Interplay of Classical and Quantum Correlations in Many-Body Systems

Aditi Sen(De)

QIC group, Harish-Chandra Research Institute (HRI), Allahabad

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Collaborators:
R. Prabhu, Ujjwal Sen

Outline

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- What is entanglement?

Outline

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Physical systems

Outline

- What is entanglement?
- Quantum many-body systems and entanglement ---brief overview

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Lectures in School

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- Ergodicity of entanglement without ergodic classical correlations

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Entanglement is useful in

- Quantum Communication ---
  - sending classical info via quantum states -- Dense coding
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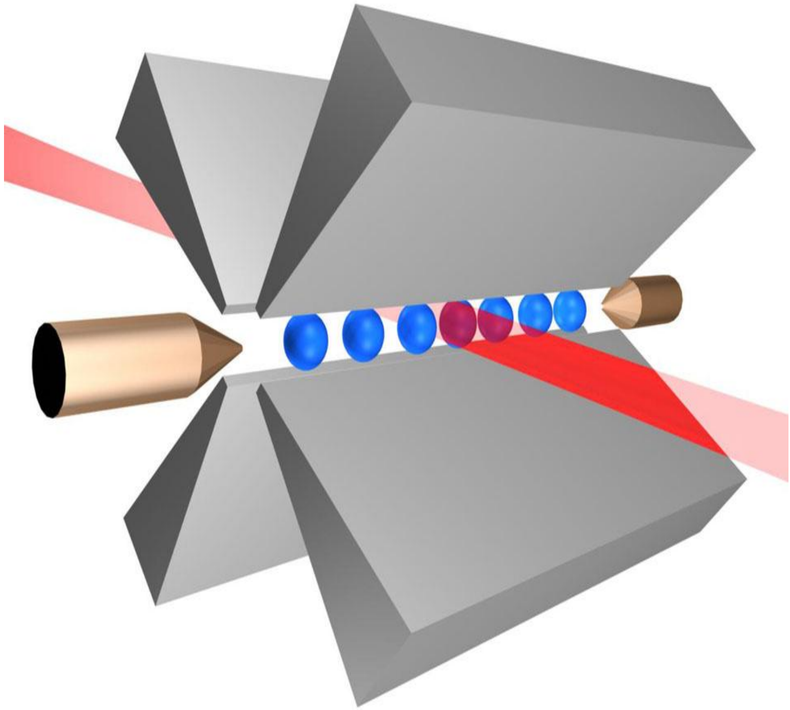
- Quantum Computation---
  - One-way quantum computer ***(Briegel, Raussendorf, PRL2003)***

Entanglement: A reality in lab

- Ion trap



R. Blatt's group in Innsbruck

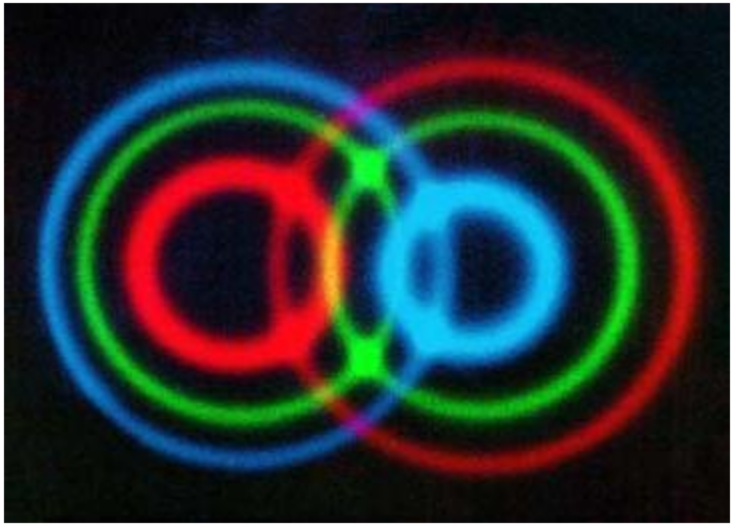
Entanglement: A reality in lab

- NMR

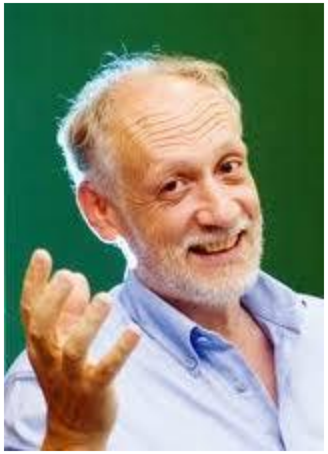
Anil Kumar’s group in Bangalore

Entanglement: A reality in lab

- Photon



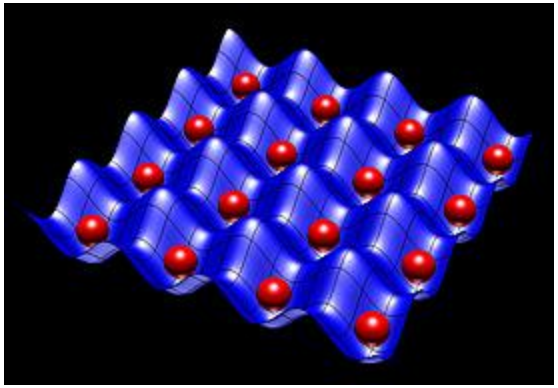
Zeilinger in Vienna;



Gisin in Geneva

Entanglement: A reality in lab

- Optical Lattice



I. Bloch's group in Munich

Entanglement: A reality in lab

And so on …………………….

Entanglement: A reality in lab

- Photon
- Ion
- Neutral atoms in optical lattice
- NMR
- Cavity QED

So on…………….

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Why this connection interesting?

- Study fundamental properties by using quantum info or vice-versa.

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- Study fundamental properties by using quantum info or vice-versa.

- Realization of quantum computer by using such systems.

Realization of spin systems in atomic gases or ion traps

VOLUME 91, NUMBER 9 PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2003

Controlling Spin Exchange Interactions of Ultracold Atoms in Optical Lattices

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[1]*Institute for Quantum Information, California Institute of Technology, mc 107-81, Pasadena, California 91125, USA*

[2]*Physics Department, Harvard University, Cambridge, Massachusetts 02138, USA*

(Received 25 October 2002; published 26 August 2003)

We describe a general technique that allows one to induce and control strong interaction between spin states of neighboring atoms in an optical lattice. We show that the properties of spin exchange interactions, such as magnitude, sign, and anisotropy, can be designed by adjusting the optical potentials. We illustrate how this technique can be used to efficiently "engineer" quantum spin systems with desired properties, for specific examples ranging from scalable quantum computation to probing a model with complex topological order that supports exotic anyonic excitations.

DOI: 10.1103/PhysRevLett.91.090402 PACS numbers: 03.75.Nt, 03.67.–a, 42.50.–p, 73.43.–f

Realization of spin systems in atomic gases or ion traps

PRL 93, 250405 (2004) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2004

Implementation of Spin Hamiltonians in Optical Lattices

J. J. García-Ripoll,[1] M. A. Martin-Delgado,[1,2] and J. I. Cirac[1]

[1]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, Garching, D-85748, Germany*

[2]*Universidad Complutense de Madrid, Fac. de CC. Físicas, Ciudad Universitaria, Madrid, E-28040, Spain*

(Received 27 April 2004; published 15 December 2004)

We propose an optical lattice setup to investigate spin chains and ladders. Electric and magnetic fields allow us to vary at will the coupling constants, producing a variety of quantum phases including the Haldane phase, critical phases, quantum dimers, etc. Numerical simulations are presented showing how ground states can be prepared adiabatically. We also propose ways to measure a number of observables, like energy gap, staggered magnetization, end-chain spins effects, spin correlations, and the string-order parameter.

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VOLUME 91, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2003

Entangling Strings of Neutral Atoms in 1D Atomic Pipeline Structures

U. Dorner,[1] P. Fedichev,[1] D. Jaksch,[1] M. Lewenstein,[2] and P. Zoller[1,2]
[1]*Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria*
[2]*Institut für Theoretische Physik, Universität Hannover, D-30167 Hannover, Germany*
(Received 6 December 2002; published 14 August 2003)

We study a string of neutral atoms with nearest neighbor interaction in a 1D beam splitter configuration, where the longitudinal motion is controlled by a moving optical lattice potential. The dynamics of the atoms crossing the beam splitter maps to a 1D spin model with controllable time dependent parameters, which allows the creation of maximally entangled states of atoms by crossing a quantum phase transition. Furthermore, we show that this system realizes protected quantum memory, and we discuss the implementation of one- and two-qubit gates in this setup.

Realization of spin systems in atomic gases or ion traps

VOLUME 92, NUMBER 20 PHYSICAL REVIEW LETTERS week ending 21 MAY 2004

Effective Quantum Spin Systems with Trapped Ions

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Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, Garching, D-85748, Germany

(Received 16 January 2004; published 20 May 2004)

We show that the physical system consisting of trapped ions interacting with lasers may undergo a rich variety of quantum phase transitions. By changing the laser intensities and polarizations the dynamics of the internal states of the ions can be controlled, in such a way that an Ising or Heisenberg-like interaction is induced between effective spins. Our scheme allows us to build an analogue quantum simulator of spin systems with trapped ions, and observe and analyze quantum phase transitions with unprecedented opportunities for the measurement and manipulation of spins.

PRL 98, 023003 (2007) PHYSICAL REVIEW LETTERS week ending 12 JANUARY 2007

Trapped Ion Chain as a Neural Network: Error Resistant Quantum Computation

Marisa Pons,[1] Veronica Ahufinger,[2] Christof Wunderlich,[3] Anna Sanpera,[4] Sibylle Braungardt,[5] Aditi Sen(De),[5] Ujjwal Sen,[5] and Maciej Lewenstein[6]

[1]*Departamento de Física Aplicada I, Universidad del País Vasco, 20600 Eibar, Spain*
[2]*ICREA and Grup d'Òptica, Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain*
[3]*Fachbereich Physik, Universität Siegen, 57068 Siegen, Germany*
[4]*ICREA and Grup de Física Teòrica, Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain*
[5]*ICFO-Institut de Ciències Fotòniques, 08860 Castelldefels (Barcelona), Spain*
[6]*ICREA and ICFO-Institut de Ciències Fotòniques, 08860 Castelldefels (Barcelona), Spain*

(Received 23 December 2005; published 9 January 2007)

We demonstrate the possibility of realizing a neural network in a chain of trapped ions with induced long range interactions. Such models permit one to store information distributed over the whole system. The storage capacity of such a network, which depends on the phonon spectrum of the system, can be controlled by changing the external trapping potential. We analyze the implementation of error resistant universal quantum information processing in such systems.

DOI: 10.1103/PhysRevLett.98.023003 PACS numbers: 03.67.Pn, 42.50.Vk, 87.18.Sn

Two Main Directions

- Entanglement of 2-party state
- Entanglement Area Law

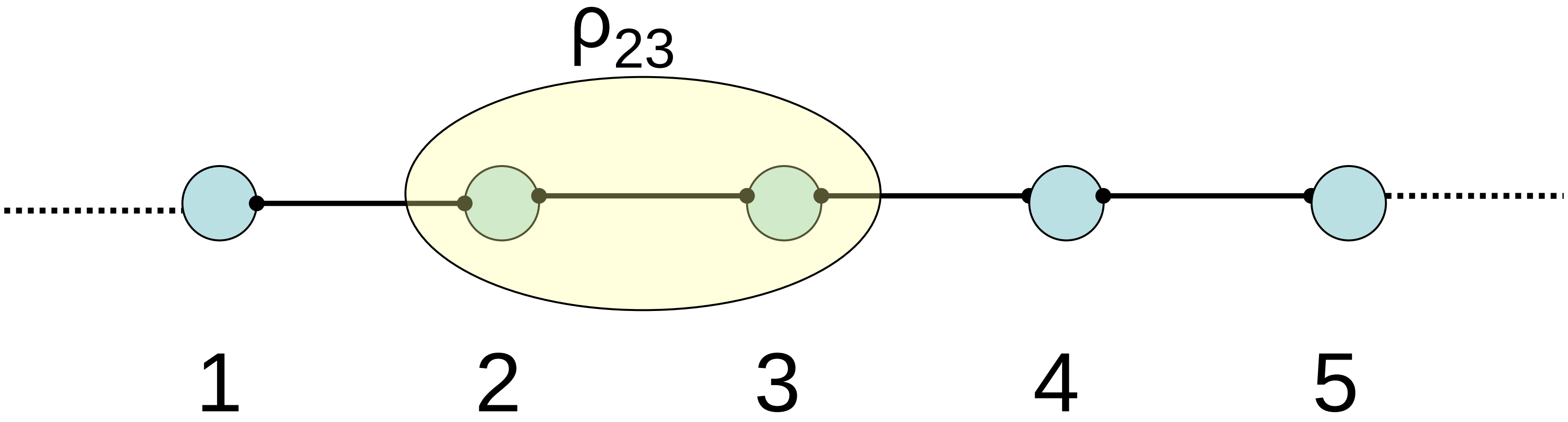
- Osterloh, Amico, Falci, & Fazio, Nature '02;
- Osborne & Nielsen, PRA '02.

