Title: Cosmology from Condensed Matter Physics: A study of out-of-equilibrium physics

Speakers: Sayantan Choudhury

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Abstract: In this work, our prime focus is to study the one to one correspondence between the conduction phenomena in electrical wires with impurity and the scattering events responsible for particle production during stochastic inflation and reheating implemented under a closed quantum mechanical system in early universe cosmology. In this connection, we also present a derivation of quantum corrected version of the Fokkerâ€“Planck equation without dissipation and its fourth-order corrected analytical solution for the probability distribution profile responsible for studying the dynamical features of the particle creation events in the stochastic inflation and reheating stage of the universe. It is explicitly shown from our computation that quantum corrected Fokkerâ€“Planck equation describes the particle creation phenomena better for Dirac delta type of scatterer. In this connection, we additionally discuss ItÃ´, Stratonovich prescription and the explicit role of finite temperature effective potential for solving the probability distribution profile. Furthermore, we extend our discussion of particle production phenomena to describe the quantum description of randomness involved in the dynamics. We also present computation to derive the expression for the measure of the stochastic nonlinearity (randomness or chaos) arising in the stochastic inflation and reheating epoch of the universe, often described by Lyapunov Exponent. Apart from that, we quantify the quantum chaos arising in a closed system by a more strong measure, commonly known as Spectral Form Factor using the principles of random matrix theory (RMT). Finally, we discuss the role of out of time order correlation function (OTOC) to describe quantum chaos in early universe cosmology.

Cosmology from Condensed Matter Physics

(A study of out-of-equilibrium physics)

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Quantum out-of-equilibrium cosmology

Authors Authors and affiliations

Sayantan Choudhury, Arkaprava Mukherjee, Prashali Chauhan, Sandipan Bhattacherjee

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Abstract

In this work, our prime focus is to study the one to one correspondence between the conduction phenomena in electrical wires with impurity and the scattering events responsible for particle production during stochastic inflation and reheating implemented under a closed quantum mechanical system in early universe cosmology. In this connection, we also present a derivation of quantum corrected version of the Fokker–Planck equation without dissipation and its fourth order corrected analytical solution for the probability distribution profile responsible for studying the dynamical features of the particle creation events in the stochastic inflation and reheating stage of the universe. It is explicitly shown from our computation that quantum corrected Fokker–Planck equation describe the particle creation phenomena better for Dirac

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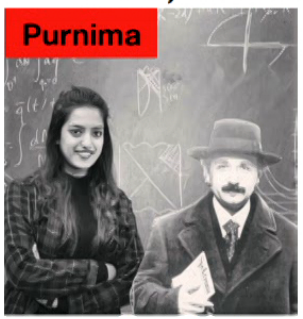

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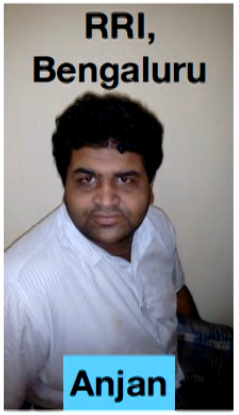

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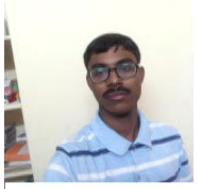

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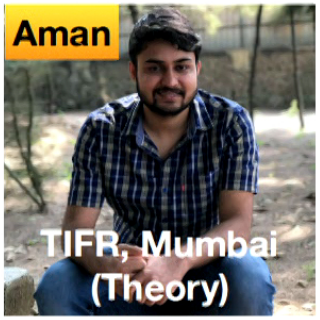

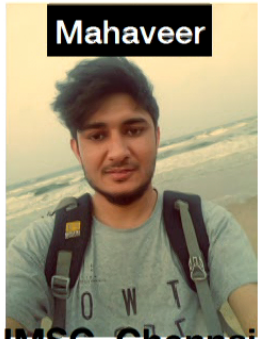

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Out-of-time-order correlators in quantum mechanics

Authors Authors and affiliations

Koji Hashimoto, Keiju Murata, Ryosuke Yoshii

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First Online: 20 October 2017

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Abstract

The out-of-time-order correlator (OTOC) is considered as a measure of quantum chaos. We formulate how to calculate the OTOC for quantum mechanics with a general Hamiltonian. We demonstrate explicit calculations of OTOCs for a harmonic oscillator, a particle in a one-dimensional box, a circle billiard and stadium billiards. For the first two cases, OTOCs are periodic in time because of their commensurable energy spectra. For the circle and stadium billiards, they are not recursive but saturate to constant values which are linear in temperature. Although the stadium billiard is a typical example of the classical chaos, an expected exponential growth of the OTOC is not found. We also discuss the classical limit of the OTOC. Analysis of a time evolution of a wavepacket in a box shows that the OTOC can deviate from its classical value at a time much earlier than the Ehrenfest time, which could be the reason of the difficulty for the numerical analyses to exhibit the exponential growth.

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Thermalization in 2D critical quench and UV/IR mixing

Authors Authors and affiliations

Gautam Mandal, Shruti Paranjape, Nilakash Sorokhaibam

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Abstract

We consider quantum quenches in models of free scalars and fermions with a generic time-dependent mass $m(t)$ that goes from m_0 to zero. We prove that, as anticipated in MSS [1], the post-quench dynamics can be described in terms of a state of the generalized Calabrese-Cardy form $|\psi\rangle = \exp[-\kappa_2 H - \sum_{n>2}^{\infty} \kappa_n W_n]|\mathrm{Bd}\rangle$. The W_n ($n = 2, 3, \ldots, W_2 = H$) here represent the conserved W_∞ charges and $|\mathrm{Bd}\rangle$ represents a conformal boundary state. Our result holds irrespective of whether the pre-quench state is a ground state or a squeezed state, and is proved without recourse to perturbation expansion in the κ_n's as in MSS. We compute exact time-dependent correlators for some specific quench protocols $m(t)$. The correlators explicitly show thermalization to a generalized Gibbs ensemble (GGE), with inverse temperature $\beta = 4\kappa_2$, and chemical potentials $\mu_n = 4\kappa_n$. In case the pre-quench state is a ground state, it is possible to retrieve the exact quench protocol $m(t)$ from the final GGE, by an application of inverse

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Journal of Statistical Mechanics: Theory and Experiment

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SPECIAL ISSUE ON QUANTUM INTEGRABILITY IN OUT OF EQUILIBRIUM SYSTEMS

Quantum quenches in 1 + 1 dimensional conformal field theories

Pasquale Calabrese[1] and John Cardy[2,3]

Published 24 June 2016 • © 2016 IOP Publishing Ltd and SISSA Medialab srl
Journal of Statistical Mechanics: Theory and Experiment, Volume 2016, June 2016
Special Issue on Quantum Integrability in Out of Equilibrium Systems

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Abstract

We review the imaginary time path integral approach to the quench dynamics of conformal field theories. We show how this technique can be applied to the determination of the time dependence of correlation functions and entanglement entropy for both global and local quenches. We also briefly review other quench protocols. We carefully discuss the limits of applicability of these results to realistic models of condensed matter and cold atoms.

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Journal of Statistical Mechanics: Theory and Experiment

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Entanglement entropy and quantum field theory

Pasquale Calabrese[1,3] and John Cardy[1,2]

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Abstract

We carry out a systematic study of entanglement entropy in relativistic quantum field theory. This is defined as the von Neumann entropy $S_A = -\mathrm{Tr}\,\rho_A \log \rho_A$ corresponding to the reduced density matrix ρ_A of a subsystem A. For the case of a 1+1-dimensional critical system, whose continuum limit is a conformal field theory with central charge c, we re-derive the result $S_A \sim (c/3)\log \ell$ of Holzhey *et al* when A is a finite interval of length ℓ in an infinite system, and extend it to many other cases: finite systems, finite temperatures, and when A consists of an arbitrary number of disjoint intervals. For such a system away from its critical point, when the correlation length ξ is large but finite, we show that $S_A \sim \mathcal{A}(c/6)\log \xi$ where $\mathcal{A}$ is the number of boundary points of A. These results are verified

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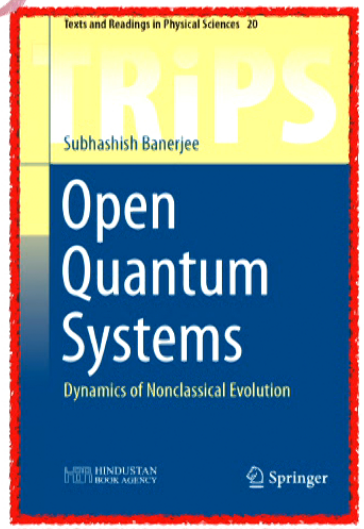
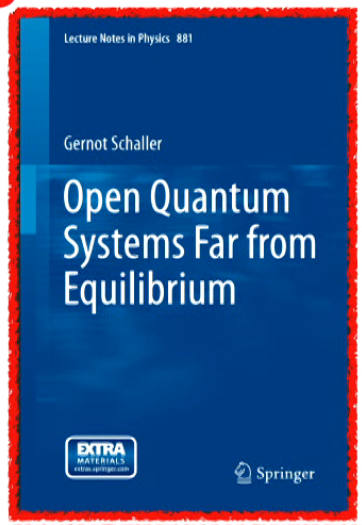
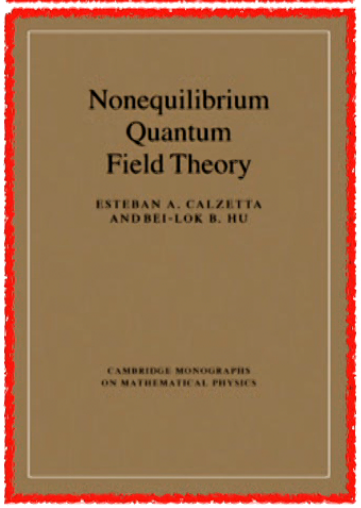
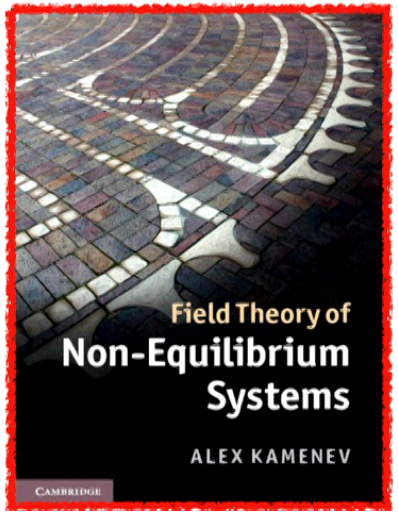
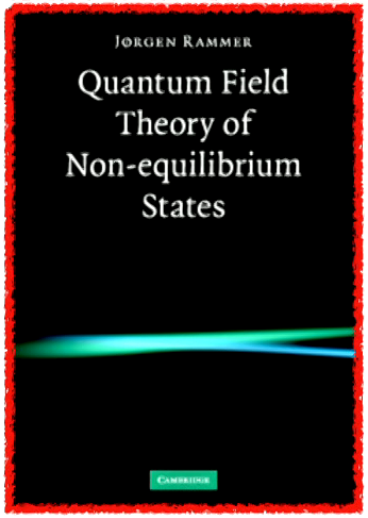










Outline

- Introduction.
- From conduction wires to Cosmology.
- Dynamical study with time dependent protocols (Quench and ETH).
- OTOC in QFT : Application to Cosmology.
- OTOC from RMT : Alternative approach to Cosmology
- Fokker-Planck equation : Probabilistic treatment in Cosmology
- Conclusion and future prospects.

- Quantum fields in an inflationary background or during reheating gives rise to the burst of particle production, which has been extensively studied in Primordial Cosmology.

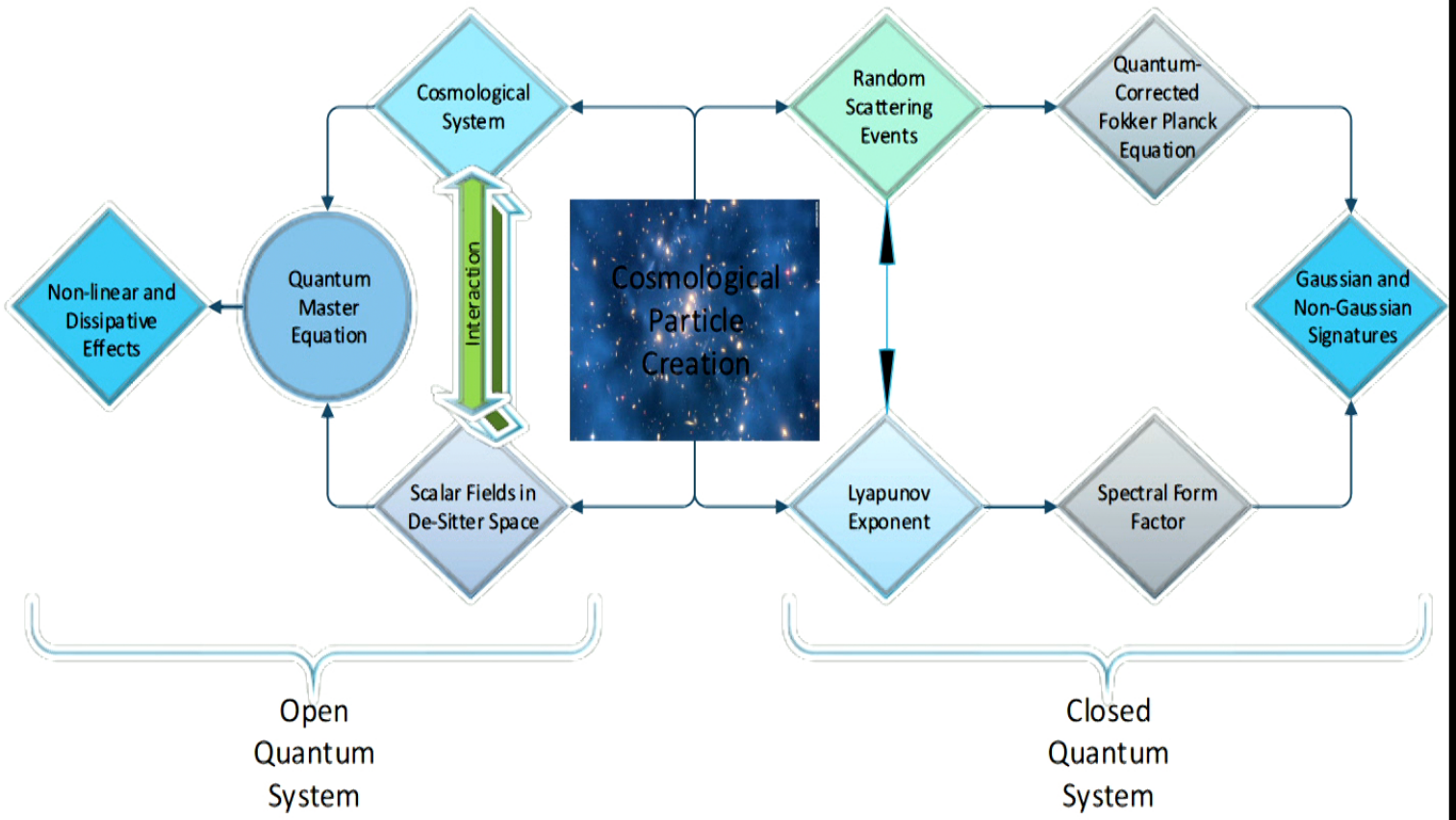
- Such phenomena has been compared to that of the scattering problem in quantum mechanics with a specific effective potential arising due to the impurity in the conduction wire.

- It is important to note that such particle production events are completely random (or chaotic) when the evolution is non-adiabatic in nature.

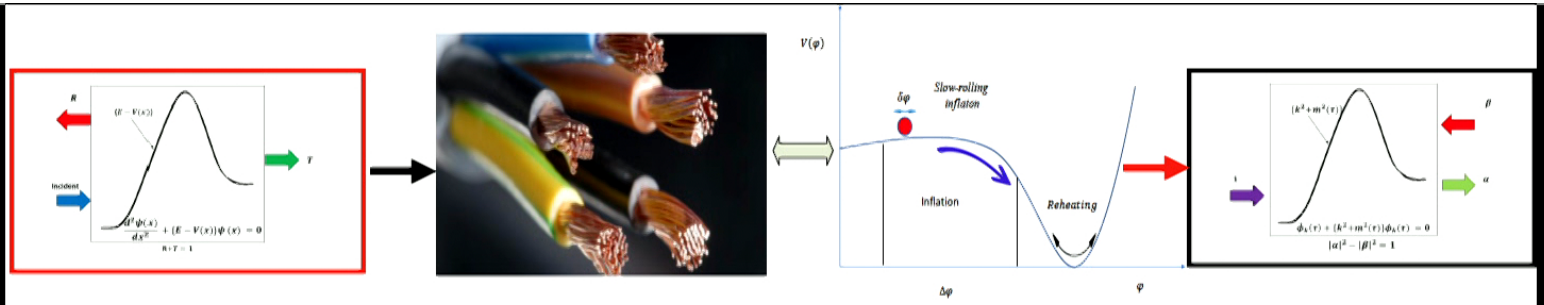
- A non-adiabatic change in the time dependent coupling of the fields (wich is actually coming from path integrating out the heavy degrees of freedom from the UV complete theory) as the background evolution of the fields passes through special points in field space produces these burst of particle creation.
- There lies a one-to-one correspondence between such cosmological events to that of the stochastic random phenomena occurring in mesoscopic systems where fluctuations in physical quantities play a significant role of producing stochastic randomness.
- The massless scalar field gets *thermalise* due to the effective time dependent interaction. The cosmological events are identified with those of the particle production stochastic random events.

