FERMILAB-SLIDES-20-048-T

Quantum simulation of phase transition in the early universe

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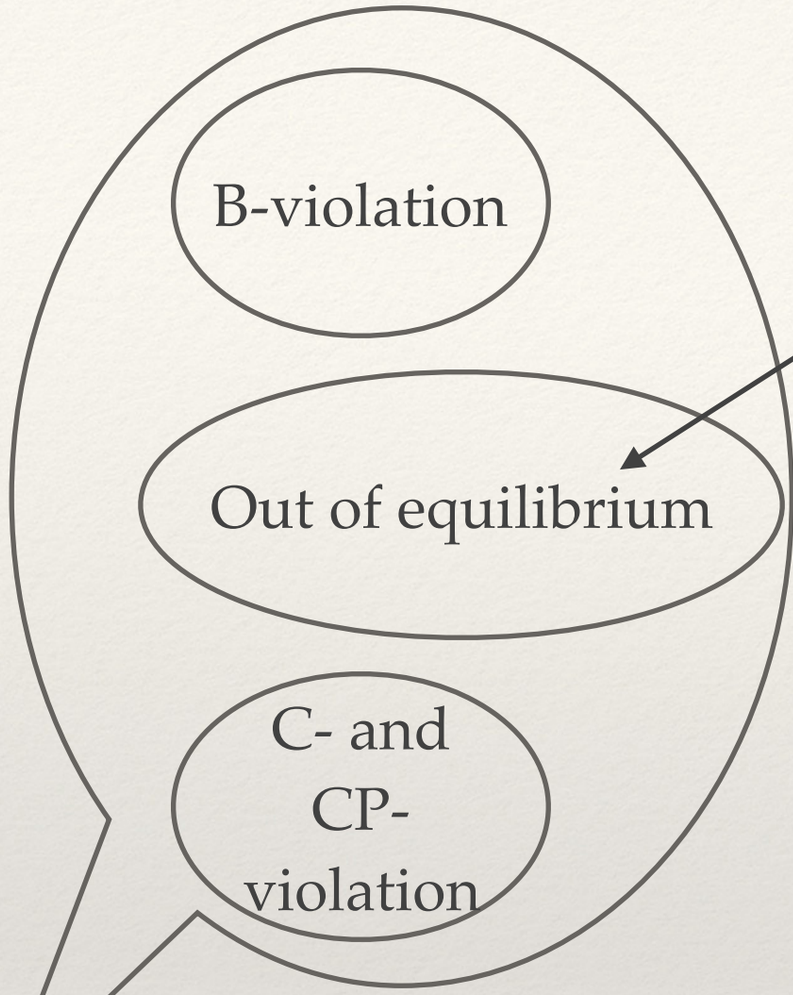
Outline

- first order phase transition in particle physics
- Quantum computing
- Ising model with external field
- Tricritical Ising model

