Metastability

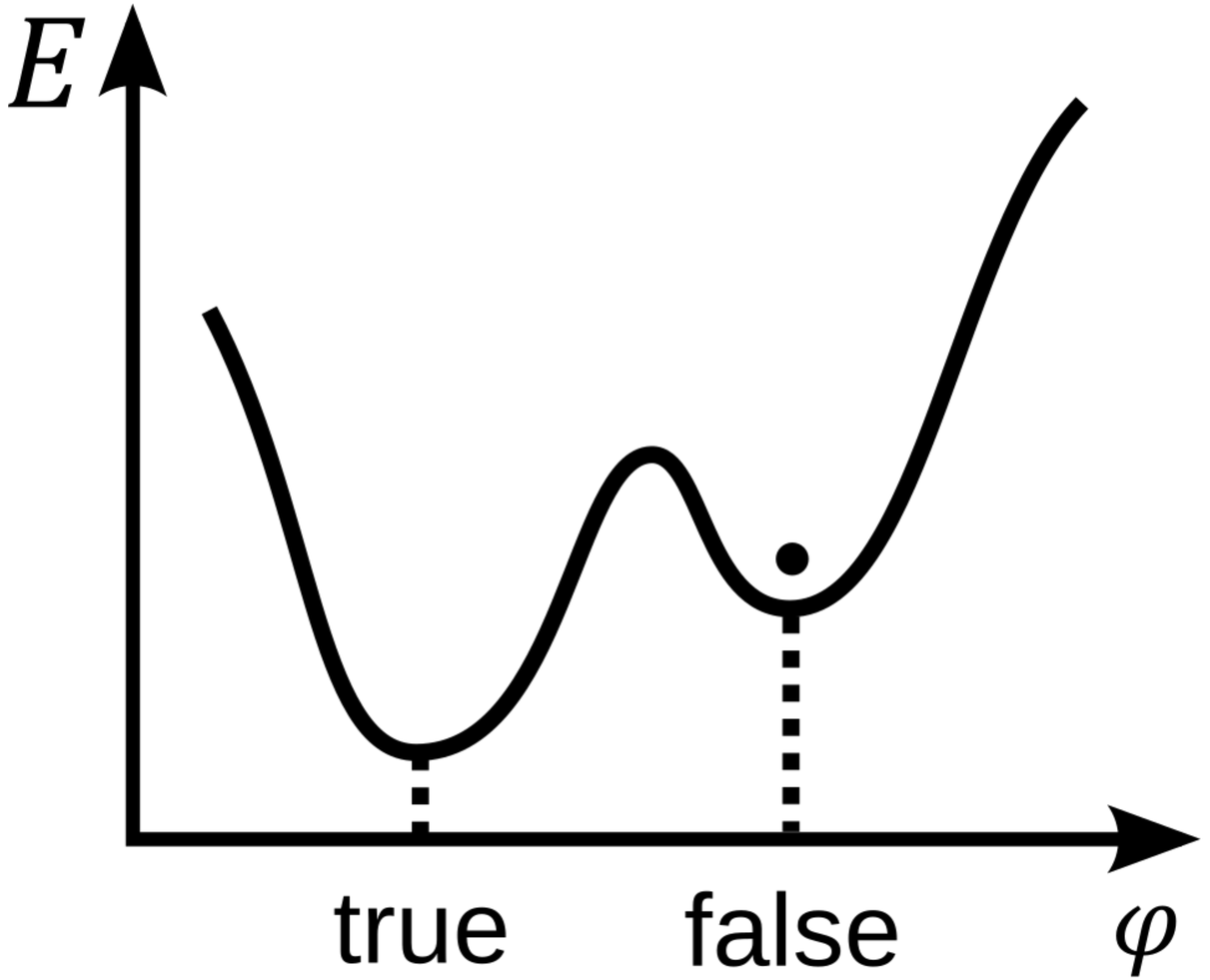
and false vacuum decay

in closed quantum systems

Luka Pavešić

University of Padova

Sep 2026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true
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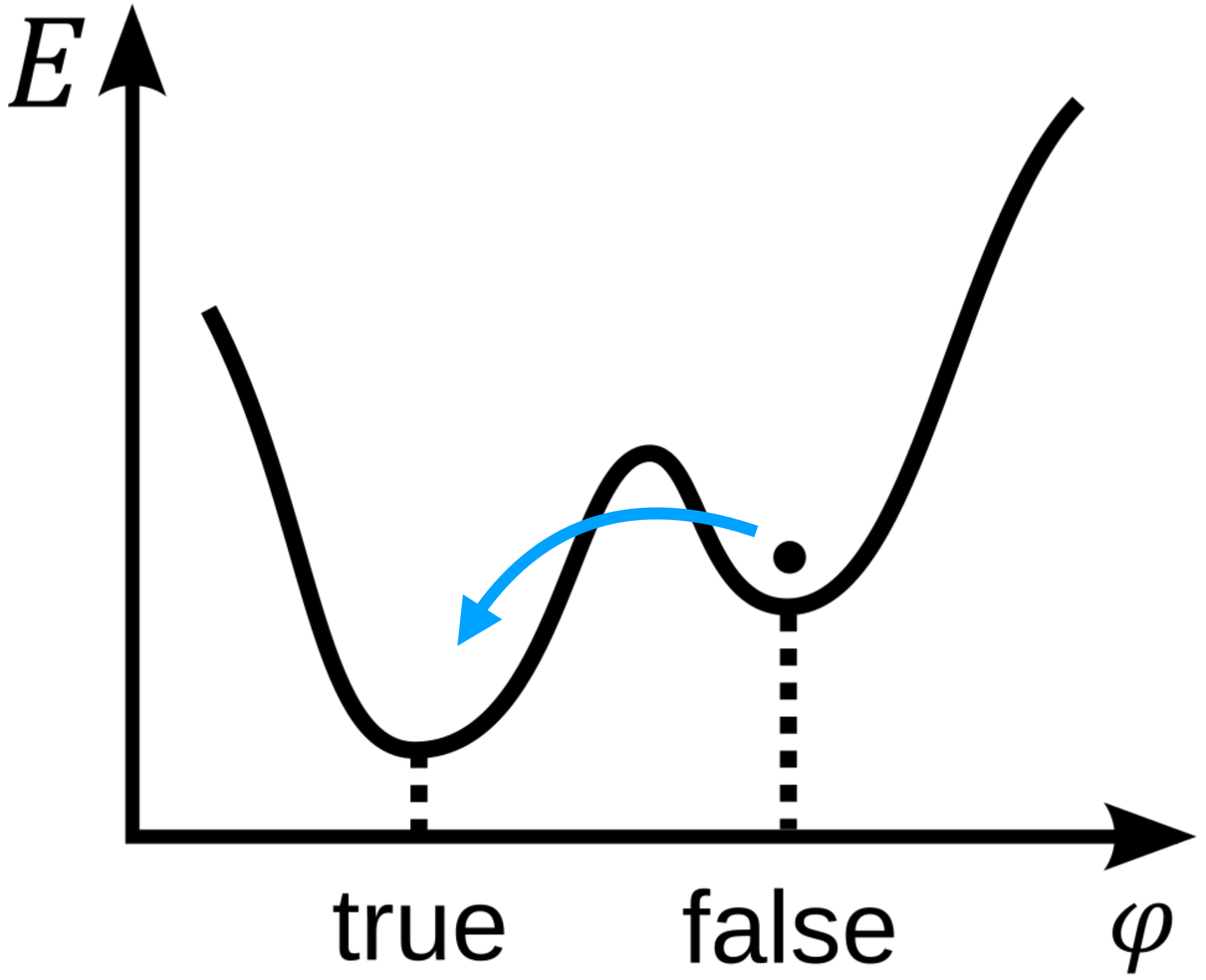
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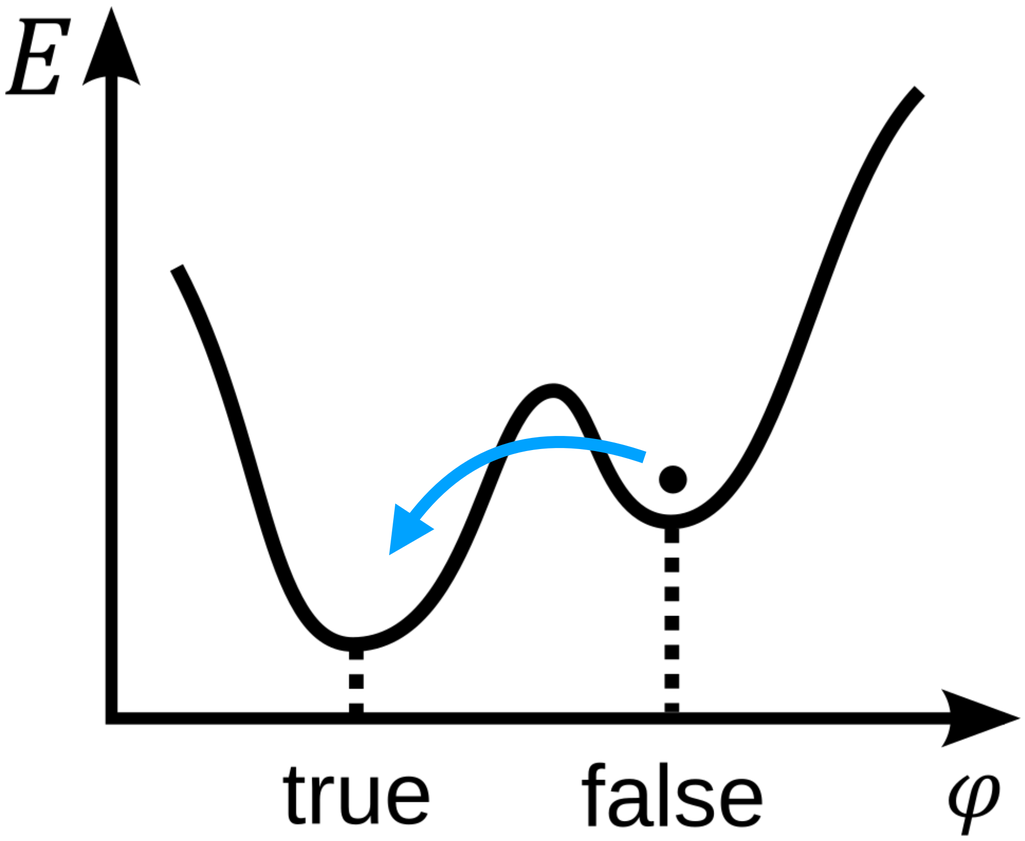
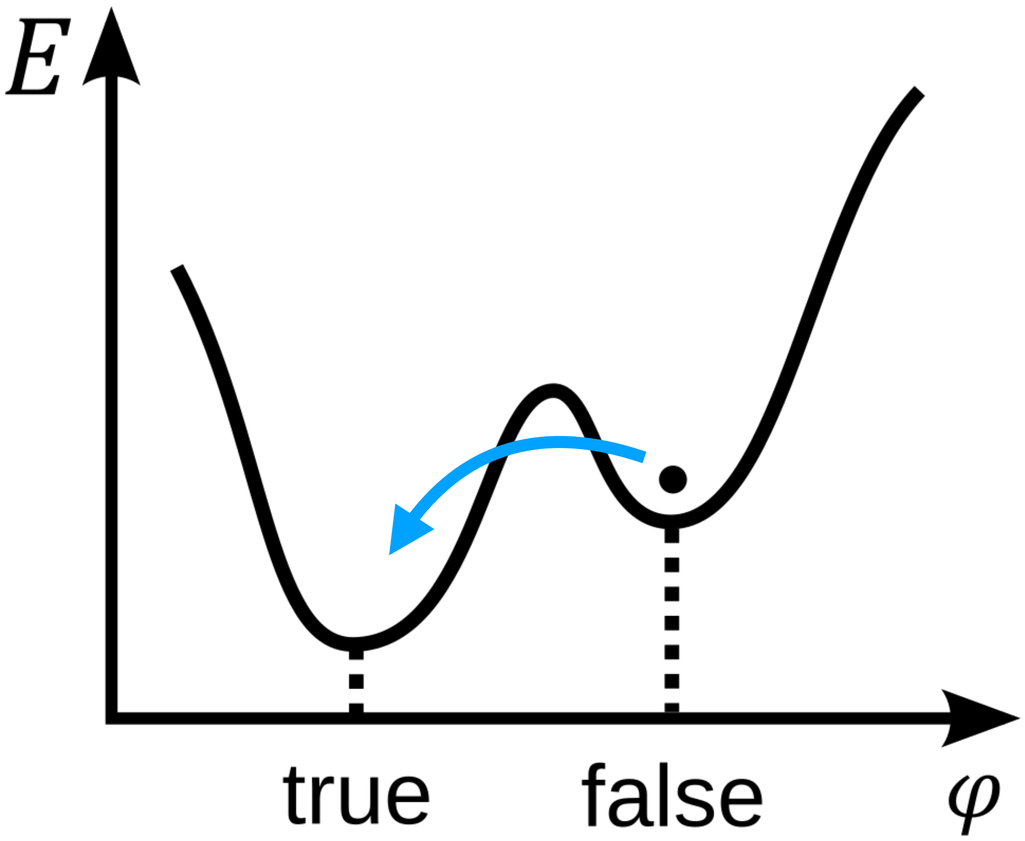
False vacuum decay?



