{d}{dx} (x\phi(x)) \\
\implies \frac{iE}{2\hbar} \int_1^N dx' 2\delta(x - x')\phi(x') &= \phi(x) + x \frac{d}{dx} \phi(x) \\
\implies \frac{iE}{\hbar} \phi(x) &= \phi(x) + x \frac{d}{dx} \phi(x) \\
\implies x \frac{d}{dx} \phi(x) &= \left( 1 - \frac{iE}{\hbar} \right) \phi(x) \\
\implies \frac{d\phi(x)}{\phi(x)} &= \left( 1 - \frac{iE}{\hbar} \right) \frac{dx}{x} \\
\implies \ln \phi(x) &= \left( 1 - \frac{iE}{\hbar} \right) \ln x + \ln C \\
\implies \phi(x) &= \frac{C}{x^{1 - \frac{iE}{\hbar}}}
\end{aligned} \tag{39}$$

$$\psi(x) = \frac{C}{x^{1/2 - \frac{iE}{\hbar}}} \tag{40}$$

with  $C = \frac{1}{\sqrt{\ln N}}$  as in Eq(30). Eq(40) fixes the functional form of  $\psi(x)$ . To find the spectrum we impose (38) at one point, say  $x = 1$ , obtaining,

$$\begin{aligned}
& \frac{iE}{2\hbar} \int_1^N dx' \text{sign}(1 - x') \phi(x') = \phi(1) \\
& \Rightarrow \frac{iE}{2\hbar} \int_1^N dx' \text{sign}(1 - x') \frac{C}{x'^{1/2 - iE/\hbar}} = \frac{C}{1^{1/2 - iE/\hbar}} \\
& \Rightarrow \frac{iE}{2\hbar} \int_1^N dx' \text{sign}(1 - x') \frac{1}{x'^{1/2 - iE/\hbar}} = 1
\end{aligned} \tag{41}$$

we know that sign function

$$\text{sign}(1 - x') = \begin{cases} 1 & 1 - x' > 0 \Rightarrow 1 > x' \\ 0 & 1 - x' = 0 \Rightarrow 1 = x' \\ -1 & 1 - x' < 0 \Rightarrow 1 < x' \end{cases}$$

Therefore

$$\begin{aligned}
& \frac{-iE}{2\hbar} \int_1^N dx' x'^{-1 + iE/\hbar} = 1 \\
& \frac{-iE}{2\hbar} \left[ \frac{x'^{iE/\hbar}}{iE/\hbar} \right]_1^N = 1 \\
& \frac{1}{2} [N^{iE/\hbar} - 1^{iE/\hbar}] = 1 \\
& N^{iE/\hbar} - 1 = -2 \\
& N^{iE/\hbar} = -1 \\
& N^{iE/\hbar} = e^{i\pi} \\
& \frac{iE}{\hbar} \ln N = i\pi \\
& E = \frac{\pi\hbar}{\ln N} \\
& E = \frac{2\pi\hbar}{\ln N} \frac{1}{2}
\end{aligned}$$

$$\therefore E_n = \frac{2\pi\hbar}{\ln N} \left[ n + \frac{1}{2} \right] \quad (42)$$

This spectrum coincides with (29) for  $\theta = \pi$ , so that the eigenstates come in pairs  $\{E_n, -E_n\}$  as corresponds to an Hermitian antisymmetric operator. Including a BCS coupling in (35), related to  $\theta$  yields the spectrum (29)[9]

We take this spectrum and wavefunction to calculate OTOC(out of time order correlator)