- **Questions**:

1. How exactly conduction wire cosmology correspondence can be built?
2. How the out-of equilibrium phenomena quantify randomness?
3. How the physics of out-of equilibrium effects the cosmological correlations?
4. If we don't know anything about the effective interactions (time dependent couplings in QFT) then how one can able to quantify randomness?
5. What is the statistical (probabilistic) interpretation of the stochastic dynamics of cosmological particle creation in scattering problem?

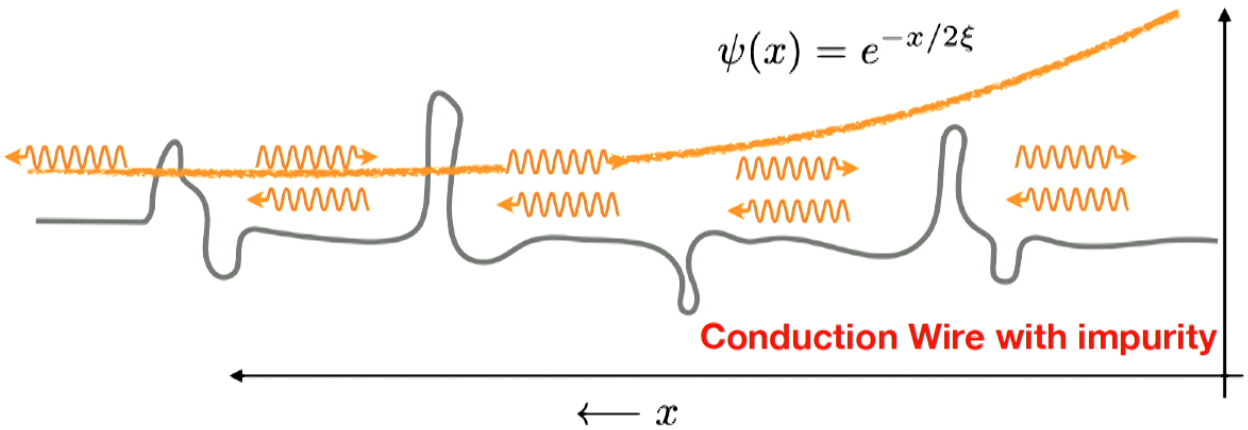

Cosmological System
Random Scattering Events
Quantum-Corrected Fokker Planck Equation
Non-linear and Dissipative Effects
Quantum Master Equation
Interaction
Cosmological Particle Creation
Gaussian and Non-Gaussian Signatures
Scalar Fields in De-Sitter Space
Lyapunov Exponent
Spectral Form Factor
Open Quantum System
Closed Quantum System

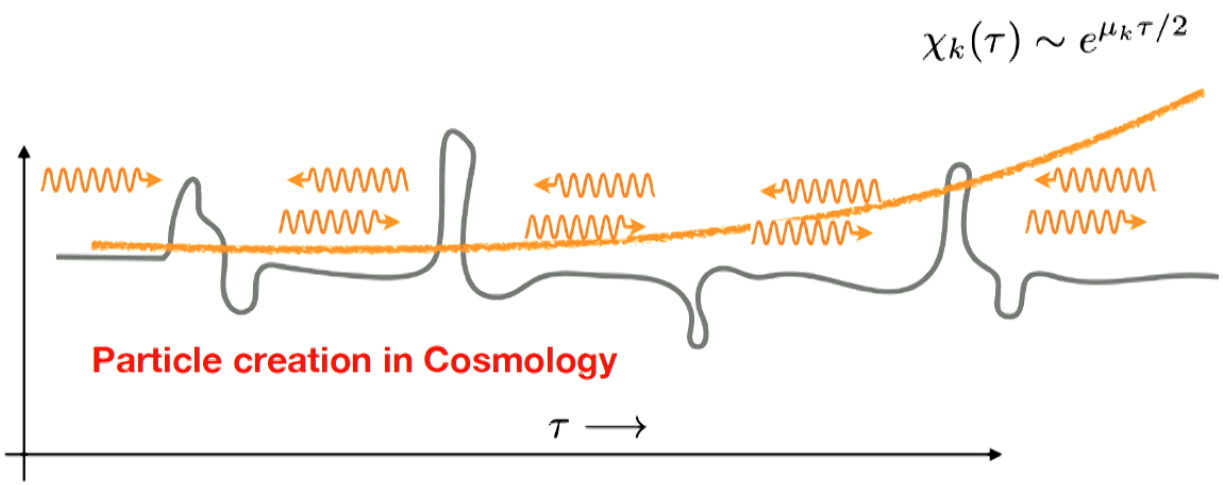
From conduction wires to Cosmology



$$\left[\frac{d^2}{dx^2} + E - V(x)\right]\psi(x) = 0 \quad \Longleftrightarrow \quad \left[\frac{d^2}{d\tau^2} + \left(k^2 + m^2(\tau)\right)\right]\phi_k(\tau) = 0$$

Scattering in conduction wire		Cosmological particle creation	
Symbol	**Physical interpretation**	**Symbol**	**Physical interpretation**
x	Distance	τ	Conformal time
V(x)	Potential	$-m^2(\tau)$	Time Dependent mass parameter
$\Psi(x)$	Wave Function	$\phi_k(\tau)$	Mode function in Fourier space
N_s	No. of Scatterers	N_s	No. of non-adiabatic events
Δx	Distance between scatterers	$\Delta\tau$	Time between non-adiabatic events
ξ	Localization length	μ_k	Mean particle production rate
$\rho(x)$	Resistance	$n_k(\tau)$	Particle occupation number
E	Energy eigen value	k^2	Wave number of Fourier modes
N_c	Number of channels	N_f	Number of fields


$\psi(x) = e^{-x/2\xi}$
Conduction Wire with impurity
$\longleftarrow x$


$\chi_k(\tau) \sim e^{\mu_k \tau/2}$
Particle creation in Cosmology
$\tau \longrightarrow$

Scattering problem with impurity in conduction wire

- Consider single impurity is localised at $x = x_j$.

- To the left (L) and the right (R) of the impurity potential, the wave-function can be written as a linear combination of right and the left-propagating waves:

$$\psi_\Delta(x) = \beta_\Delta \exp\left(ikx\right) + \alpha_\Delta \exp\left(-ikx\right) \qquad \text{where } \Delta = L, R,$$

- The map between the Bogoliubov coefficients (β_R, α_R) from the right (R) and (β_L, α_L) from the left (L) side can be expressed :

$$\mathscr{B}_R = \mathscr{M}_j \, \mathscr{B}_L, \qquad \mathscr{B}_\Delta = \begin{pmatrix} \beta_\Delta \\ \alpha_\Delta \end{pmatrix} \qquad \text{where } \Delta = L, R, \quad \mathscr{M}_j = \begin{pmatrix} \frac{1}{t_j^*} & \frac{-r_j^*}{t_j^*} \\ \frac{-r_j}{t_j} & \frac{1}{t_j} \end{pmatrix}$$

Scattering problem with impurity in conduction wire

- For N_s number of scatterers one can generalise the transfer matrix as:

$$\mathcal{M} \equiv \mathcal{M}(N_s) = \prod_{j=1}^{N_s} \mathcal{M}_j = \mathcal{M}_{N_s} \otimes \mathcal{M}_{N_s-1} \otimes \ldots\ldots \otimes \mathcal{M}_3 \otimes \mathcal{M}_2 \otimes \mathcal{M}_1$$

- For $N_s = 2$ number of scatterers transmission probability can be written as:

$$T = \frac{T_1 T_2}{|1 - \sqrt{R_1 R_2} e^{i\theta}|^2} \qquad T_j = t_j^* t_j, \quad R_j = r_j^* r_j \qquad \forall j = 1,2$$

$$\langle \log T \rangle_\theta = \log T_1 + \log T_2 + \underbrace{2\langle \log \left| 1 - \sqrt{R_1 R_2} e^{i\theta} \right| \rangle_\theta}_{=0} = \log \left(\prod_{j=1}^{2} T_j \right) = \sum_{j=1}^{2} \log T_j .$$

$$\langle \log T \rangle_\theta = \log \left(\prod_{j=1}^{N_s} T_j \right) = \sum_{j=1}^{N_s} \log T_j = -N_s \gamma$$ ← Lyapunov Exponent

Impurity and the associated phase is random and uniformly distributed over the range

$$0 < \theta < 2\pi$$

Dynamical study with time dependent protocols

$$S = -\frac{1}{2}\int d^4x\sqrt{-g}(g^{\mu\nu}\partial_\mu\chi\ \partial_\nu\chi - m^2(\tau)\chi^2) = \frac{1}{2}\int \frac{d^3k}{(2\pi)^3}d\tau\ a^2(\tau)\left|\frac{d\chi_k(\tau)}{d\tau}\right|^2 - a^2(\tau)(k^2+m^2(\tau))\,|\chi_k(\tau)|^2$$

$$\chi(-k,\tau) = \chi^*(k,\tau)$$

$$\chi(\mathbf{x},\tau) = \int \frac{d^3k}{(2\pi)^3}\ \chi_k(\tau)\ e^{i\mathbf{k}.\mathbf{x}}$$

$$a(\tau) = \begin{cases} -\frac{1}{H\tau}, & \text{De Sitter} \\ -\frac{1}{H\tau}(1+\epsilon), & \text{Quasi De Sitter} \end{cases},$$

$$\epsilon = -\frac{1}{H^2}\frac{dH}{dt} = -\frac{1}{a(\tau)H^2}\frac{dH}{d\tau}$$ **Slow-roll parameter**

Use field redefinition:

$$\phi_k(\tau) \equiv a(\tau)\ \chi_k(\tau)$$

$$S = \frac{1}{2}\int \frac{d^3k}{(2\pi)^3}d\tau\left(\left|\frac{d\phi_k(\tau)}{d\tau} - \frac{1}{a(\tau)}\frac{da(\tau)}{d\tau}\phi_k(\tau)\right|^2 - (k^2+m^2(\tau))\,|\phi_k(\tau)|^2\right)$$

$$\left[\frac{d^2}{d\tau^2} + \frac{1}{a(\tau)}\frac{da(\tau)}{d\tau}\frac{d}{d\tau} + \left(k^2 + m^2(\tau) - \left(\frac{1}{a(\tau)}\frac{da(\tau)}{d\tau}\right)^2\right)\right]\phi_k(\tau) = 0$$ **Klien Gordon equation**

Reheating approximation

$$k/a >> m >> H$$

$$\left[\frac{d^2}{d\tau^2} + (k^2 + m^2(\tau))\right]\phi_k(\tau) = 0$$

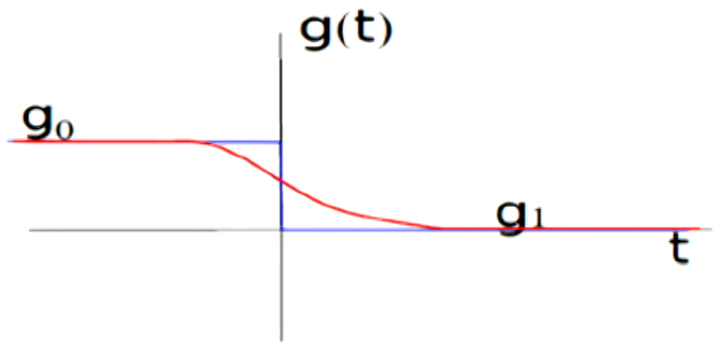
Our job is to solve this EOM for different time dependent protocols

What is Quantum Quench?

Quantum quench is a protocol in which one prepare a quantum system in an eigenstate of one Hamiltonian and then have the system evolve dynamically in time under a different Hamiltonian. After that the system thermalise. This change sometimes identified as quench.

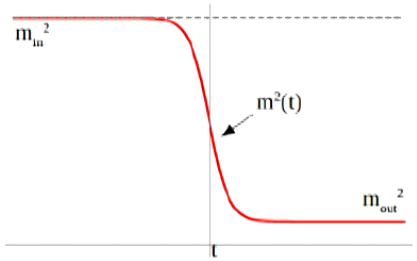
Consider a quantum system in its ground state. Turn on a time-dependent coupling $g(t)$ for some time up to $t = t_1$.

$$\text{e.g.} \quad H(t) = -J \sum_{i=1}^{L} [\sigma_i^x \sigma_{i+1}^x + g(t)\sigma_i^z]$$

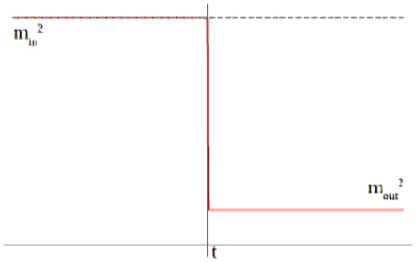


The post-quench dynamics is described by a final Hamiltonian H and an 'initial state' $|\psi_1\rangle$, which depends on $g(t)$.

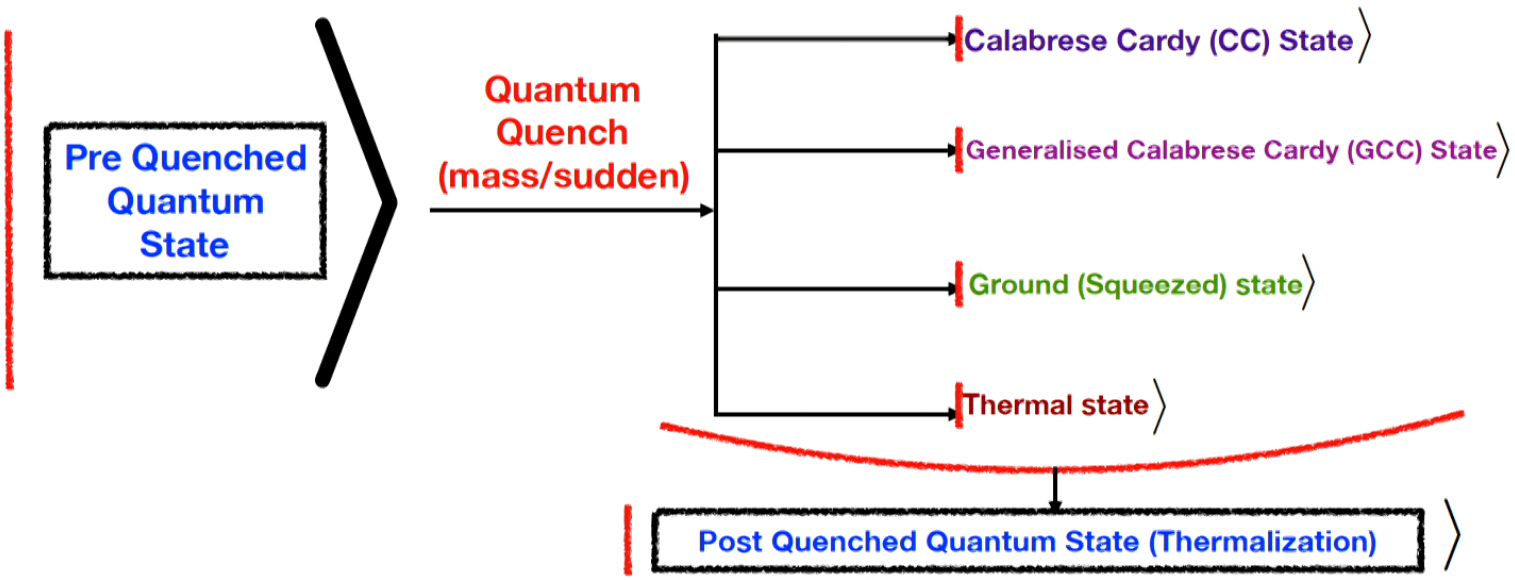
What is Quantum Quench?