- Vidal, et al., PRL'03;
- Korepin, PRL'04

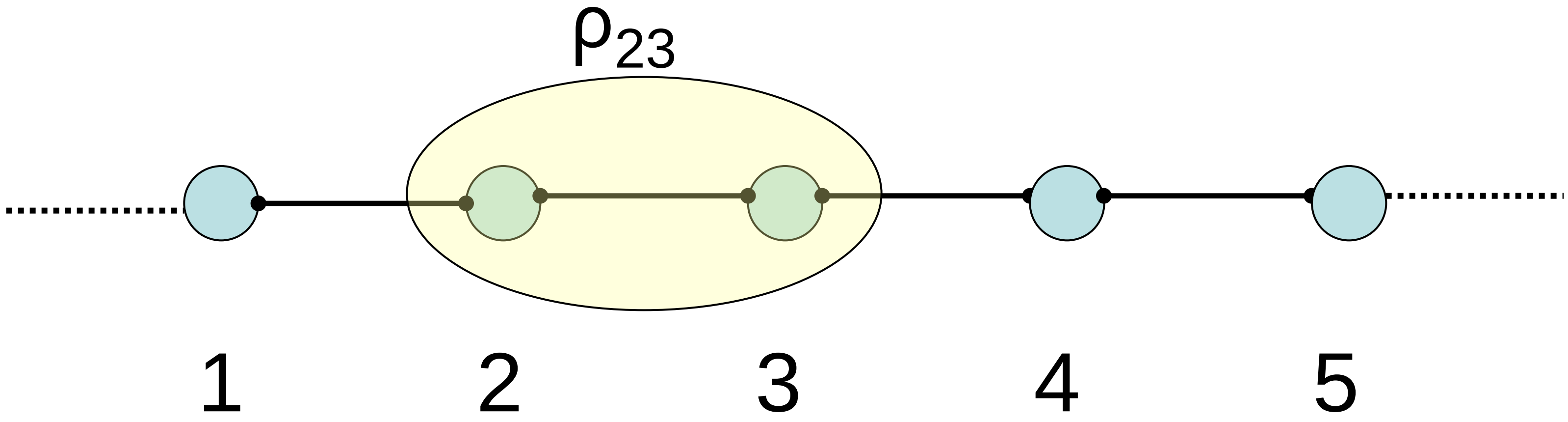
Lewenstein, Sanpera, Ahufinger, Damski, ASD, Sen, Adv Phys. 56, 243 ('07);

Amico, Fazio, Osterloh, Vedral, RMP 80, 517 '08

Example

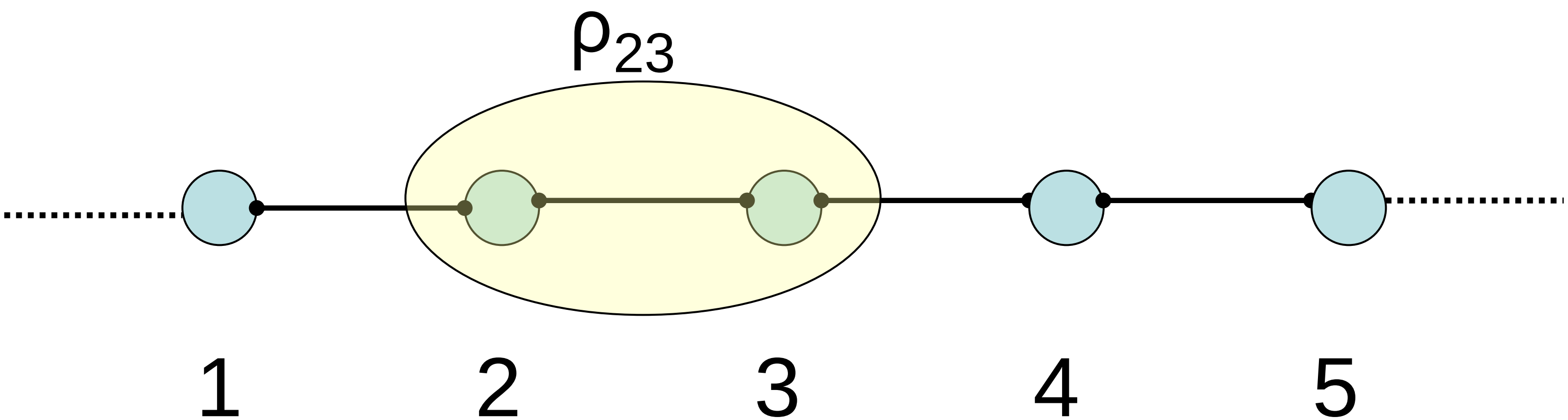


Example



Nearest Neighbor (NN) entanglement: $E(\rho_{23})$

Example



Nearest Neighbor (NN) entanglement: $E(\rho_{23})$

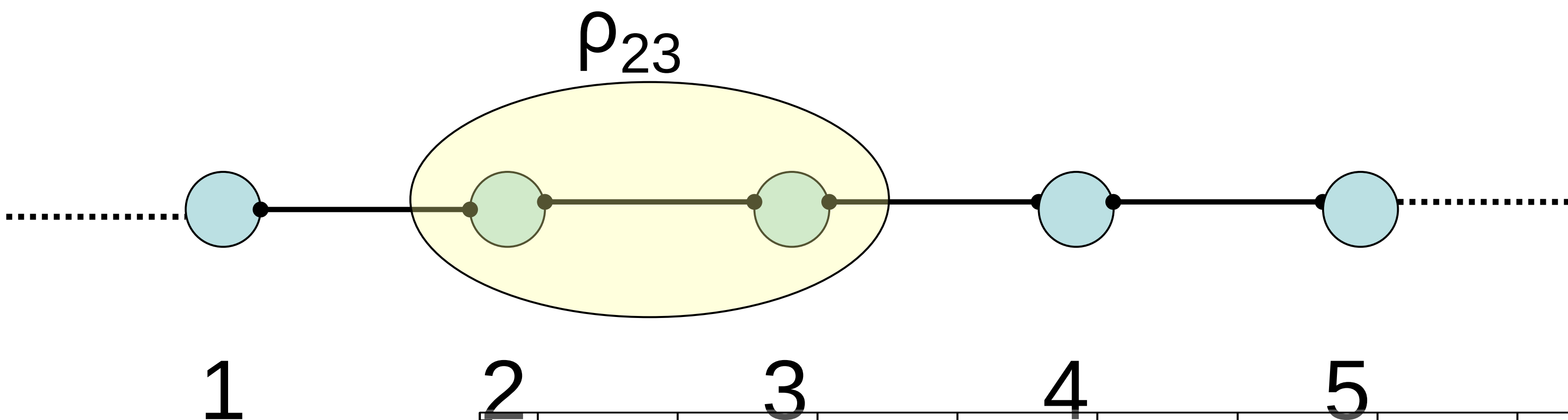
1D transverse Ising:
Ground state two-site entanglement remains short ranged while correlation length diverges.
Entanglement, however, does show signs of criticality.

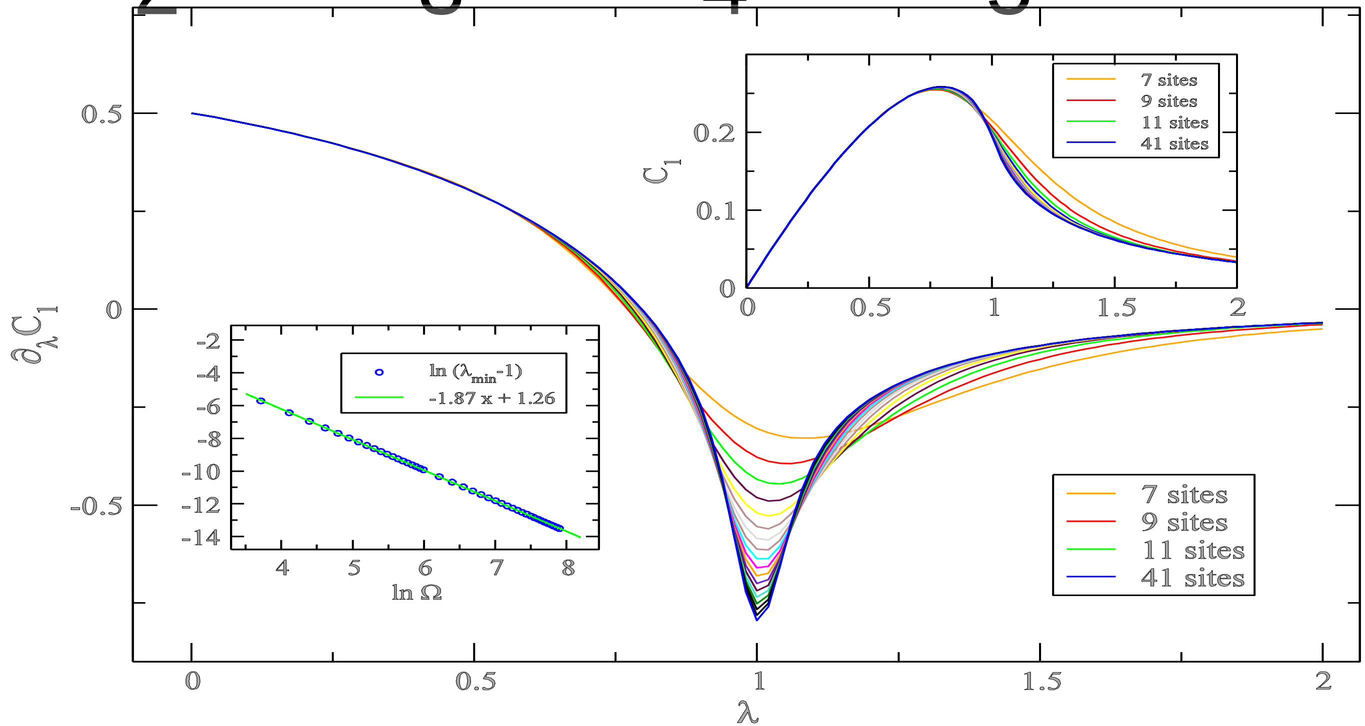
Osterloh, Amico, Falci, & Fazio, Nature '02; Osborne & Nielsen, PRA '02.

Example

$$H = -(J/2)\Sigma\sigma^z_i\sigma^z_{i+1} - h\Sigma\sigma^x_i$$

$$\lambda = J/(2h)$$





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Entanglement wt Classical Correlations

Such multipartite states exist

D. Kaszlikowski, ASD, U. Sen, V. Vedral, A. Winter, PRL ’08

Entanglement wt Classical Correlations

Such multipartite states exist

Such bipartite states do not exist

Bipartite entanglement always has a "background" of bipartite classical correlations.

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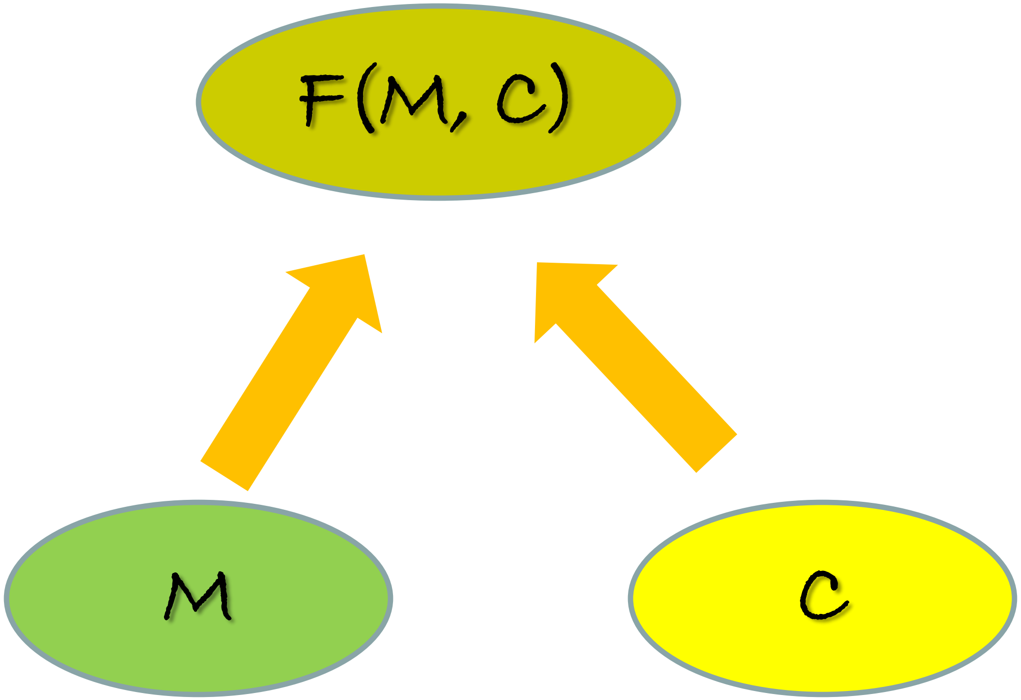
Is it true therefore that properties of bipartite ent are always inherited from those of bipartite classical correlations?

Prop. Entanglement wt prop. of correlations



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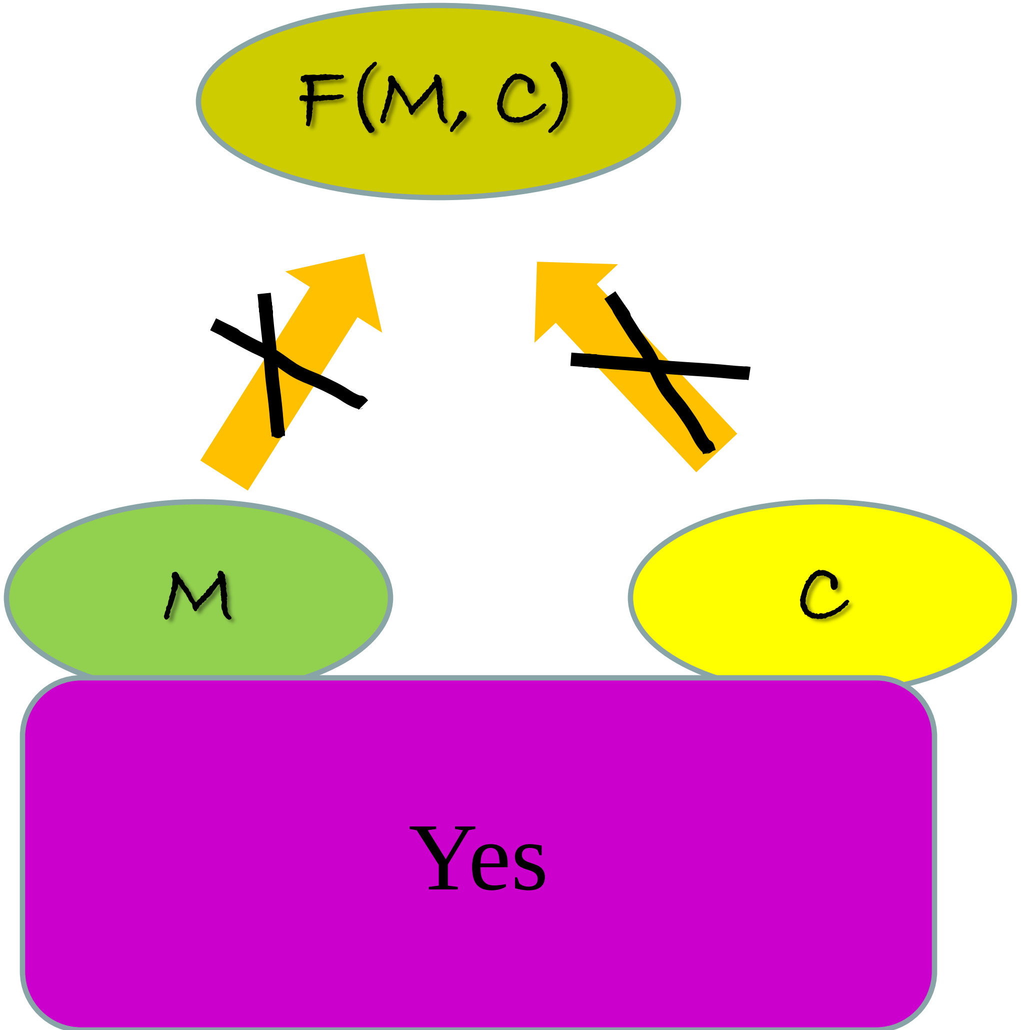

Entanglement in Dynamics

R. Prabhu, ASD, U. Sen, arXiv:1103.3836

XY spin model

XY spin model

This model is exactly solvable.