Degrassi et al., *Higgs mass and vacuum stability in the Standard model at NNLO*, JHep, 2012.

Historically: the Higgs field is probably in a metastable configuration.

False vacuum decay?



Coleman, Fate of the false vacuum:
Semiclassical theory, PRD, 1977

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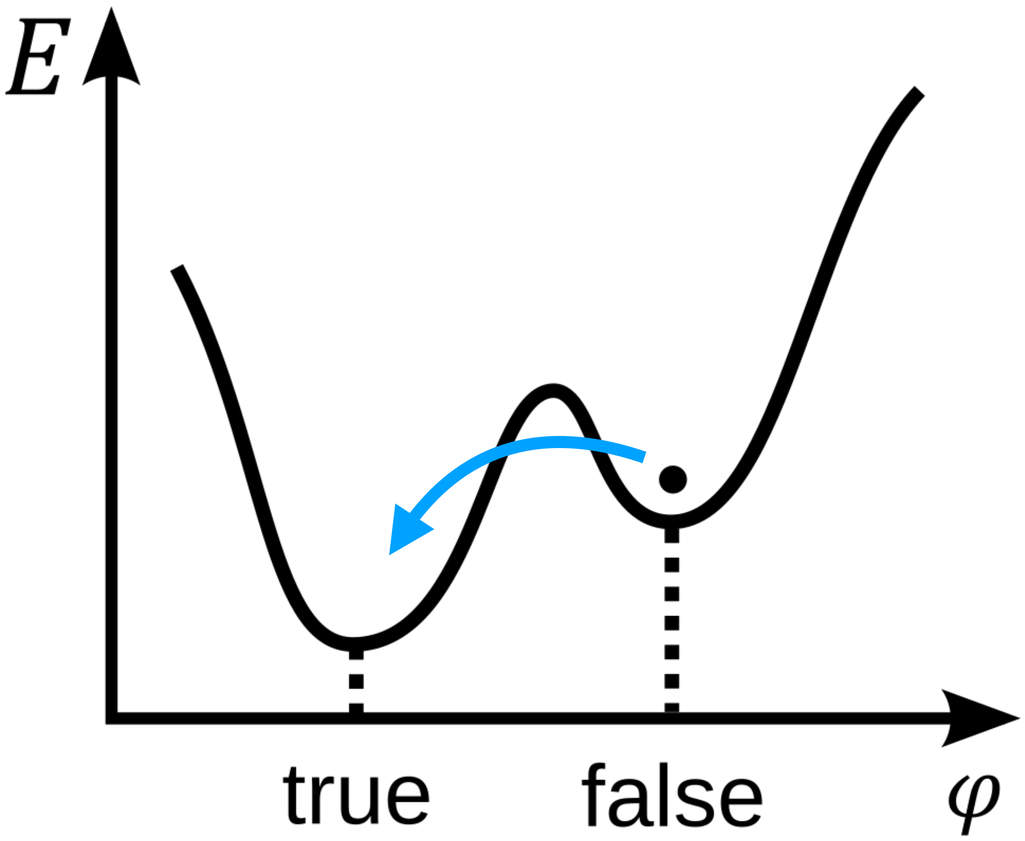

Thus the thing to compute is the probability of decay of the false vacuum per unit time per unit volume, Γ/V. Of course, such a computation would be bootless were it not for cosmology. An infinitely old universe must be in a true vacuum, no matter how slowly the false vacuum decays.

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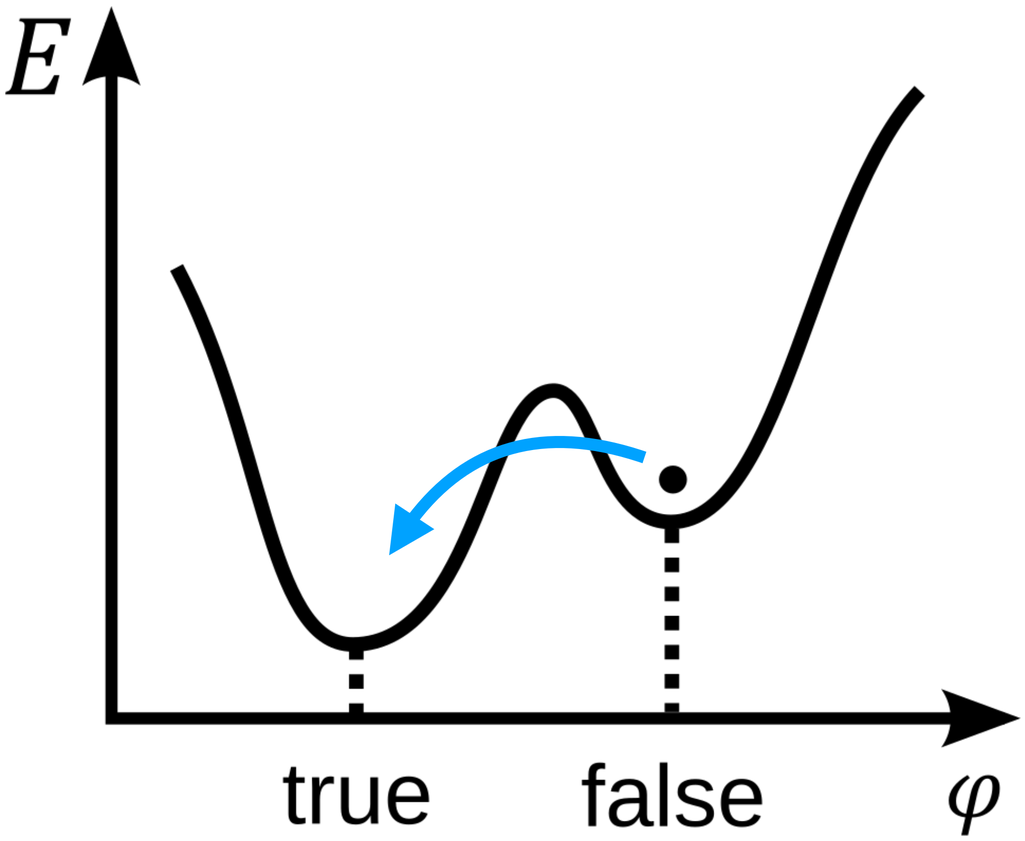