(a) Mass quench



(b) Quench in sudden limit



Some technical details

$$|\psi(0)\rangle = |0_{in}\rangle = \exp\left[\frac{1}{2}\sum_{\vec{k}} \gamma(k) a^\dagger_{out}(\vec{k}) a^\dagger_{out}(-\vec{k})\right] |0_{out}\rangle$$

$$\gamma(k) = \beta^*(k)/\alpha^*(k)$$

$$|\psi(0)\rangle = |0_{in}\rangle = \exp\left[\frac{1}{2}\sum_{\vec{k}} \kappa(k) a^\dagger_{out}(\vec{k}) a_{out}(\vec{k})\right] \exp\left[-\frac{1}{2}\sum_{\vec{k}} a^\dagger_{out}(\vec{k}) a^\dagger_{out}(-\vec{k})\right] |0_{out}\rangle$$

$$\kappa(k) = -\frac{1}{2}\log(-\gamma(k)) = \sum_{i=1}^{\infty} \kappa_i k^{i-1} = \kappa_1 + \kappa_2 k + \kappa_3 k^2 + \ldots$$

$$|\psi(0)\rangle = |0_{in}\rangle = \exp\left[-\sum_{i=1}^{\infty} \kappa_i Q_i\right] \exp\left[-\frac{1}{2}\sum_{\vec{k}} a^\dagger_{out}(\vec{k}) a^\dagger_{out}(-\vec{k})\right] |0_{out}\rangle$$

$$Q_i = \sum_{\vec{k}} |\vec{k}|^{i-1} a^\dagger_{out}(\vec{k}) a_{out}(\vec{k})$$

$$|CC\rangle = \exp[-\kappa H]|\psi(0)\rangle$$

$$|gCC\rangle = \exp\left[-\sum_{i=1}^{\infty} \kappa_i Q_i\right]|\psi(0)\rangle$$

Some technical details

$$\kappa(k) = -\frac{1}{2}\log(-\gamma(k)) = \sum_{i=1}^{\infty} \kappa_i k^{i-1} = \kappa_1 + \kappa_2 k + \kappa_3 k^2 + \ldots$$

post-quench state	$\lvert gCC\rangle$	$\lvert CC\rangle\big\rvert_{m_{out}=0}$	$\lvert gCC_4\rangle\big\rvert_{m_{out}=0}$	$\lvert 0_{in}\rangle$
form of $\kappa(k)$	$\kappa(k)$	$\kappa_2 k$	$\kappa_2 k + \kappa_4 k^2$	$\frac{1}{2}\log\left(\frac{\sqrt{k^2+m^2}+\sqrt{k^2+m_{out}^2}}{\sqrt{k^2+m^2}-\sqrt{k^2+m_{out}^2}}\right)$

Quantum correlation due to quench

$\langle\psi(0)\|\phi(\vec{x_1},t)\phi(\vec{x_2},t)\|\psi(0)\rangle$		
$\|\psi(0)\rangle$	$\mathbf{d=3}$	$\mathbf{d=4}$
Ground state	$\frac{-m^2}{16\pi^{5/2}\sqrt{mt}}e^{-2mt}\left(1+\mathcal{O}(mr)^2\right)\left(1+\mathcal{O}(mt)^{-1}\right)$	$\frac{m}{128\pi^2}\frac{1}{t^2}+\mathcal{O}(\frac{1}{t^4})$
CC state	$\frac{-1}{16\kappa_2^2}e^{-\pi t/\kappa_2}(1+\mathcal{O}(\frac{r}{\kappa_2})^2)+\mathcal{O}\left(e^{-2\pi t/\kappa_2}\right)$	$\frac{1}{128\pi^2\kappa_2}\frac{1}{t^2}+\mathcal{O}(\frac{1}{t^4})$
gCC_4 state	$\frac{-(1+\pi^2\kappa_4+\cdots)}{16\kappa_2^2}e^{-\frac{\pi t}{\kappa_2}(1+\frac{\pi^2}{4}\kappa_4+\cdots)}(1+\mathcal{O}(\frac{r}{\kappa_2})^2)+\mathcal{O}\left(e^{-2\pi t/\kappa_2}\right)$	$\frac{1}{128\pi^2\kappa_2}\frac{1}{t^2}+\frac{3r^2+16\kappa_2^2+24\kappa_4/\kappa_2}{2048\pi^2\kappa_2}\frac{1}{t^4}+\mathcal{O}(\frac{1}{t^6})$

$$r \equiv \left|\vec{x}_1-\vec{x}_2\right|$$

Quantum correlation due to quench

$r \equiv |\vec{x}_1 - \vec{x}_2|$

$\langle\psi(0)\|\partial_t\phi(\vec{x_1},t)\partial_t\phi(\vec{x_2},t)\|\psi(0)\rangle$		
$\|\psi(0)\rangle$	$\mathbf{d=3}$	$\mathbf{d=4}$
Ground state	$\frac{-m^4}{16\pi^{3/2}\sqrt{mt}}e^{-2mt}\left(1+\mathcal{O}(mr)^2\right)\left(1+\mathcal{O}(mt)^{-1}\right)$	$\frac{3m}{256\pi^2}\frac{1}{t^4}+\mathcal{O}(\frac{1}{t^6})$
CC state	$\frac{-\pi^2}{64\kappa_2^4}e^{-\pi t/\kappa_2}(1+\mathcal{O}(\frac{r}{\kappa_2})^2)+\mathcal{O}\left(e^{-2\pi t/\kappa_2}\right)$	$\frac{3}{256\pi^2\kappa_2}\frac{1}{t^4}+\mathcal{O}(\frac{1}{t^6})$
gCC_4 state	$\frac{-\pi^2(1+\frac{3\pi^2\kappa_4}{2}+\cdots)}{64\kappa_2^4}e^{-\frac{\pi t}{\kappa_2}(1+\frac{\pi^2}{4}\kappa_4+\cdots)}(1+\mathcal{O}(\frac{r}{\kappa_2})^2)+\mathcal{O}\left(e^{-2\pi t/\kappa_2}\right)$	$\frac{3}{256\pi^2\kappa_2}\frac{1}{t^4}-\frac{15r^2+80\kappa_2^2+120\kappa_4}{2048\pi^2\kappa_2 t^6}+\mathcal{O}(\frac{1}{t^8})$

$\langle\psi(0)\|\partial_t\phi(\vec{x_1},t)\partial_t\phi(\vec{x_2},t)\|\psi(0)\rangle$		
$\|\psi(0)\rangle$	$\mathbf{d=1}$	$\mathbf{d=2}$
Ground state	$\frac{m^2}{8\pi^{1/2}\sqrt{mt}}e^{-2mt}\left(1+\mathcal{O}(mr)^2\right)\left(1+\mathcal{O}(mt)^{-1}\right)$	$-\frac{m}{32\pi t^2}+\mathcal{O}(\frac{1}{t^4})$
CC state	$\frac{\pi}{8\kappa_2^2}e^{-\pi t/\kappa_2}(1+\mathcal{O}(\frac{r}{\kappa_2})^2)+\mathcal{O}\left(e^{-2\pi t/\kappa_2}\right)$	$-\frac{1}{32\pi\kappa_2 t^2}+\mathcal{O}(\frac{1}{t^4})$
gCC_4 state	$\frac{\pi(1+\pi\kappa_4+\cdots)}{8\kappa_2^2}e^{-2t\left(\frac{\pi}{2\kappa_2}+\frac{\pi^3\kappa_4+\cdots}{8\kappa_2}\right)}(1+\mathcal{O}(\frac{r}{\kappa_2})^2)+\mathcal{O}\left(e^{-2\pi t/\kappa_2}\right)$	$-\frac{1}{32\pi\kappa_2 t^2}-\frac{8\kappa_2^3+12\kappa_4+3\kappa_2 r^2}{128\pi\kappa_2^3 t^4}+\mathcal{O}(\frac{1}{t^6})$

Quantum correlation due to quench

$r \equiv |\vec{x}_1 - \vec{x}_2|$

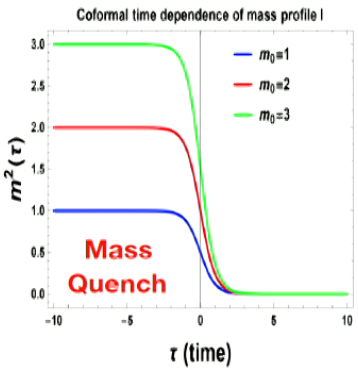
$\langle gCC\|\phi(\vec{x_1},t)\phi(\vec{x_2},t)\|gCC\rangle$	
$d=1$	$-\frac{\mathrm{csch}(2m_{out}\kappa_1)}{4\sqrt{\pi}}\cos\left(2m_{out}t+\frac{\pi}{4}\right)\frac{1}{\sqrt{m_{out}t}}+\mathcal{O}\left(\frac{1}{(m_{out}t)^{3/2}}\right)$
$d=2$	$-\frac{m_{out}\,\mathrm{csch}(2m_{out}\kappa_1)}{8\pi}\cos\left(2m_{out}t+\frac{\pi}{2}\right)\frac{1}{m_{out}t}+\mathcal{O}\left(\frac{1}{(m_{out}t)^{2}}\right)$
$d=3$	$-\frac{m_{out}^2\,\mathrm{csch}(2m_{out}\kappa_1)}{16\pi^{3/2}}\cos\left(2m_{out}t+3\frac{\pi}{4}\right)\frac{1}{(m_{out}t)^{3/2}}+\mathcal{O}\left(\frac{1}{(m_{out}t)^{5/2}}\right)$
$d=4$	$-\frac{m_{out}^3\,\mathrm{csch}(2m_{out}\kappa_1)}{32\pi^{2}}\cos\left(2m_{out}t+\pi\right)\frac{1}{(m_{out}t)^{2}}+\mathcal{O}\left(\frac{1}{(m_{out}t)^{3}}\right)$

$\langle 0_{in}\|\phi(\vec{x_1},t)\phi(\vec{x_2},t)\|0_{in}\rangle$	
$d=1$	$\frac{(m_{out}^2-m^2)}{8\sqrt{\pi}mm_{out}}\cos\left(2m_{out}t+\frac{\pi}{4}\right)\frac{1}{\sqrt{m_{out}t}}+\mathcal{O}\left(\frac{1}{(m_{out}t)^{3/2}}\right)$
$d=2$	$\frac{(m_{out}^2-m^2)}{16\pi m}\cos\left(2m_{out}t+\frac{\pi}{2}\right)\frac{1}{m_{out}t}+\mathcal{O}\left(\frac{1}{(m_{out}t)^{2}}\right)$
$d=3$	$\frac{(m_{out}^2-m^2)m_{out}}{32\pi^{3/2}m}\cos\left(2m_{out}t+\frac{3\pi}{4}\right)\frac{1}{(m_{out}t)^{3/2}}+\mathcal{O}\left(\frac{1}{(m_{out}t)^{5/2}}\right)$
$d=4$	$\frac{(m_{out}^2-m^2)m_{out}^2}{64\pi^{2}m}\cos\left(2m_{out}t+\pi\right)\frac{1}{(m_{out}t)^{2}}+\mathcal{O}\left(\frac{1}{(m_{out}t)^{3}}\right)$

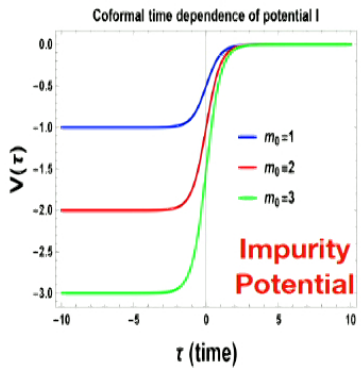
Quenched protocols:

$$m^2(\tau) = \begin{cases} \frac{m_0^2}{2}\left[1-\tanh(\rho\tau)\right], & \textbf{Profile I} \\ m_0^2\,\mathrm{sech}^2(\rho\tau), & \textbf{Profile II} \\ m_0^2\,\Theta(-\tau). & \textbf{Profile III} \end{cases},$$

Protocol I: $m^2(\tau) = m_0^2(1-\tanh(\rho\tau))/2$

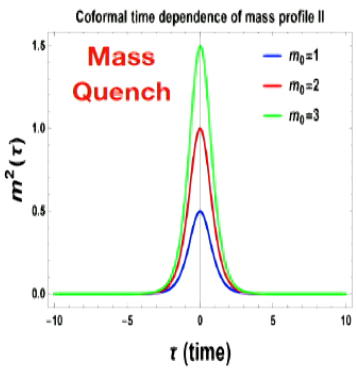


(a) $m^2(\tau)$ vs τ profile.

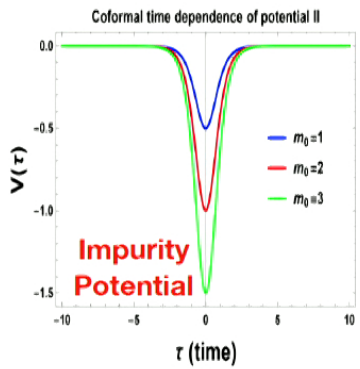


(b) $V(\tau)$ vs τ profile.

Protocol II: $m^2(\tau) = m_0^2\,\mathrm{sech}^2(\rho\tau)$

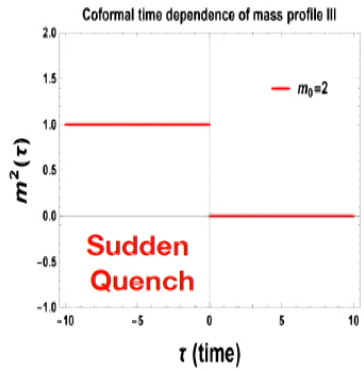


(a) $m^2(\tau)$ vs τ profile.

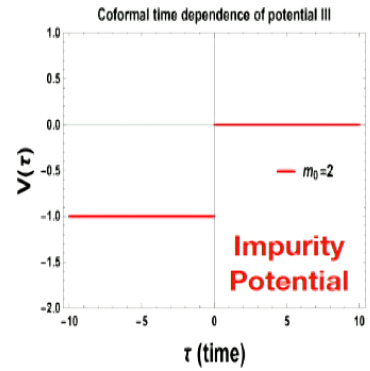


(b) $V(\tau)$ vs τ profile.

Protocol III: $m^2(\tau) = m_0^2\,\Theta(-\tau)$



(a) $m^2(\tau)$ vs τ profile.

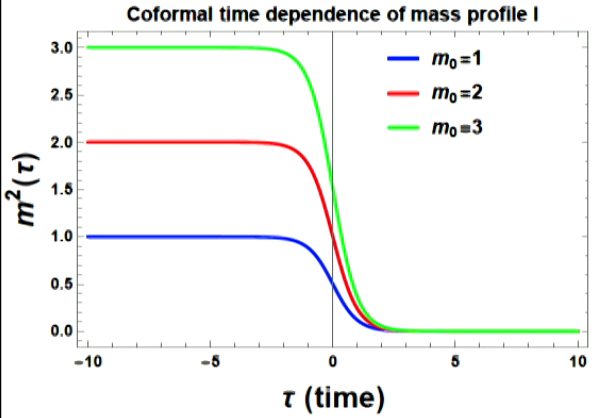


(b) $V(\tau)$ vs τ profile.

$$V(\tau) = \begin{cases} -\frac{m_0^2}{2}\left[1-\tanh(\rho\tau)\right], & \textbf{Profile I} \\ -m_0^2\,\mathrm{sech}^2(\rho\tau), & \textbf{Profile II} \\ -m_0^2\,\Theta(-\tau). & \textbf{Profile III} \end{cases}$$

Example:

$$m^2(\tau) = m_0^2(1 - \tanh(\rho\tau))/2$$



Quantum solution:

$$\phi_k(\tau) = a_{in}(k)u_{in}(k,\tau) + a_{in}^\dagger(-k)u_{in}^*(-k,\tau) = a_{out}(k)u_{out}(k,\tau) + a_{out}^\dagger(-k)u_{out}^*(-k,\tau)$$

$$a_{in}(k) = \alpha^*(k)a_{out}(k) - \beta^*(k)a_{out}^\dagger(-k), \quad a_{out}(k) = \alpha(k)a_{in}(k) + \beta^*(k)a_{in}^\dagger(-k)$$

$$u_{in}(k,\tau) = \frac{e^{-i\omega_{in}\tau}}{\sqrt{2\omega_{in}}}\, {}_2F_1\left(\frac{i\omega_-}{\rho}, -\frac{i\omega_+}{\rho}; 1 - \frac{i\omega_{in}}{\rho}; -e^{2\rho\tau}\right)$$

$$u_{out}(k,\tau) = \frac{e^{-i\omega_{out}\tau}}{\sqrt{2\omega_{out}}}\, {}_2F_1\left(\frac{i\omega_-}{\rho}, \frac{i\omega_+}{\rho}; \frac{i\omega_{out}}{\rho} + 1; -e^{-2\rho\tau}\right)$$

$$\omega_{in} = \sqrt{k^2 + m_0^2}, \quad \omega_{out} = |k|, \quad \omega_\pm = \frac{1}{2}(\omega_{out} \pm \omega_{in}).$$

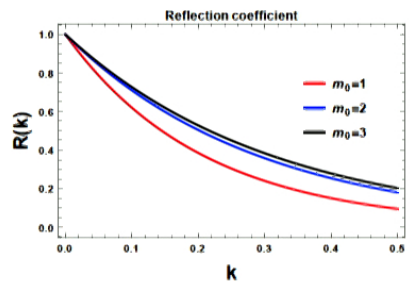
Bogoliubov coefficients:

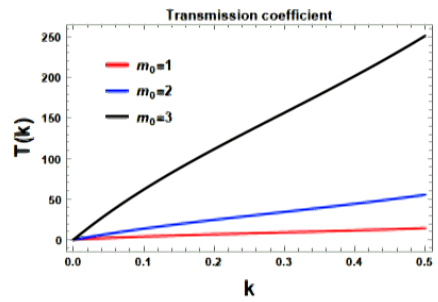
$$\alpha(k) = \sqrt{\frac{\omega_{out}}{\omega_{in}}}\, \frac{\Gamma\left(-\frac{i\omega_{out}}{\rho}\right)\Gamma\left(1 - \frac{i\omega_{in}}{\rho}\right)}{\Gamma\left(-\frac{i\omega_+}{2\rho}\right)\Gamma\left(1 - \frac{i\omega_+}{2\rho}\right)} \qquad \beta(k) = \sqrt{\frac{\omega_{out}}{\omega_{in}}}\, \frac{\Gamma\left(\frac{i\omega_{out}}{\rho}\right)\Gamma\left(1 - \frac{i\omega_{in}}{\rho}\right)}{\Gamma\left(\frac{i\omega_-}{2\rho}\right)\Gamma\left(1 + \frac{i\omega_-}{2\rho}\right)}$$

Optical properties:

$$T(k) = 1/|\alpha(k)|^2, R(k) = |\beta(k)|^2/|\alpha(k)|^2,$$

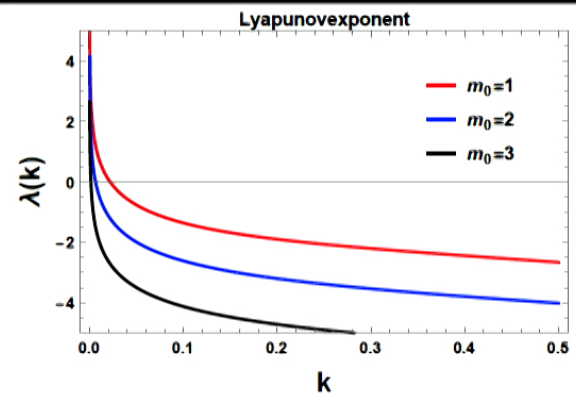
$$|\alpha(k)|^2 - |\beta(k)|^2 = 1 \Rightarrow R + T = 1$$





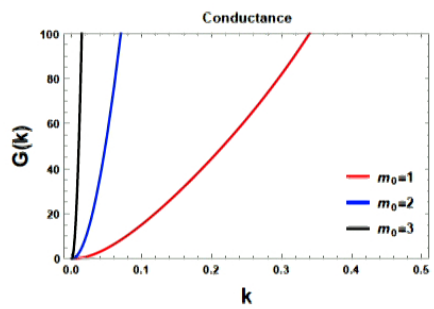
Chaotic property:

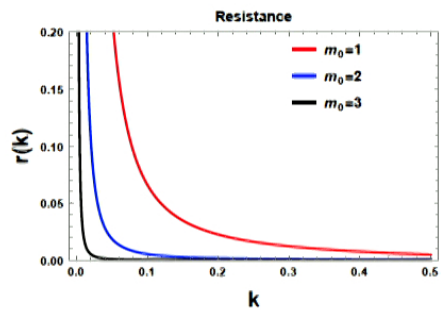
$$\lambda(k) = -\log T(k) = 2\log|\alpha(k)|$$



Conduction properties:

$$r(k) = 1/G(k) = \exp(2\lambda(k))$$





What is OTOC ?

- Out-of-time-ordered correlator (OTOC) is something like

$$\langle \hat{A}(t)\hat{B}(t')\hat{A}(t)\hat{B}(t')\rangle \qquad (t \neq t')$$

Larkin, Ovchinnikov (1968)

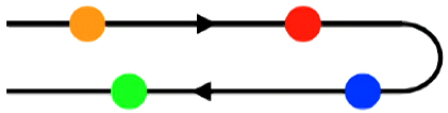
- More precisely, we define

Time-ordered correlator: $\langle \hat{O}_1(t_1)\hat{O}_2(t_2)\cdots\hat{O}_i(t_i)\cdots\hat{O}_{n-1}(t_{n-1})\hat{O}_n(t_n)\rangle$

where $t_1 \leq t_2 \leq \cdots \leq t_i \geq \cdots \geq t_{n-1} \geq t_n$

$\langle\cdots\rangle \equiv \mathrm{Tr}(\hat{\rho}\cdots)$ $\quad \hat{O}_i$: Hermite

$\hat{\rho} = e^{-\beta\hat{H}}/Z$



Out-of-time-ordered correlator is defined as those that cannot be written in the above form.

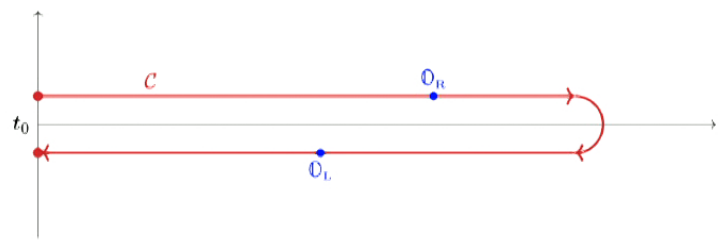
What is OTOC ?

- Out-of-time-ordered correlator (OTOC) is something like

$$\langle \hat{A}(t)\hat{B}(t')\hat{A}(t)\hat{B}(t')\rangle \qquad (t \neq t')$$

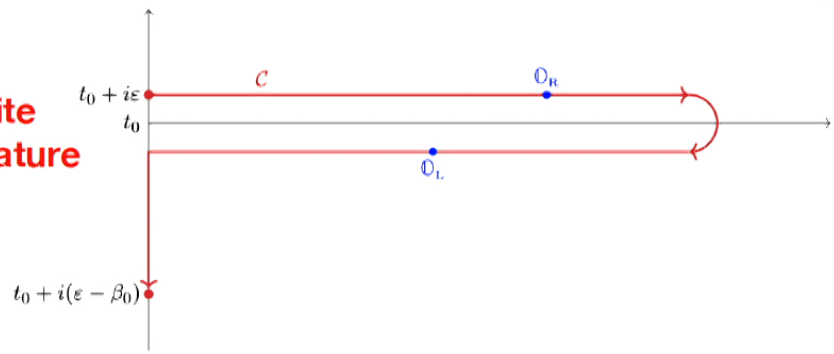
Larkin, Ovchinnikov (1968)

At zero temperature



Schwinger Keldysh formalism

At finite temperature



Why out-of-time-order correlators?

- A test for black hole horizons? $\lambda_L = \frac{2\pi}{\beta}$ and MSS bound
- Probe of quantum chaos, access finite N effects
- Probe of thermalization, localization vs thermalization
- Bounds on transport? Other bounds on quantum dynamics?
- Precision measurement? [Davis-Bentsen-Schleier-Smith PRL '16]
- Probe of new physics in Cosmology (reheating)

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OTOC in QFT

- Non-equilibrium physics is described by OTOC: $\langle W(\tau)\rangle_\beta = 0 = \langle V(0)\rangle_\beta$

$$\mathscr{C}(\tau) = -\left\langle \left[W(\tau), V(0)\right]^2 \right\rangle = -\frac{1}{Z}\mathrm{Tr}\left\{\exp(-\beta H)\left[W(\tau), V(0)\right]^2\right\}$$ **(Hermitian)**

$$\mathcal{C}(\tau) = -\langle [W(\tau), V(0)]^\dagger [W(\tau), V(0)]\rangle = -\frac{1}{Z}\mathrm{Tr}\left\{\exp(-\beta H)\,[W(\tau), V(0)]^\dagger [W(\tau), V(0)]\right\},$$ **(Not-Hermitian)**

$$Z = \mathrm{Tr}\left\{\exp[-\beta H]\right\}$$ **(Partition function)**

$$X(t) = e^{iHt}\, X(0)\, e^{-iHt}$$

(Heisenberg picture)

Hamiltonian of the QFT model

$$\beta = \frac{1}{T} \quad \text{with } k_B = 1$$

OTOC in QFT

- Non-equilibrium physics is described by OTOC: $\langle W(\tau)\rangle_\beta = 0 = \langle V(0)\rangle_\beta$

$$\mathcal{C}(\tau) = -\mathrm{Tr}\left\{\rho\,[W(\tau), V(0)]^2\right\},$$ **(Hermitian)**

$$\rho = \frac{1}{Z}\, e^{-\beta H}$$

Thermal Density Matrix

$$\mathcal{C}(\tau) = -\mathrm{Tr}\left\{\rho\,[W(\tau), V(0)]^\dagger\,[W(\tau), V(0)]\right\},$$ **(Not-Hermitian)**

$$Z = \mathrm{Tr}\left\{\exp[-\beta H]\right\}$$ **(Partition function)**

$$X(t) = e^{iHt}\, X(0)\, e^{-iHt}$$

(Heisenberg picture)

Hamiltonian of the QFT model

$$\beta = \frac{1}{T} \quad \text{with } k_B = 1$$

- OTOC actually captures the effect of perturbation by the operator V(0) on the later time measurement on the operator $W(\tau)$

- Two point function (commutator) decay in the large time limit, Three point function (and any odd point) are zero due to the he Kubo Martin Schwinger (KMS) condition (time translational symmetry), which can be shown using Schwinger Keldysh formalism of the closed time path of the real time finite temperature field theory .

- Four point function (square of commutator) good measure for OTOC.

OTOC in QFT

- Any 2n (n=2,3,4…) higher point functions are allowed to quantify OTOC:

$$C(t) = \langle X(t)Y(0)Y(0)X(t)\rangle_\beta + \langle Y(0)X(t)X(t)Y(0)\rangle_\beta - 2\,\mathrm{Re}\left[\langle Y(0)X(t)X(t)Y(0)\rangle_\beta\right]$$

$$t >> t_d \sim \beta = \frac{1}{T}$$ **(Dissipation time scale)**

$$\langle X(t)Y(0)Y(0)X(t)\rangle_\beta \approx \langle X(t)X(t)\rangle_\beta\langle Y(0)Y(0)\rangle_\beta + \mathcal{O}\left(e^{-t/t_d}\right),$$

$$\langle Y(0)X(t)X(t)Y(0)\rangle_\beta \approx \langle X(t)X(t)\rangle_\beta\langle Y(0)Y(0)\rangle_\beta + \mathcal{O}\left(e^{-t/t_d}\right).$$

$$C(t) = 2\,\left\{\langle X(t)X(t)\rangle_\beta\langle Y(0)Y(0)\rangle_\beta - \mathrm{Re}\left[\langle Y(0)X(t)X(t)Y(0)\rangle_\beta\right]\right\} + \mathcal{O}\left(e^{-t/t_d}\right)$$

$$\mathcal{C}(t) = \frac{C(t)}{\langle X(t)X(t)\rangle_\beta\langle Y(0)Y(0)\rangle_\beta} = -\frac{\langle [X(t),Y(0)]^2\rangle_\beta}{\langle X(t)X(t)\rangle_\beta\langle Y(0)Y(0)\rangle_\beta} \approx 2\left\{1 - \frac{\mathrm{Re}\left[\langle Y(0)X(t)X(t)Y(0)\rangle_\beta\right]}{\langle X(t)X(t)\rangle_\beta\langle Y(0)Y(0)\rangle_\beta}\right\}$$

Normalized four point OTOC

OTOC in QFT

For Chaotic OTOC:

$$\mathcal{C}(t) \approx 2\left\{1 - \frac{1}{N^2}e^{\lambda_L t} + \mathcal{O}\left(\frac{1}{N^4}\right)\right\} \implies \lambda_L \approx \frac{1}{t}\ln\left(N^2 \frac{\mathrm{Re}\left[\langle Y(0)X(t)X(t)Y(0)\rangle_\beta\right]}{\langle X(t)X(t)\rangle_\beta \langle Y(0)Y(0)\rangle_\beta}\right)$$

$$N \sim \frac{1}{\sqrt{G_N}} = \sqrt{8\pi}M_{\mathrm{P}}$$ **(Number of dof)**

$$\lambda_L \leq \frac{2\pi}{\beta} = 2\pi T \quad \text{where} \quad \beta = \frac{1}{T} \quad \text{with} \quad \hbar = 1 = c, \quad k_B = 1$$

Ref.: Maldacena, Shenker and Stanford, arXiv: 1503.01409, JHEP 08 (2016) 106

$$\boxed{\frac{\mathrm{Re}\left[\langle Y(0)X(t)X(t)Y(0)\rangle_\beta\right]}{\langle X(t)X(t)\rangle_\beta \langle Y(0)Y(0)\rangle_\beta} \leq \frac{1}{N^2}\, e^{\frac{2\pi t}{\beta}}}$$

OTOC in QFT

QUASICLASSICAL METHOD IN THE THEORY OF SUPERCONDUCTIVITY

A. I. LARKIN and Yu. N. OVCHINNIKOV

Institute of Theoretical Physics, USSR Academy of Sciences

Submitted June 6, 1968

Zh. Eksp. Teor. Fiz. 55, 2262–2272 (December, 1968)

It is shown that replacement of quantum-mechanical averages by the average values of the corresponding classical quantities over all trajectories with a prescribed energy is not valid in the general case. The dependence of the penetration depth on the field is found without making any assumptions about the weakness of the interaction between the electrons and the field of the impurities; the case of very dirty films is also considered.

$$\langle [p_z(t)\, p_z(0)]^2 \rangle = h^2 \left\langle \left(\frac{\partial \mathbf{p}_z(t)}{\partial z(0)} \right)^2 \right\rangle, \tag{26}$$

$$X_j^i = \left\langle \left(\frac{\partial p_i(t)}{\partial r_j(0)} \right)^2 \right\rangle \qquad X_j^i = \frac{m^2}{18} \left[\frac{1}{t_0^2} f\left(\frac{t}{t_0}\right) (3\delta_{ij} - 1) + \frac{1}{t_1^2} f\left(\frac{t}{t_1}\right) \right], \tag{30}$$

$$f(t) = e^t + 2e^{-t/2} \sin\left(\frac{\sqrt{3}}{2} t - \frac{\pi}{6} \right)$$

At large times the wave packet is completely washed out. In order to evaluate the average of the square of the commutator in this region, it is necessary to use not the quasiclassical formulas (26) and (30) but the difference between expressions (25) and (24).

OTOC in QFT

Semiclassical limit:

Early times

$$X(t) = e^{iq(t)/a},\ Y(0) = e^{ip(0)/b},\ \mathcal{C}(t) = 2\left[1 - e^{-\langle[q(t),p(0)]\rangle/ab}\right] + \cdots$$

Butterfly effect

$$\langle[q(t),p(0)]\rangle \approx i\,\{q(t),p(0)\}_{\rm PB} = i\frac{\partial q(t)}{\partial q(0)} = i\ e^{\lambda_L t}$$

:Ehrenfest time scale:
time scale for significant decay of

$$e^{-\langle[q(t),p(0)]\rangle/ab}$$

$$t_* = \frac{1}{\lambda_L}\ln(ab) = \frac{1}{\lambda_L}\ln(N)$$

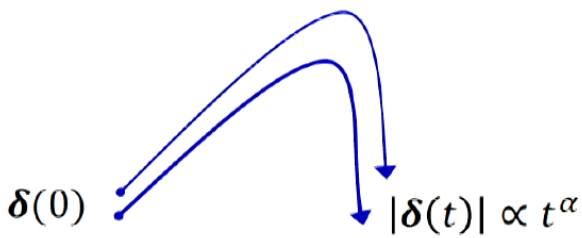
OTOC in QFT

Classical chaos: Instability of trajectories

- Quantified by the **Lyapunov exponent**

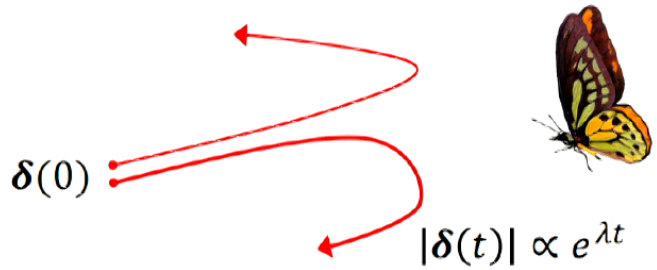
$$\lambda \equiv \max_{\boldsymbol{\delta}(0)} \lim_{t\to\infty} \frac{1}{t} \ln \frac{|\boldsymbol{\delta}(t)|}{|\boldsymbol{\delta}(0)|}$$

Stable (regular, quasiperiodic) trajectories



At most **polynomial** divergence

Unstable (chaotic) trajectories



Exponential divergence

(of a bunch of neigbouring trajectories)

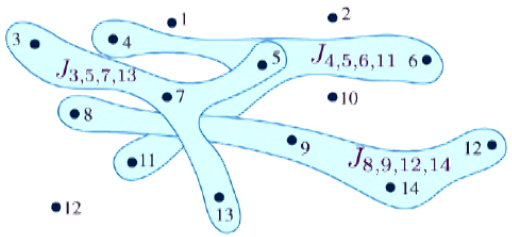
OTOC in QFT

Sachdev-Ye-Kitaev model

- Random all-to-all interacting Majorana fermions:

$$H = \frac{1}{4!}\sum_{i,j,k,l=1}^{N} J_{ijkl}\psi_i\psi_j\psi_k\psi_l$$

Kitaev (2015)



$$\overline{J^2_{ijkl}} = \frac{3!J^2}{N^3}, \quad \overline{J_{ijkl}} = 0 \quad \{\psi_i, \psi_j\} = \delta_{ij}$$