Jordan-Wigner transformation

$$H = \sum [(1+\gamma)\, \sigma_i^x \sigma^x_{i+1} + (1-\gamma)\, \sigma_i^y \sigma^y_{i+1}]$$

$$+ h(t) \sum \sigma^z_i$$

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$$+\, h(t) \sum \sigma^z_i$$

External magnetic field

h(t) = a, t=0

= 0, t>0

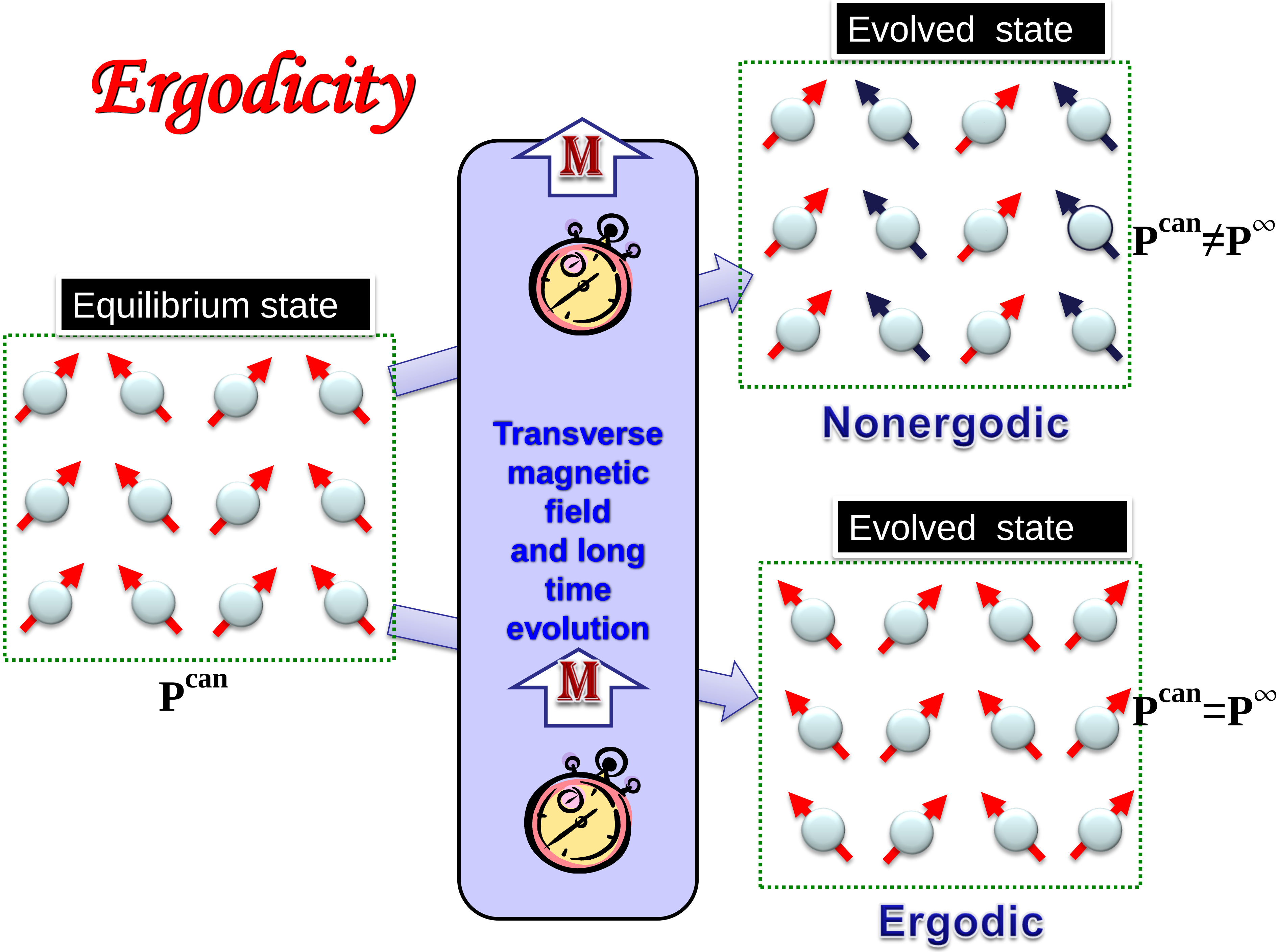
Entanglement in dynamics of many body systems

Magnetization -- Barouch, McCoy, & Dresden, 1970s.

Bipartite entanglement--

ASD, Sen, & Lewenstein,

Phys. Rev. A (Rapid Com.) 2004.



Ergodicity
Equilibrium state
P^{can}
M
Transverse magnetic field and long time evolution
M
Evolved state
$P^{can} \neq P^{\infty}$
Nonergodic
Evolved state
$P^{can} = P^{\infty}$
Ergodic

Ergodicity

P is nonergodic

if

for a given T,

$$P^{\infty}(T, h(t), \gamma) \neq P^{can}(T', h(t = \infty\ ), \gamma), \forall\ T'$$

XY spin model

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$$H = \sum [(1+\gamma)\,\sigma_i^x \sigma^x_{i+1} + (1-\gamma)\,\sigma_i^y \sigma^y_{i+1}]$$

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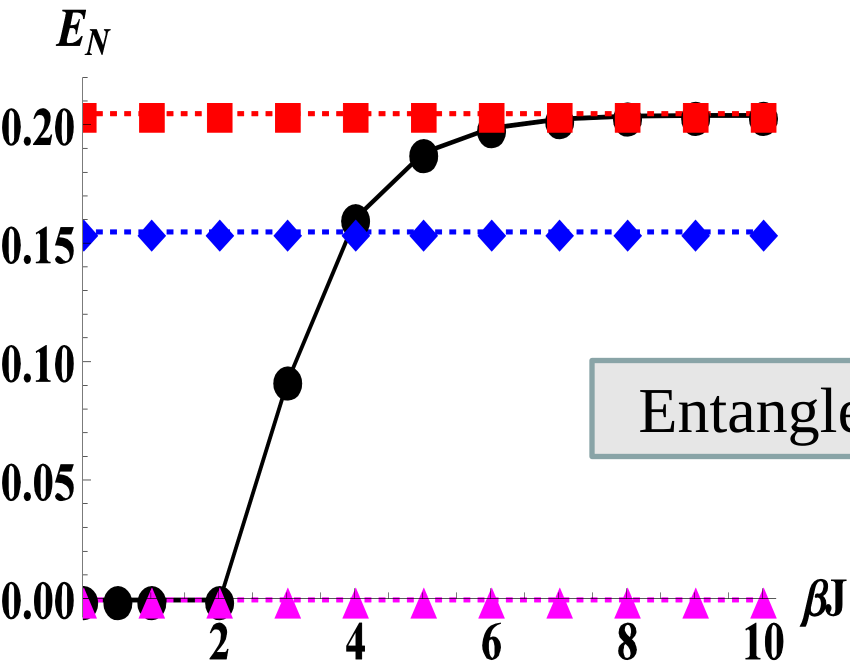
External magnetic field

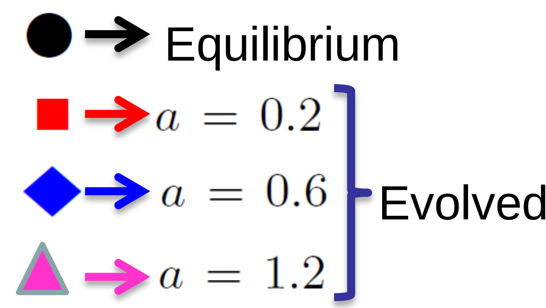
h(t) = a, t=0

= 0, t>0

Infinite XY Spin Chain



Entanglement



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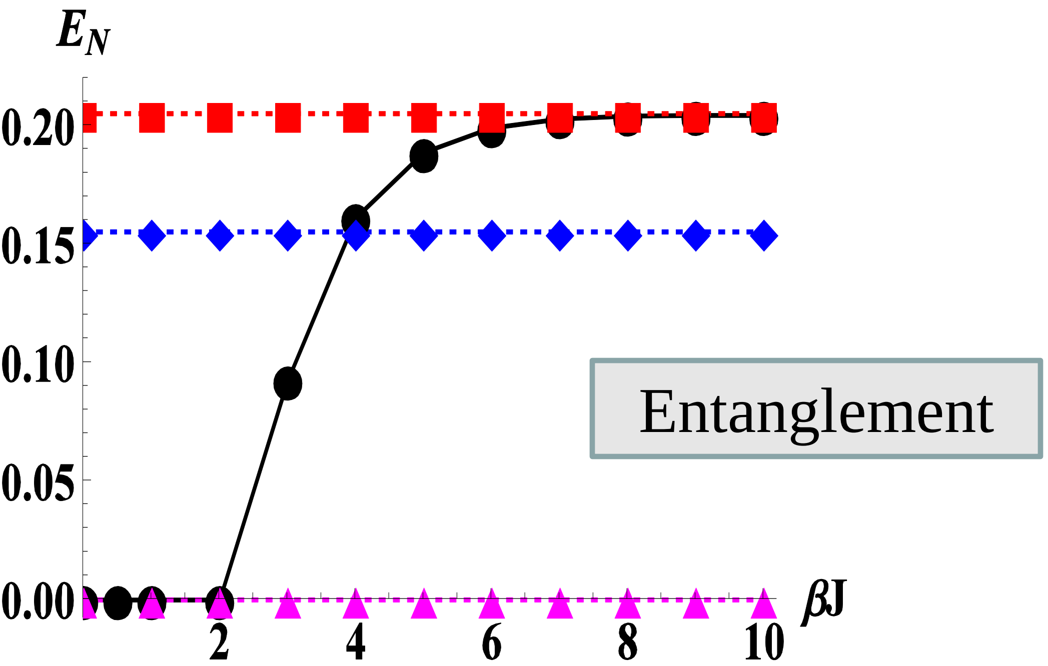
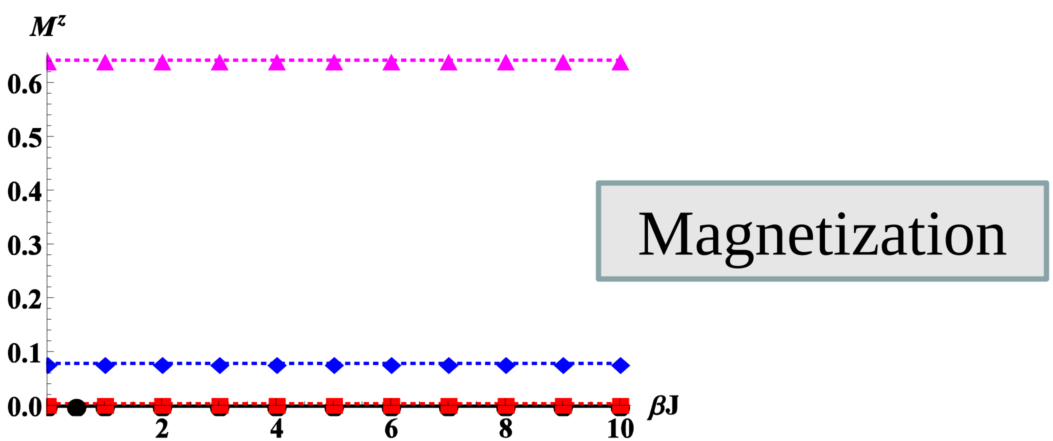
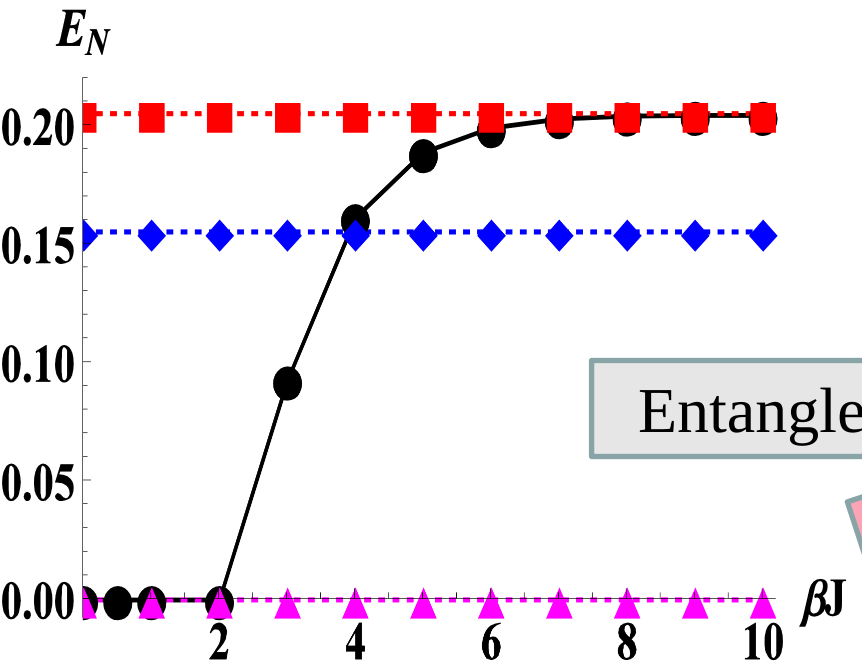