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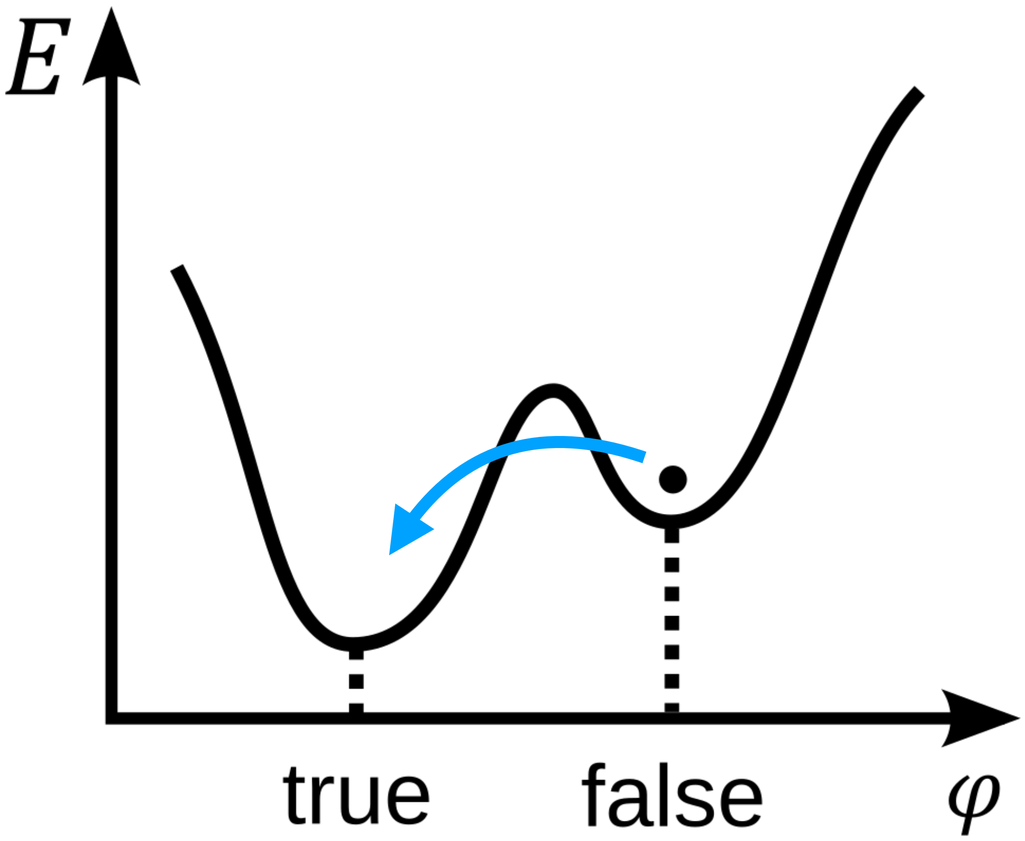

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However, the universe is not infinitely old. At the time of the big bang, the energy per unit volume was very high, and the state of the universe was very far from any vacuum, true or false. As the universe expanded and cooled down, it might well have settled into a false vacuum instead of a true one. The relevant parameter for describing

False vacuum decay?

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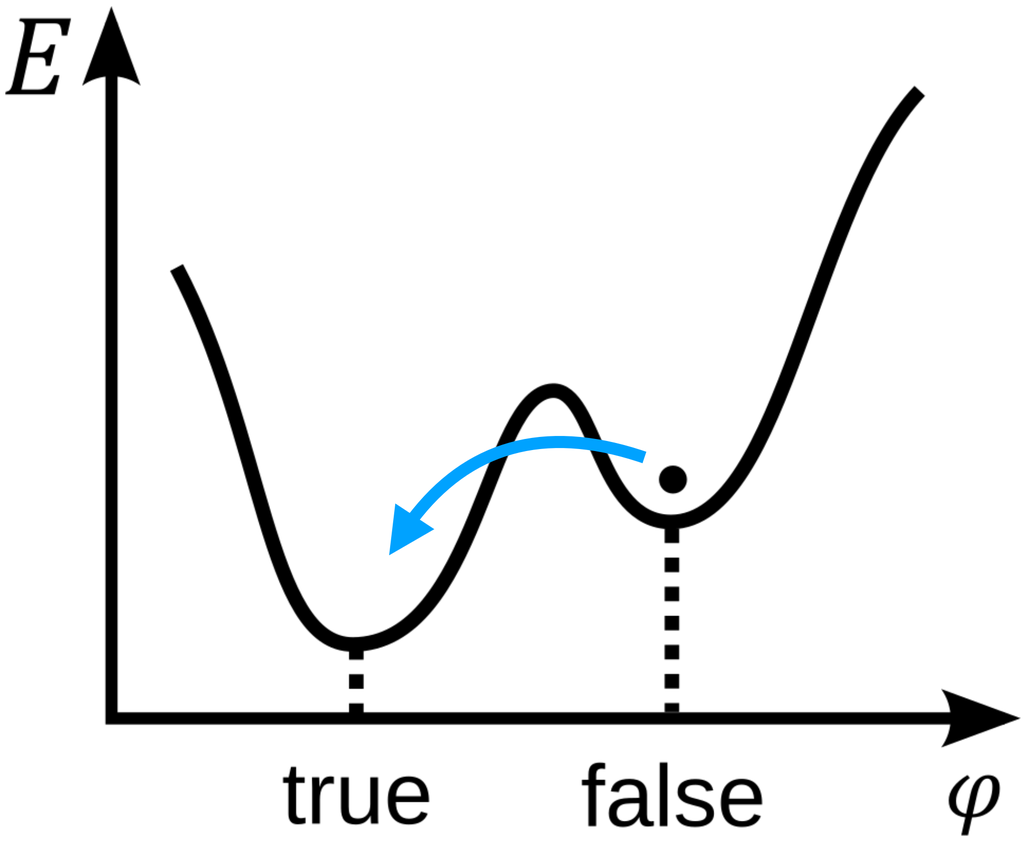

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If this time is on the order of milliseconds, the universe is still hot when the false vacuum decays, even on the scale of high-energy physics, and the zero-temperature computation of Γ/V is inapplicable. If this time is on the order of years, the decay of the false vacuum will lead to a sort of secondary big bang with interesting cosmological consequences. If this time is on the order of 10^9 yr, we have occasion for anxiety.

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More broadly: metastability in many-body systems

False vacuum is a canonical example of a metastable state.

Yin, Surace, Lucas, Theory of Metastable states in Many-Body Quantum Systems, PRX, 2025

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False vacuum is a canonical example of a metastable state.

1st order phase transitions: supercooling, phase separation, domain formation

long-lived states: state preparation and preservation, many-body memories

quantum dynamics: a special case of slow thermalisation

Yin, Surace, Lucas, Theory of Metastable states in Many-Body Quantum Systems, PRX, 2025

The critical bubble theory

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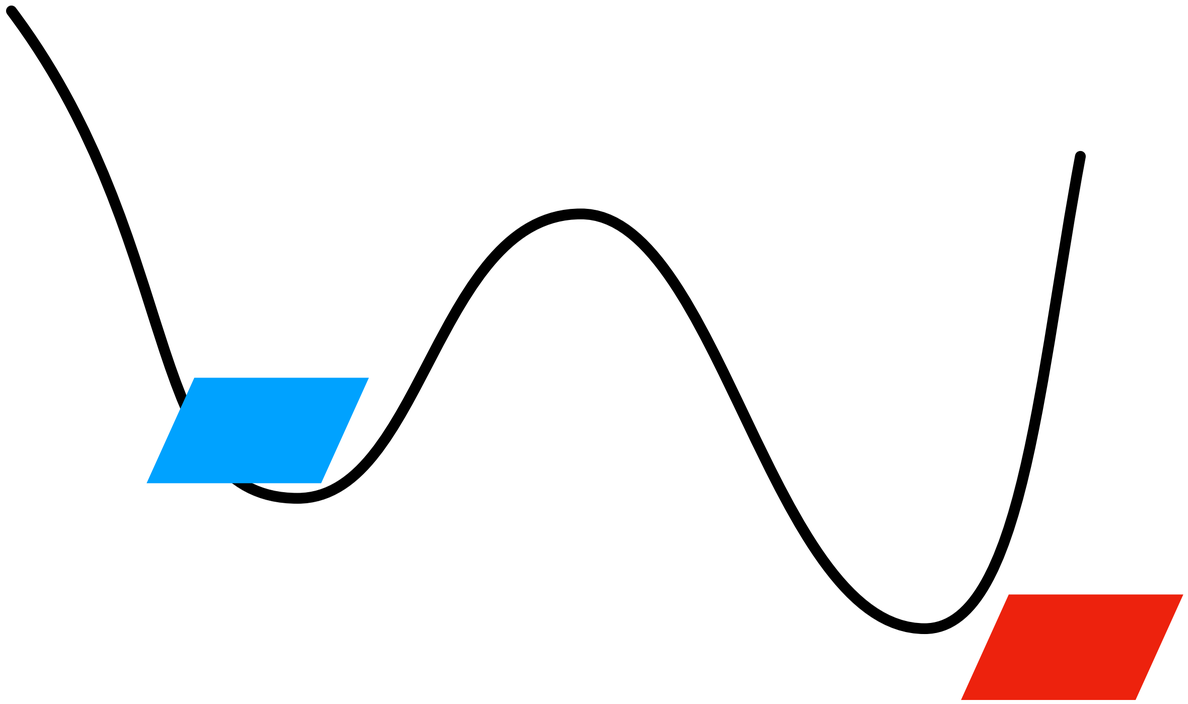