EW phase transition

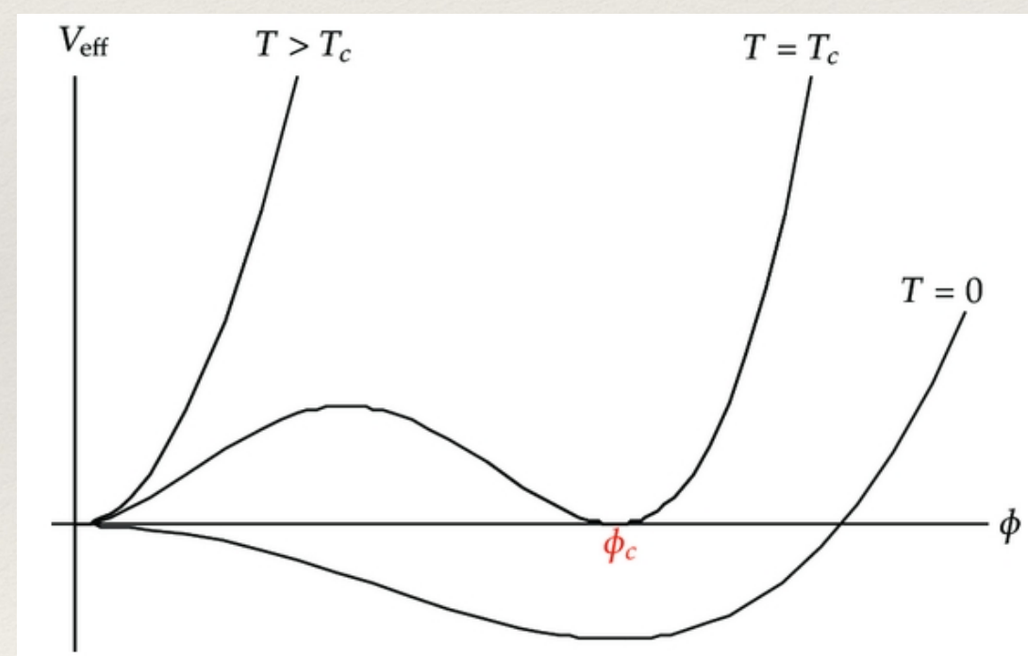
Matter anti-matter asymmetry



heavy particle decay (leptogenesis)

first order phase transition (EW baryongenesis)

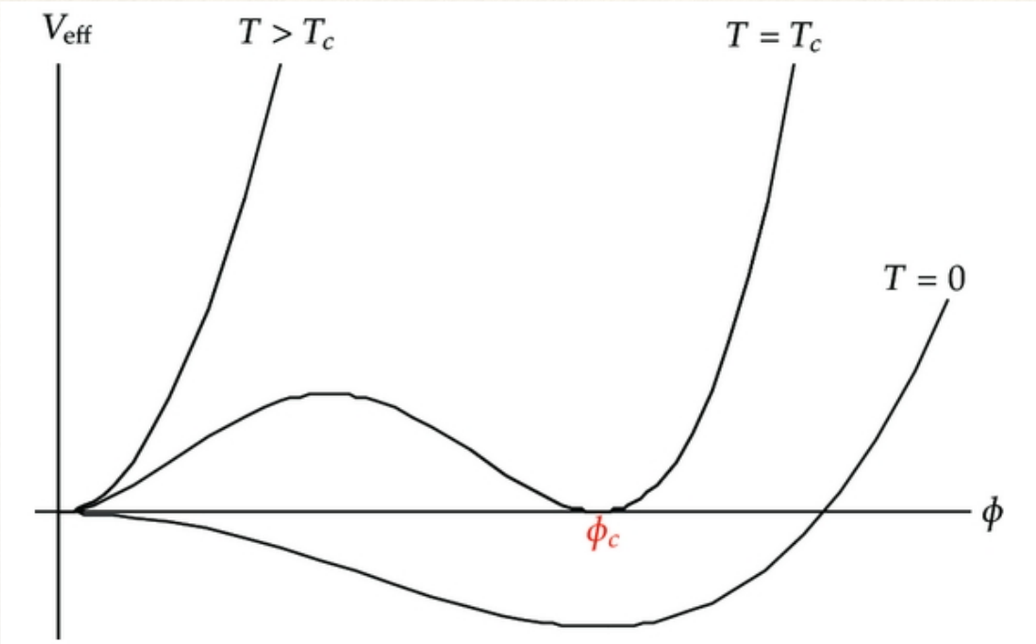
$$V(\phi, T) = m^2(T)\phi^2 - E(T)\phi^3 + \lambda(T)\phi^4$$



discontinuous order parameter

EW phase transition

first order phase transition
(EW baryongenesis)



$$V(\phi, T) = m^2(T)\phi^2 - E(T)\phi^3 + \lambda(T)\phi^4$$

SM: crossover if Higgs mass
larger than 80GeV (lattice)

BSM: perturbative calculation,
thermal potential only up to one-loop,
High T expansion to leading order

If first order: understand non-equilibrium dynamics?

dynamics of bubble nucleation, nucleation temperature, particle production, etc.

lattice field theory? Intractable sign problem.

