QUANTUM COMPLEXITY

AND

CHAOTIC DYNAMICS

ON EXTREMAL BLACK HOLE HORIZONS

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PLAN OF THE TALK

- 1) STRECHED HORIZON HOLOGRAPHY OF THE BH PHYSICAL PROCESSES

EXPONENTIALLY FAST SPREADING AND MIXING OF INFALLING WAVE PACKETS -
TRANSVERSE AND LONGITUTINAL STRECHING OF INFALLING STRINGS WRAPPING THE HORIZON-
FAST SCRAMBLING-

=> CHAOTIC S-MATRIX OF THE STRECHED HORIZON

- 2) CONSTRUCTION OF S-MATRIX

- CONSTRUCTION OF A CONCRETE TOY MODEL
  FOR A UNITARY AND CHAOTIC S-MATRIX
  IN A **FINITE DIMENSIONAL** HILBERT SPACE,H, OF BLACKHOLE
  MICROSTATES **dimH=Exp[S**]

  APPROPRIATE TO DESCRIBE

- A) THE TRANSITION FROM LOCALIZED WAVE PACKETS TO
  COMPLETELY DELOCALIZED RANDOM PURE STATES
  REALIZING THE EIGENSTATE THERMALIZATION HYPOTHESIS
  OF PAGE-DEUTSCH-BERRY-SREDNICKI

- B) TO ALLOW AN EXPONENTIALLY FAST THERMALIZATION
  SATURATING THE SCRAMBLING TIME BOUND
  OF HAYDEN-PRESKILL, SEKINO-SUSSKIND

  C)QUANTUM COMPLEXITY OF S-MATRIX

- 3) SETTING UP THE PROBLEM

- OLD AND LARGE NEAR EXTREMAL BH'S

- ASSUME THAT THE BH MICROSTATES CAN BE DESCRIBED BY FINITE QUANTUM MECHANICS (FQM)

  OF THE MICROSCOPIC DEGREES OF FREEDOM

  LEAVING INSIDE THE STRECHED HORIZON'S UNIVERSAL

  GEOMETRY =AdS2 XΣ , Σ=COMPACT

- RESTRICT TO RADIAL MOTION AND DISCRETIZE
- AdS2[R]=SL[2,R]/SO[1,1,R]
- → AdS2[N]=SL[2,ZN]/SO[1,1,ZN]

- CONSTRUCT THE AdS2 S-MATRIX

  OF PROBE STRING BITS SUPERDCONFORMAL QM

  BY SL[2,ZN] ISOMETRY QUANTUM MAPS

- MOTIVATION

1)THE EIGENSTATE THERMALIZATION HYPOTHESIS

GAUSSIAN PDF OF EIGENSTATE' S PROB VALUES

FLAT PDF OF EIGENSTATE'S PHASES

2) SATURATION OF THE SCRAMBLING TIME BOUND

3) RELATION OF QUANTUM COMPLEXITY WITH

BH ENTROPY

RECENT WORK

- Modular discretization of the AdS2/CFT1 Holography

  M.Axenides,E.Floratos,S.Nicolis

  JHEP 1402(2014)109 arXiv:1306.5670

- Chaotic Information Processing by Extremal Black Holes

  M.Axenides,E.G.Floratos,S.Nicolis

  Int. J. Mod. Phys. D24 (2015) 1542.0122 arXiv:1504.00483

- Quantum cat map dynamics on AdS2
  Minos Axenides, Emmanuel Floratos,
  Stam Nicolis
- arXiv:1608.07845

- Quantum Complexity of Chaotic Dynamics
  on the Horizons of Extremal BHs
  Emmanuel Floratos
  arXiv:2017xxxx to appear soon
- Quantum Circuits for the Fractional Fourier Transform
- Emmanuel Floratos,Archimedes Pavlidis
- arXiv:2017xxx to appear soon

EXTREMAL BH'S
NEAR HORIZON AdS2 UNIVERSAL GEOMETRY
AND
SUPERCONFORMAL DYNAMICS

EXTREMAL BLACK HOLES, U[1] CHARGES=> MASS=CHARGE

- **TEMPERATURE=ZERO, NO HAWKING RADIATION**
- **FINITE ENTROPY=AREA=FUNCTION OF U[1] CHARGES(?)**
- **SINGLE HORIZON,TIME LIKE INTERIOR AND EXTERIOR REGIONS**
- **UNIVERSAL AdS2 RADIAL AND TIME GEOMETRY,IN THE NEAR HORIZON REGION=>SL[2,R] ISOMETRY , DOUBLE BOUNDARY**

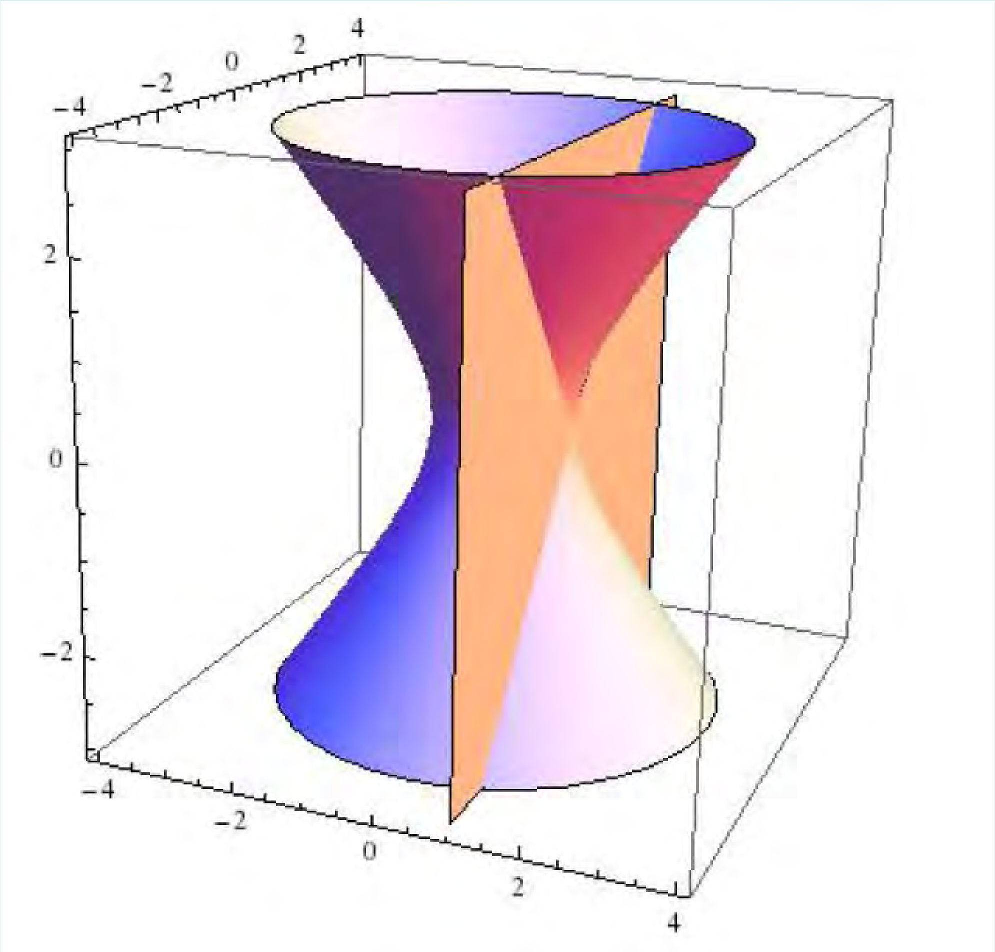
- **SCQM FOR BPS PARTICLES IN THE NEAR HORIZON REGION**

(TOWNSEND,STROMINGER,KALOSH,…)

- **GROUND STATE FOR REISNER -NOESTROM , ALL HAWKING RADIATION GONE - ENERGY(M-Q)**

AdS2
NEAR HORIZON DEOMETRY OF EXTREMAL BH s

$$x_0^2 + x_1^2 - x_2^2 = 1$$



WEYL ACTION OF SL[2,R] ON AdS2

To every point $x_\mu \in \mathrm{AdS}_2$, $\mu = 0,1,2$, we assign the traceless and real, 2×2 matrix

$$\mathsf{M}(x) \equiv \begin{pmatrix} x_0 & x_1 + x_2 \\ x_1 - x_2 & -x_0 \end{pmatrix} \tag{2.3}$$

Its determinant is $\det \mathsf{M}(x) = -x_0^2 - x_1^2 + x_2^2 = -1$.