- The model is maximally chaotic, i.e.,

$$\langle\psi_i(t)\psi_j(0)\psi_i(t)\psi_j(0)\rangle \sim f_0 - \frac{f_1}{N}\exp\left(\frac{2\pi t}{\beta}\right) + O(N^{-2})$$

- Holographic dual to black holes.

$$\frac{\mathrm{tr}[\rho^{\frac{1}{2}}W(t)\varphi(0)\rho^{\frac{1}{2}}W(t)\varphi(0)]}{\mathrm{tr}[\rho^{\frac{1}{2}}W\rho^{\frac{1}{2}}W]} \sim c_0 - c_1\exp\left(\frac{2\pi t}{\beta}\right) + \cdots$$

Shenker, Stanford (2014, 2015), …

OTOC in QFT

For Harmonic oscillator:

Semiclassical and classical both results are same.

$$x(t) = x(0)\cos\omega t + \frac{2}{\omega}p(0)\sin\omega t,$$

$$p(t) = p(0)\cos\omega t - \frac{\omega}{2}x(0)\sin\omega t$$

$$\mathcal{C}(t) = -\langle[x(t), p(0)]^2\rangle = -(i\cos\omega t)^2 = \cos^2\omega t$$

In Cosmology: Quantum correlations during reheating

$$\mathcal{C}(t) = -\langle[\phi(t), \Pi_\phi(0)]^2\rangle, -\langle[\phi(t), \phi(0)]^2\rangle, -\langle[\Pi_\phi(t), \Pi_\phi(0)]^2\rangle$$

or

$$\mathcal{C}(t) = -\langle[\zeta(\mathbf{k}, t), \Pi(\mathbf{k}, 0)]^2\rangle, -\langle[\zeta(\mathbf{k}, t), \zeta(\mathbf{k}, 0)]^2\rangle, -\langle[\Pi(\mathbf{k}, t), \Pi(\mathbf{k}, 0)]^2\rangle$$

OTOC in the Sky

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Abstract

The out-of-time-ordered correlation (OTOC) function is treated as a measure of quantum chaos in the context of condensed matter field theory when the system is out-of-equilibrium. We demonstrate a method using which one can explicitly compute the expression for the OTOC for out-of-equilibrium quantum field theory (OOEQFT) with a general Hamiltonian in presence of curved gravitational background geometry. We demonstrate explicit calculations of OTOCs for a massless, partially massless and massive scalar field in the planar coordinate patch of De Sitter space. For these cases, we show that OTOCs are periodic in time coordinate because of their commensurable energy spectra. Further, we also demonstrate the classical limit of the OTOC to comment on getting the classical chaos from the present three different cases in the inflationary patch of De Sitter space. Next, we compute the expression for Lyapunov exponent and verify that whether our derived result is consistent with the saturation bound obtained for quantum chaos in finite temperature quantum field theory setup, $\lambda_L \leq 2\pi/\beta$, where β is the inverse of the De Sitter temperature. Further, we have studied contour dependence in the regularised OTOC which lead to contour independence of physical Lyapunov spectra of De Sitter space. Next, we provide a kinetic theory interpretation of the regularized OTOC. Also, we discuss the relation between experimentally measured quantity, the Loschmidt echo and the regularised OTOC in De Sitter space. We have also studied the classical limit of the OTOC derived in the De Sitter space. Finally, using the obtained results from OTOC we propose new time dependent cosmological correlation function, which can be treated as new theoretical probe in the context of primordial cosmology (specifically for reheating).

Keywords: Out of equilibrium QFT, QFT of De Sitter space, Theoretical Cosmology.

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[2] *NOTE: This project is the part of the non-profit virtual international research consortium "Quantum Structures of the Space-Time & Matter".*

upcoming work

OTOC from RMT: Alternative approach to Cosmology

RMT basics

- Here one can consider GUE, GSE, GOE, CUE etc statistical ensembles.

- If the Hamiltonian is time-reversal symmetric the required distribution will be invariant under orthogonal transformation. Else, it is invariant under unitary transformation.

- In the thermodynamic limit (N → ∞) eigen value of density of random matrices showed a universal behaviour characterised by Wigner's Semicircle law.

- The results seemed to be applicable to a varied class of quantum system displaying chaotic behaviour. Chaos was also a hallmark of a few-body Hamiltonian (N finite), but better diagnostic for quantum systems was devised in which nearest neighbour spacing distribution (NNSD) of eigenvalues of the system will be chaotic if distribution is Wigner Dyson type:

$$P(\omega) = A_\gamma \omega^\gamma e^{-\gamma\omega}, \quad \gamma = 1 \text{ (GOE)}, \; 2 \text{ (GUE)}, \quad 4 \text{ (GSE)}$$

RMT basics

Wigner Dyson Statistical Ensembles

Element of matrix	Type of ensemble	Relation
Elements are real +symmetric	(GOE) Gaussian Orthogonal Ensemble	time reversal symmetric Hamiltonian
Elements are complex + Hermitian	(GUE) Gaussian Unitary Ensemble	broken time reversal symmetric Hamiltonian
Elements are quaternion + Hermitian	(GSE) Gaussian Sympletic Ensemble	-

Properties of Gaussian matrix ensemble in Random Matrix Theory (RMT).

The joint probability distribution of such random matrix, which is characterized by the Gaussian potential is given by the following expression:

$$P(M)dM = \exp\left(-\frac{1}{2}trM^2\right)dM = \exp\left(-\frac{1}{2}\sum_{i=1}^{N}x_{ii}^2\right)\exp\left(-\sum_{i\neq j}^{N}x_{ii}^2\right)\prod_{i\leqslant j=1}^{N}dx_{ij}.$$

N= rank of the random matrix M

$$M \to U^{-1}MU \Longrightarrow P(U^{-1}MU) = P(M)$$

U=Orthogonal/Unitary similar matrix

RMT basics

β	Ensemble type	Gaussian ensemble	E_N^β	Circular ensemble	U_N^β
1	orthogonal	GOE	S_N	COE	O_N
2	unitary	GUE	H_N	CUE	U_N
4	symplectic	GSE	Q_N	CSE	Sp_{2N}

- the *Circular Orthogonal Ensemble* **COE** of real orthogonal matrices,
- the *Circular Unitary Ensemble* **CUE** of complex unitary matrices,
- the *Circular Symplectic Ensemble* **CSE** of complex symplectic matrices.

RMT basics

Partition function: $$Z = \int dM \; e^{-\mathrm{Tr}[V(M)]}$$

V(M)=Random Potential

$$M = U^{-1}\Lambda U, \quad \Lambda = \mathrm{diag}(\lambda_i) \forall \; i = 1, \cdots, N$$

$$dM = \prod_{1 \le i \le j \le N} |\lambda_i - \lambda_j|^\beta \prod_{k=1}^{N} d\lambda_k \; dU_{\mathrm{Haar}}$$

Integral measure:

A. Wigner Dyson ensembles: **(3 ensambles)**

$$dM = \prod_{i<j} |\lambda_i - \lambda_j|^\gamma \prod_k d\lambda_k \quad \gamma = 1 \; (\mathrm{GOE}), 2 \; (\mathrm{GUE}), 4 \; (\mathrm{GSE})$$

B. Altland-Zirnbauer ensembles: (α, γ) ensemble

$$dM = \prod_{i<j} |\lambda_i^2 - \lambda_j^2|^\gamma \prod_k |\lambda_k|^\alpha d\lambda_k$$ **(7 ensambles)**

Total ensembles in RMT= 3 (Wigner Dyson)+7(Altland Zirnbauer)=10

RMT basics

$$Z = \prod_{i=1}^{N} \int d\lambda_i \; e^{-N^2 S(\lambda_1, \cdots, \lambda_N)}, \quad \gamma = 1 \text{ (GOE)}, 2 \text{ (GUE)}, 4 \text{ (GSE)}$$

$$S(\lambda_1, \cdots, \lambda_N) = \frac{1}{N} \sum_{i=1}^{N} V(\lambda_i) + \gamma \sum_{i<j}^{N} \ln |\lambda_i - \lambda_j|$$

RMT basics

The solution obtained in the large N limit is analogues to the solution obtained from the WKB approximation in Schrödinger equation.

General Distribution function for random eigenvalues

$$\rho(\lambda) = \frac{1}{2\pi}\mathcal{R}(\lambda)\sqrt{-\Sigma(\lambda)} = \frac{1}{2\pi}\sum_{k=1}^{\infty} a_{n-k}\lambda^{(n-k+1)}\prod_{i=1}^{n}(\lambda - a_{2i-1})(\lambda - a_{2i}) \quad \forall \text{ general } n,$$

$$\mathcal{R}(\lambda) = \sum_{k=1}^{\infty} a_{n-k}\lambda^{(n-k+1)} \qquad \forall \text{ general } n,$$

$$\Sigma(\lambda) = \prod_{i=1}^{n}(\lambda - a_{2i-1})(\lambda - a_{2i}) \qquad \forall \text{ general } n.$$

:NOTE:

All the coefficients are determined using the method of resolvent which captures the spectral properties of an operator (spectral decomposition) in the analytic structure of the holomorphic functional in complex plane.

RMT basics

Cornell University

We gratefully acknowledge support from the Simons Foundation and member institutions.

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High Energy Physics - Theory

JT Gravity and the Ensembles of Random Matrix Theory

Douglas Stanford, Edward Witten

(Submitted on 7 Jul 2019 (v1), last revised 22 Jul 2019 (this version, v2))

We generalize the recently discovered relationship between JT gravity and double-scaled random matrix theory to the case that the boundary theory may have time-reversal symmetry and may have fermions with or without supersymmetry. The matching between variants of JT gravity and matrix ensembles depends on the assumed symmetries. Time-reversal symmetry in the boundary theory means that unorientable spacetimes must be considered in the bulk. In such a case, the partition function of JT gravity is still related to the volume of the moduli space of conformal structures, but this volume has a quantum correction and has to be computed using Reidemeister-Ray-Singer "torsion." Presence of fermions in the boundary theory (and thus a symmetry $(-1)^F$) means that the bulk has a spin or pin structure. Supersymmetry in the boundary means that the bulk theory is associated to JT supergravity and is related to the volume of the moduli space of super Riemann surfaces rather than of ordinary Riemann surfaces. In all cases we match JT gravity or supergravity with an appropriate random matrix ensemble. All ten standard random matrix ensembles make an appearance -- the three Dyson ensembles and the seven Altland-Zirnbauer ensembles. To facilitate the analysis, we extend to the other ensembles techniques that are most familiar in the case of the original Wigner-Dyson ensemble of hermitian matrices. We also generalize Mirzakhani's recursion for the volumes of ordinary moduli space to the case of super Riemann surfaces.

Comments: 106 pages plus appendices. v2: new section 5.5; minor corrections especially in Appendix A; references added

Subjects: **High Energy Physics - Theory (hep-th)**; Mathematical Physics (math-ph); Algebraic Geometry (math.AG); Geometric Topology (math.GT)

Cite as: arXiv:1907.03363 [hep-th]
(or arXiv:1907.03363v2 [hep-th] for this version)

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RMT basics

Cornell University

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Mathematical Physics

Random matrices

Bertrand Eynard, Taro Kimura, Sylvain Ribault

(Submitted on 15 Oct 2015 (v1), last revised 5 Jul 2018 (this version, v2))

We provide a self-contained introduction to random matrices. While some applications are mentioned, our main emphasis is on three different approaches to random matrix models: the Coulomb gas method and its interpretation in terms of algebraic geometry, loop equations and their solution using topological recursion, orthogonal polynomials and their relation with integrable systems. Each approach provides its own definition of the spectral curve, a geometric object which encodes all the properties of a model. We also introduce the two peripheral subjects of counting polygonal surfaces, and computing angular integrals.

Comments: 196 pages, v2: major revision and expansion, 32 exercises added
Subjects: **Mathematical Physics (math-ph)**; Statistical Mechanics (cond-mat.stat-mech); High Energy Physics - Theory (hep-th)
Cite as: arXiv:1510.04430 [math-ph]
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Greg W. Anderson, Alice Guionnet, Ofer Zeitouni

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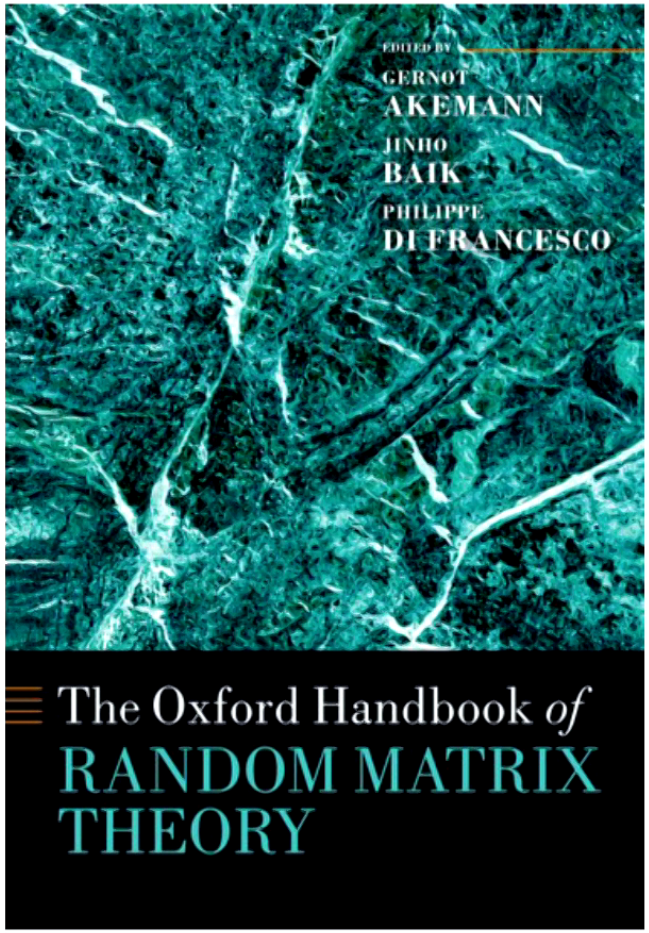
RMT basics



Good reference

OTOC in RMT

GUE 2 point function:

$$\langle \mathcal{O}_1(0)\mathcal{O}_2(t)\rangle_{\rm GUE} = \int dH\ \langle \mathcal{O}_1(0)\mathcal{O}_2(t)\rangle$$

$$\mathcal{O}_2(t) = e^{-iHt}\mathcal{O}_2(0)e^{iHt} \text{ Heisenberg Picture}$$

$$H \to UHU^\dagger \Longrightarrow d(UHU^\dagger) = dH$$

Connected 2 point function

$$\langle\langle \mathcal{O}_1\mathcal{O}_2\rangle\rangle_C = \langle \mathcal{O}_1\mathcal{O}_2\rangle - \langle \mathcal{O}_1\rangle\langle \mathcal{O}_2\rangle.$$

Spectral Form Factor

$$\langle \mathcal{O}_1(0)\mathcal{O}_2(t)\rangle_{\rm GUE} = \int\int dH\ dU\ \langle \mathcal{O}_1(0)U\ e^{-iHt}\ U^\dagger\mathcal{O}_2(0)U\ e^{iHt}U^\dagger\rangle = \langle \mathcal{O}_1\rangle\langle \mathcal{O}_2\rangle + \frac{\mathbf{SFF}(t)-1}{\mathcal{I}^2-1}\langle\langle \mathcal{O}_1\mathcal{O}_2\rangle\rangle_{\rm C}$$

Dimensionality of the Hilbert space

$$\boxed{\langle \mathcal{O}_1(0)\mathcal{O}_2(\tau)\rangle_{\rm GUE} = \begin{cases} \dfrac{\mathbf{SFF}(\tau)-1}{\mathcal{I}^2-1}, & \mathcal{O}_1 = \mathcal{O}_2 \\ 0, & \mathcal{O}_1 \neq \mathcal{O}_2 \end{cases},}$$

Special case:

$$\langle \mathcal{O}_1(0)\mathcal{O}_2(t)\rangle_{\rm GUE} = \frac{\mathbf{SFF}(t)}{\mathcal{I}^2} \quad \text{when} \quad \mathcal{O}_2(t) = \mathcal{O}_1^\dagger, \quad \mathbf{SFF(t)} >> 1$$

OTOC in RMT

GUE 4 point function:

$$\langle \mathcal{O}_1(0)\mathcal{O}_2(\tau)\mathcal{O}_3(0)\mathcal{O}_4(\tau)\rangle_{\rm GUE} = \int\int dH\ dU\ \langle \mathcal{O}_1 U \exp[-iH\tau]U^\dagger \mathcal{O}_2 U \exp[iH\tau]U^\dagger \mathcal{O}_3 U \exp[-iH\tau]U^\dagger \mathcal{O}_4 U \exp[iH\tau]U^\dagger\rangle,$$