What about we do a real simulation with quantum computer?

Quantum Computing

Real-time Minkowski space evolution

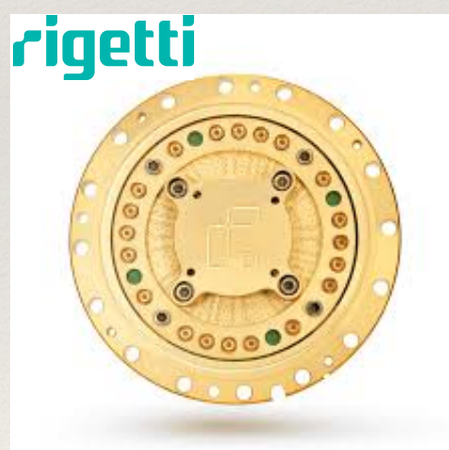
Exponentially-large Hilbert spaces

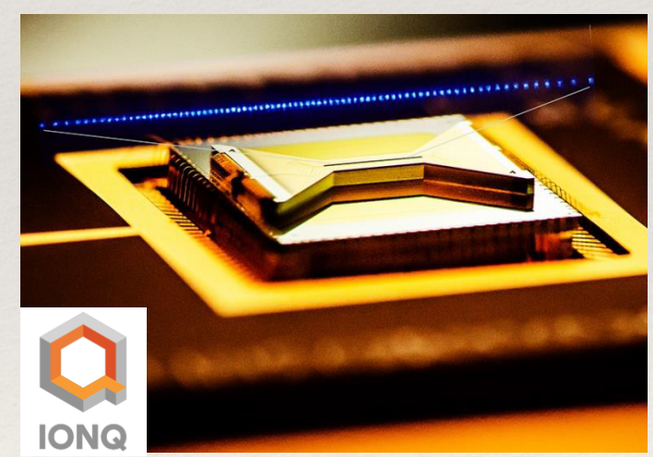
Mitigated sign problems

Integral over phases

etc..

Phase transition,
Non-equilibrium dynamics





Quantum Computing

However, Noisy Intermediate-Scale Quantum (NISQ) era: **50-100 qubits**

So limited resources in the near future.