The action of any $\mathsf{A} \in SL(2,\mathbb{R})$ on AdS_2 is defined through the non-linear mapping

$$\mathsf{M}(x') = \mathsf{A}\mathsf{M}(x)\mathsf{A}^{-1} \tag{2.4}$$

This induces an $SO(1,2)$ transformation on $(x_\mu)_{\mu=0,1,2}$,

$$x' \equiv \mathsf{L}(\mathsf{A})x \tag{2.5}$$

Choosing as the origin of coordinates the base point $\boldsymbol{p} \equiv (1,0,0)$, its stability group $SO(1,1)$ is the group of Lorentz transformations in the $x_0 = 0$ plane of $\mathscr{M}^{1,2}$ or equivalently, the "scaling" subgroup D of $SL(2,\mathbb{R})$

$$\mathsf{D} \ni \mathsf{S}(\lambda) \equiv \begin{pmatrix} \lambda & 0 \\ 0 & \lambda^{-1} \end{pmatrix} \tag{2.6}$$

for $\lambda \in \mathbb{R}^*$.

For this choice of the stability point, we define the coset h_A by decomposing A as

$$\mathsf{A} = h_\mathsf{A}\mathsf{S}(\lambda_\mathsf{A}) \tag{2.7}$$

Thus, we associate uniquely to every point $x \in \mathrm{AdS}_2$ the corresponding coset representative $h_\mathsf{A}(x)$.

ARITHMETIC DISCRETIZATION OF AdS2=SL[2,R]/SO[1,1] =>AdS2[N]=SL[2,Z[N]]/SO[1,1,[Z[N]]

X0^2+X1^2-X2^2=1 MOD[N]

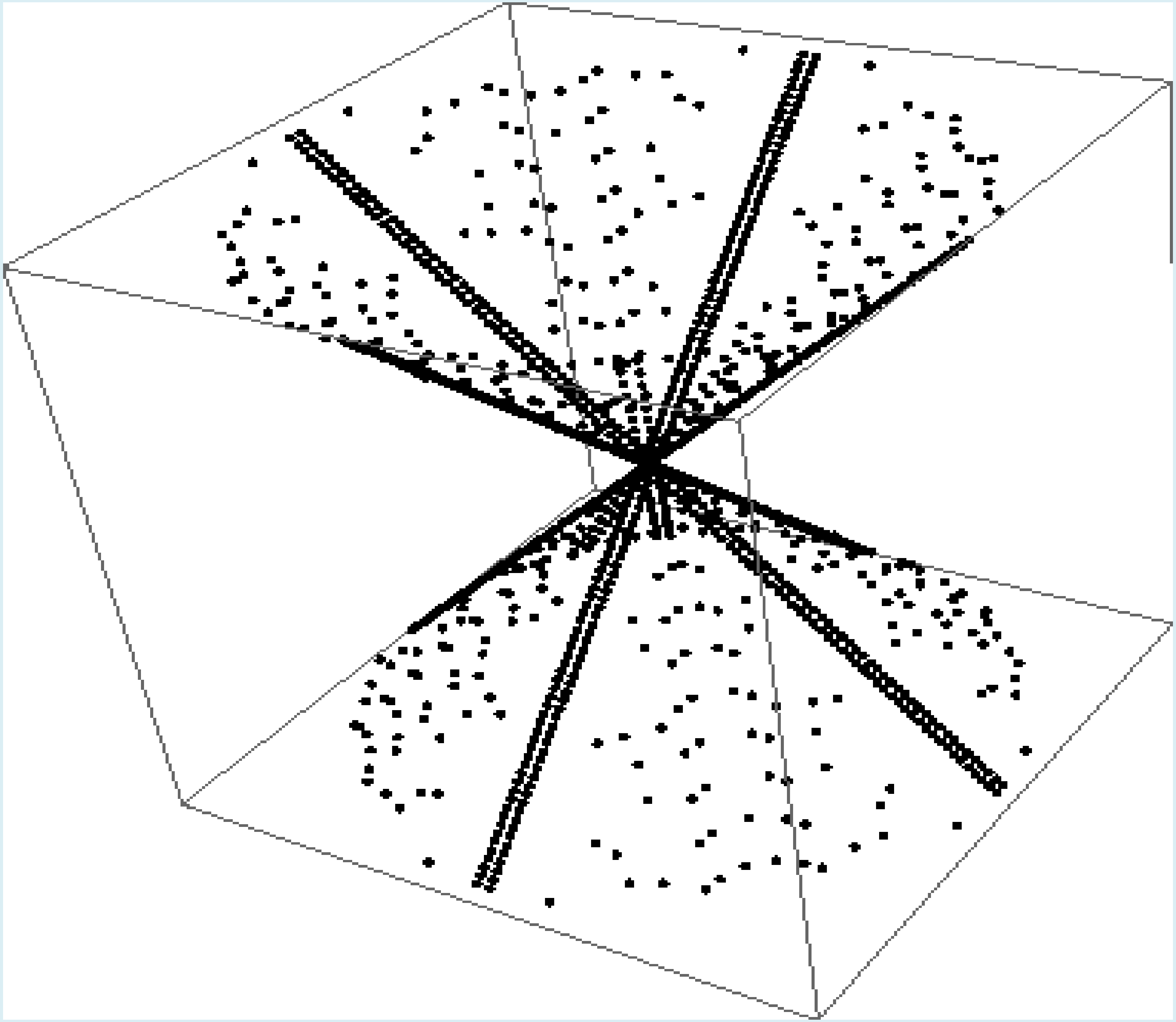
ALL INTEGER SOLUTIONS MOD[N]=> DISCRETE SET OF POINTS=ADS2[N]

X0=A- M B,
X1=B+M A
X2=M A,B,M=0,1,..,N-1

A^2+B^2=1 MOD[N], DISCRETE CIRCLE S1[N]

ROTATING THE ‘LINE’, { X0=0,X1=M,X2=M M=0,1,2,..,N-1} AROUND S1[N]

SO[1,1,Z[N]] STABILITY GROUP OF P: X0=1,X1=X2=0



QUANTIZATION OF THE AdS2[N] STRECHED HORIZON

- POINTS =>h =COSETS OF SL[2,N]/SO[1,1,N]
- QUANTUM POINTS |h>=U[h] |0>
- |0> GROUND STATE OF U[SO[1,1,N]]
- NON-COMMUTATIVE MANIFOLD

  THROUGH COHERENT STATES(H.GROSSE)

  CLASSICAL ACTION OF ISOMETRIES

  |h>=>U[A]|h>=|Ah>

HORIZON HOLOGRAPHY -COMPLEMENTARITY – CHAOS

SUSSKIND-’T HOOFT (1993-1994):

BLACK HOLE COMPLEMENTARITY PRINCIPLE =>
INFALLING STRING AT STRING SCALES FROM THE HORIZON SUFFERS LARGE TRANSVERSE AND LONGITUTINAL STRECHING AND WRAPS EXPONENTIALLY FAST THE STRECHED HORIZON =>CHAOS AND HOLOGRAPHY

1) FOR BOTH OBSERVERS , TOTAL HILBERT SPACE H=HA x HB
NO VIOLATION OF ANY PHYSICAL LAW

2) THEIR OBSERVABLES ARE COMPLEMENTARY LIKE POSITION AND MOMENTUM

THOSE OF THE INFALLING OBSERVER CAN BE RECONSTRUCTED FROM THE OBSERVABLES OF THE STATIONARY ‘s ONE (and vice versa).

THE CORRESPONDING “FOURIER TRANSFORM”
IS A CHAOTIC UNITARY MATRIX-RELATED TO THE S-MATRIX of
PURE INFALLING STATES TO UNITARY THERMAL HAWKING RADIATION

3) ALL THE INFORMATION OF THE INFALLING
OBSERVER IS PROCESSED BY THE INTERIOR OF THE
BLACK HOLE CHAOTIC DYNAMICS .