576 terms in the expansion

$$\langle \mathcal{O}_1(0)\mathcal{O}_2(\tau)\mathcal{O}_3(0)\mathcal{O}_4(\tau)\rangle_{\rm GUE} \simeq \langle \mathcal{O}_1\mathcal{O}_2\mathcal{O}_3\mathcal{O}_4\rangle \times \frac{\mathbf{SFF}_4(\tau)}{\mathcal{I}^4},$$

Dimensionality of the Hilbert space

Four point Spectral Form Factor

$$\begin{aligned}\mathbf{SFF}_4(\tau) &\equiv \langle Z(\tau)Z(\tau)Z^*(\tau)Z^*(\tau)\rangle_{\rm GUE}\\ &= \int D\lambda \sum_{i,j,k,l} \exp[i(\lambda_i+\lambda_j+\lambda_k+\lambda_m)\tau]\\ &= \mathcal{I}^4 \frac{J_1^4(2\tau)}{\tau^4} + \frac{\tau}{2}(\tau-2)\\ &\sim \frac{\mathcal{I}^6}{\pi^2\tau^6} + \frac{\tau}{2}(\tau-2),\end{aligned}$$

For any general 2p point GUE OTOC:

$$\boxed{\langle \mathcal{O}_1(0)\mathcal{Q}_1(\tau)\cdots\mathcal{O}_p(0)\mathcal{Q}_p(\tau)\rangle_{\rm GUE} \simeq \langle \mathcal{O}_1\mathcal{Q}_1\cdots\mathcal{O}_p\mathcal{Q}_p\rangle \times \frac{\mathbf{SFF}_{2p}(\tau)}{\mathcal{I}^{2p}}.}$$

OTOC in RMT

Averaged 2 point correlation function:

$$\int d\mathcal{O}\ \langle \mathcal{O}(0)\mathcal{O}^\dagger(\tau)\rangle :\equiv \frac{1}{\mathcal{I}}\int d\mathcal{O}\ \mathrm{Tr}\left(\mathcal{O}\exp[-iH\tau]\mathcal{O}^\dagger\exp[iH\tau]\right)$$
$$= \frac{1}{\mathcal{I}^3}\sum_{k=1}^{\mathcal{I}^2}\mathrm{Tr}\left(\mathcal{O}_k\exp[-H\tau]\mathcal{O}_k^\dagger\exp[iH\tau]\right).$$

First moment of the Haar ensemble: $\int d\mathcal{O}\ \mathcal{O}\mathcal{D}\mathcal{O}^\dagger = \frac{1}{\mathcal{I}}\mathrm{Tr}(\mathcal{D})\ \mathbf{I},$

(Constraint Condition)

$$\textbf{Quantum averaged OTOC} = \int d\mathcal{O}\ \langle \mathcal{O}(0)\mathcal{O}^\dagger(\tau)\rangle$$
$$= \frac{1}{\mathcal{I}^2}|\mathrm{Tr}(\exp[-iH\tau])|^2$$
$$= \frac{1}{\mathcal{I}^2}\mathbf{SFF}(\tau) \propto \textbf{Two point SFF}.$$

SFF in RMT

- Consider TDS at finite temperature:

$$|\bar{\Psi}(\beta,t)\rangle_{\mathbf{TDS}} = \frac{1}{\sqrt{Z(\beta)}}\sum_n \exp\left[-\left(it+\frac{\beta}{2}\right)E_n\right]|n\rangle_1\otimes|n\rangle_2 \quad Z(\beta)=\mathrm{Tr}\left(e^{-\beta H}\right)=\sum_n e^{-\beta E_n}$$

where 1 and 2 stands for two identical copies of the eigenstate of the Hamiltonian H, which are CPT conjugate of each other.

- Survival amplitude or overlap:

$$\mathcal{M}(\beta,t)=\langle\Psi(\beta,0|\Psi(\beta,t)\rangle=\frac{1}{Z(\beta)}\sum_n e^{-(it+\beta)E_n}$$

- Survival probability or Fidelity:

$$\mathbf{S}_2(t)=\begin{cases}\sum_{m,n,m\neq n} e^{-it(E_m-E_n)}, & \beta=1/T\to 0\\ 0, & \beta=1/T\to\infty\end{cases}$$

2 point SFF

$$\mathcal{P}(\beta,t)=|\mathcal{M}(\beta,t)|^2=\frac{1}{|Z(\beta)|^2}\left(\sum_{m,n,m\neq n} e^{-\beta(E_m+E_n)}e^{-it(E_m-E_n)}+\sum_n e^{-2\beta E_n}\right)$$
$$=\frac{1}{|Z(\beta)|^2}\left(|Z(\beta+it)|^2+|Z(2\beta)|^2\right)$$
$$=\mathbf{S}_2(t)+\mathbf{N}(\beta),$$

$$\mathbf{S}_2(t)=\frac{1}{|Z(\beta)|^2}\sum_{m,n,m\neq n} e^{-\beta(E_m+E_n)}e^{-it(E_m-E_n)}=\frac{|Z(\beta+it)|^2}{|Z(\beta)|^2}.$$

$$\mathbf{N}(\beta)=\frac{|Z(2\beta)|^2}{|Z(\beta)|^2}=\lim_{T\to\infty}\frac{1}{T}\int_{t=0}^{T}dt\ \mathcal{P}(\beta,t)=\widetilde{\mathcal{P}(\beta)}.$$

SFF in RMT

- Here OTOC in RMT can be written in energy eigen basis can be written as:

$$\mathscr{C}(\tau) = \frac{1}{|Z(\beta)|^2} \sum_{n,m} c_{n,m}(\tau) \exp[-\beta(E_n + E_m)]$$

$$c_{n,m}(\tau) = -\langle n | [e^{-iH\tau}, x]^2 | m \rangle = \exp\left[-i(E_n - E_m)\tau\right]$$

Quantum OTOC = 2 pt SFF

Thermal Green's function and two point SFF in RMT

- Thermal Green's function: $G(\beta,\tau) = G_{dc}(\beta,\tau) + G_c(\beta,\tau)$

- Disconnected Green's function:

$$G_{dc}(\beta,\tau) = \left[\frac{\langle Z(\beta+i\tau)\rangle\langle Z(\beta-i\tau)\rangle}{\langle Z(\beta)\rangle^2}\right]_{GUE} = \frac{\int d\lambda\ d\mu\ e^{-\beta(\lambda+\mu)}\ e^{-i\tau(\lambda-\mu)}\ \langle D(\lambda)\rangle\langle D(\mu)\rangle}{\int d\lambda\ d\mu\ e^{-\beta(\lambda+\mu)}\ \langle D(\lambda)\rangle\langle D(\mu)\rangle}$$

- Connected Green's function:

$$G_c(\beta,\tau) = G(\beta,\tau) - G_{dc}(\beta,\tau) = \left[\frac{\langle |Z(\beta+i\tau)|^2\rangle_{\rm GUE}}{\langle Z(\beta)\rangle^2_{\rm GUE}}\right] - \left[\frac{\langle Z(\beta+i\tau)\rangle\langle Z(\beta-i\tau)\rangle}{\langle Z(\beta)\rangle^2}\right] = \frac{\int d\lambda\ d\mu\ e^{-\beta(\lambda+\mu)}\ e^{-i\tau(\lambda-\mu)}\ \langle D(\lambda)D(\mu)\rangle_c}{\int d\lambda\ d\mu\ e^{-\beta(\lambda+\mu)}\ \langle D(\lambda)\rangle\langle D(\mu)\rangle}$$

- Here GUE= Gaussian Unitary Ensemble average

Thermal Green's function and two point SFF in RMT

- Thermal Green's function: $G(\beta,\tau) = G_{dc}(\beta,\tau) + G_c(\beta,\tau)$

- Disconnected Green's function:

$$G_{dc}(\beta,\tau) = \left[\frac{\langle Z(\beta+i\tau)\rangle\langle Z(\beta-i\tau)\rangle}{\langle Z(\beta)\rangle^2}\right]_{GUE} = \frac{\int d\lambda\ d\mu\ e^{-\beta(\lambda+\mu)}\ e^{-i\tau(\lambda-\mu)}\ \langle D(\lambda)\rangle\langle D(\mu)\rangle}{\int d\lambda\ d\mu\ e^{-\beta(\lambda+\mu)}\ \langle D(\lambda)\rangle\langle D(\mu)\rangle}$$

- Connected Green's function:

$$G_c(\beta,\tau) = G(\beta,\tau) - G_{dc}(\beta,\tau) = \left[\frac{\langle |Z(\beta+i\tau)|^2\rangle_{\rm GUE}}{\langle Z(\beta)\rangle^2_{\rm GUE}}\right] - \left[\frac{\langle Z(\beta+i\tau)\rangle\langle Z(\beta-i\tau)\rangle}{\langle Z(\beta)\rangle^2}\right] = \frac{\int d\lambda\ d\mu\ e^{-\beta(\lambda+\mu)}\ e^{-i\tau(\lambda-\mu)}\ \langle D(\lambda)D(\mu)\rangle_c}{\int d\lambda\ d\mu\ e^{-\beta(\lambda+\mu)}\ \langle D(\lambda)\rangle\langle D(\mu)\rangle}$$

- Here GUE= Gaussian Unitary Ensemble average

- For general even order polynomial random potential density function of the eigenvalues of the random matrices can be expressed as:

$$\rho(\lambda) = \frac{1}{\pi}\sqrt{4a^2-\lambda^2}\ \sum_{k=1}^{n} a_{n-k}\lambda^{2(n-k)} \qquad \forall \text{ even n}$$

Thermal Green's function and two point SFF in RMT

- One point function on the semi-circle as given by:

$$Z(\beta \pm i\tau)\rangle_{\text{nGUE}} = \int d\lambda \; e^{\mp i\tau\lambda} \; e^{-\beta\lambda} \; \langle\rho(\lambda)\rangle_{\text{nGUE}} = \int_{-2a}^{2a} d\lambda \; e^{\mp i\tau\lambda} \; e^{-\beta\lambda} \; \rho(\lambda)$$

After simplification we get:

$$\begin{aligned}
\langle Z(\beta \pm i\tau)\rangle_{\text{nGUE}} &= \frac{1}{\pi}\int_{-2a}^{2a} d\lambda \; e^{\mp i\tau\lambda} \; e^{-\beta\lambda} \; \sqrt{4a^2-\lambda^2} \; \sum_{k=1}^{n} a_{n-k}\lambda^{2(n-k)} \qquad \forall \text{ even n} \\
&= \sum_{k=1}^{n} a_{n-k} \; a^2 \left(-a^2\right)^{-2k} 4^{n-k} \Bigg[\left(e^{2i\pi k} + e^{2i\pi n}\right) a^{2(k+n)} \Gamma\left(-k+n+\frac{1}{2}\right) \\
&\qquad \times {}_1\tilde{F}_2\left(-k+n+\frac{1}{2}; \frac{1}{2}, -k+n+2; a^2(\beta \pm i\tau)^2\right) \\
&\qquad + a(\beta \pm i\tau)\left(a^{2k}(-a)^{2n} - (-a)^{2k}a^{2n}\right)\Gamma(-k+n+1) \\
&\qquad \times {}_1\tilde{F}_2\left(-k+n+1; \frac{3}{2}, -k+n+\frac{5}{2}; a^2(\beta \pm i\tau)^2\right)\Bigg]
\end{aligned}$$

where ${}_1\tilde{F}_2\left(A; B, C; D\right)$ is the regularized Hypergeometric function.

Thermal Green's function and two point SFF in RMT

- Two point connected density function:

$$\langle D(\lambda)D(\mu)\rangle_c = -\frac{\sin^2[N(\lambda-\mu)]}{(\pi N(\lambda-\mu))^2} + \frac{1}{\pi N}\delta(\lambda-\mu)$$

- Connected Green's function on semi-circle:

$$G_c(\tau) = \frac{1}{N^2}\int d\lambda\ d\mu\ e^{-i\tau(\lambda-\mu)}\ \left[-\frac{\sin^2[N(\lambda-\mu)]}{(\pi N(\lambda-\mu))^2} + \frac{1}{\pi N}\delta(\lambda-\mu)\right]$$

- Use $\lambda+\mu = E, \quad \lambda-\mu=\omega, \quad d\lambda\ d\mu = dE\ d\omega$

- Consequently, we get:

$$G_c(\beta,\tau) = \frac{2\pi}{N^2}\delta(\beta)\int_{-\infty}^{\infty} d\omega\ e^{-i\tau\omega}\ \left[-\frac{1}{\pi^2}\frac{\sin^2[N\omega]}{(N\omega)^2} + \frac{1}{\pi N}\delta(\omega)\right] \qquad \delta(\beta) = \frac{1}{2\pi}\int_{-\infty}^{\infty} dE\ e^{-\beta E}.$$

- We choose our working region at E=0 (at high temperature limit)

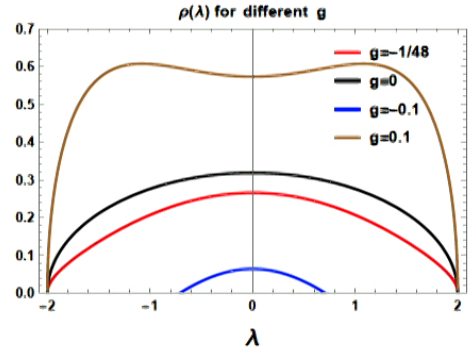
$$S(\tau) = N^2 G_c(\tau) = \int_{-\infty}^{\infty} d\omega\ e^{-i\tau\omega}\ \left[-\frac{1}{\pi^2}\frac{\sin^2[N\omega]}{(N\omega)^2} + \frac{1}{\pi N}\delta(\omega)\right] = \begin{cases} \frac{\tau}{(2\pi N)^2} - \frac{1}{N} + \frac{1}{(\pi N)}, & \tau < 2\pi N \\ \frac{1}{\pi N}, & \tau > 2\pi N \end{cases}$$

Example: Quartic Random Potential

$$V(M) = \frac{1}{2}M^2 + gM^4$$

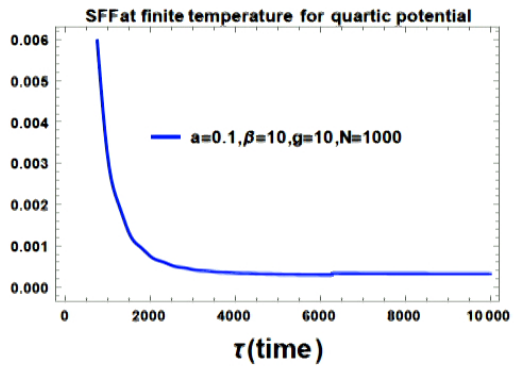
$$\rho(\lambda) = \frac{1}{\pi}\left(\frac{1}{2} + 4ga^2 + 2g\lambda^2\right)\sqrt{4a^2 - \lambda^2}$$

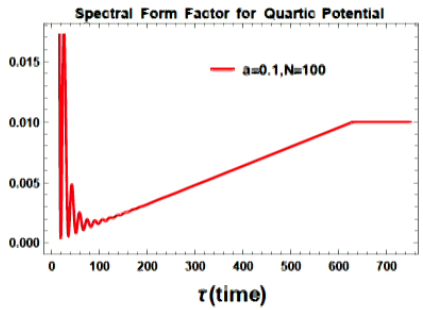
g=0 Wigner semi-circle distribution law

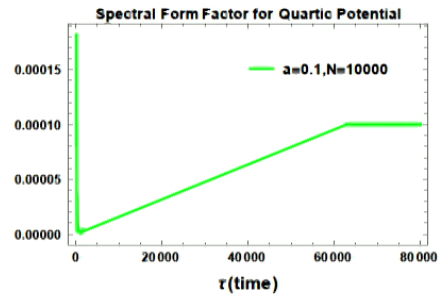


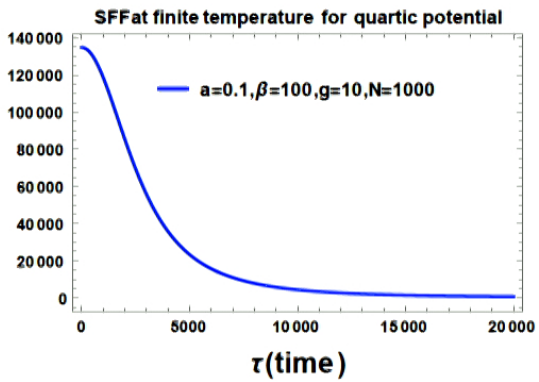
$$\mathbf{SFF}(\beta,\tau) \equiv \begin{cases} \dfrac{\beta^4}{(\beta^2+\tau^2)^2}\dfrac{1}{\left[(24a^2g+1)\,\beta I_1(2a\beta) - 24agI_2(2a\beta)\right]^2} \\ \quad \times \left[\left(24a^2g+1\right)(\beta+i\tau)I_1(2a(\beta+i\tau)) - 24agI_2(2a(\beta+i\tau))\right] \\ \quad \times \left[\left(24a^2g+1\right)(\beta-i\tau)I_1(2a(\beta-i\tau)) - 24agI_2(2a(\beta-i\tau))\right] \\ \quad + \dfrac{\tau}{(2\pi N)^2} - \dfrac{1}{N} + \dfrac{1}{(\pi N)}, & \tau < 2\pi N \\ \\ \dfrac{\beta^4}{(\beta^2+\tau^2)^2}\dfrac{1}{\left[(24a^2g+1)\,\beta I_1(2a\beta) - 24agI_2(2a\beta)\right]^2} \\ \quad \times \left[\left(24a^2g+1\right)(\beta+i\tau)I_1(2a(\beta+i\tau)) - 24agI_2(2a(\beta+i\tau))\right] \\ \quad \times \left[\left(24a^2g+1\right)(\beta-i\tau)I_1(2a(\beta-i\tau)) - 24agI_2(2a(\beta-i\tau))\right] \\ \quad + \dfrac{1}{\pi N}, & \tau > 2\pi N \end{cases}$$