Challenge: we cannot simply discretize our field theory

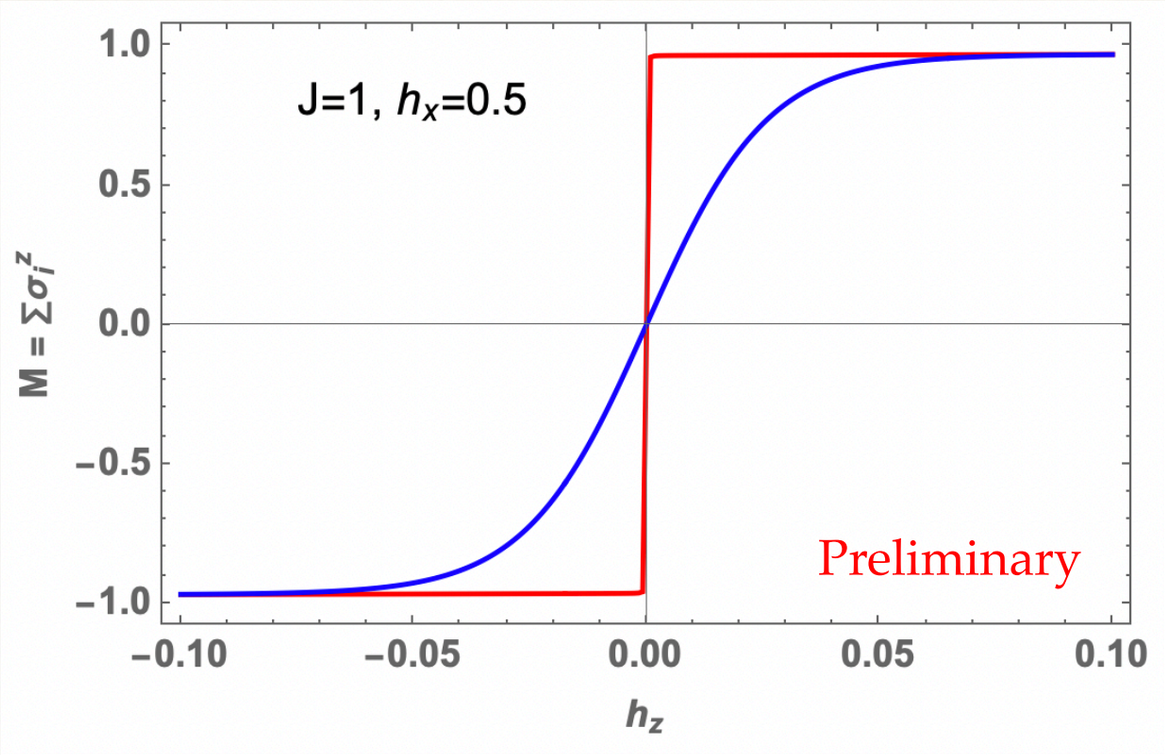
<u>The very first step</u>

toy model with FOPT
time evolution in our expanding universe

Ising model with external field

$$H_{IL} = -J \sum_{<i,j>} \sigma_i^z \sigma_j^z - h_z \sum_i \sigma_i^z - h_x \sum_i \sigma_i^x$$

1D



FOPT only at zero temperature
Tc=0.

Can we still learn something,
e.g.
nucleation time (phase transition time)?

Ising model with external field

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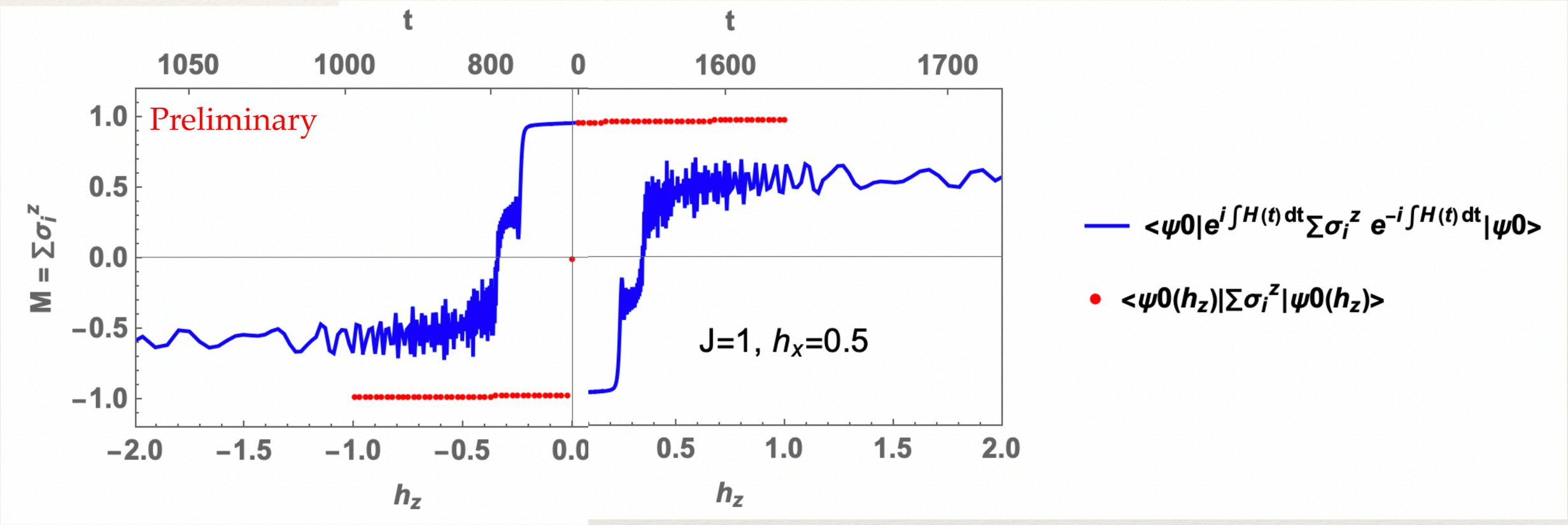
1D@T=0