BECAUSE OF NO-LOSS OF INFORMATION AND UNITARITY
IT SHOULD BE HOLOGRAPHICALLY STORED ON THE
STRECHED HORIZON (THROUGH CHAOTIC MIXING)

dimH(Hilbert space of Horizon's microstates)

=Exp[A/4] , A=AREA OF THE HORIZON

4) THE OUTGOING HAWKING RADIATION AFTER
HORIZON THERMALIZATION, IT ENCODES
THE HORIZON'S STORED INFORMATION IN ITS
CORRELATIONS

- <u>2007 PRESKILL-HAYDEN</u>

MUCH FASTER ENTANGLEMENT OF THE BH INTERIOR AND EXTERIOR REGIONS
IN ORDER TO AVOID QUANTUM CLONING OF THE SAME QUBITS
BY EXTERIOR AND INTERIOR OBSERVERS
(NICE-SLICE OBSERVERS EXIST!)

IT IMPLIES FAST CHAOTIC MIXING ON THE STRECHED HORIZON
EXPONENTIALLY FAST DIFFUSION(BUT HOW?DYNAMICS)

BH SCRAMBLING TIME = Log[R/lp]

- <u>2008 SUSSKIND-SEKINO</u>

SCRAMBLING TIME BOUND CONJECTURE

CHAOTIC SCRAMBLING-NON LOCAL HYPERDIFUSION
MATRIX MODEL INTERACTIONS FOR THE MICROSCOPIC DOF'
(CAUSAL SATURATION OF SCRAMBLING TIME)

<u>**BLACK HOLES ARE THE UNIVERSE'S FASTEST SCRAMBLERS!**</u>

DISCRETE CONFORMAL DYNAMICS

ARNOLD CAT MAP A={{1,1},{1,2}},

WEYL ACTION ON AdS2[N]

PROPERTIES

a)STRONG ARITHMETIC CHAOS

(ARNOLD,FORD,BERRY VOROS,VIVALDI,DI VIZENZO)

b)HOLOGRAPHY=>NON LOCAL REDUNDANT STORAGE OF INFORMATION

c)MIXING TIME -LIAPUNOV EXPONENT

d)GENERATION OF KOLMOGOROV –SINAI ENTROPY

BASIC PROPERTY OF ARNOLD CAT MAP =FIBONACCI CHAOS

A^n={{f(2n-1),f(2n)},{f(2n),f(2n+1)}},

f(n) FIBONACCI INTEGERS

f[n+1]=f[n]+f[n-1];f[0]=0,f[1]=1

FOR ANY INTEGER N

Periods of A MOD[N] A^(T(N))=IdentityMatrix MOD[N]

DYSON:IF N=f[m] → T(N)=2 m

BUT SINCE FOR m->INFINITY f[m]->Exp[c m],c=log[Goldenratio]

WE OBTAIN T[N]->Log[N]

LOGARITHMIC TIME CHAOTIC MIXING(SCRAMBLING)
For FIBONACCI SEQUENCE OF INTEGER HILBERT SPACE DIMENSIONS

KOLMOGOROV ENTROPY

PROCESSING OF INFORMATION BY AREA PRESERVING MAPS

GENERALIZED ARNOLD CAT MAPS A={{a,b},{c,d}} in SL[2,Z[N]]
(r,s)->(r,s)A ,ModN

MIXING TIME= ½ OF THE PERIOD OF THE MATRIX A

ARNOLD CAT MAP MIXES THE ENTIRE PHASE SPACE IN LOGARITHMIC TIME

T[MIXING]=LOG[N]=S[KOLMOGOROV ENTROPY]

FINITE –DISCRETE QUANTUM MECHANICS

$J[r,s]=\omega^{(rs/2)}P^r Q^s$,

Heis-Weyl group

QUANTIZATION 0F CAT MAPS $A \Rightarrow U[A]$,

UNITARY N DIM IRREP OF $SL[2,Z[N]]$

$U[A]J[r,s]U[A]^{(-1)}=J[(r,s)A]$ (WEIL)

$U[AB]=U[A]U[B]$ FOR N=PRIME INTEGER->EXACT- NOT PROJECTIVE!

ONE-TIME STEP EVOL OF STATES=>SCHRODINGER EQUATION FOR DISCRETE MAPS

$|n+1\rangle=U[A]|n\rangle$, $|0\rangle$ A GIVEN INITIAL STATE

- <u>U[A](k,l)=1/Sqrt[N] ω^[-1/2b (ak^2+d l^2-2 k l)], k,l,=0,1,2,..,N-1</u>

, ω=Exp[2 π i/N],   U[A]^n=U[A^n] !

EXAMPLES

1)HARMONIC OSCILLATOR   A={{0,-1},{1,0}}

U[A](k,l)=1/Sqrt[N] ω^(kl)=F , Q-FOURIER=FFT

HARMONIC OSCILLATOR GROUP SO[2,Z[N]]
(BALIAN-ITZYKSON 1986)

A={{a,-b},{b,a}}   a^2+b^2=1 MOD[N},a,b=0,1,2,..,N-1
FOR N=prime integer=4 k+(-)1,ORDER OF THE GROUP 4k.

ANY INTEGER (COARSE GRAINING)FACTORIZATION,

- $N=N1xN2$,$N=Exp[R^2]$, $R^2 \Rightarrow R1^2 + R2^2$
- SL[2,Z[N]]=SL[2,Z[N1]]xSL[2,Z[N2]]
- A[N]=A[N1]A[N2]
- H[N]=H[N1]+H[N2], SCHWINGER HEIS-WEYL FACTORIZATION
- U[A[N]]=U[A[N1]]U[A[N2]]

FAST QUANTUM MAPS $N^2 \rightarrow N \log N$

- S[N]=S[N1]+S[N2] ADDITIVITY OF COARSE GRAINED ENTROPIES

EIGENSTATE THERMALIZATION SENARIO
PAGE,DEUTSCH,BERRY,SREDNICKI

IF THE EIGENSTATES OF A CLOSED QM SYSTEM ARE RANDOM

(RANDOM PHASES AND GAUSSIAN DISTRIBUTED AMPLITUDES)

THEN ANY INITIAL PURE STATE OF A SUBSYSTEM THERMALIZES TO
THE THERMAL DENSITY MATRIX OF THE SUBSYSTEM

RELATION TO THE INFORMATION PARADOX

2013 SREDNICKI TALK TO KITP

ARNOLD QUANTUM CAT MAP A={{1,1},{2,1}}

EXACT CONSTRUCTION OF THE SPECTRUM AND EIGENSTATES FOR N=p,prime,

LINEAR SPECTRUM

RANDOM EIGENSTATES ->LINEAR COMBINATIONS OF MULTIPLICATIVE CHARACTERS OF GF[P]