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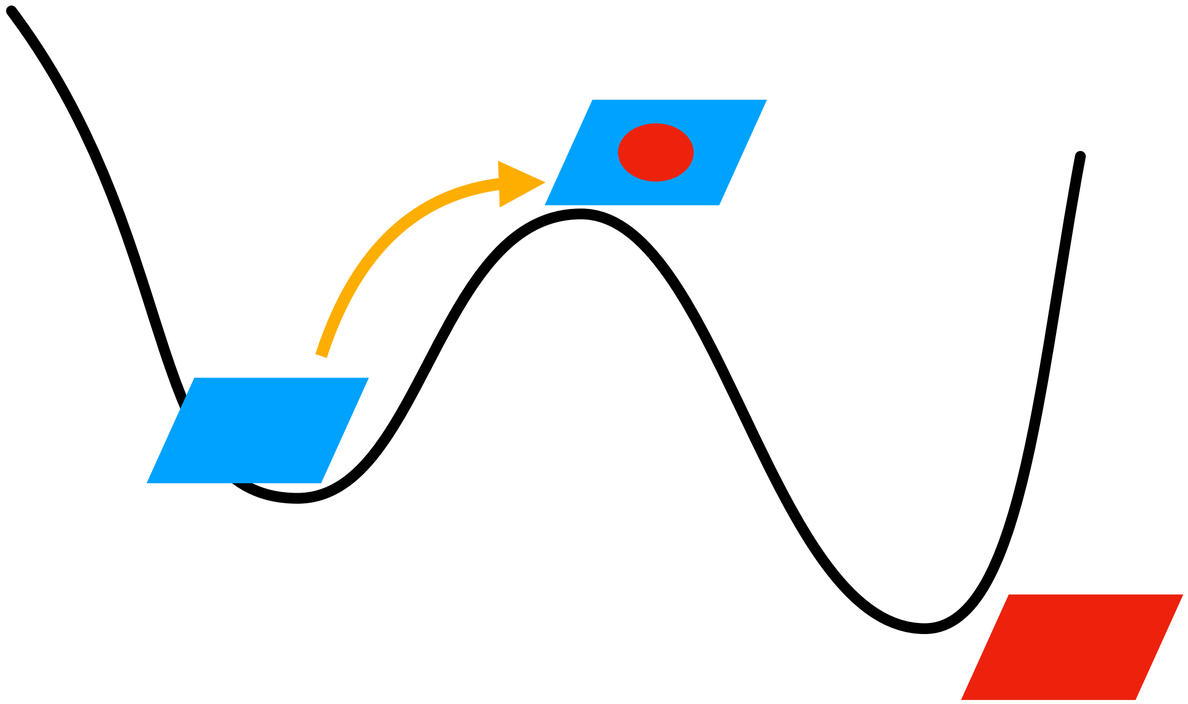
The decay is a collective event:



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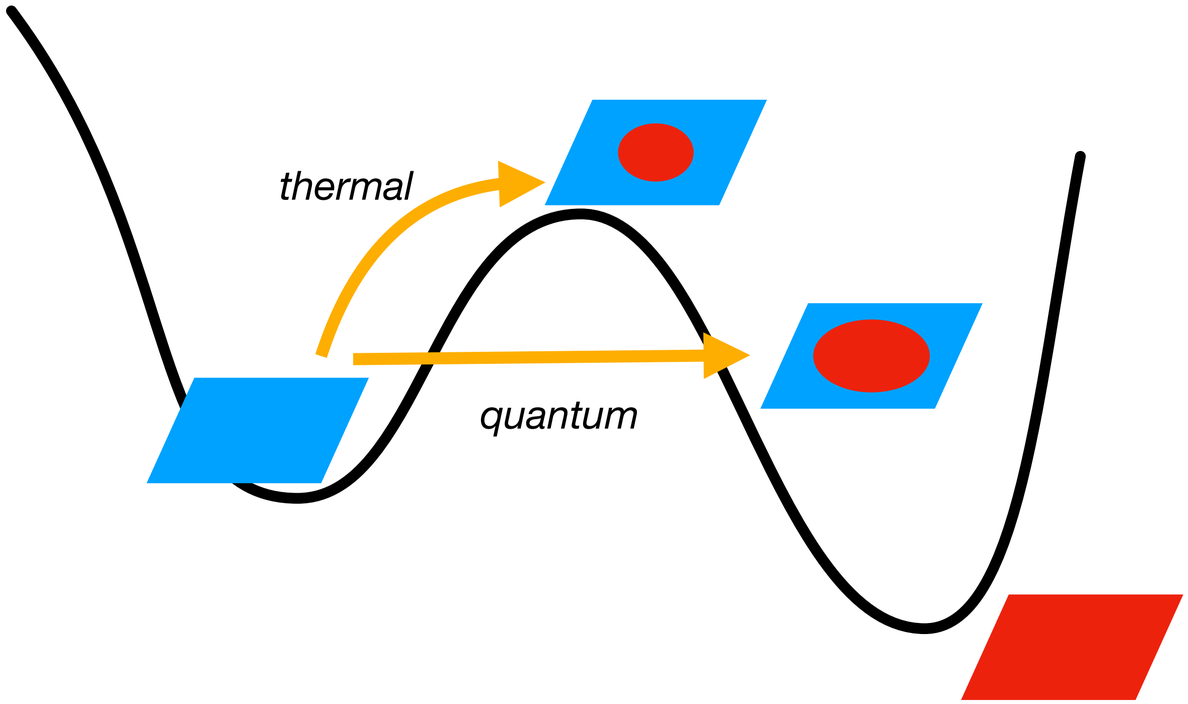
The ***quantum*** decay is a collective ***tunnelling*** event:



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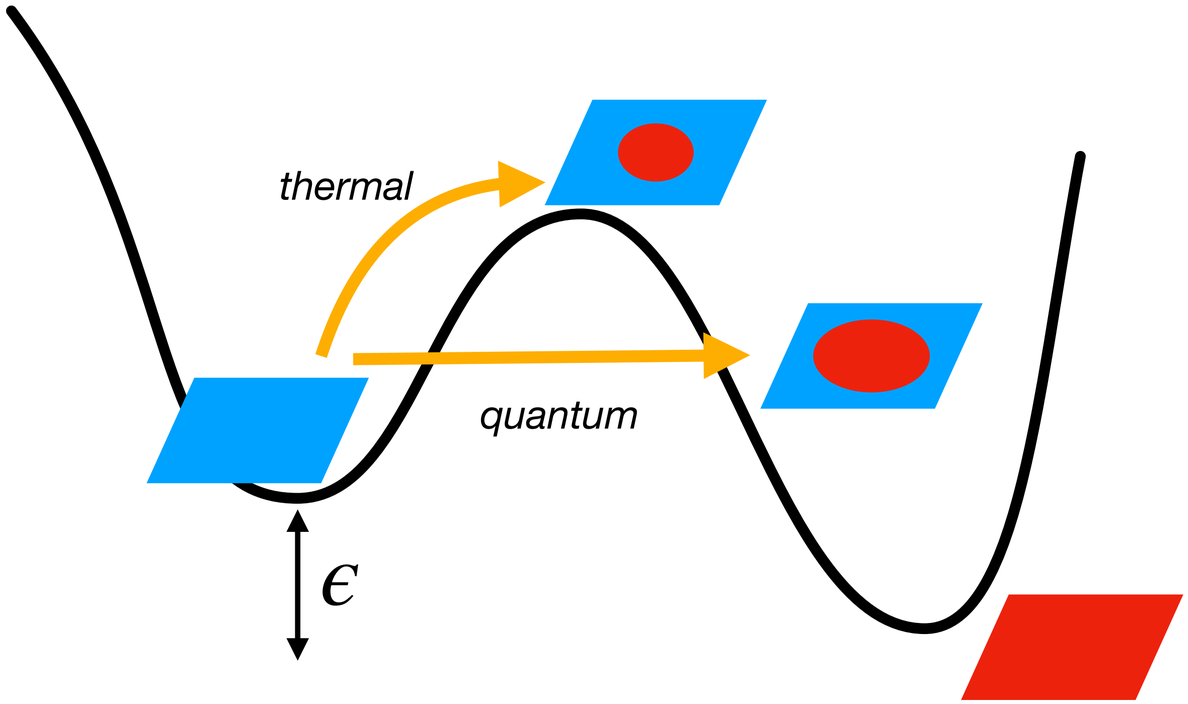