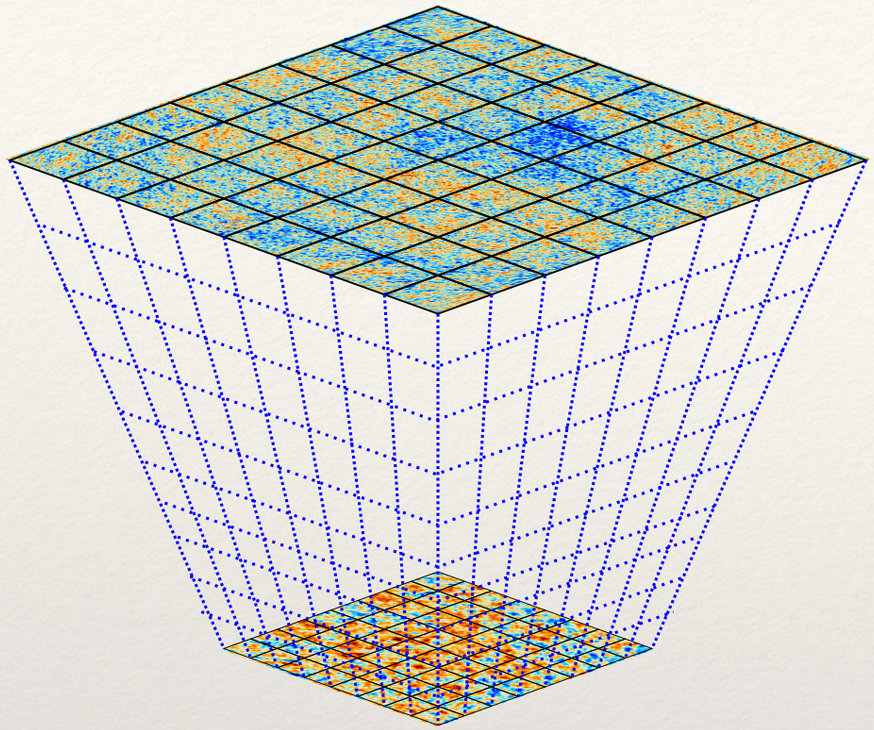


Hysteresis-like behavior: hints for the exact nucleation time?

nucleation time differs from the time with T=Tc

[Janne Ignatius, hep-ph/9312293]

Ising model with external field



$$H_{IL} = -J \sum_{<i,j>} \sigma_i^z \sigma_j^z - h_z \sum_i \sigma_i^z - h_x \sum_i \sigma_i^x$$