## 4 Out-of-Time-Order Correlator of $H = xp$

The out-of-time-order correlator (OTOC) is typically defined by [11]

$$C_T \equiv - \langle [W(t), V(0)]^2 \rangle \quad (43)$$

where  $\langle \dots \rangle$  represents the thermal average.  $W(t)$  and  $V(t)$  are operators as time in  $t$  in the Heisenberg representation. The OTOC, first introduced in a calculation of a vertex correction of a current for a superconductor[12], was recently turned out to be considered as a measure of the magnitude of quantum chaos. A naive argument for the relation between the OTOC and chaos is as follows[13]. Consider position and momentum operators,  $x(t)$  and  $p(t)$ , in a quantum system. We can define an OTOC as  $C_T = - \langle [x(t), p(0)]^2 \rangle$ . Taking a naive semiclassical limit, we would be able to replace the commutator  $[x(t), p(0)]$  by the Poisson bracket  $i\hbar\{x(t), p(0)\}_{PB} = i\hbar \frac{\delta x(t)}{\delta x(0)}$ . For a classically chaotic system with a Lyapunov exponent  $\lambda$ , we have  $\frac{\delta x(t)}{\delta x(0)} \sim e^{\lambda t}$  because of sensitivity to initial condition. Thus, the OTOC should grow as  $\sim \hbar^2 e^{2\lambda t}$  and we can read off the quantum Lyapunov exponent  $\lambda$  from it. The quantization of a classically chaotic system may provide a positive quantum Lyapunov exponent of the OTOC. Historically, the nearest neighbour distribution (NND) for the energy level spectrum has been used to quantify quantum chaos [?]. For integrable and non-integrable systems, it is considered that NNDs are given by Poisson and Wigner distributions. The OTOC is expected to be another measure of quantum chaos. A possible distinction from the classical chaotic system is that the OTOC does not grow eternally but saturates at the Ehrenfest time  $t_E$ . The Ehrenfest time is defined by the time scale beyond which the wave function spreads

over the whole system. It is roughly characterized as a boundary between a particle-like behavior and a wave-like behavior of the wave function.

In the definition of OTOC, we consider the thermal average of  $-\langle [W(t), V(0)]^2 \rangle$ . When we take thermal average, we need to consider the four point operator  $\langle [W(t), V(0)]^2 \rangle$  instead of two point operator  $\langle [W(t), V(0)] \rangle$ . The reason is as follows. Assuming that we can replace the commutator by Poisson bracket by semiclassical limit,  $\langle [W(t), V(0)] \rangle$  would also show the exponential growth  $\sim e^{\lambda t}$ . However, its coefficient can be both positive and negative. By taking the thermal average, their contributions would be canceled. From the quantum theory point of view,  $\langle [W(t), V(0)] \rangle$  measures the correlation between  $W(t)$  and  $V(0)$ . Therefore, the two point function decays as  $t \rightarrow \infty$  and cannot show the chaotic behavior.

First we formulate how to calculate the OTOC for generic quantum mechanics. In particular, by the reason described above, we choose  $W = x$  and  $V = p$  to measure a possible indication of quantum chaos. We consider the out-of-time-order correlator (OTOC) defined by

$$C_T \equiv -\langle [x(t), p(0)]^2 \rangle \quad (44)$$

where  $\langle \mathcal{O} \rangle \equiv \frac{\text{tr}[e^{-\beta H} \mathcal{O}]}{\text{tr}[e^{-\beta H}]}$ . Here we define  $\frac{1}{\beta}$  with the temperature of the system  $T$ . We will omit the argument of Heisenberg operators for  $t = 0$ ;  $\mathcal{O} \equiv \mathcal{O}(0)$ . Taking energy eigenstates as the basis of the Hilbert space, we can rewrite the OTOC as

$$C_T(t) = \frac{1}{Z} \sum_n e^{-\beta E_n} c_n(t) \quad (45)$$

$$c_n \equiv -\langle n | [x(t), p(0)]^2 | n \rangle \quad (46)$$

where  $H|n\rangle = E_n|n\rangle$ . We will refer the OTOC for a fixed energy eigenstate,  $c_n(t)$ , as a microcanonical OTOC. On the other hand, we will refer  $C_T(t)$  as a thermal OTOC. Once we compute microcanonical OTOCs, we can obtain the thermal OTOC by taking their thermal average. Let us rewrite the microcanonical OTOC using matrix element of  $x$  and  $p$  for numerical calculations. Using the completeness relation  $1 = \sum_m |m\rangle\langle m|$ , we rewrite the microcanonical OTOC as