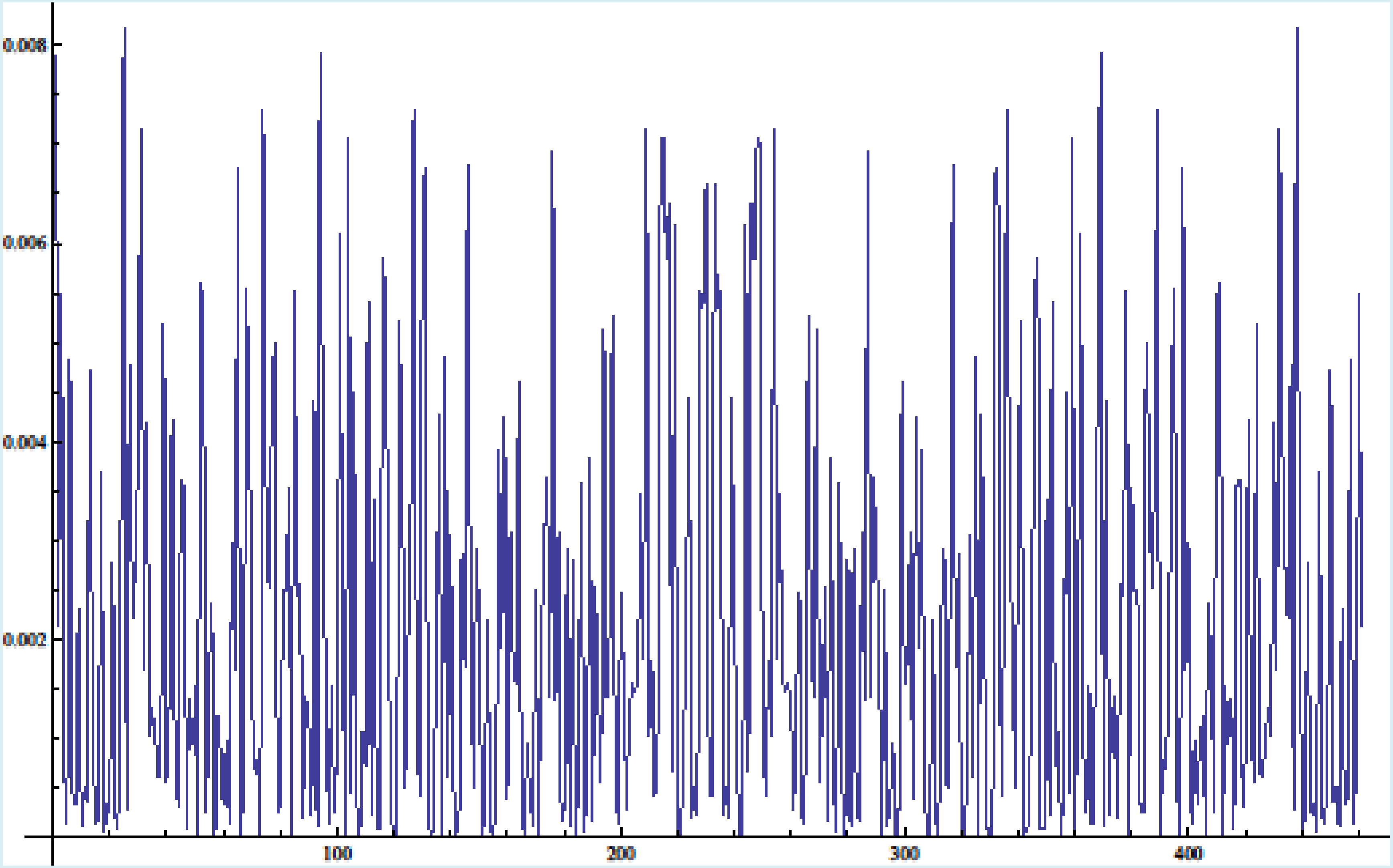
1)RANDOM PHASES
2)GAUSSIAN RANDOM AMPLITUDES

BUT SCARS(VOROS.,NONEMACHER)F
FOR SEQUENCES OF N's WITH SHORT PERIODS

QUANTUM CHAOS, STRONG MIXING

- **FACTORIZATION FOR ARNOLD CAT MAPS IMPLIES LOGARITHMIC IMPROVEMENT FROM N^2->N LOGN**
- **USING QUANTUM CIRCUITS FOR THE IMPLEMENTATION OF THE QUANTUM MAP AND COUNTING THE NUMBER OF GATES NLOGN->(LOGN)^2**
- **EXACTLY AS FOR THE QUANTUM FOURIER FACTORIZATION ALGORITHM OF SHOR.**

- N=461,T[461]=23 ,GROUND STATE,PHI=0



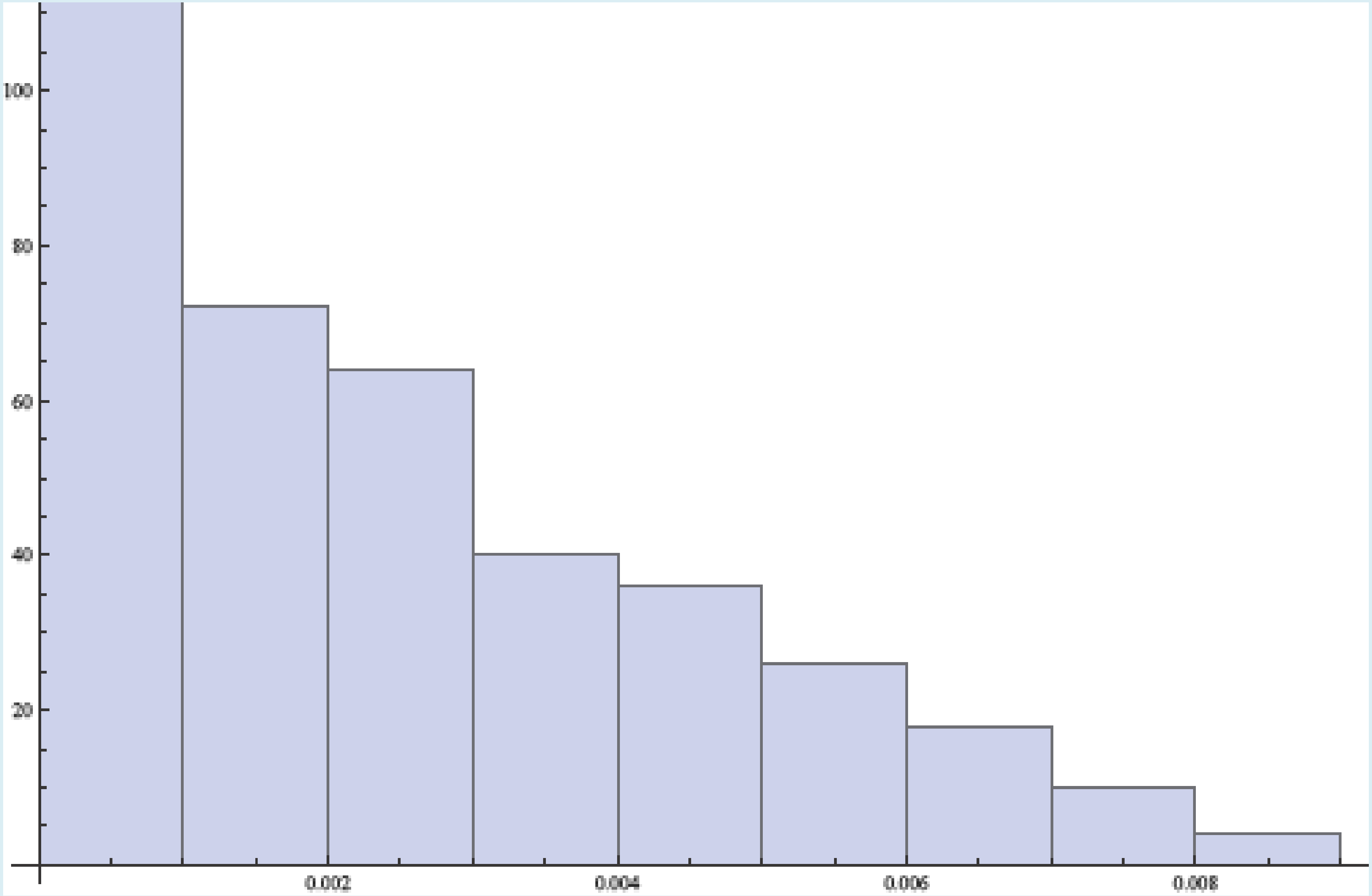
Quantum Complexity of QACM

- Ford-Mantica
- 1990!
- Classical complexity of ACM -> N=2^n
- Quantum Complexity of ACM ->n^2
- ->Violation of Classical Quantum correspondence,NO semiclassical limit
- M Berry Quantum Chaology
- Complexity is not a physical observable