Set h_z = 0 and take the continuum limit: free fermion theory

$$\mathcal{L} = \frac{1}{2}\bar{\Psi}(i\gamma^i \partial_i - m)\Psi$$

$$\Psi = \sqrt{c}\begin{pmatrix} \psi \\ \psi^\dagger \end{pmatrix}$$

$$imc = \Delta$$

$$c = 2Ja, \Delta = 2J - 2h_x$$

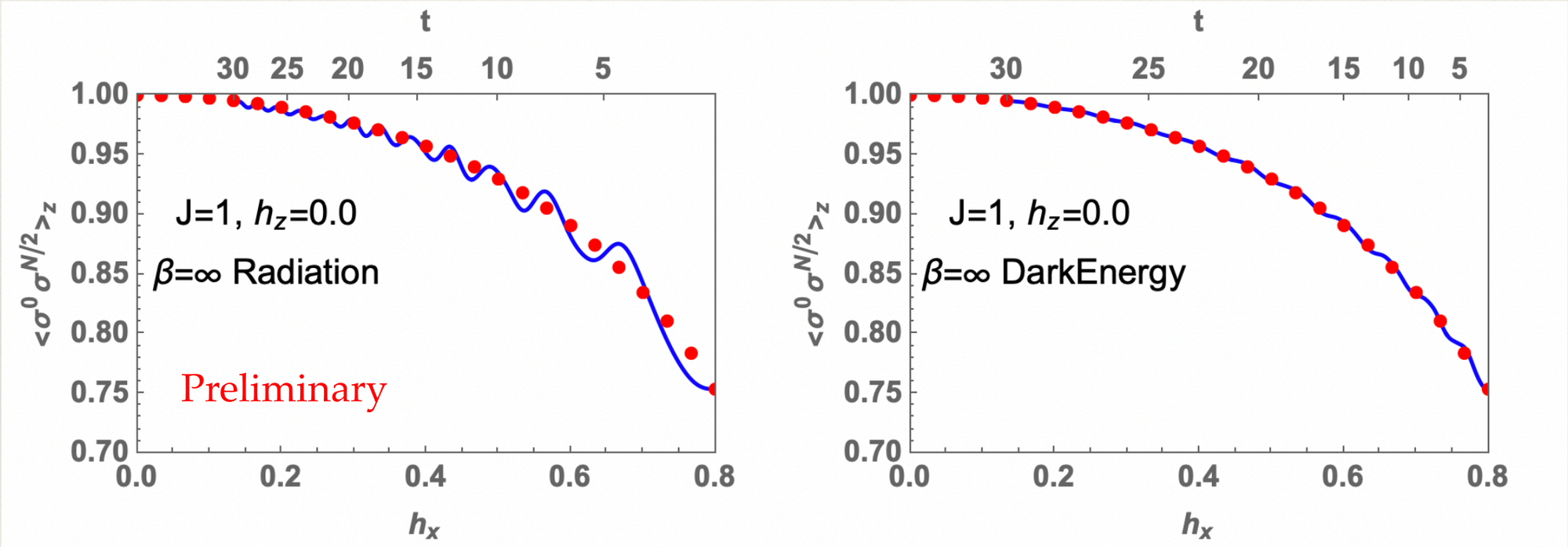
Ising model with external field

$$S_g = \frac{1}{2}\int d^2x\sqrt{-G}\bar{\Psi}(i\gamma^\mu\nabla_\mu - m)\Psi$$

$$ds^2 = R^2(\tau)(d\tau^2 - dx^2)$$ FRW metric

Time evolution for h_x

$$\frac{1 - h_x(t)/J}{1 - h_x(t_0)/J} = \frac{R(t)}{R_0}$$



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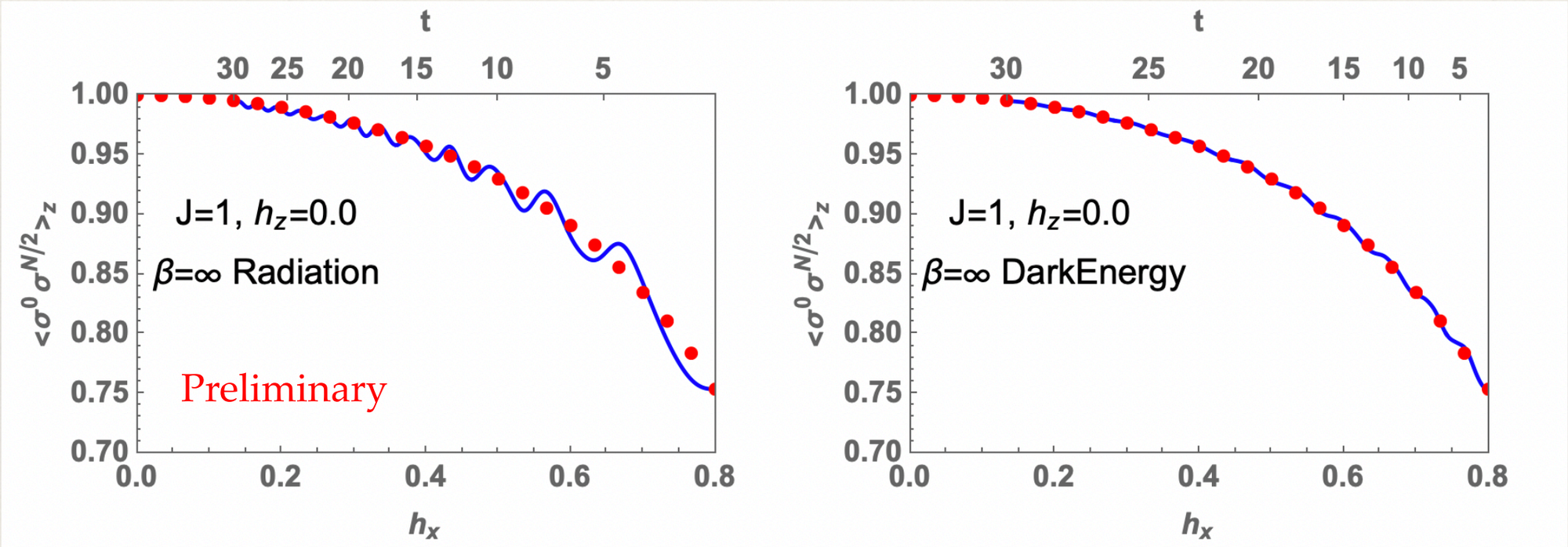