A bubble that is large enough can grow:

$$E(r) = \sigma r - \epsilon r^2$$

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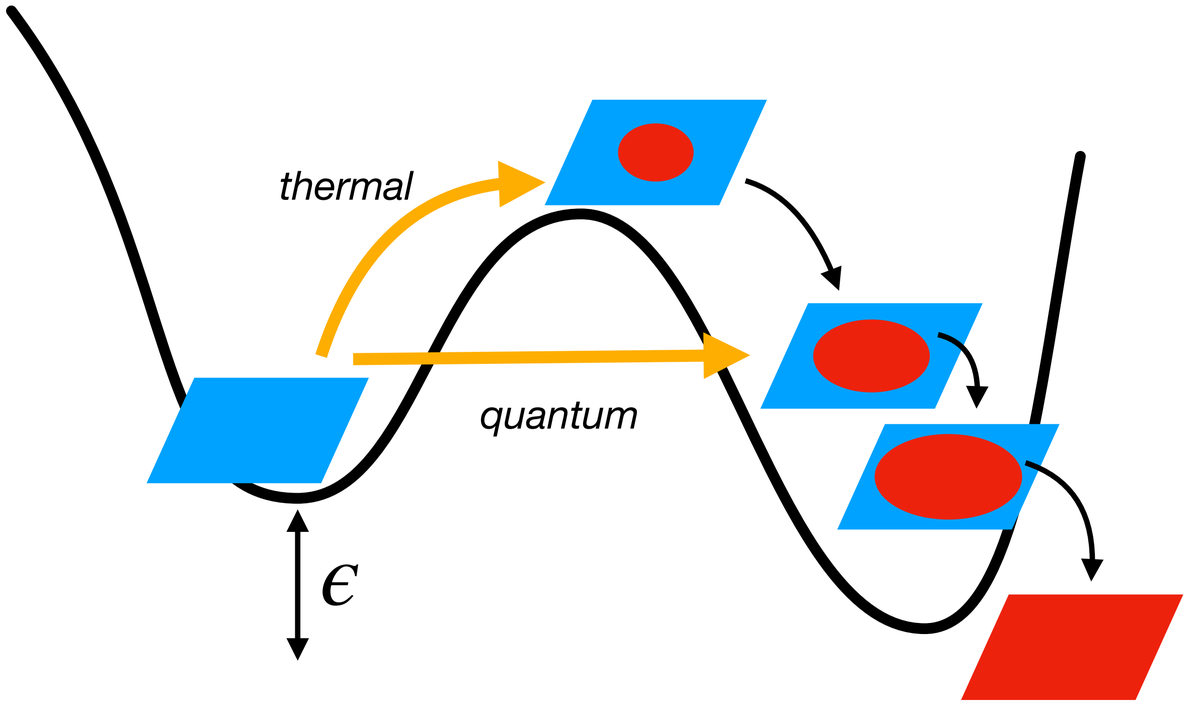

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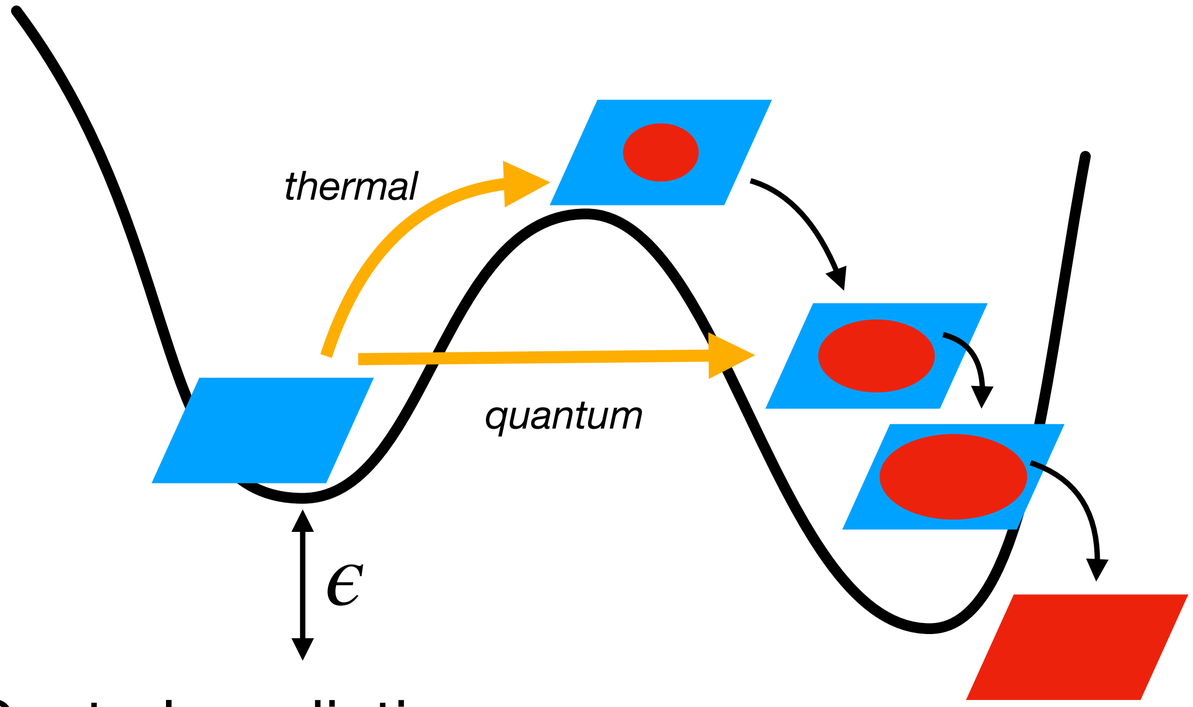


A bubble that is large enough can grow:

$$E(r) = \sigma r - \epsilon r^2$$

Central prediction:

the nucleation rate is ***exponentially suppressed*** in the ***bubble's action***:

$\varphi(t) \propto e^{-\gamma t}$, with $\gamma \propto e^{-S}$.

The quantum version has little experimental support:

Lagnese et al., *False vacuum decay in quantum spin chains*, PRB, 2021

iMPS test of FVD in an Ising spin chain, confirming analytical results from

S. B. Rutkevich, Decay of the metastable phase in d=1 and d=2 Ising models, 1999

Zenesini et al., *False vacuum decay via bubble formation in ferromagnetic superfluids*, Nat. Phys., 2024

Bubble formation in superfluids, interpreted as thermal decay.

Chao et al., *Probing False Vacuum Decay and Bubble Nucleation in a Rydberg Atom Array*, PRL, 2026

Relaxation of a Rydberg atom chain of 24 atoms.

False vacuum decay in a two-dimensional quantum spin system

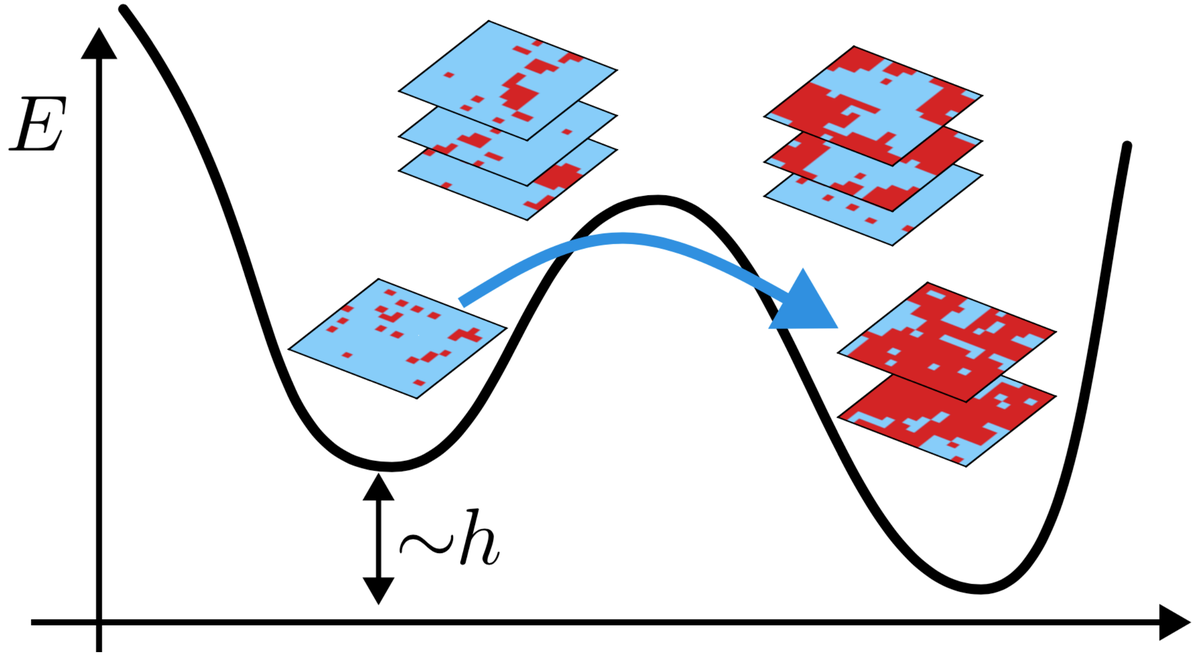
Luka Pavešić,[1,2,*] Ian G. Moss,[3,†] and Simone Montangero[1,2,‡]