● → Equilibrium

■ → $a = 0.2$
◆ → $a = 0.6$
▲ → $a = 1.2$
} Evolved

Infinite XY Spin Chain

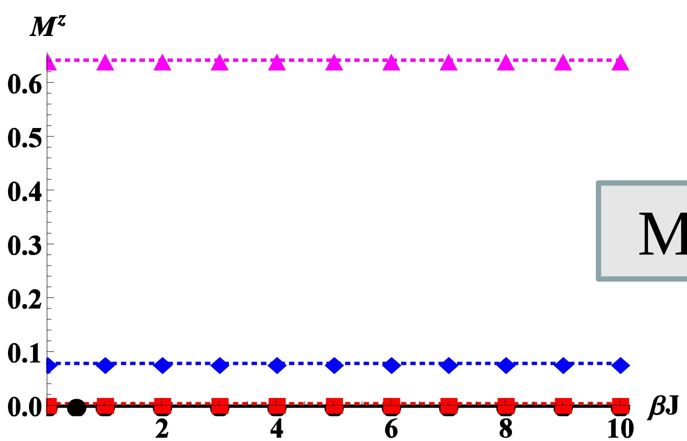


Entanglement

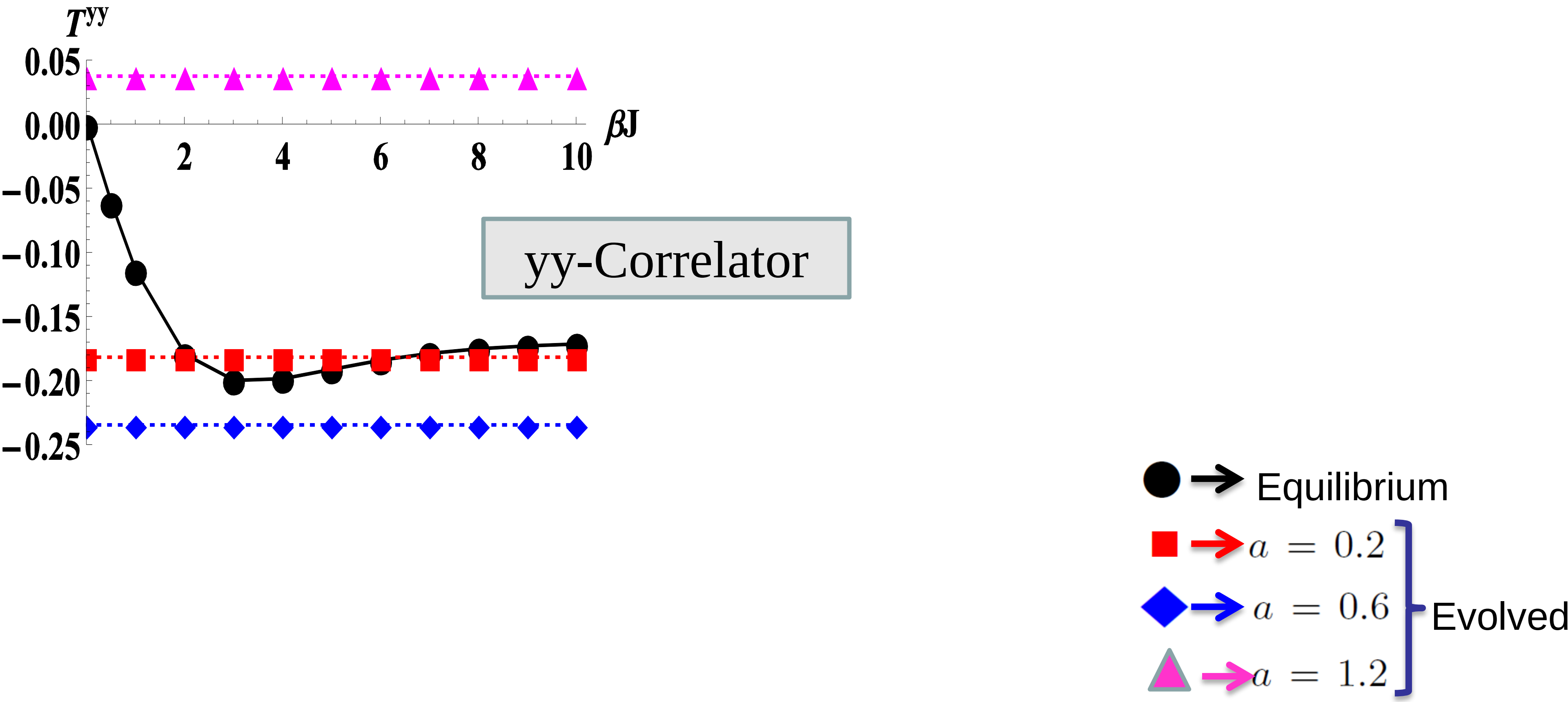
Ergodic Entanglement
Nonergodic Magnetization

Equilibrium

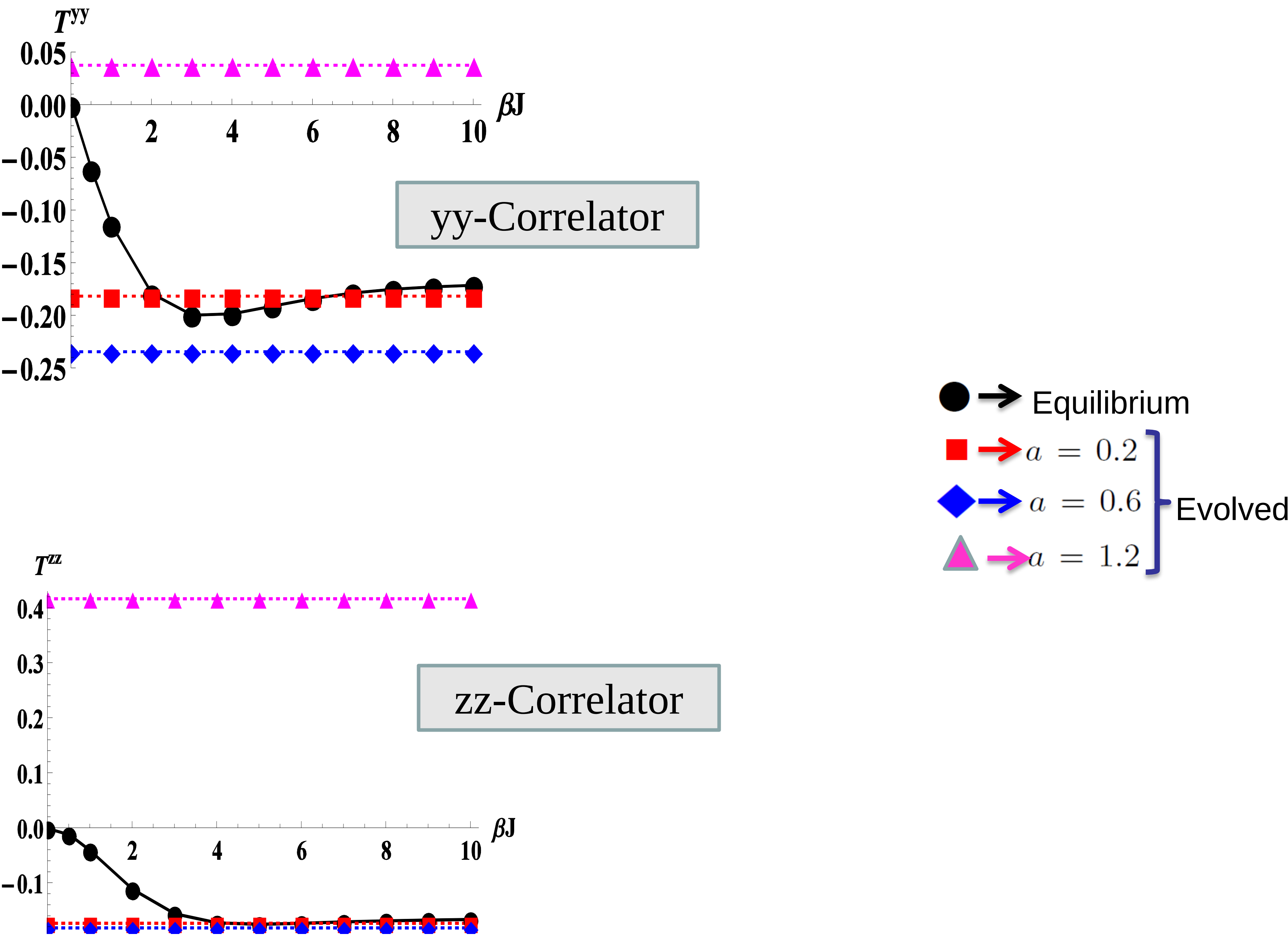
$a = 0.2$
$a = 0.6$
$a = 1.2$
Evolved

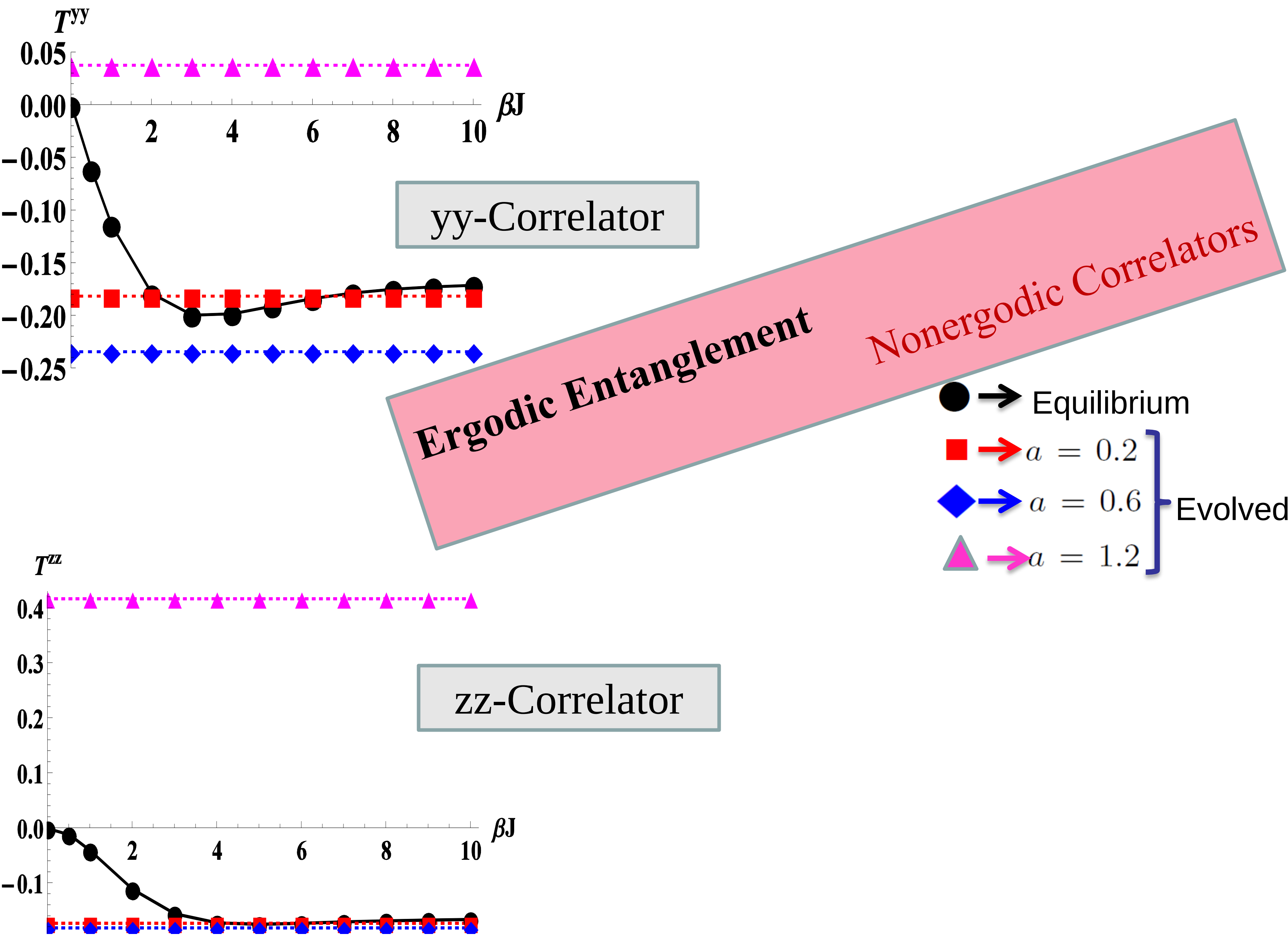


Magnetization



T^{yy}
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.25
2
4
6
8
10
βJ
yy-Correlator
Equilibrium
$a = 0.2$
$a = 0.6$
$a = 1.2$
Evolved


T^{yy}
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.25
2
4
6
8
10
βJ
yy-Correlator
T^{zz}
0.4
0.3
0.2
0.1
0.0
−0.1
2
4
6
8
10
βJ
zz-Correlator
Equilibrium
$a = 0.2$
$a = 0.6$
$a = 1.2$
Evolved



T^{yy}
0.05
0.00
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yy-Correlator
Ergodic Entanglement
Nonergodic Correlators
Equilibrium
$a = 0.2$
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T^{zz}
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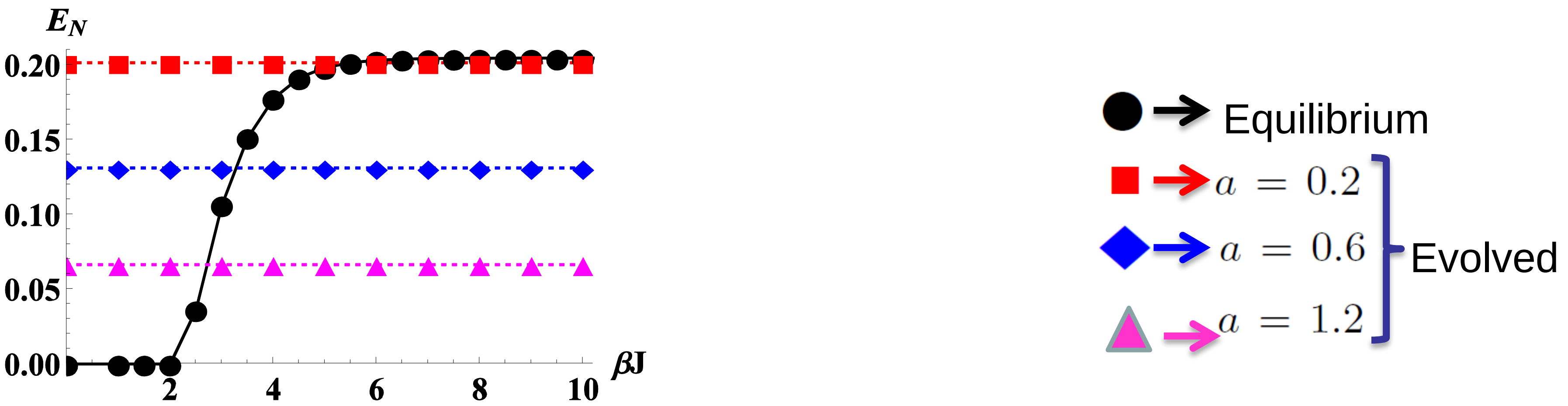
6
8
10
βJ
zz-Correlator

Nonergodic correlations and magnetization can lead to ergodic entanglement

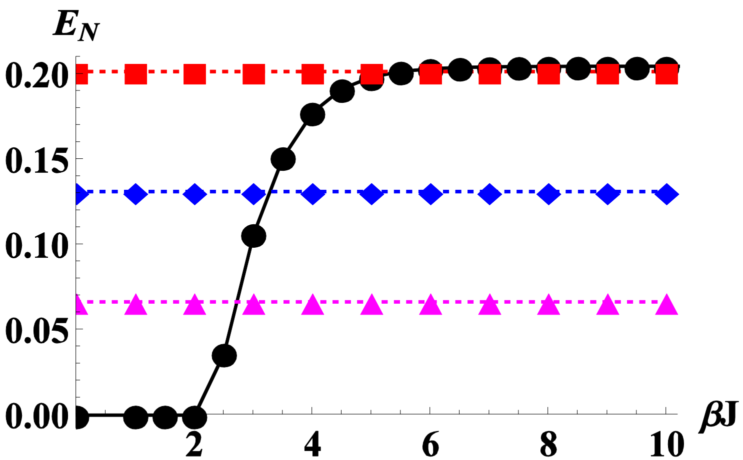
Nonergodic correlations and magnetization can lead to ergodic entanglement

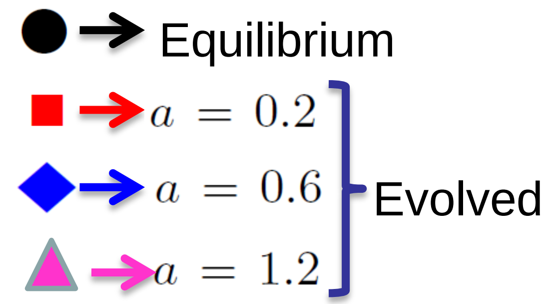
Is this generic?