With h_z =0, second order phase transition @ zero Temperature

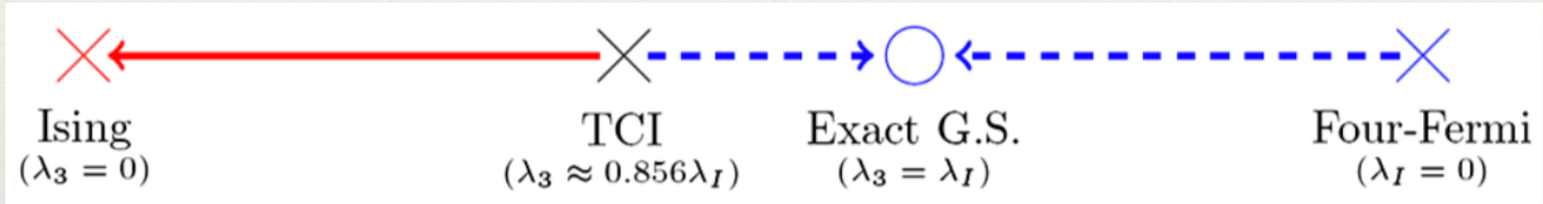
Hints for out-of equilibrium when the coupling is changing rapidly?

Tricritical Ising Model

Adding interactions?

[Edward O'Brien, Paul Fendley]

$$H_{tri} = -2\lambda_I \sum_i (\sigma_i^z \sigma_{i+1}^z + \sigma_i^x) + \lambda_3 \sum_i (\sigma_i^x \sigma_{i+1}^x \sigma_{i+2}^x + \sigma_i^z \sigma_{i+1}^z \sigma_{i+2}^x)$$



irrelevant four fermion operator in the continuum limit

what can we learn from the evolution of this system in the expanding universe?

long adventure ahead!

Questions in particle physics– QC oriented

In the NISQ era, larger system, better story to tell about the QFT in the continuum limit.

Other questions in particle physics calling for QC (Real time dynamics):

Bubble nucleation and gravitational wave during FOPT

Parton shower

Fragmentation

Sphaleron production in High energy collisions (topological) [in progress]

Multi-particle production (non-perturbative) [in progress]

Thank you

Back up

IBM superconducting transmon qubit (artifical atom, solid-state QC, Josephson junction):

Q System One: 20 qubits, Jan 2019

14th QC: 53 qubits, Oct 2019;

Rigetti:

28 qubits, Nov 2019

D-wave: superconducting devices

5000 qubits, named advantage, mid 2020

IONQ: trapped ion

Aiming for 100+ qubits