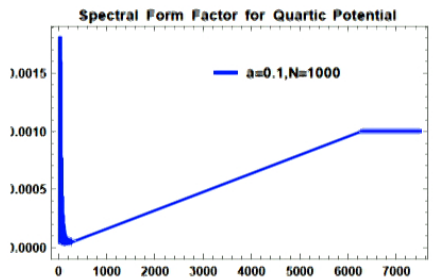
Example: Quartic Random Potential











Bound on SFF from theory : $-\frac{1}{N}\left(1-\frac{1}{\pi}\right) \leq \mathrm{SFF} \leq \frac{1}{\pi N} \quad \forall \tau, \;\; 0 \leq \beta(=1/T) \leq \infty$

Fokker Planck Equation: Probabilistic approach in Cosmology

Constructing Fokker Planck Equation in Cosmology

- The probability density for particle position of Brownian motion in a random system can be expressed in terms of Smoluchowski equation:

$$P(M;\tau+\delta\tau) = \int_{-\infty}^{\infty} P(M_1,\tau)\; P(M_2,\delta\tau)\; dM_2 = \langle P(M_1,\tau)\rangle_{M_2}$$

- For Markovian process, Smoluchowski equation describes a two point conditional probability distribution satisfying the following criteria:

$$P_2(Y_1,t_1\,|\,Y_3,t_3) = \int_{-\infty}^{\infty} dY_2\; P_2(Y_1,t_1\,|\,Y_2,t_2)\; P_3(Y_1,t_1;Y_2,t_2\,|\,Y_3,t_3) \qquad \text{for } t_1 < t_2 < t_3$$

- The time evolution of the probability density function can be expressed as:

$$\partial_\tau P(M,\tau) = \frac{\langle \delta M\rangle_{M_2}}{\delta\tau}\partial_M P(M,\tau) + \frac{\langle \delta M\delta M\rangle_{M_2}}{\delta\tau}\partial_M\partial_M P(M,\tau) + \ldots$$

Constructing Fokker Planck Equation in Cosmology

- Applying Maximum entropy ansatz Smoluchowski equation can be re-expressed as:

$$P(n;\tau+\delta\tau) = \int d\theta\; P(n,\theta;\tau+\delta\tau) = \int d\theta\; \langle P(n+\delta n,\theta+\delta\theta;\tau)\rangle_{\delta\tau} = \langle P(n+\delta n;\tau)\rangle_{\delta\tau}$$

- Now, using Taylor expansion we get:

$$\langle P(n+\delta n;\tau)\rangle_{\delta\tau} = \langle P(n;\tau)\rangle_{\delta\tau} + \left\{ \frac{\partial P(n;\tau)}{\partial n}\frac{\partial\langle\delta n\rangle_{\delta\tau}}{\partial\tau} + \frac{1}{2!}\frac{\partial^2 P(n;\tau)}{\partial n^2}\frac{\langle(\delta n)^2\rangle_{\delta\tau}}{\delta\tau} \right\}\delta\tau + \cdots$$

$$P(n;\tau+\delta\tau) = P(n;\tau) + \frac{\partial P(n;\tau)}{\partial\tau}\delta\tau + \frac{1}{2!}\frac{\partial^2 P(n;\tau)}{\partial\tau^2}(\delta\tau)^2 + \cdots$$

- Further equating coefficient of $\delta\tau$ we get:

$$\frac{\partial P(n;\tau)}{\partial\tau} = \frac{\partial P(n;\tau)}{\partial n}\frac{\langle\delta n\rangle_{\delta\tau}}{\delta\tau} + \frac{1}{2}\frac{\partial^2 P(n;\tau)}{\partial n^2}\frac{\langle(\delta n)^2\rangle_{\delta\tau}}{\delta\tau} + \ldots$$

$$\langle\delta n\rangle_{\delta\tau} = (1+2n)\langle n_2\rangle = \mu\delta\tau(1+2n)$$

$$\langle(\delta n)^2\rangle_{\delta\tau} = 2n(n+1)\langle n_2\rangle + (1+6n+6n^2)\langle n_2\rangle^2 = 2n(n+1)\mu\delta\tau + (1+6n+6n^2)(\mu\delta\tau)^2$$

Fokker Planck Equation : $$\frac{1}{\mu_k}\frac{\partial P(n;\tau)}{\partial\tau} = (1+2n)\frac{\partial P(n;\tau)}{\partial n} + n(1+n)\frac{\partial^2 P(n;\tau)}{\partial n^2}$$

1st order Fokker Planck Equation

Fokker Planck Equation : $$\frac{1}{\mu_k}\frac{\partial P(n;\tau)}{\partial \tau} = (1+2n)\frac{\partial P(n;\tau)}{\partial n} + n(1+n)\frac{\partial^2 P(n;\tau)}{\partial n^2}$$

$$P(n;\tau) = \frac{1}{2\sqrt{\mu_k n(n+1)\tau\pi}} \exp\left[-n\left(\mu_k(n+1)\tau + \frac{1}{4\mu_k\tau(n+1)} + 1\right)\right]$$

2nd order Fokker Planck Equation

$$\frac{n^2}{2}(1+n)^2\frac{\partial^4 P(n;\tau)}{\partial n^4}+2n\left(1+3n+2n^2\right)\frac{\partial^3 P(n;\tau)}{\partial n^3}+\left(1+6n+6n^2\right)\frac{\partial^2 P(n;\tau)}{\partial n^2}=\frac{1}{\mu_k^2}\frac{\partial^2 P(n;\tau)}{\partial \tau^2}$$

$$P(n;\tau)=\left(\pi(n^2-\mu_k^2\tau^2)\right)^{-1}\left[n\sin(Ln)\cos(L\mu_k\tau)-\mu_k\tau\cos(Ln)\sin(L\mu_k\tau)\right]-(4\pi\mu_k n)^{-1}\left[i\left\{\mathrm{Ci}(-L(n+\mu_k\tau))\right.\right.$$
$$\left.\left.-\mathrm{Ci}(L(n+\mu_k\tau))\right\}-\mathrm{Ci}(-L(n-\mu_k\tau))+\mathrm{Ci}(L(n-\mu_k\tau))-2i\left\{\mathrm{Si}(L(n+\mu_k\tau))-\mathrm{Si}(L(n-\mu_k\tau))\right\}\right]$$

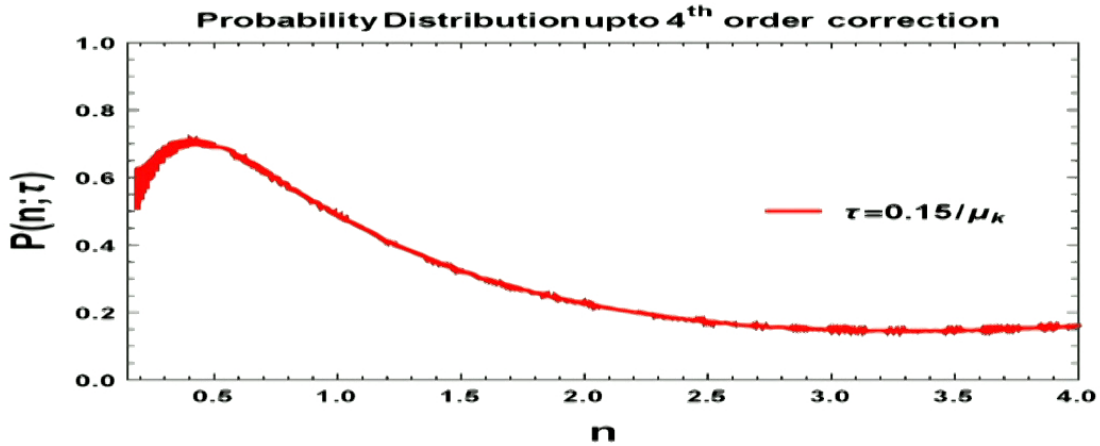
4rth order Fokker Planck Equation

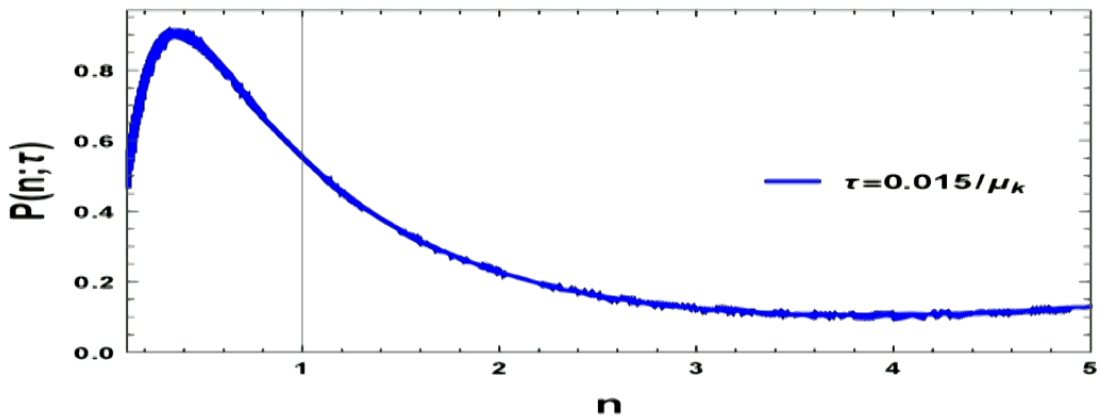
$$70n^4(1+n)^4\frac{\partial^8 P(n;\tau)}{\partial n^8} + 140n^3(1+2n)\frac{\partial^7 P(n;\tau)}{\partial n^7} + 30n^2(1+n)^2(3+14n+14n^2)\frac{\partial^6 P(n;\tau)}{\partial n^6}$$

$$+20n(1+n)(1+2n)(1+7n+7n^2)\frac{\partial^5 P(n;\tau)}{\partial n^5} + (1+20n+90n^2+140n^3+70n^4)\frac{\partial^4 P(n;\tau)}{\partial n^4} = \frac{1}{\mu_k^4}\frac{\partial^4 P(n;\tau)}{\partial \tau^4}$$

$$P(n;\tau) = -(2\pi)^{-1}\int_{-p}^{q} dk\; e^{ikn}\left\{\frac{(k^2n^2\mu_k^2+2kn\mu_k+6)}{4k^3n^3\mu_k^3}\; e^{-\mu_k k\tau} + \frac{(k^2n^2\mu_k^2-2kn\mu_k+6)}{4k^3n^3\mu_k^3}\; e^{\mu_k k\tau}\right.$$
$$\left. + \frac{(k^2n^2\mu_k^2-6)}{2k^3n^3\mu_k^3}\sin(\mu_k k\tau) + \frac{1}{k^2n^2\mu_k^2}\cos(\mu_k k\tau)\right\}$$

4rth order corrected distribution function





Small NG in <n_k(t)n_k(t')n_k(t''')> but larger than primordial one

Statistical Moments

1st Order Master Equation :

$$\frac{1}{\mu_k}\frac{\partial\langle F\rangle}{\partial\tau} = \left\langle (1+2n)\frac{\partial F}{\partial n} + n(n+1)\frac{\partial^2 F}{\partial n^2}\right\rangle$$

2nd Order Master Equation :

$$\frac{1}{\mu_k^2}\frac{\partial^2\langle F\rangle}{\partial\tau^2} = \left\langle \frac{n^2}{2}(1+n)^2\frac{\partial^4 F}{\partial n^4} + 2n\left(1+3n+2n^2\right)\frac{\partial^3 F}{\partial n^3} + \left(1+6n+6n^2\right)\frac{\partial^2 F}{\partial n^2}\right\rangle$$

3rd Order Master Equation :

$$\frac{1}{\mu_k^3}\frac{\partial^3\langle F\rangle}{\partial\tau^3} = \left\langle \frac{n^3}{6}(1+n)^3\frac{\partial^6 F}{\partial n^6} + \frac{3n^2}{2}(1+n)^2(1+2n)\frac{\partial^5 F}{\partial n^5}\right.$$

$$\left. +3n(1+n)(1+5n+5n^2)\frac{\partial^4 F}{\partial n^4} + (1+2n)(1+10n+10n^2)\frac{\partial^3 F}{\partial n^3}\right\rangle$$

4rth Order Master Equation :

$$\frac{1}{\mu_k^4}\frac{\partial^4\langle F\rangle}{\partial\tau^4} = \left\langle 70n^4(1+n)^4\frac{\partial^8 F}{\partial n^8} + 140n^3(1+2n)\frac{\partial^7 F}{\partial n^7}\right.$$

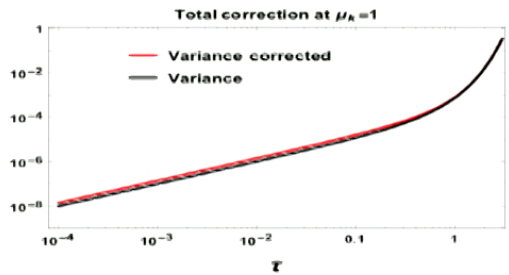
$$\left. +30n^2(1+n)^2(3+14n+14n^2)\frac{\partial^6 F}{\partial n^6} + 20n(1+n)(1+2n)(1+7n+7n^2)\frac{\partial^5 F}{\partial n^5} + (1+20n+90n^2+140n^3+70n^4)\frac{\partial^4 F}{\partial n^4}\right\rangle$$

where $\langle F(n)\rangle(\tau) \equiv \int dn\ F(n)P(n;\tau)$

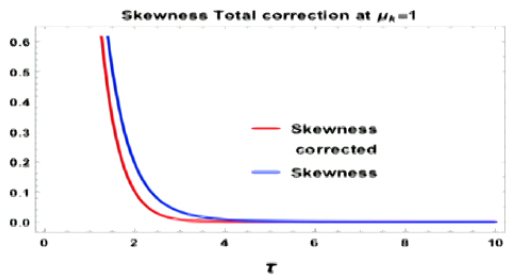
Statistical Moments

1st	$\frac{1}{\mu_k}\frac{\partial\langle n\rangle}{\partial\tau} = \langle(1+2n)\rangle = 1+2\langle n\rangle$
1st	$\frac{1}{\mu_k}\frac{\partial\langle n^2\rangle}{\partial\tau} = \langle 2n(1+2n)+2n(1+n)\rangle = \langle 4n+6n^2\rangle = 4\langle n\rangle + 6\langle n^2\rangle$
2nd	$\frac{1}{\mu_k^2}\frac{\partial^2\langle n^2\rangle}{\partial\tau^2} = \langle 2(1+6n+6n^2)\rangle = 12\langle n\rangle + 12\langle n^2\rangle + 2$
1st	$\frac{1}{\mu_k}\frac{\partial\langle n^3\rangle}{\partial\tau} = \langle 3n^2(1+2n)+6n(1+n)\rangle = \langle 6n+9n^2+6n^3\rangle = 6\langle n\rangle + 9\langle n^2\rangle + 6\langle n^3\rangle$
2nd	$\frac{1}{\mu_k^2}\frac{\partial^2\langle n^3\rangle}{\partial\tau^2} = \langle 12n(1+3n+3n^2)+6n(1+6n+6n^2)\rangle = 18\langle n\rangle + 72\langle n^2\rangle + 60\langle n^3\rangle$
3rd	$\frac{1}{\mu_k^3}\frac{\partial^3\langle n^3\rangle}{\partial\tau^3} = \langle 6(1+2n)(1+10n+10n^2)\rangle = 72\langle n\rangle + 180\langle n^2\rangle + 120\langle n^3\rangle + 6$
1st	$\frac{1}{\mu_k}\frac{\partial\langle n^4\rangle}{\partial\tau} = \langle 4n^3(1+2n)+12n^2(1+n)\rangle = \langle 16n^3+20n^4\rangle = 16\langle n^3\rangle + 20\langle n^4\rangle$
2nd	$\frac{1}{\mu_k^2}\frac{\partial^2\langle n^4\rangle}{\partial\tau^2} = \langle 12n^2(1+n)^2+48n^2(1+3n+2n^2)+12n^2(1+6n+6n^2)\rangle = 72\langle n^2\rangle + 240\langle n^3\rangle + 180\langle n^4\rangle$
3rd	$\frac{1}{\mu_k^3}\frac{\partial^3\langle n^4\rangle}{\partial\tau^3} = \langle 72n(1+n)(1+5n+5n^2)+24n(1+2n)(1+10n+10n^2)\rangle = 96\langle n\rangle + 720\langle n^2\rangle + 1440\langle n^3\rangle + 840\langle n^4\rangle$
4rth	$\frac{1}{\mu_k^4}\frac{\partial^4\langle n^4\rangle}{\partial\tau^4}\langle 24(1+20n+90n^2+140n^3+70n^4)\rangle = 480\langle n\rangle + 2160\langle n^2\rangle + 3360\langle n^3\rangle + 1680\langle n^4\rangle + 24$

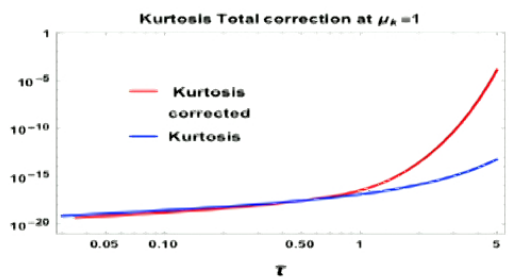
Statistical Moments



(a)Time evolution of variance.