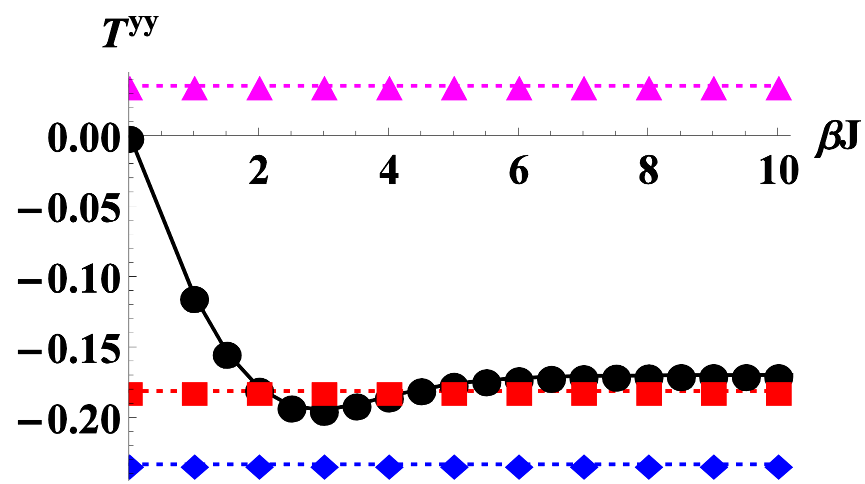
Finite XY Spin Chain



Finite XY Spin Chain







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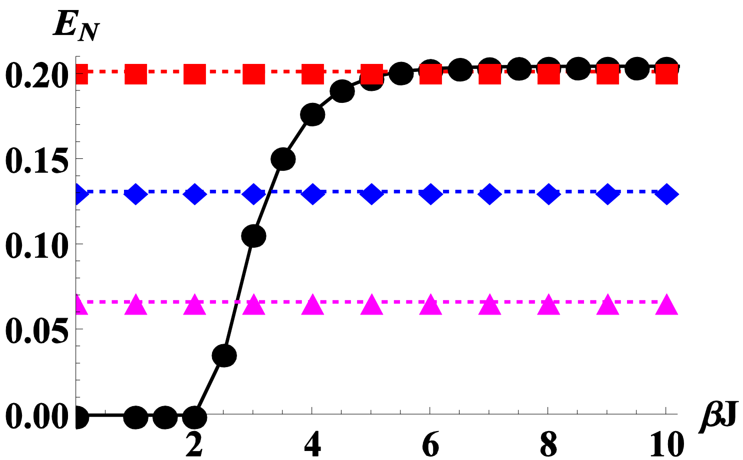
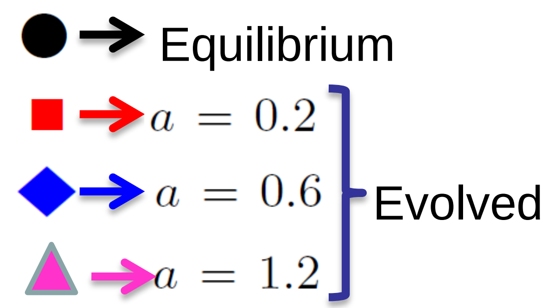
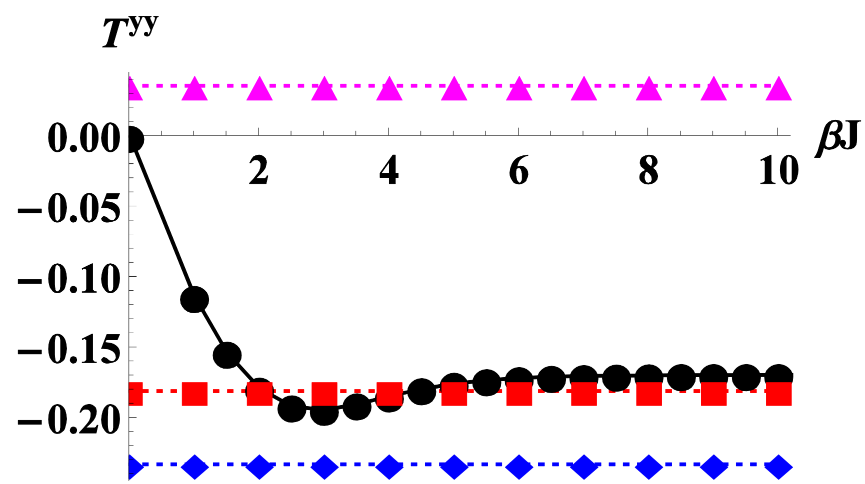
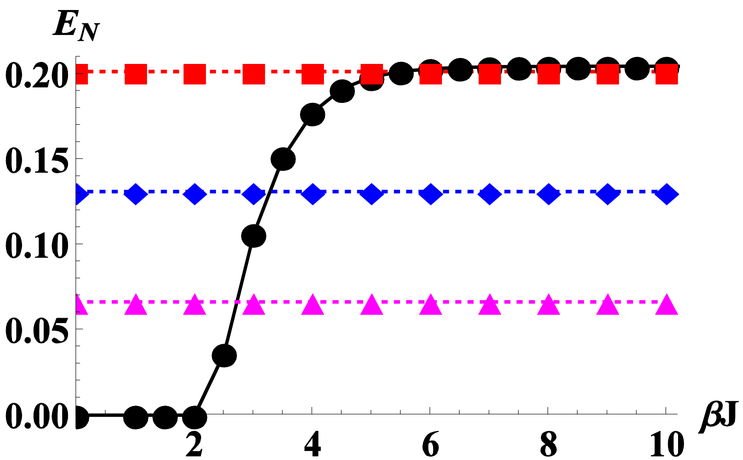


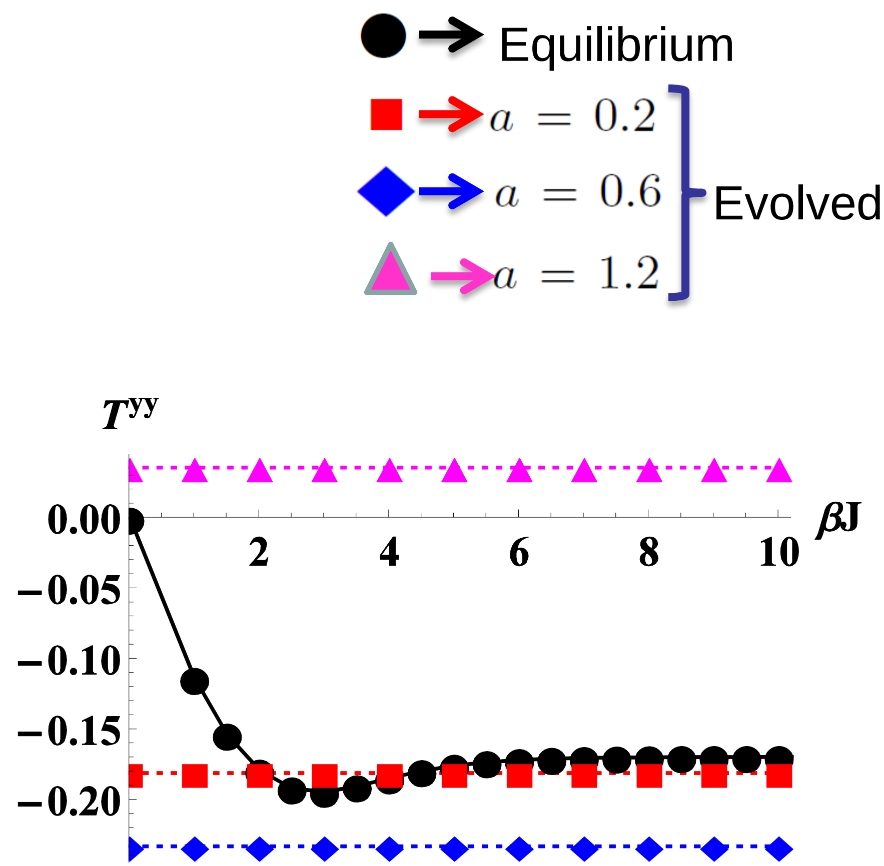


Possible to tune magnetic field,
entanglement is ergodic
while its constituent quantities
are all nonergodic



Finite XY Spin Chain





Possible to tune magnetic field,
entanglement is ergodic
while its constituent quantities
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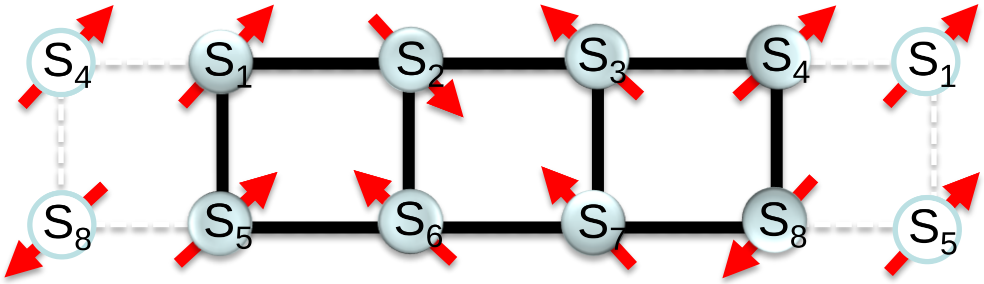
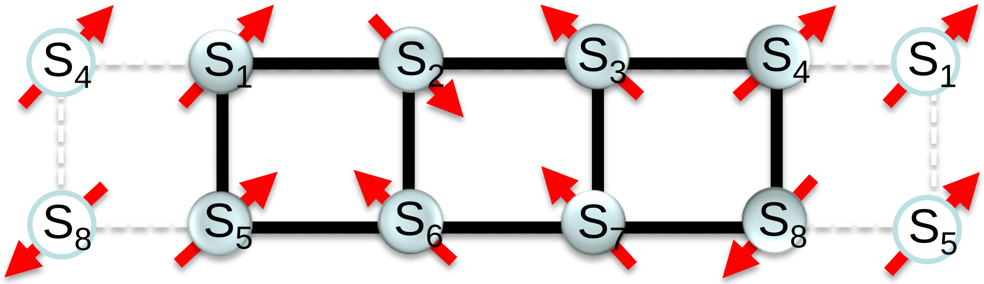
Finite system mimics infinite one!!

Ladder



Entanglement remains ergodic for high magnetic field

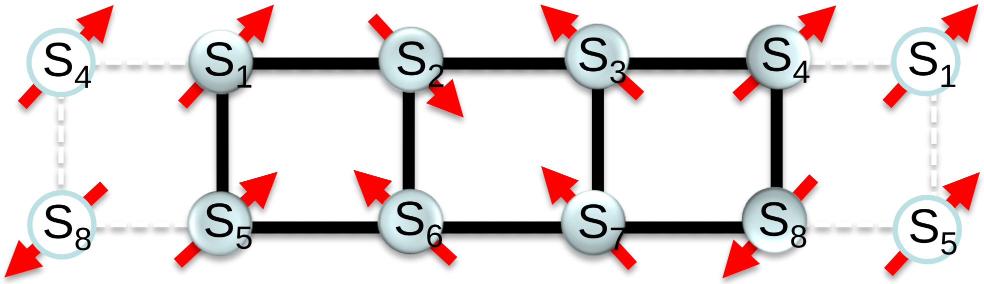
Ladder



Entanglement remains ergodic for high magnetic field

For the same field, some correlations, magnetization remain nonergodic

Ladder

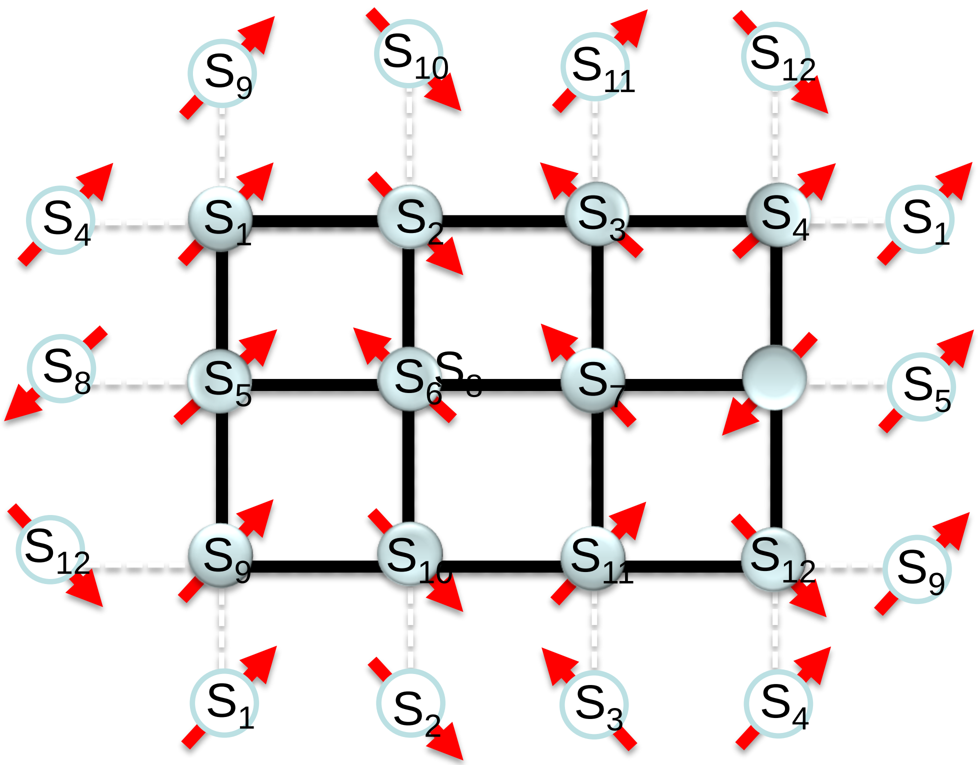


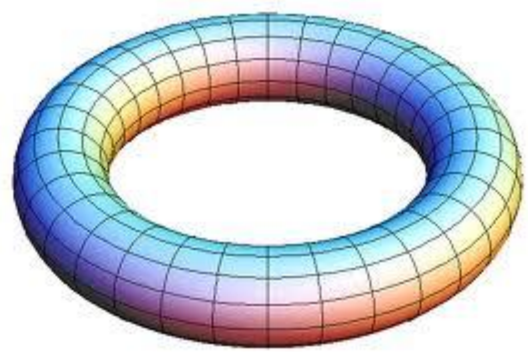
Entanglement remains ergodic for high magnetic field