[1] *Dipartimento di Fisica e Astronomia "G. Galilei", Università degli Studi di Padova, via Marzolo 8, I-35131 Padova, Italy*
[2] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Padova, I-35131 Padova, Italy*
[3] *School of Mathematics, Statistics and Physics, Newcastle University, Newcastle Upon Tyne, NE1 7RU, UK*





arXiv:2607.01994



We numerically test FVD in the quantum Ising model in 2D

$$H = -J \sum_{\langle ij \rangle} Z_i Z_j - g \sum_i X_i - h \sum_i Z_i$$

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spins are aligned in the Z direction



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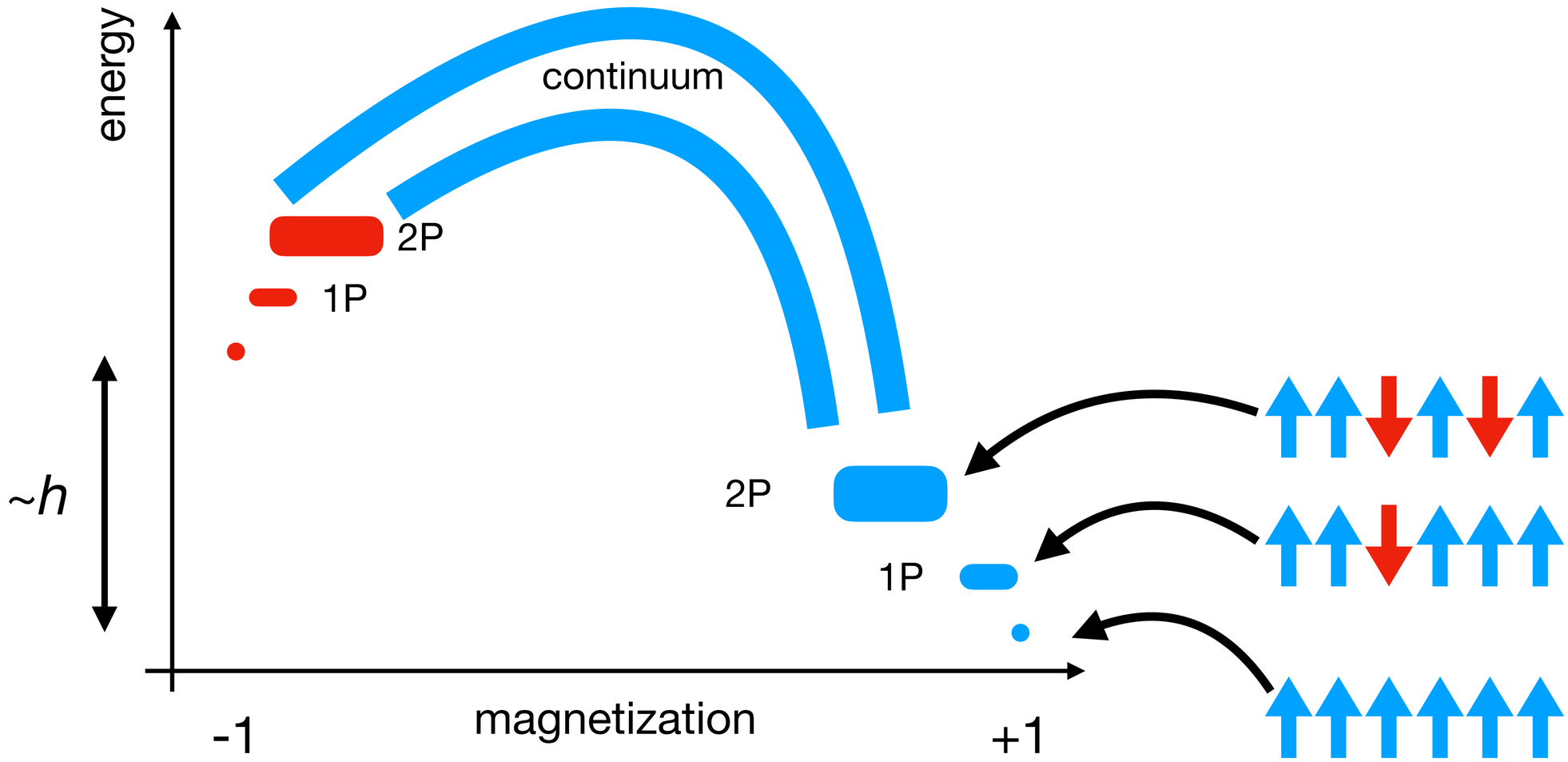
energy
continuum
2P
1P
~h
2P
1P
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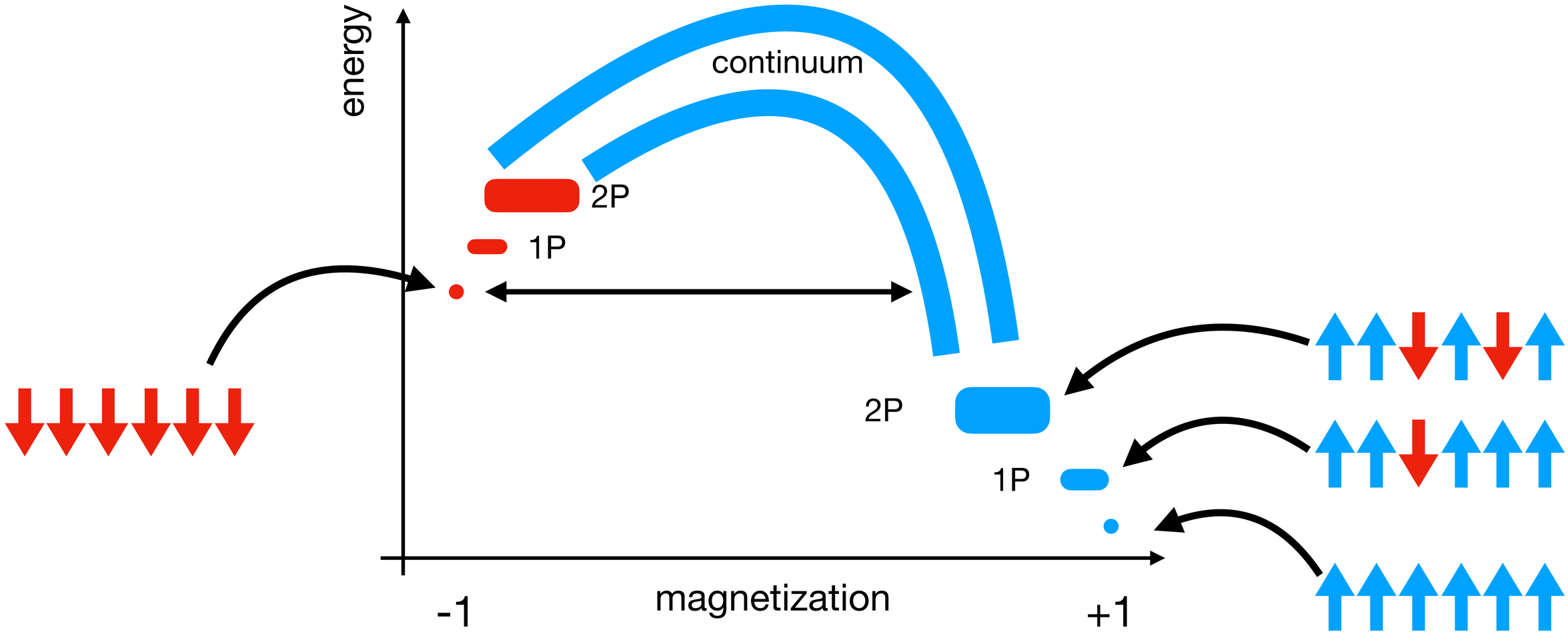
magnetization
+1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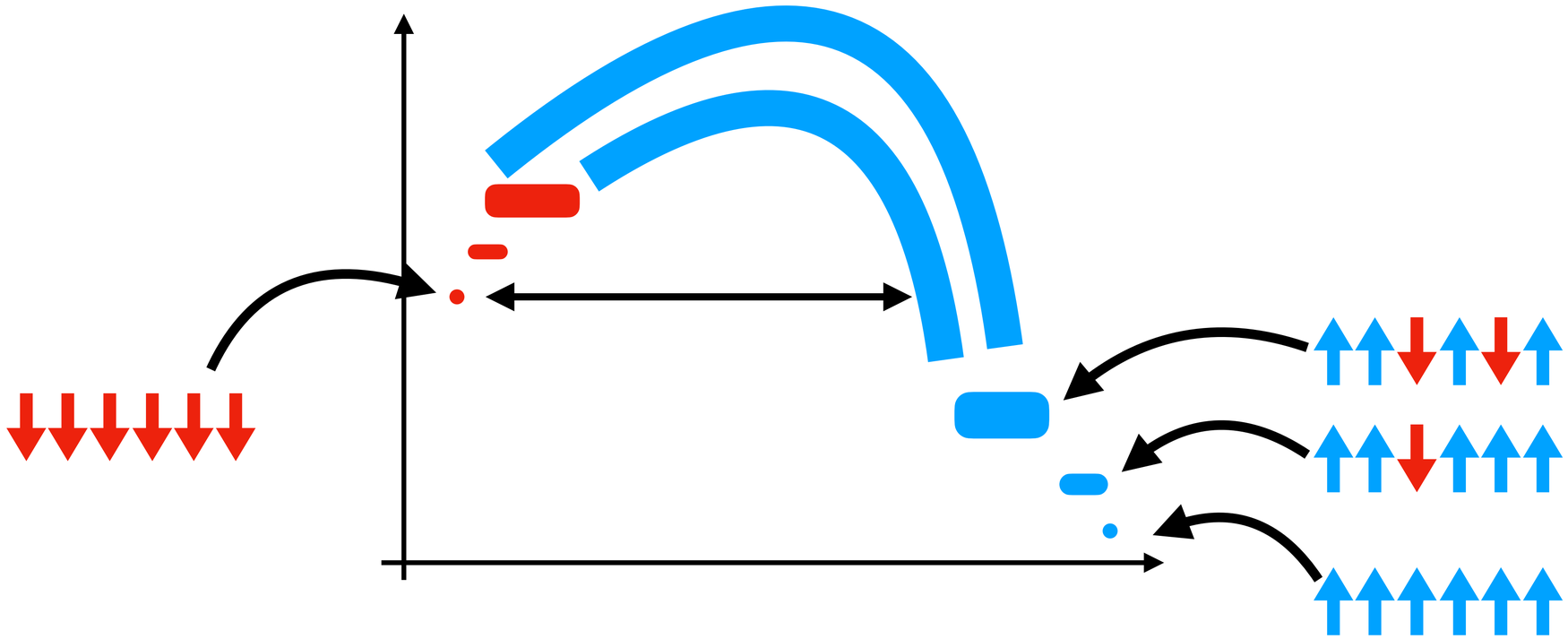