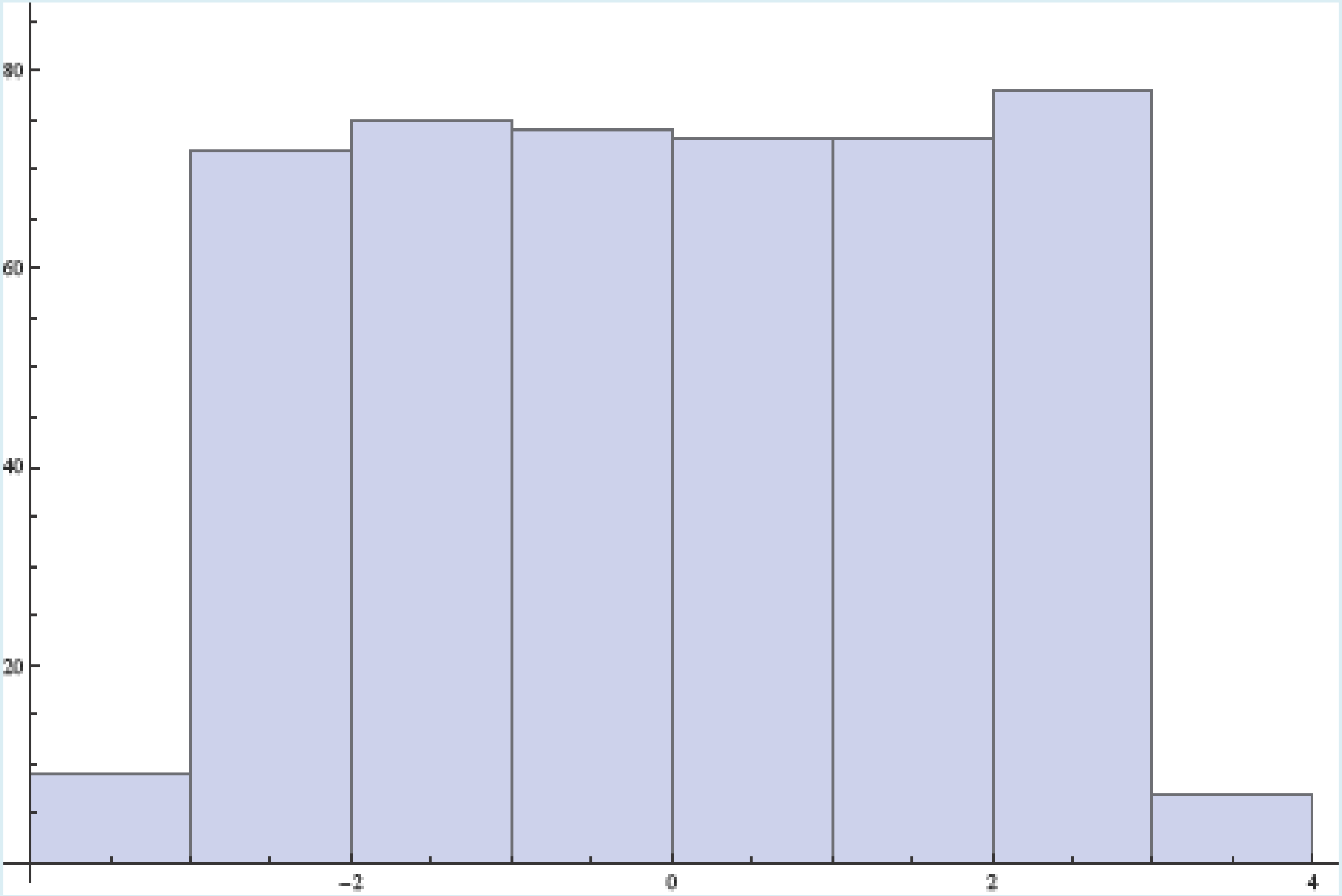
Quantum Complexity EPR=ER

- Ryu-Takayanagi
- Susskind-Maldacena
- Quantum Complexity Mesurable Quantity
- Einsteins EQNS out of Variations of Entanglement Entropy
- ACM={{0,-1},{1,0}}.L.{{0,1},{-1,0}}.L
- L={{1,0},{1,1}}
- U[A] complexity =complexity of Quantum Fourier Transform=n^2,for large n number of qubits
- Quantum Circuit,SHORs
- U[L] diagonal unitary operator ,complexity =n^2
- E.Floratos,D.Pavlidis to appear in arXives and in JQC