For the same field, some correlations, magnetization remain nonergodic

Mimicking 1D

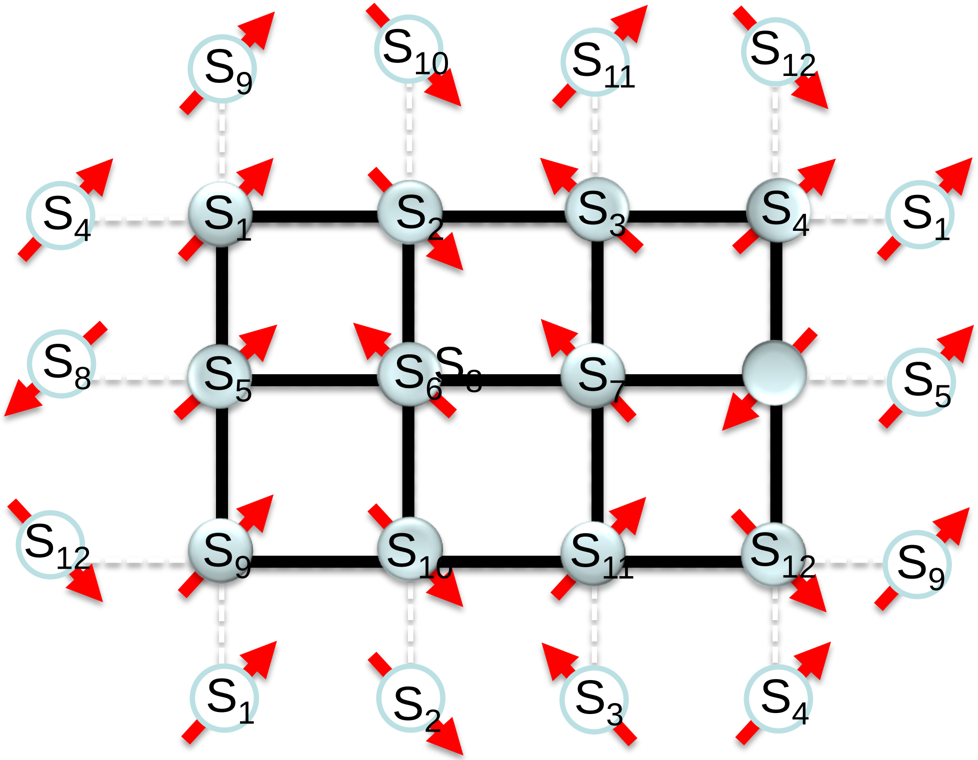
2D Finite System

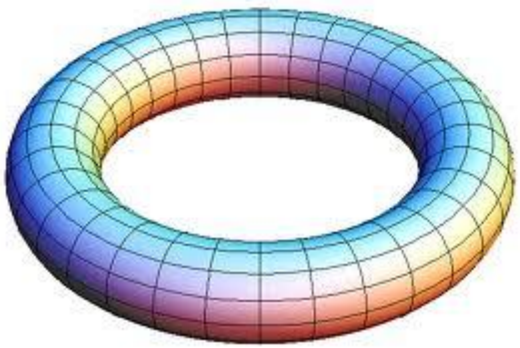




2D Finite System

∃ magnetic field for which entanglement still remains ergodic





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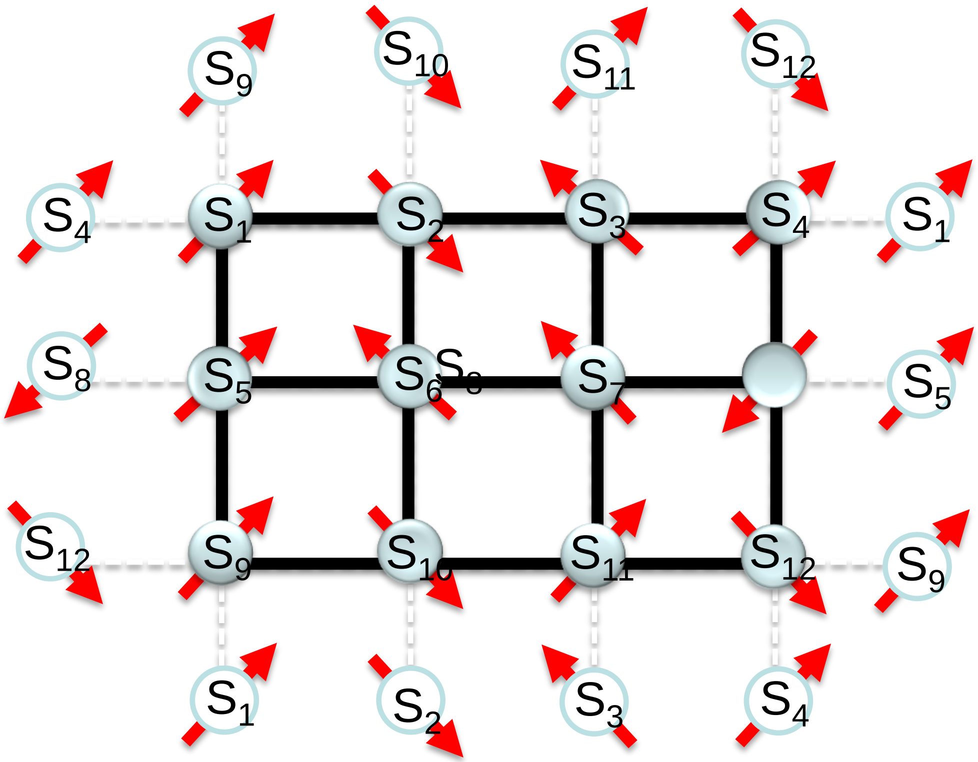

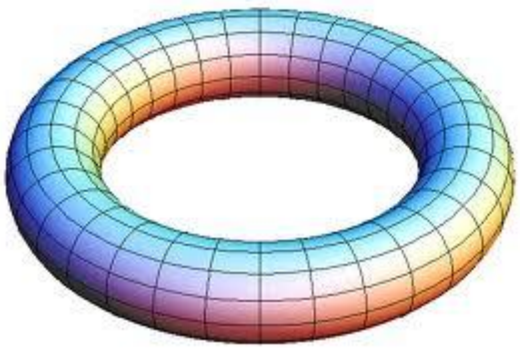

For the same field, magnetization remains nonergodic;

2D Finite System

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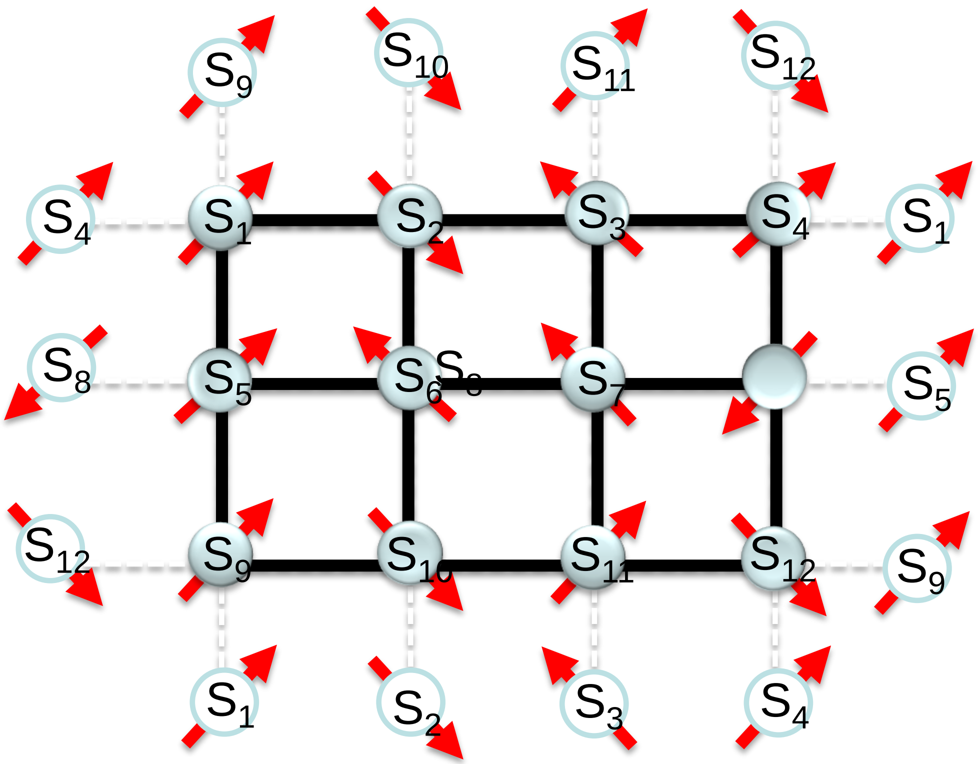
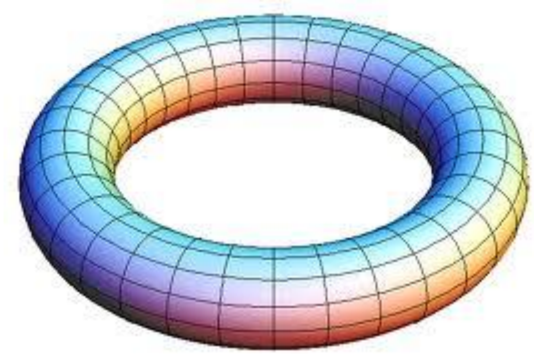
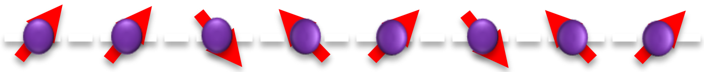




For the same field, magnetization remains nonergodic;

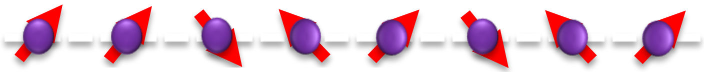
$T^{zz}(a, \beta)$ is now nonergodic.

Ergodic entanglement with nonergodic correlations



Low dimensional systems,

Ergodic entanglement with nonergodic correlations



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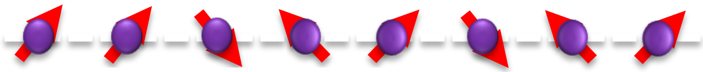
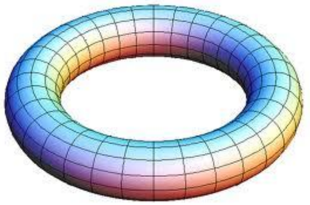
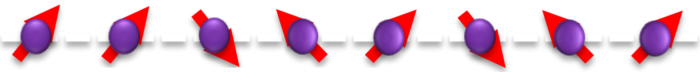


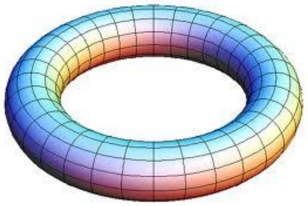
Low dimensional systems,



Ergodic entanglement with nonergodic correlations



Low dimensional systems,



quantum correlations can have statistical mechanical properties, which are not inherited from the same in classical correlations and magnetizations

Outline

- What is entanglement?
- Quantum many-body systems and entanglement ---brief overview
- Ergodicity of entanglement without ergodic classical correlations
- Quantum correlation measure--Discord
- Opposite statistical behavior between entanglement-separability paradigm and information-theoretic paradigms

Quantum Correlation Measure: Discord

- Total Correlations: Mutual Information

$$I(\rho_{AB}) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$$

- $S(\sigma) = -\, \mathrm{tr}\,(\sigma \log_2 \sigma) \equiv$ **von Neumann entropy**

Quantum Correlation Measure: Discord

- Total Correlations: Mutual Information

$$I(\rho_{AB}) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$$

Classical Correlations:

$$J(\rho_{AB}) = S(\rho_A) - S(\rho_{A|B})$$

Quantum Correlation Measure: Discord

- Total Correlations: Mutual Information

$$I(\rho_{AB}) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$$

Classical Correlations:

$$J(\rho_{AB}) = S(\rho_A) - S(\rho_{A|B})$$

- $S(\sigma_{A|B}) = \min_{\{B_i\}} \sum_i p_i S(\sigma_{A|i})$

Quantum Correlation Measure: Discord

- Total Correlations: Mutual Information

$$I(\rho_{AB}) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$$

Classical Correlations:

$$J(\rho_{AB}) = S(\rho_A) - S(\rho_{A|B})$$

Discord ≡ Total - Classical ≡ $\mathbf{I(\rho_{AB}) - J(\rho_{AB})}$

Quantum Correlation Measure: Discord

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$$I(\rho_{AB}) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$$

Classical Correlations:

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Henderson-Vedral, J. Phys. A’01;
Olliver,-Zurek, PRL’02

$$\text{Discord} \equiv \text{Total} - \text{Classical} \equiv \mathbf{I(\rho_{AB}) - J(\rho_{AB})}$$

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Opposite Statistical Mechanical Behavior of Quantum Correlation Measures

R. Prabhu , ASD, U. Sen

arXiv: 1112.1856

XY spin model

This model is exactly solvable.