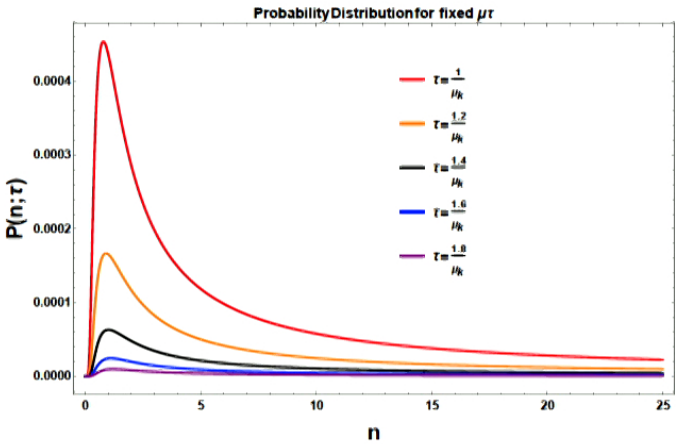
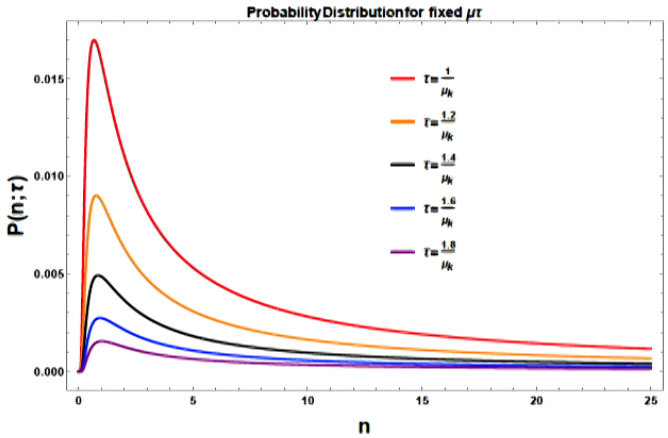


(b)Time evolution of skewness.



(c)Time evolution of kurtosis.

Ito & Stratonovitch

Ito	Stratonovitch
$$\frac{\partial P(n;\tau)}{\partial \tau} = \frac{\partial^2}{\partial n^2}\left(n(n+1)P(n;\tau)\right)$$	$$\frac{\partial P(n;\tau)}{\partial \tau} = \frac{\partial}{\partial n}\left(\sqrt{n(n+1)}\frac{\partial}{\partial n}\left(\sqrt{n(n+1)}P(n;\tau)\right)\right)$$
$$P(n,\tau) = \frac{1}{2\sqrt{\pi}\sqrt{n(n+1)\tau\mu_k}}\exp\left[-\frac{((4n+2)\tau\mu_k+n)^2}{4n(n+1)\tau\mu_k}\right]$$	$$P(n,\tau) = \frac{1}{2\sqrt{\pi}\sqrt{n(n+1)\tau\mu_k}}\exp\left[-\frac{9(2n+1)^2\tau\mu_k}{16n(n+1)}\right]$$
	

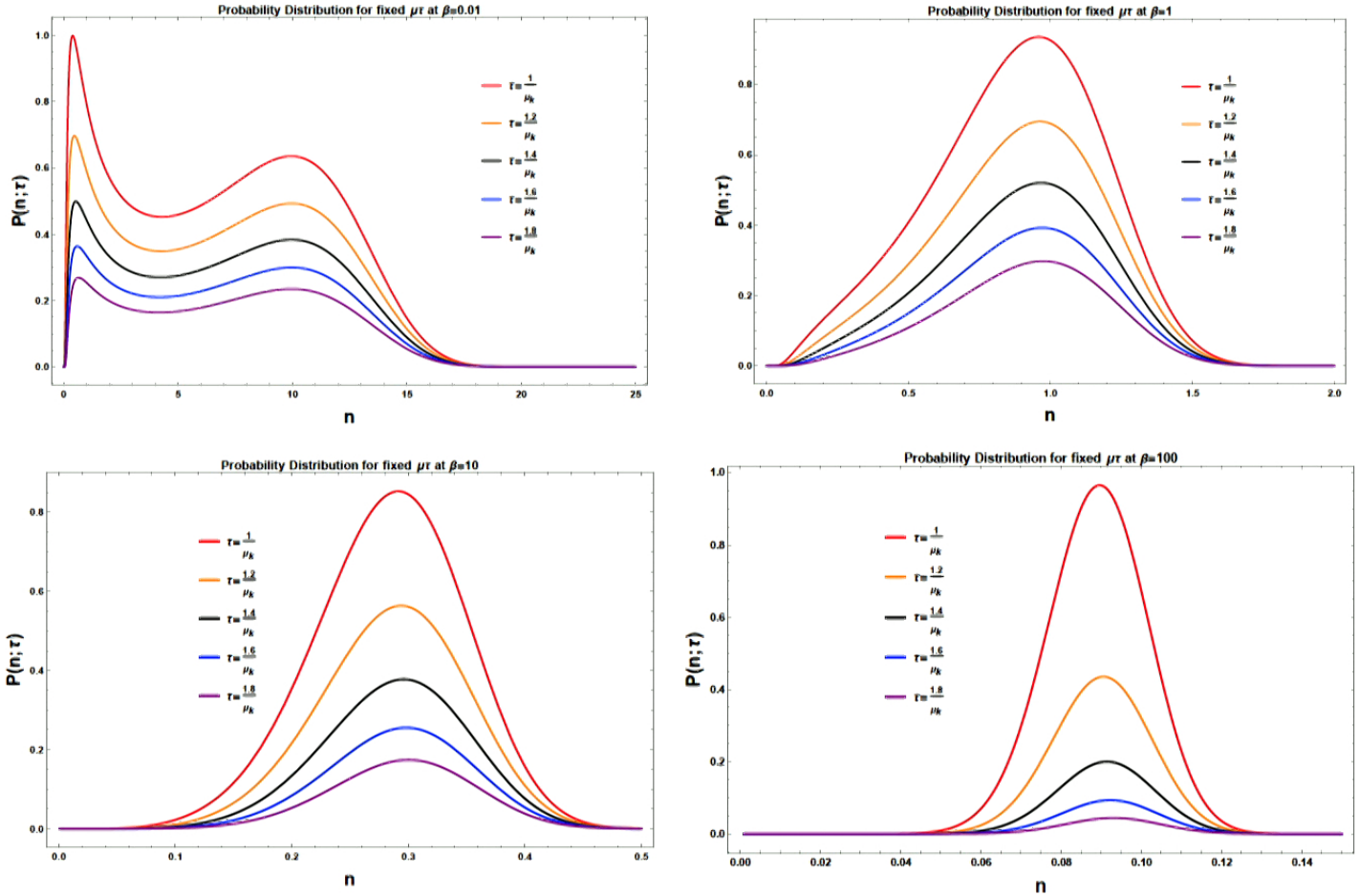
Generalised Fokker Planck Equation $\beta \neq 0$

$$\frac{\partial}{\partial n}\left(n(n+1)\frac{\partial W(n;\tau)}{\partial n}\right) - U(n)W(n;\tau) = \frac{\partial W(n;\tau)}{\partial \tau}$$

$$U(n) = \left[\frac{\beta^2}{4}n(n+1)\left(\frac{\partial V(n)}{\partial n}\right)^2 - \frac{\beta}{2}n(n+1)\left(\frac{\partial^2 V(n)}{\partial n^2}\right) - \frac{\beta}{2}\left(\frac{\partial(n(n+1))}{\partial n}\right)\left(\frac{\partial V(n)}{\partial n}\right)\right] \qquad V(n) = n^2$$

$$P(n;\tau) = \exp\left(-\frac{\beta}{2}V(n)\right) W(n;\tau) = \frac{1}{2\sqrt{\pi}\sqrt{n(n+1)\tau\mu_k}} \exp\left[-\frac{(n-\mu_k(2n\tau+\tau))^2}{4n(n+1)\tau\mu_k} - \frac{\beta n^2}{2} - \beta n\left\{n(\beta n(n+1)-3)-2\right\}\right]$$

Generalised Fokker Planck Equation $\beta \neq 0$



Conclusion

- We have provided the analogy between particle creation in primordial cosmology and scattering problem inside a conduction wire in presence of impurities.
- We have studied the same problem where the particle interactions are not known at the level of action. For this purpose we use Random Matrix Theory.
- We have solved the dynamics of the particle creation problem by studying the higher order corrections in the Fokker Planck equation for previously mentioned random system.
- We have also provided the expression for the two point quantum correlation function, which is known as Spectral Form Factor (SFF) for both in finite and zero temperature. SFF is actually a more strong measure to find chaotic behaviour of a dynamical system compared to Lyapunov exponent. We get saturating behaviour of SFF at late time scale, which indicates that it has an upper-bound.

- We have provided a model independent upper and lower bound of SFF, $-1/N(1-1/\pi) \leq \mathbf{SFF} \leq 1/\pi N$

- We have also established the equivalence of OTOC and SFF in the context of RMT.

- The higher order corrected probability distribution function obtained from the solution of Fokker Planck Equation carries the signature of non-Gaussianity due to the presence of non vanishing skewness and kurtosis.

- OTOC in De Sitter (Global/Static/Planar) space (Cosmology).
- Application in Black Hole Physics.
- Role of quantum entanglement in Cosmology.
- Quantum quench and eigenstate thermalisation in Cosmology.
- Extension of the idea in case of open quantum systems (Cosmology).

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Relating the curvature of De Sitter Universe to Open Quantum Lamb Shift Spectroscopy

Sandipan Bhattacherjee, Hardik Bohra, Sayantan Choudhury, Prashali Chauhan, Arkaprava Mukherjee, Purnima Narayan, Sudhakar Panda, Abinash Swain

(Submitted on 20 May 2019)

In this paper, our prime objective is to connect the curvature of our observable De Sitter Universe with the spectroscopic study of entanglement of two atoms in an open quantum system (OQS). The OQS considered in our work is made up of two atoms which are represented by Pauli spin tensor operators projected along any arbitrary direction. They mimic the role of a pair of freely falling Unruh De-Witt detectors, which are allowed to non-adiabatically interact with a conformally coupled massless probe scalar field in the De Sitter background. The effective dynamics of the atomic detectors are actually an outcome of their non-adiabatic interaction, which is commonly known as the Resonant Casimir Polder Interaction (RCPI) with the thermal bath. We find from our analysis that the RCPI of two stable entangled atoms in the quantum vacuum states in OQS depends on the De Sitter space-time curvature relevant to the temperature of the thermal bath felt by the static observer. We also find that, in OQS, RCPI produces a new significant contribution appearing in the effective Hamiltonian of the total system and thermal bath under consideration. This will finally give rise to Lamb Spectroscopic Shift, as appearing in the context of atomic and molecular physics. This analysis actually plays a pivotal role to make the bridge between the geometry of our observed Universe to the entanglement in OQS through Lamb Shift atomic spectroscopy. Thus, we are strongly aiming to connect the curvature of the background space-time of our Universe to open quantum Lamb Shift spectroscopy by measuring the quantum properties of a two entangled OQS in the atomic experiment.

Comments: 50 pages, 7 figures, This project is the part of the non-profit virtual international research consortium "Quantum Structures of the Space-Time & Matter"

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High Energy Physics - Theory

Open Quantum Cosmology: A study of two body quantum entanglement in static patch of De Sitter space

Samim Akhtar, Sayantan Choudhury, Satyaki Chowdhury, Debopam Goswami, Sudhakar Panda, Abinash Swain

(Submitted on 26 Aug 2019)

In this work, our prime objective is to study non-locality and long-range effect of two-body correlation using quantum entanglement from the various information-theoretic measure in the static patch of De Sitter space using a two-body Open Quantum System (OQS). The OQS is described by two entangled atoms which are surrounded by a thermal bath, which is modelled by a massless probe scalar field. Firstly, we partially trace over the bath field and construct the Gorini Kossakowski Sudarshan Lindblad (GSKL) master equation, which describes the time evolution of the reduced subsystem density matrix. This GSKL master equation is characterized by two components, these are-Spin chain interaction Hamiltonian and the Lindbladian. To fix the form of both of them, using Schwinger-Keldysh formalism we compute the Wightman functions for probe massless scalar field. Using this result along with the large time equilibrium behaviour we obtain the analytical solution for reduced density matrix. Further using this solution we compute Von-Neumann entropy, Rényi entropy, logarithmic negativity, entanglement of formation, concurrence and quantum discord in a static patch of De Sitter space. Finally, we have studied the violation of Bell-CHSH inequality, which is the key ingredient to study non-locality in primordial cosmology.

Comments: 108 pages (73 pages paper including references + 35 pages Appendix), 21 figures, 2 tables, This project is the part of the non-profit virtual international research consortium "Quantum Structures of the Space-Time & Matter"

Subjects: **High Energy Physics - Theory (hep-th)**; General Relativity and Quantum Cosmology (gr-qc); Quantum Physics (quant-ph)

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- Samim Akhtar
- Sayantan Choudhury
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Bell violation in the sky

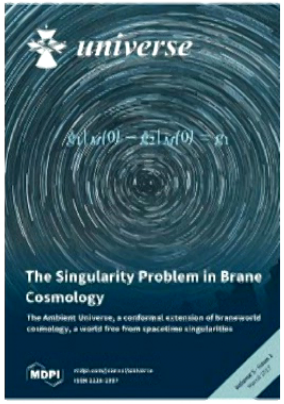
Authors Authors and affiliations

Sayantan Choudhury, Sudhakar Panda, Rajeev Singh

Open Access | Regular Article - Theoretical Physics
First Online: 30 January 2017

Abstract

In this work, we have studied the possibility of setting up Bell's inequality violating experiment in the context of cosmology, based on the basic principles of quantum mechanics. First we start with the physical motivation of implementing the Bell inequality violation in the context of cosmology. Then to set up the cosmological Bell violating test experiment we introduce a model independent theoretical framework using which we have studied the creation of new massive particles by implementing the WKB approximation method for the scalar fluctuations in the presence of additional time-dependent mass contribution in the cosmological perturbation theory. Here for completeness we compute the total number density and the energy density of the newly created particles in terms of the Bogoliubov coefficients using the WKB approximation method. Next using the background scalar fluctuation in the presence of a new time-dependent mass contribution, we explicitly compute the expression for the one point and



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Bell Violation in Primordial Cosmology

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Abstract

In this paper, we have worked on the possibility of setting up an Bell's inequality violating experiment in the context of primordial cosmology following the fundamental principles of quantum mechanics. To set up this proposal, we have introduced a model-independent theoretical framework using which we have studied the creation of new massive particles for the scalar fluctuations in the presence of an additional time-dependent mass parameter. Next we explicitly computed the one-point and two-point correlation functions from this setup. Then, we comment on the measurement techniques of isospin breaking interactions of newly introduced massive particles and its further prospects. After that, we give an example of the string theory-originated axion monodromy model in this context. Finally, we provide a bound on the heavy particle mass parameter for any

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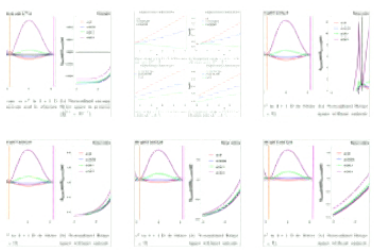

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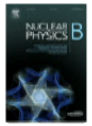

Quantum entanglement in de Sitter space from stringy axion: An analysis using α vacua

Sayantan Choudhury [a, b], Sudhakar Panda [c, d, e]

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https://doi.org/10.1016/j.nuclphysb.2019.03.018

Abstract

In this work, we study the phenomena of quantum entanglement by computing de Sitter entanglement entropy from von Neumann measure. For this purpose we consider a bipartite quantum field theoretic set up for axion field, previously derived from **Type II B** string theory compactified to four dimensions. We consider the initial vacuum to be CPT invariant non-adiabatic α vacua state under $\mathbf{SO(1,4)}$ isometry, which is characterised by a real one-parameter family. To implement this technique we use a $\mathbf{S^2}$ which divide the de Sitter into two exterior and interior sub-regions. First, we derive the wave function of axion in an open chart for α vacua by

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