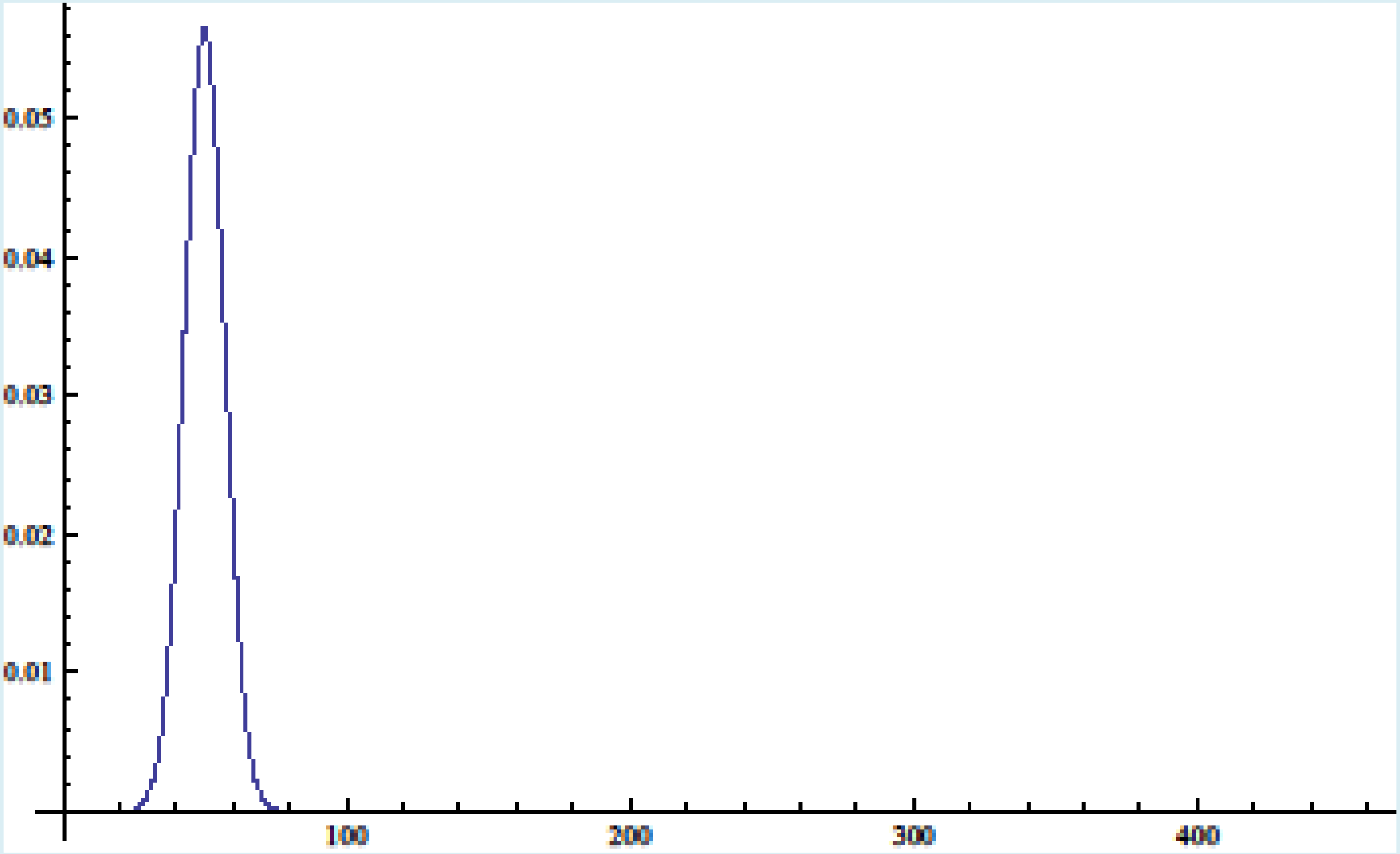
• GROUND STATE AMPLSQUARE DF



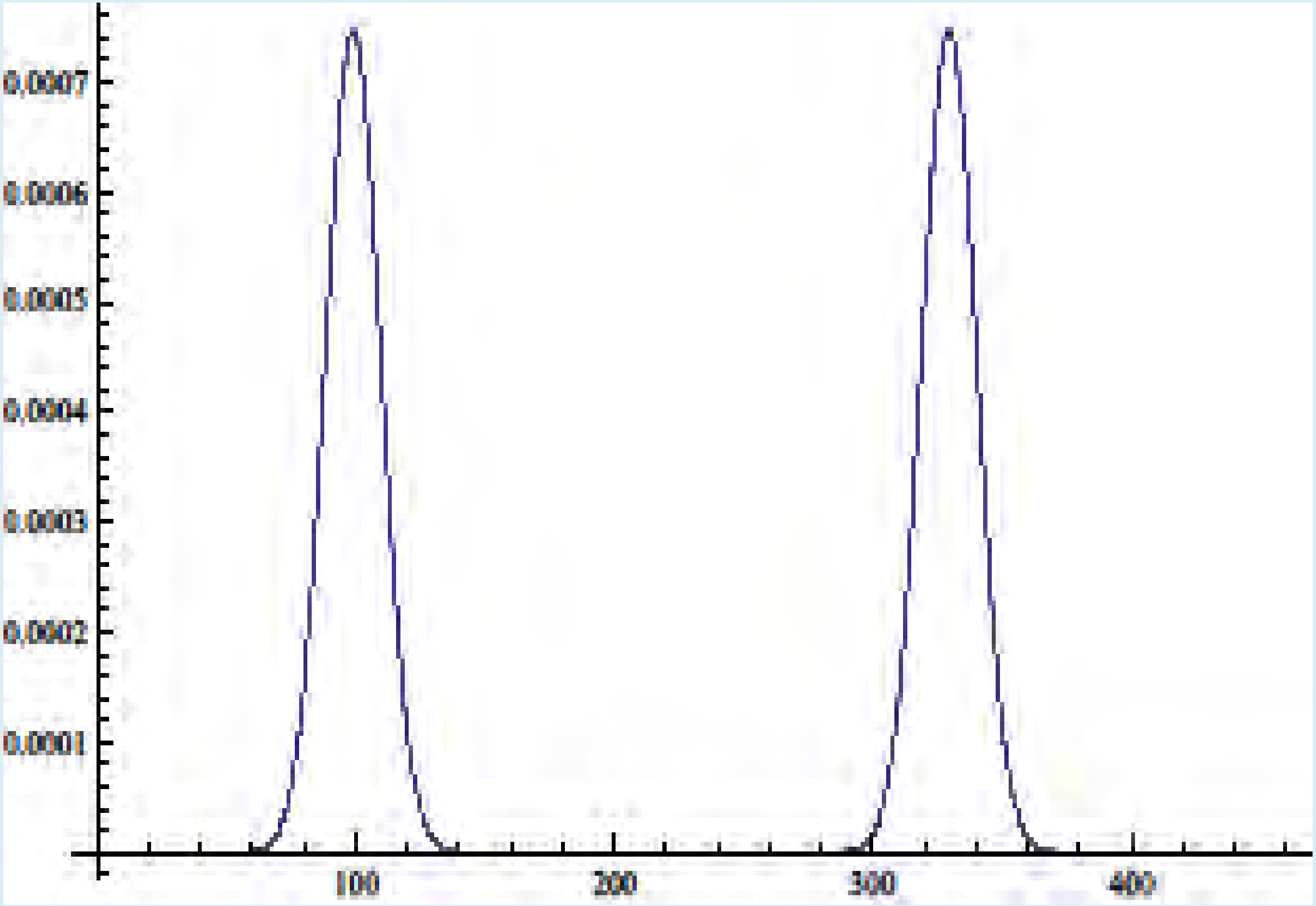
- GROUND STATE PHASE DF



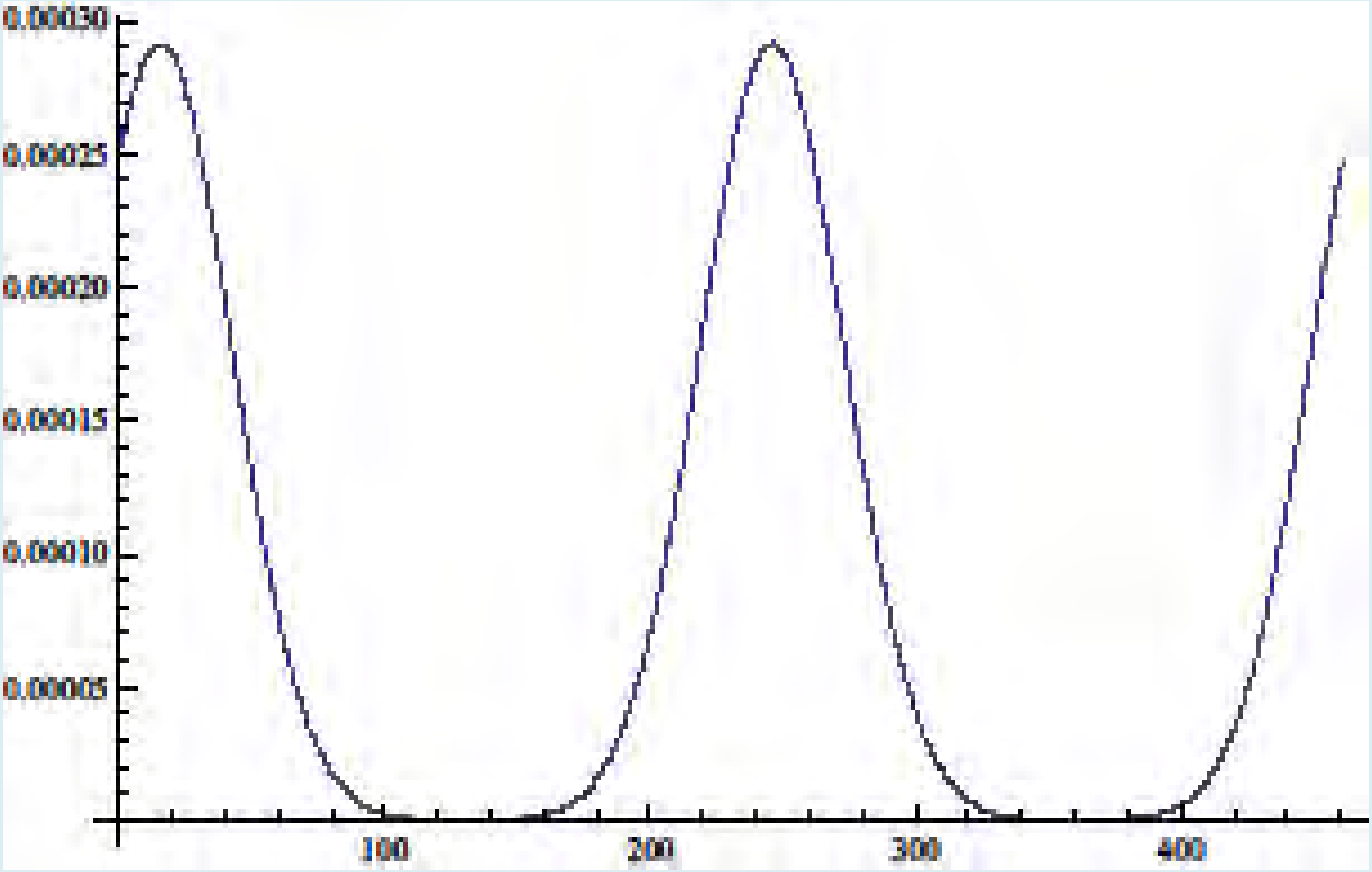
- SCATTERING EXPERIMENT, N=p=461
- GAUSSIAN WF AT T=0