Questions:

-decay rate: the bubble nucleation is ***exponentially suppressed*** in its ***action***: $\varphi(t) \propto e^{-\gamma t}$, with $\gamma \propto e^{-S}$.

-critical bubble size: from the radius of the instanton at t=0.

-interface tension

The procedure:

1) find the ground state for (g, h) (DMRG)

2) quench (g, h) —> (g, -h)

The initial state is a close approximation to the FV eigenstate.

3) measure Z(t) as a signature of the false/true vacuum

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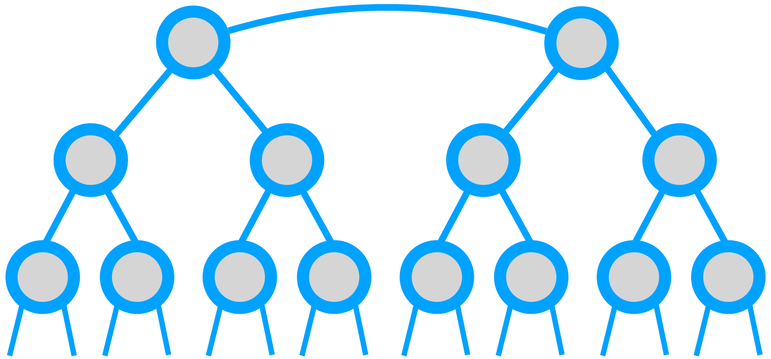
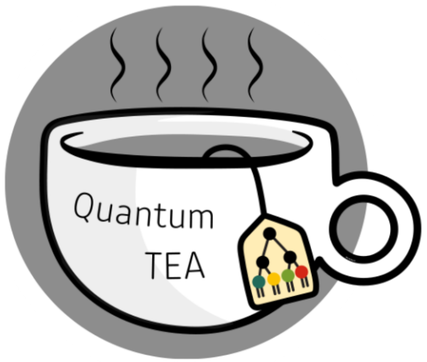
We do it with tensor networks





We expect:

F(t) to ***decay exponentially:*** $F(t) \sim e^{-\gamma t}$

Exponentially suppressed decay rate: $\gamma \sim e^{q/h^2}$

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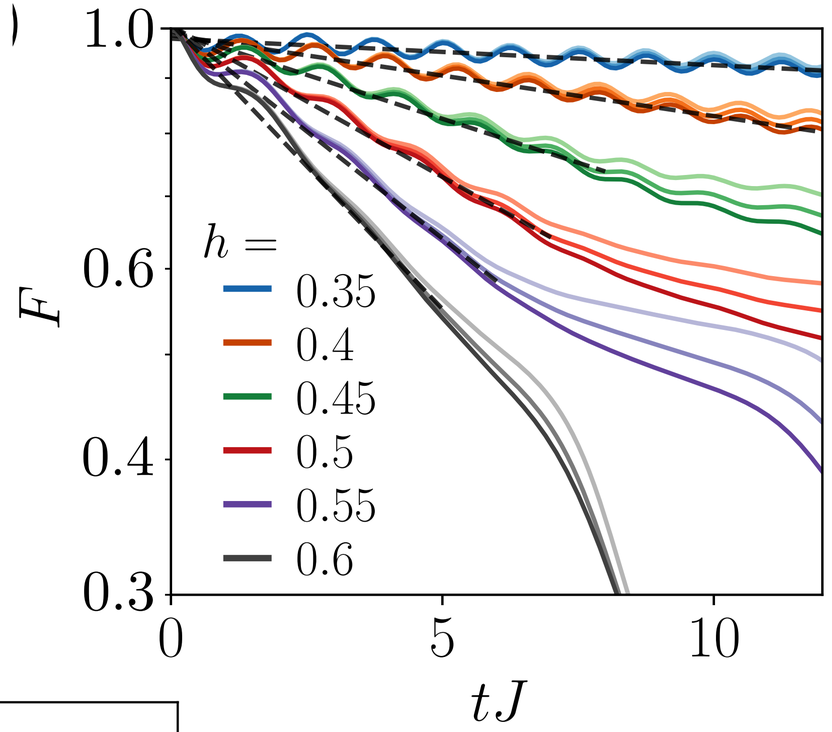

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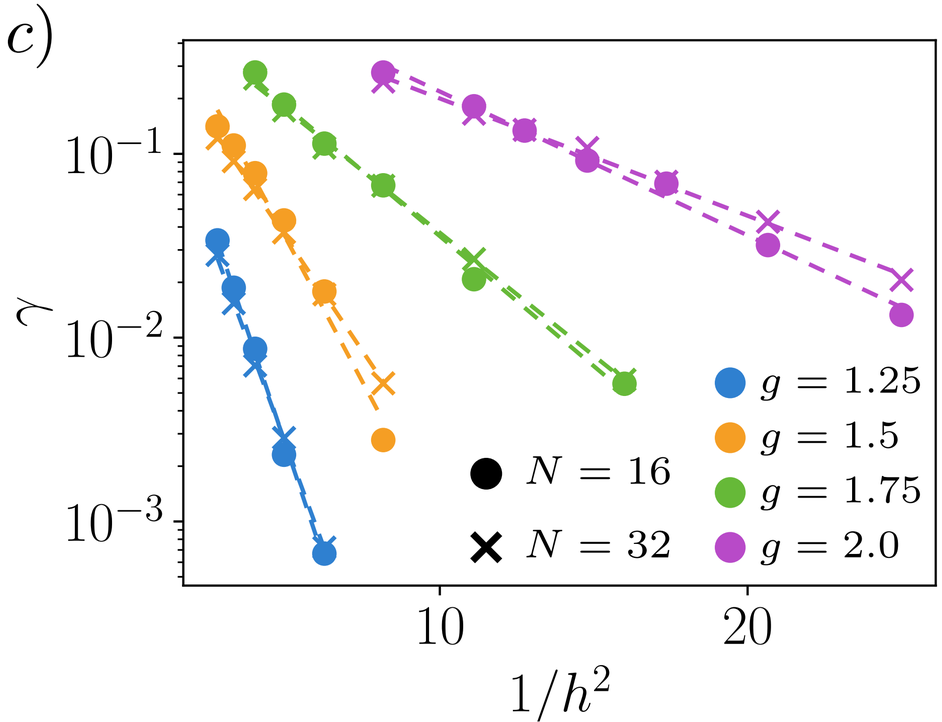
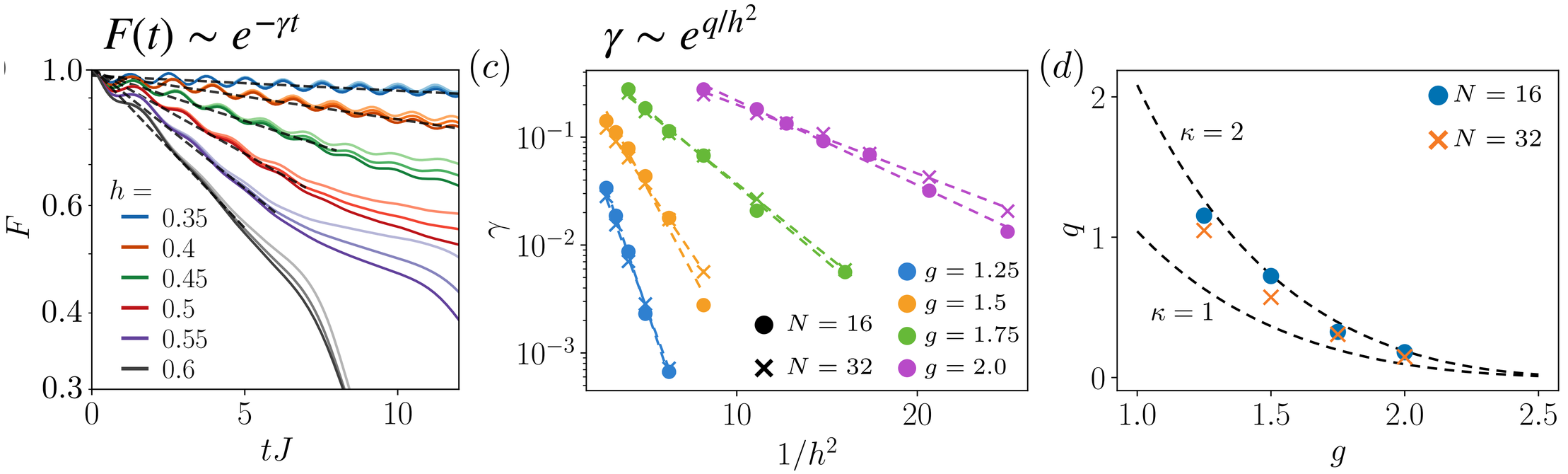