Jordan-Wigner transformation

$$H = \sum [(1+\gamma)\,\sigma_i^x \sigma^x_{i+1} + (1-\gamma)\,\sigma_i^y \sigma^y_{i+1}]$$

$$+\, h(t) \sum \sigma^z_i$$

External magnetic field

h(t) = a, t=0

= 0, t>0

Are Quantum Correlation measures Ergodic?

For low field,
all quantum correlation measures are ergodic in any dimension

Are Quantum Correlation measures Ergodic?

For low field,
all quantum correlation measures are ergodic in any dimension

provided $H = H_{int} - h(t)\, H_{mag}$ and $h(t) \begin{cases} = a, & t=0 \\ = 0, & t>0 \end{cases}$

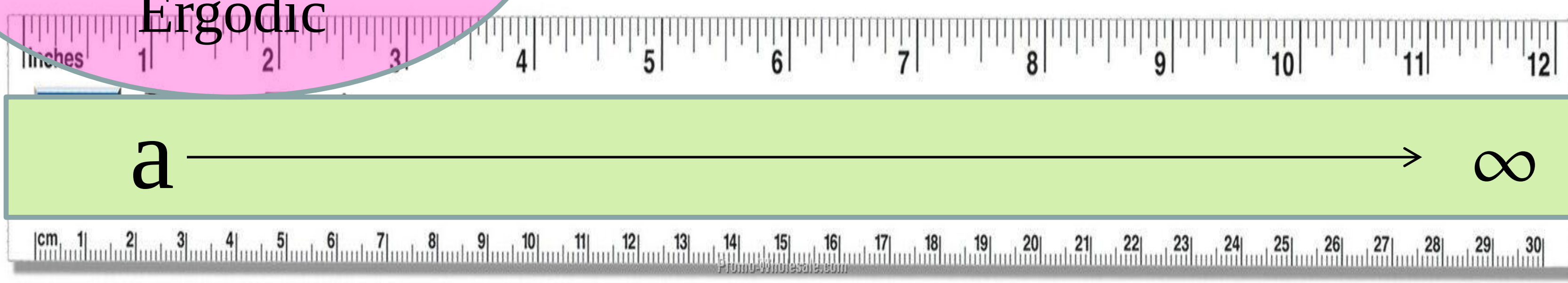
$[H_{int}, H_{mag}] \neq 0$

Entanglement Measures

vs.

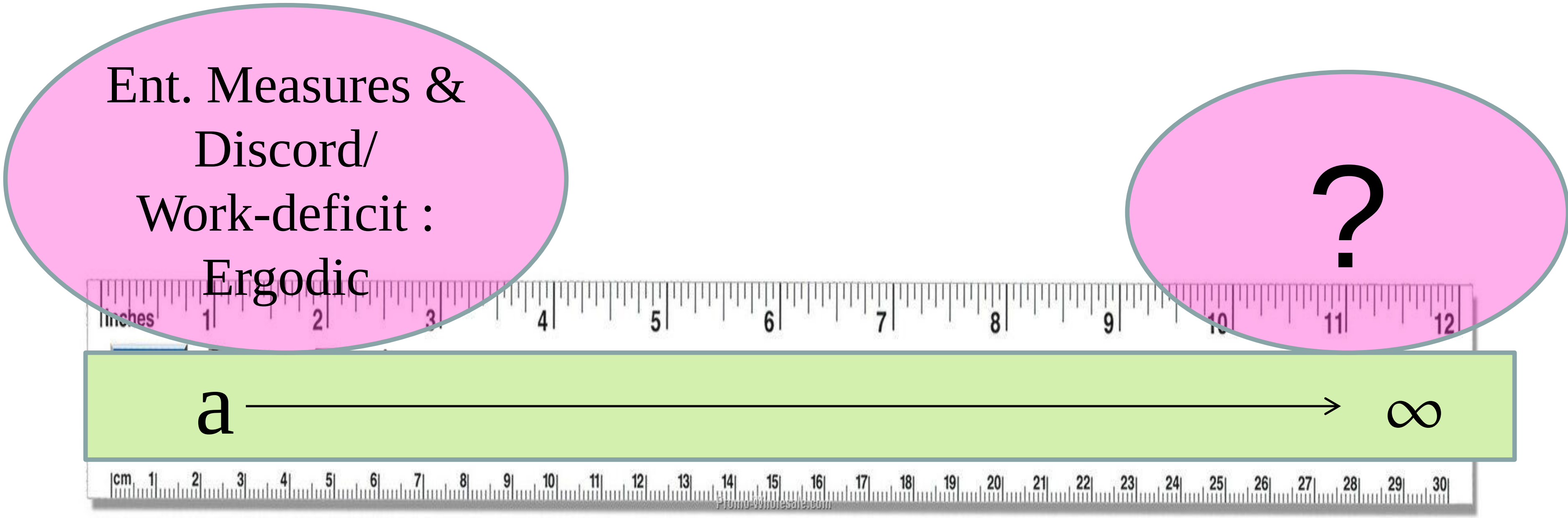
Information -Theoretic Measures

Ent. Measures &
Discord/
Work-deficit :
Ergodic



$a \longrightarrow \infty$

Entanglement Measures
vs.
Information -Theoretic Measures



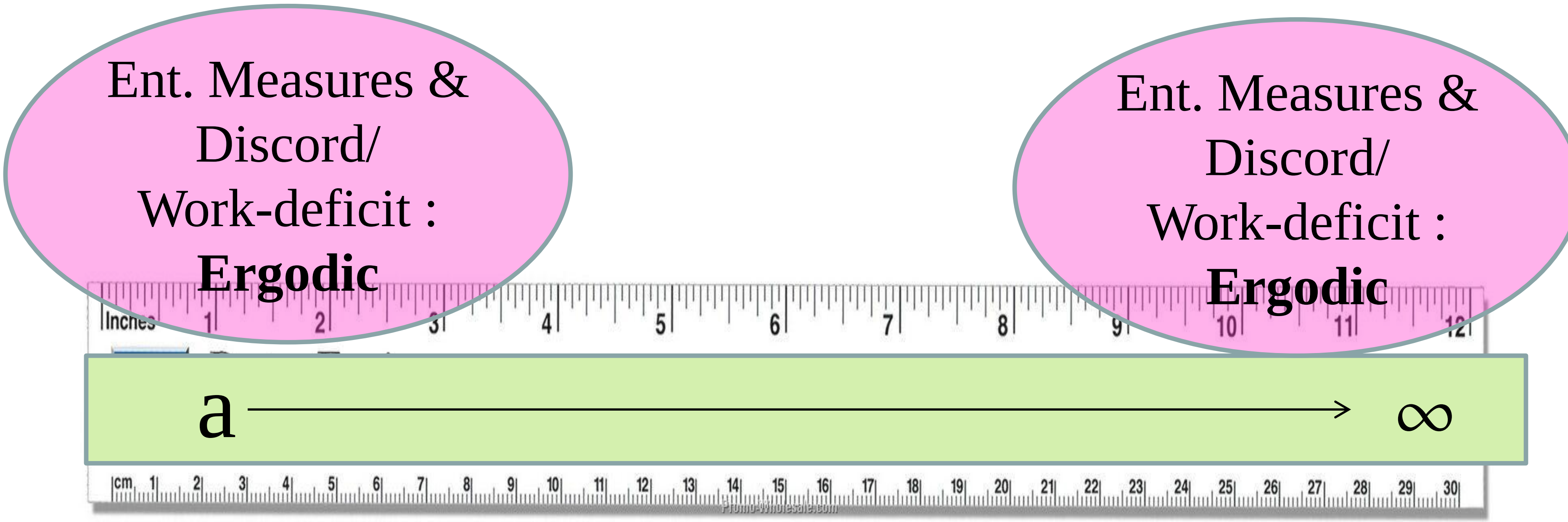
Are Quantum Correlation measures Ergodic?

For high fields,
all quantum correlation measures are again ergodic for infinite XY spin chain

provided $H = \sum [(1+\gamma)\, \sigma_i^x \sigma_{i+1}^x + (1-\gamma)\, \sigma_i^y \sigma_{i+1}^y] + h(t) \sum \sigma_i^z$

and $h(t) \begin{cases} = a, & t=0 \\ = 0, & t>0 \end{cases}$

Entanglement Measures
vs.
Information -Theoretic Measures



Entanglement Measures

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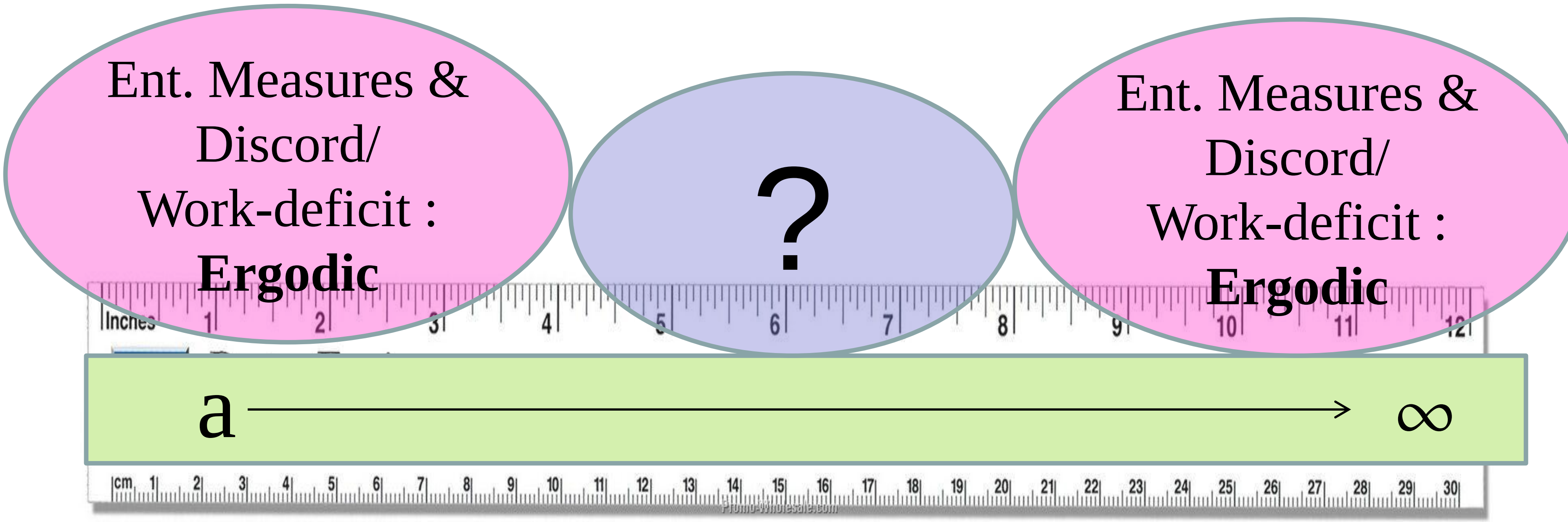
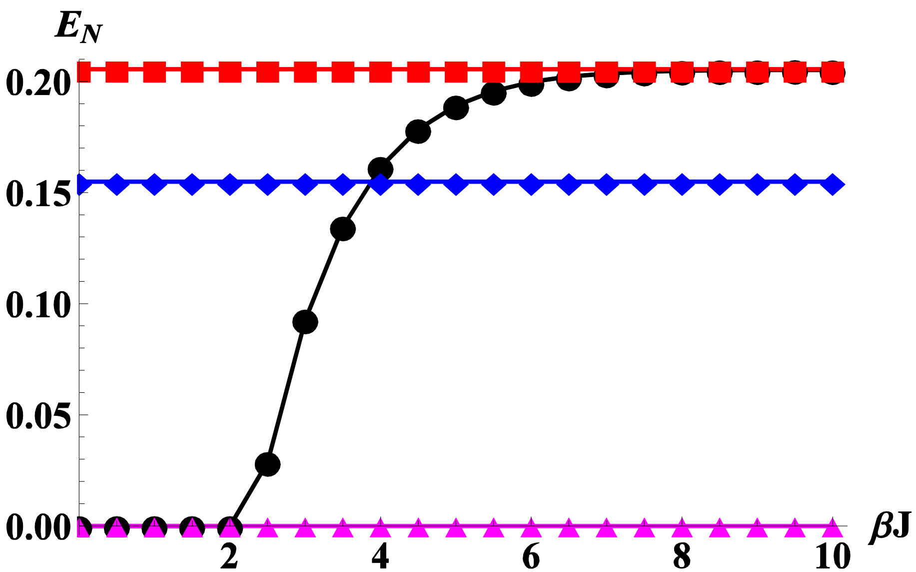
Information -Theoretic Measures



Entanglement Measures
vs.
Information -Theoretic Measures

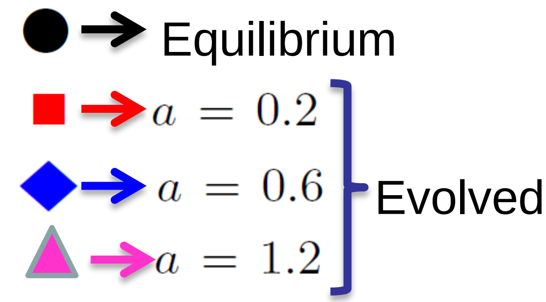
For moderate fields,

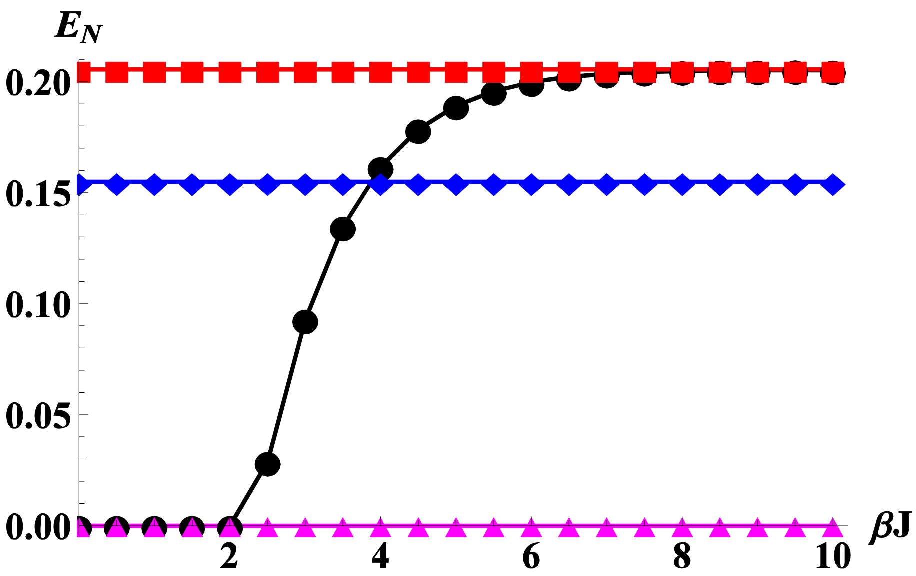


Entanglement

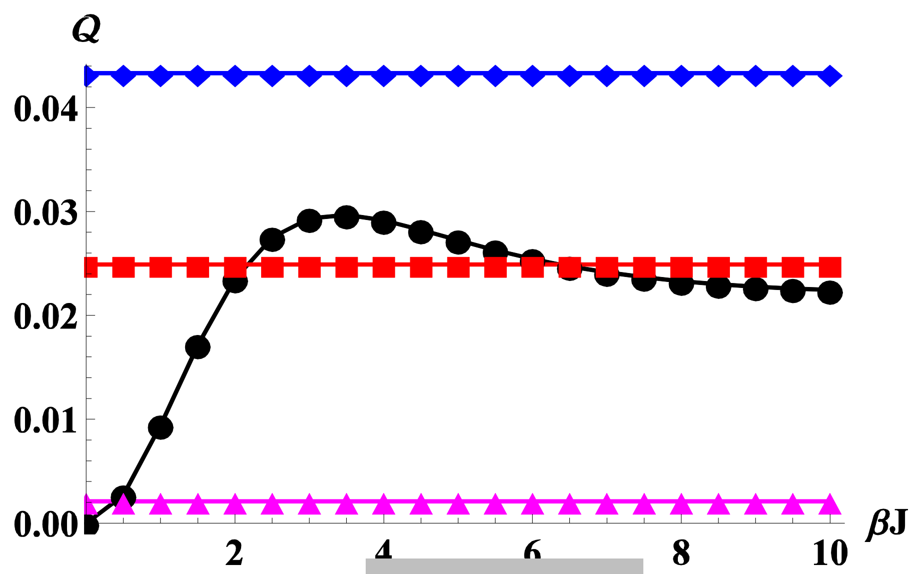
Entanglement Measures
vs.
Information -Theoretic Measures