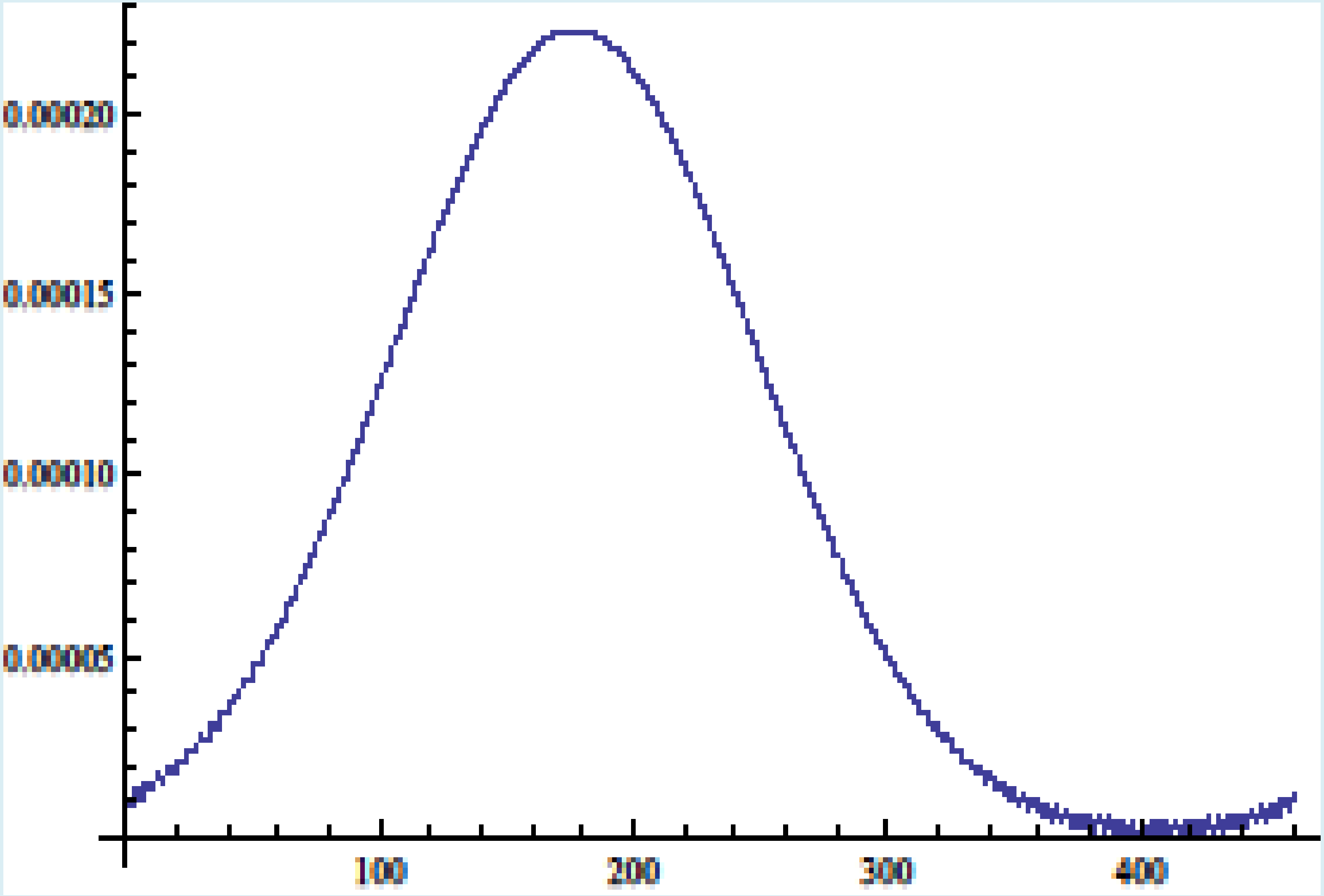
- TIME=1



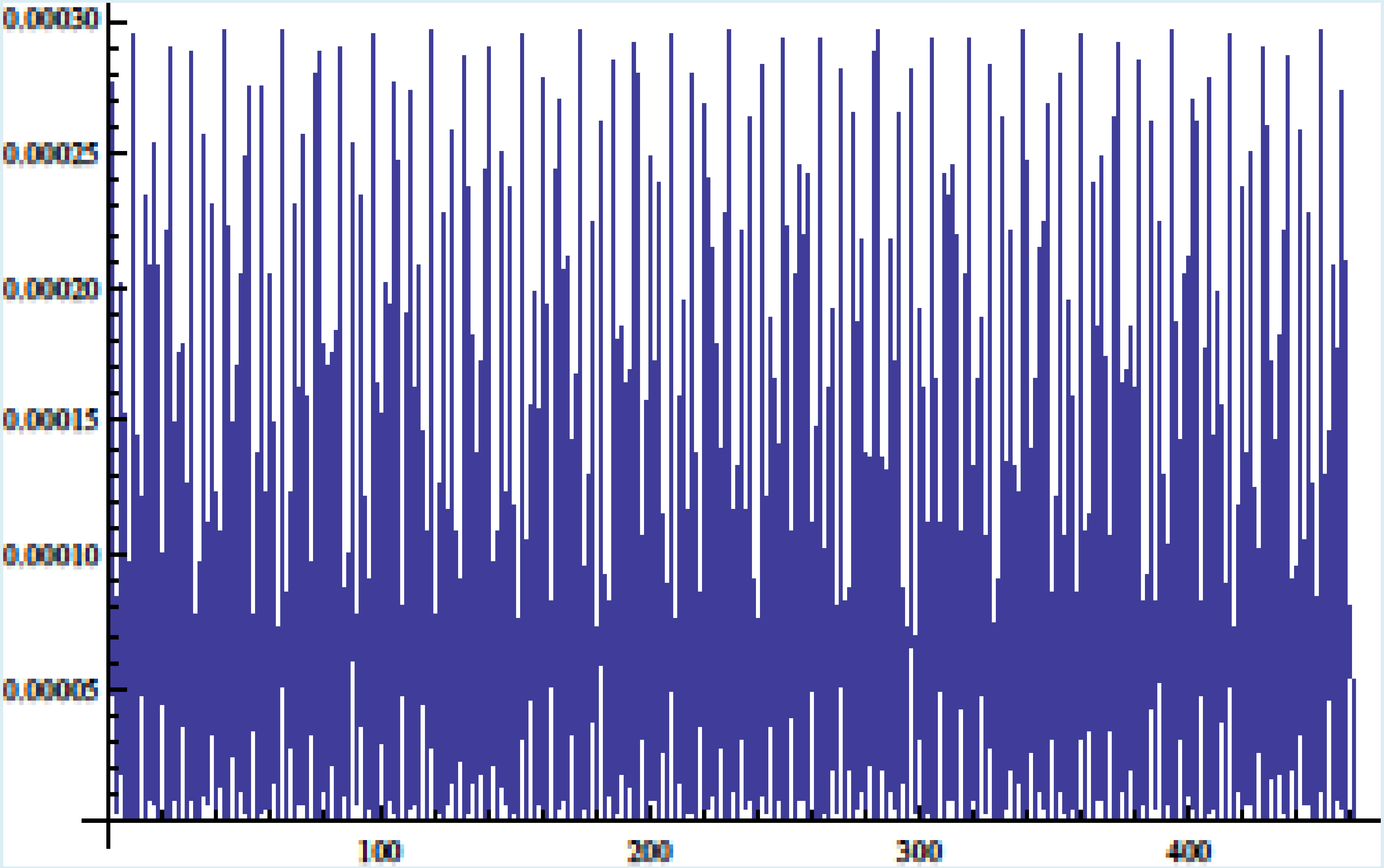
- T=3



- T=3

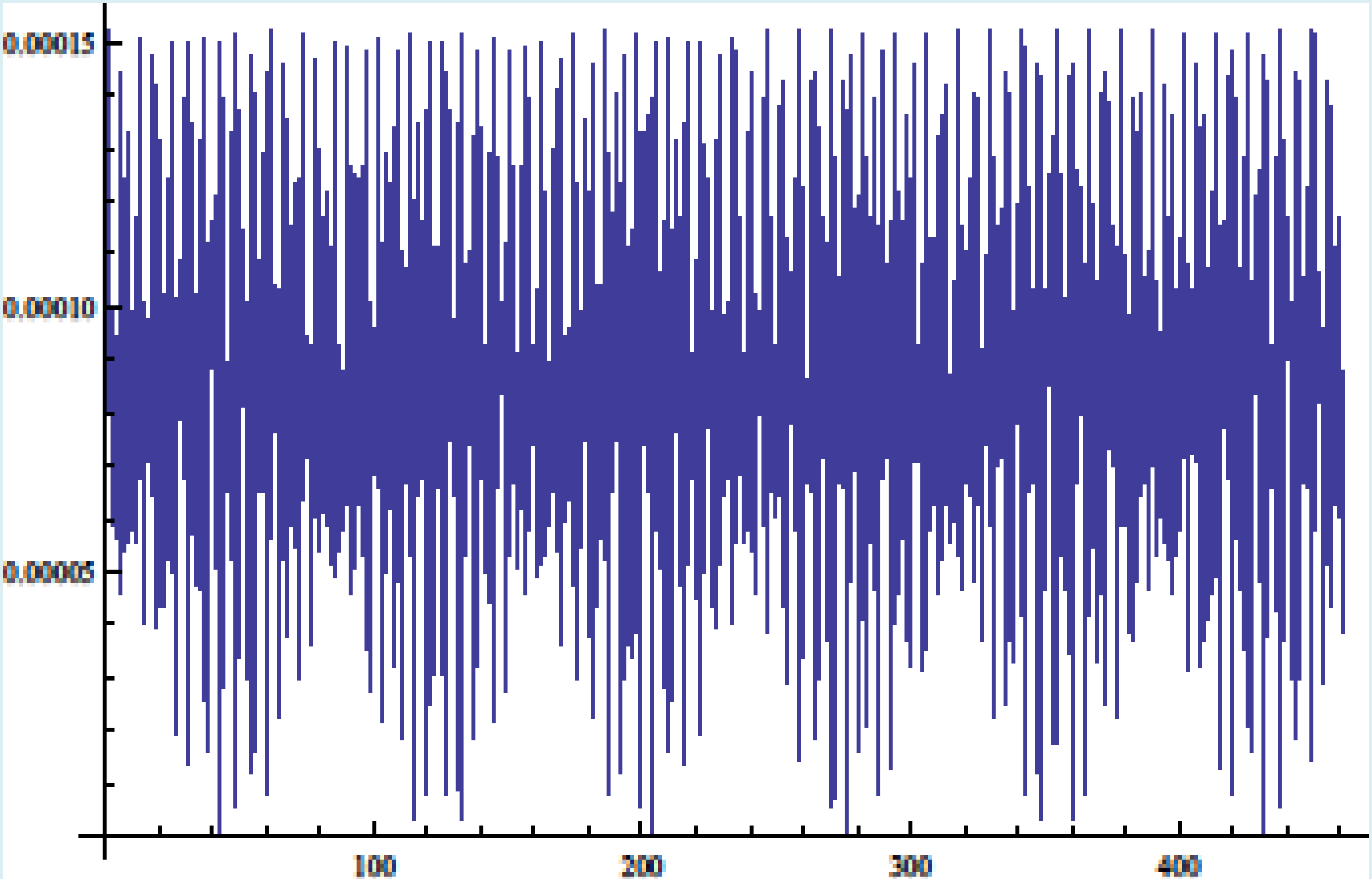


- T=4

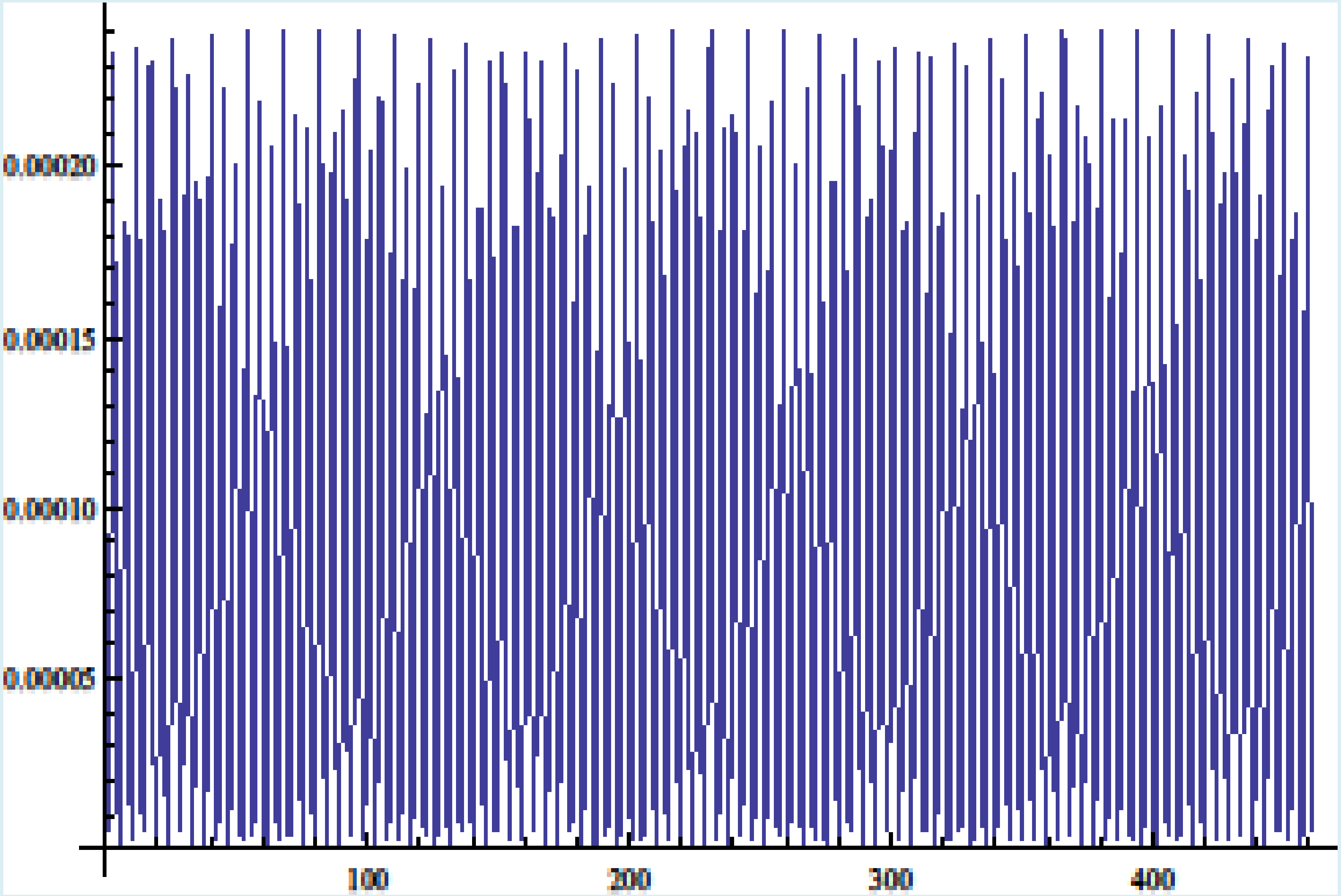


0.000030
0.000025
0.000020
0.000015
0.000010
0.000005
100
200
300
400

- T=6



- T=7



CONCLUSIONS

COMPLEMENTARITY IS BASED ON THE ASSUMPTION OF THE SCRAMBLING TIME BOUND IN ORDER TO AVOID QUANTUM CLONING AND ENCODE HOLOGRAPHICALLY FAST ENOUGH THE INFALLING INFORMATION ON THE CORRELATIONS OF

THE EMMITED HAWKING RADIATION

DISCRETIZING AdS2 RADIAL AND TIME NEAR HORIZON GEOMETRY OF EXTREMAL BLACKHOLES AND AT THE SAME TIME PRESERVING THE ALGEBRAIC STRUCTURE OF THE ISOMETRIES NECESSARILY LEADS TO THE MOD[N] ARITHMETIC DISCRETIZATION WITH HOLOGRAPHY AdS2[N]/CFT1[N],THIS CLASSICAL STRUCTURE IS LIFTED AT THE QUANTUM LEVEL

THROUGH FINITE QUANTUM MECHANICS

THE QUANTUM CAT MAP CHAOTIC DYNAMICS

ON THE DISCRETIZED HORIZON AdS2[N] ,

THERMALIZES THE INFORMATION ,DUE TO THEIR RANDOM EIGENSTATES,(ETH),

IN LOGARITHMIC TIME

AND THUS IT SATURATES

THE SCRAMBLING TIME BOUND

COMPLEXITY OF THE QACM GROWS AS n^2=Log[S]^2