$$c_n(t) = \sum_m b_{nm}(t) b_{nm}^*(t) \quad (47)$$

$$b_{nm}(t) \equiv -i \langle n | [x(t), p(0)] | m \rangle \quad (48)$$

Note that  $b_{nm}(t)$  is Hermitian:  $b_{nm}(t) = b_{nm}^*(t)$ . Substituting  $x(t) = e^{iHt} x e^{-iHt}$  and inserting the completeness relation again, we obtain

$$\begin{aligned} b_{nm}(t) &= -i \langle n | [e^{iHt} x e^{-iHt}, p] | m \rangle \\ &= -i \langle n | [e^{iHt} x e^{-iHt} p - p e^{iHt} x e^{-iHt}] | m \rangle \\ &= -i \left[ \sum_k \langle n | e^{iHt} x e^{-iHt} | k \rangle \langle k | p | m \rangle - \sum_k \langle n | p | k \rangle \langle k | e^{iHt} x e^{-iHt} | m \rangle \right] \\ &= -i \left[ \sum_k \langle n | e^{iE_n t} x e^{-iE_k t} | k \rangle \langle k | p | m \rangle - \sum_k \langle n | p | k \rangle \langle k | e^{iE_k t} x e^{-iE_m t} | m \rangle \right] \\ &= -i \sum_k [e^{iE_{nk} t} x_{nk} p_{km} - e^{iE_{km} t} p_{nk} x_{km}] \end{aligned}$$

$$\therefore b_{nm}(t) = -i \sum_k [e^{iE_{nk} t} x_{nk} p_{km} - e^{iE_{km} t} p_{nk} x_{km}] \quad (49)$$

where  $E = E_n - E_m$ ,  $x_{nm} \equiv \langle n | x | m \rangle$ ,  $p_{nm} \equiv \langle n | p | m \rangle$ . In this expression, there are matrix components of  $p$ . They are not desirable since numerical derivatives of wave functions lose the numerical accuracy. For a natural Hamiltonian with the form,

$$H = \sum_{i=1}^N p_i^2 + U(x_1, \dots, x_N) \quad (50)$$

we can express  $p_{nm}$  using  $x_{nm}$ . We know from canonical commutation relation

$$[x, p] = i \quad (\hbar = 1)$$

Therefore



$$\begin{aligned}
[H, x] &= [p^2 + U(x), x] \\
&= [p^2, x] + [U(x), x] \\
&= p[p, x] + [p, x]p \\
&= -ip - ip
\end{aligned}$$

$$\therefore [H, x] = -2ip \quad (51)$$

Applying  $\langle m | \cdots | n \rangle$  to the both sides of the equation, we obtain

$$\begin{aligned}
\langle m | [H, x] | n \rangle &= \langle m | -2ip | n \rangle \\
\langle m | (Hx - xH) | n \rangle &= -2i \langle m | p | n \rangle \\
\langle m | (E_m x - x E_n) | n \rangle &= -2ip_{mn} \\
E_{mn} x_{mn} &= -2ip_{mn} \\
p_{mn} &= \frac{i}{2} E_{mn} x_{mn}
\end{aligned}$$

Substituting this expression into (49) we have

$$\begin{aligned}
b_{nm}(t) &= \frac{-i}{2} \sum_k (e^{iE_{nk}t} x_{nk} E_{km} x_{km} - e^{iE_{km}t} E_{nk} x_{nk} x_{km}) \\
b_{nm}(t) &= \frac{1}{2} \sum_k x_{nk} x_{km} (E_{km} e^{iE_{nk}t} - E_{nk} e^{iE_{km}t}) \quad (52)
\end{aligned}$$

Now we can take this equation to calculate OTOC of Berry-Keating Hamiltonian from (40) and (42).

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