For moderate fields,





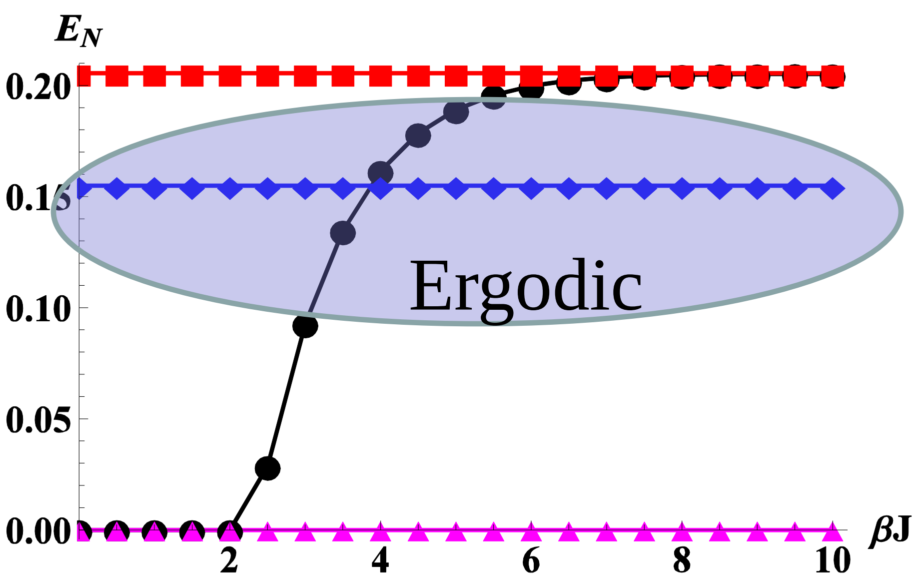
Entanglement



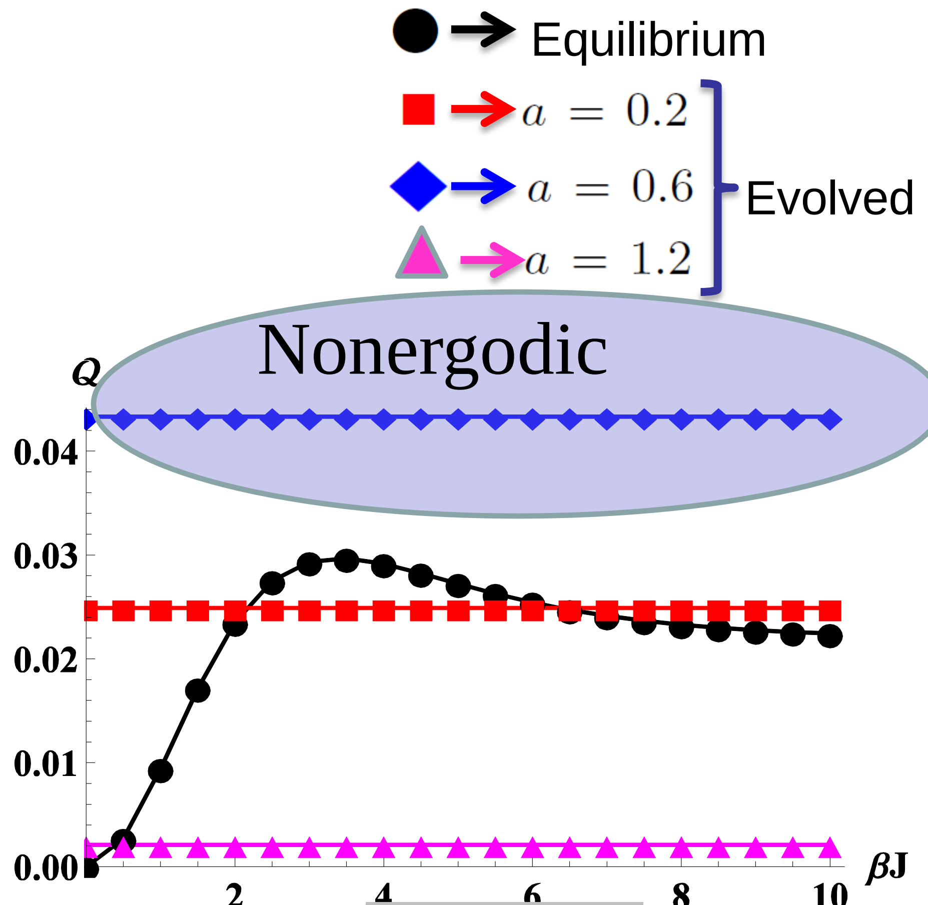
Discord

Entanglement Measures
vs.
Information -Theoretic Measures

For moderate fields,



Entanglement

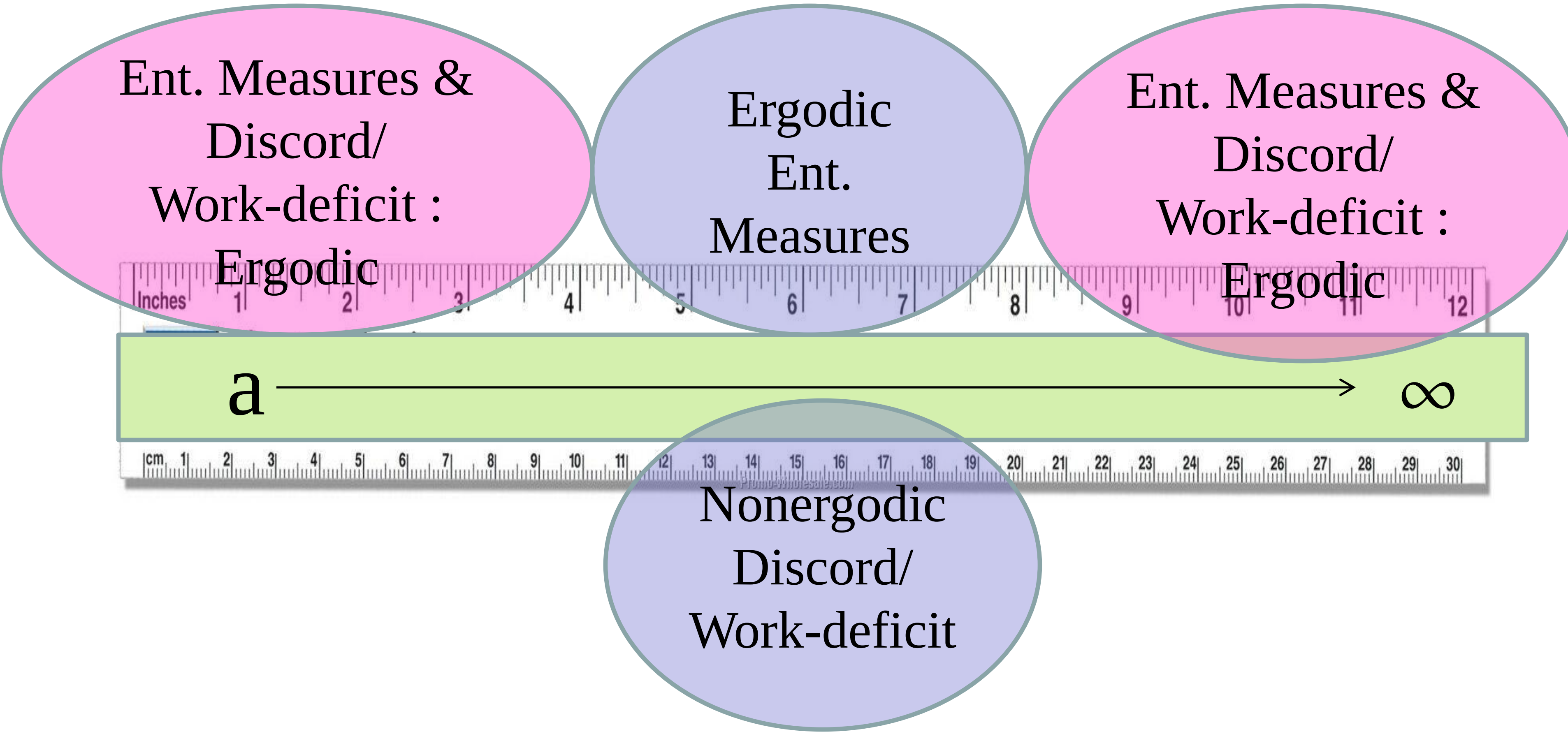


Discord

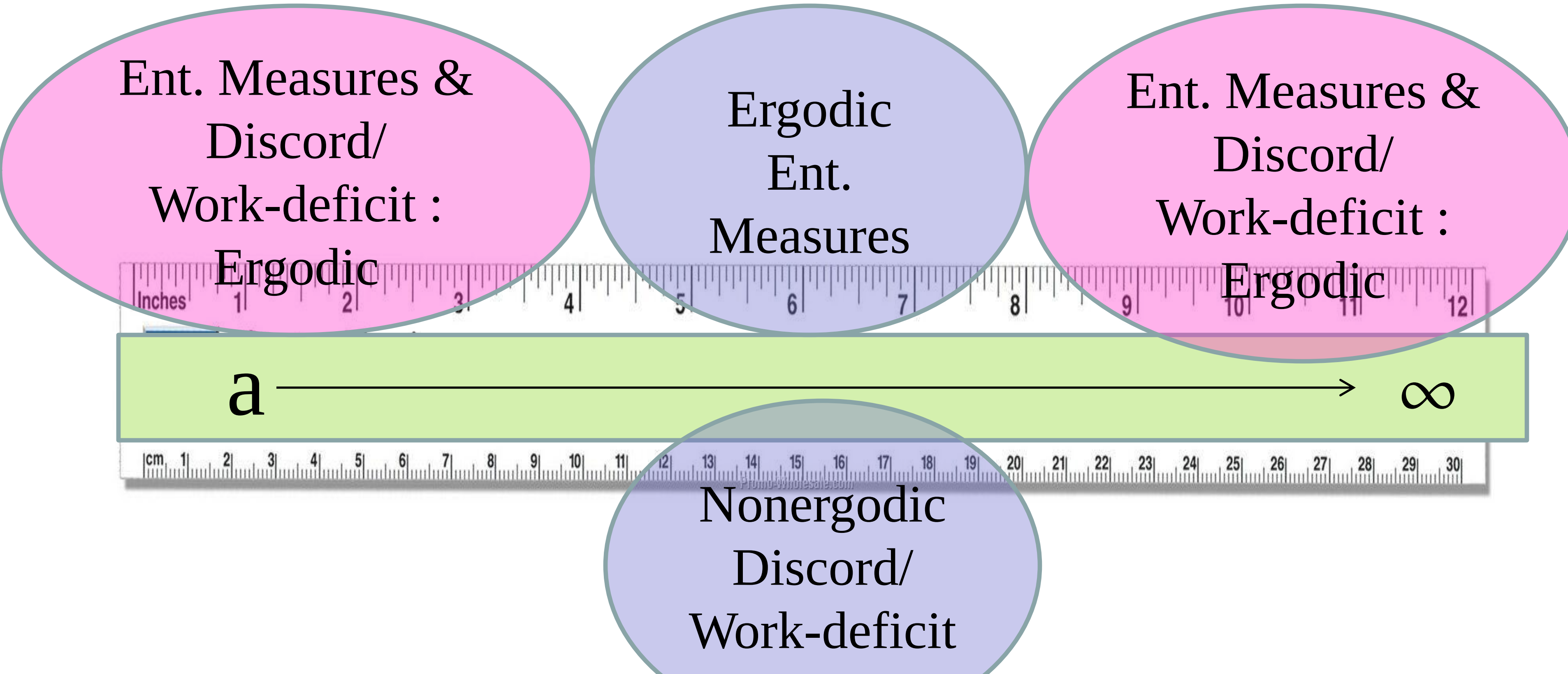
Entanglement Measures

vs.

Information -Theoretic Measures



Entanglement Measures vs. Information -Theoretic Measures



Generic for 1D, Ladder & Two-dimension

Conclusion

Entanglement is ergodic while correlation functions are nonergodic.

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Opposite statistical mechanical behavior of two paradigms

Conclusion

Entanglement is ergodic while correlation functions are nonergodic.

Opposite statistical mechanical behavior of two paradigms:

Entanglement-separability paradigm
&
Information theoretic paradigm

Conclusion

Entanglement is ergodic while correlation functions are nonergodic.

Opposite statistical mechanical behavior of two paradigms:

Entanglement-separability paradigm
&
Information theoretic paradigm

Ergodic entanglement while nonergodic discord/workdeficit

QIC Group @ HRI


Gracias
Terima kasih
Thank you!
Téngi nian bún