We expect:

Semi-classical QFT gives a prediction for the ***interface tension*** q:



Size of the critical bubble

true 2D correlators are too expensive, and there is too many of them

so:

$$C_L = \left\langle (1 - n_{i-1}) \cdot \boxed{n_i \cdot \ldots n_{i+L}} \cdot (1 - n_{i+L+1}) \right\rangle$$

bubble of *linear* size L



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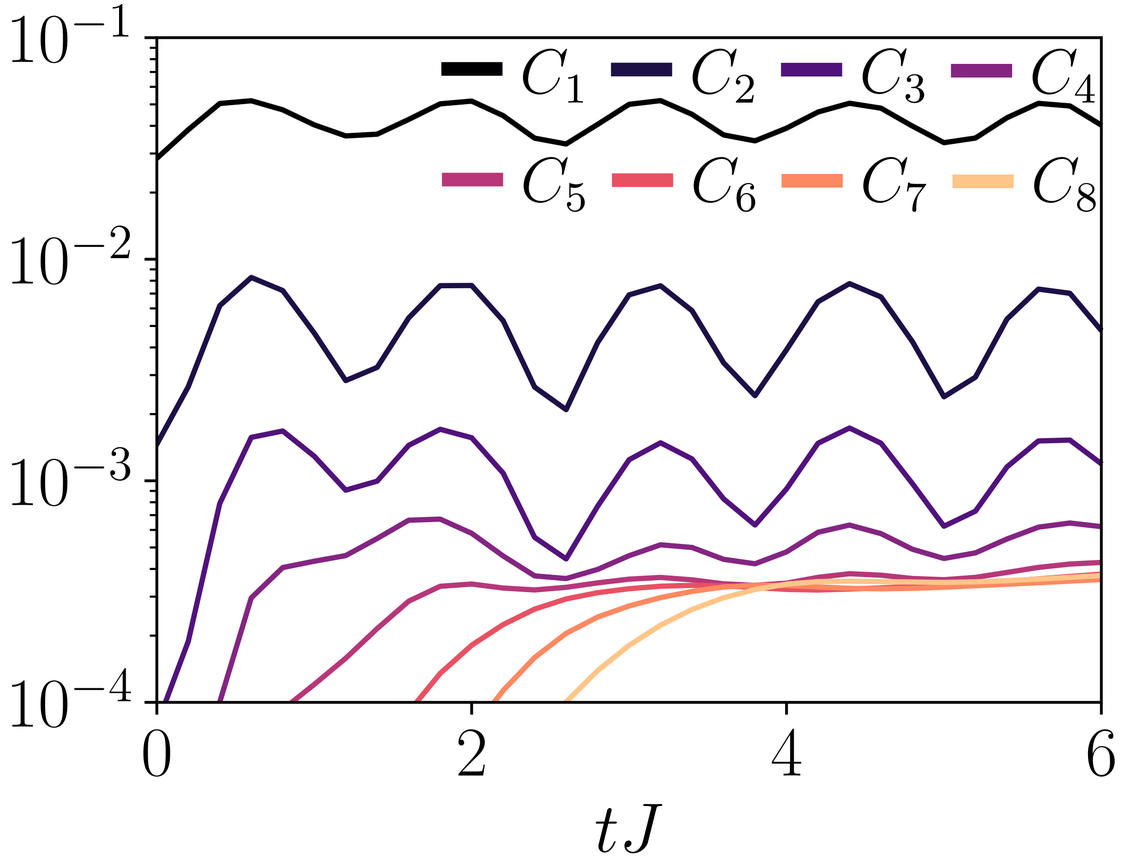

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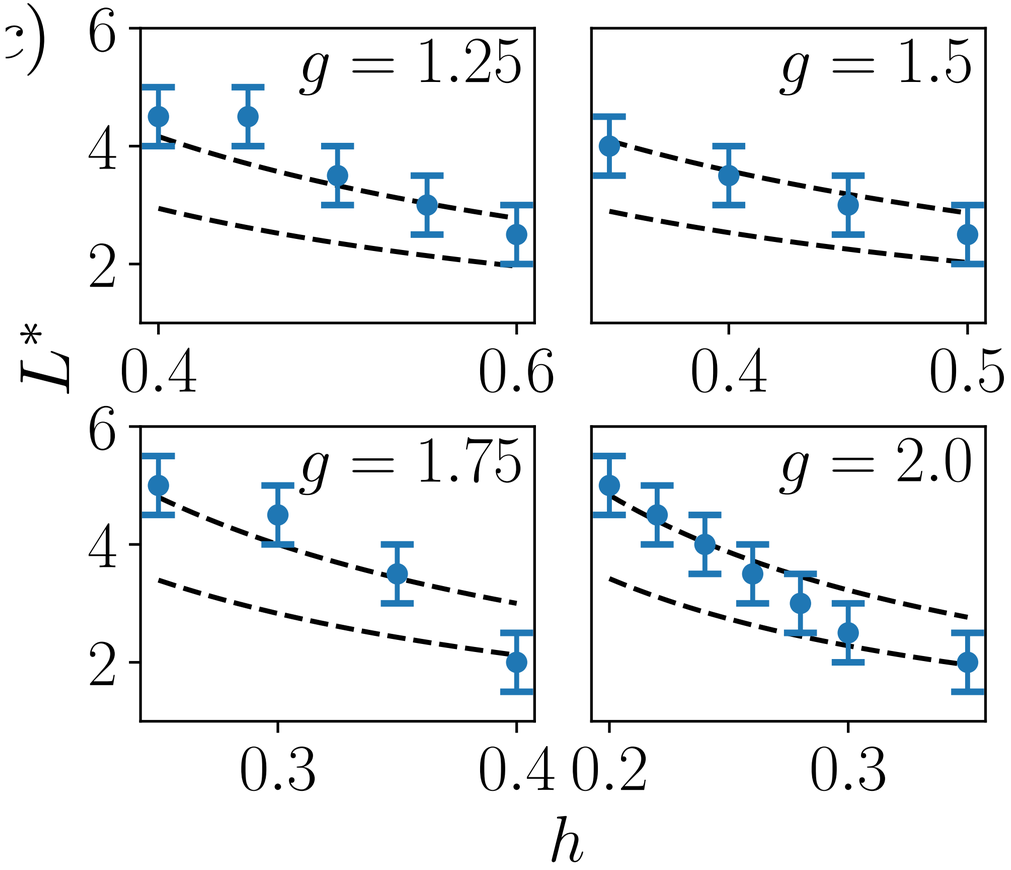
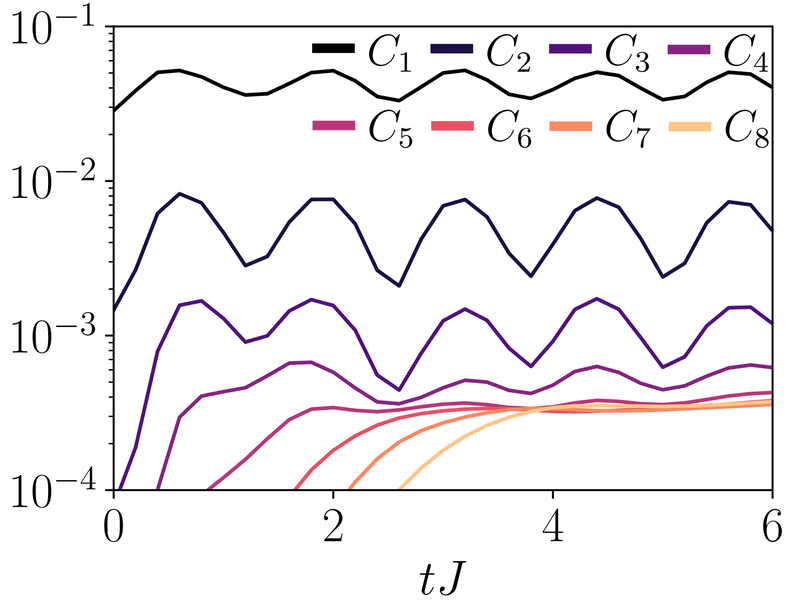
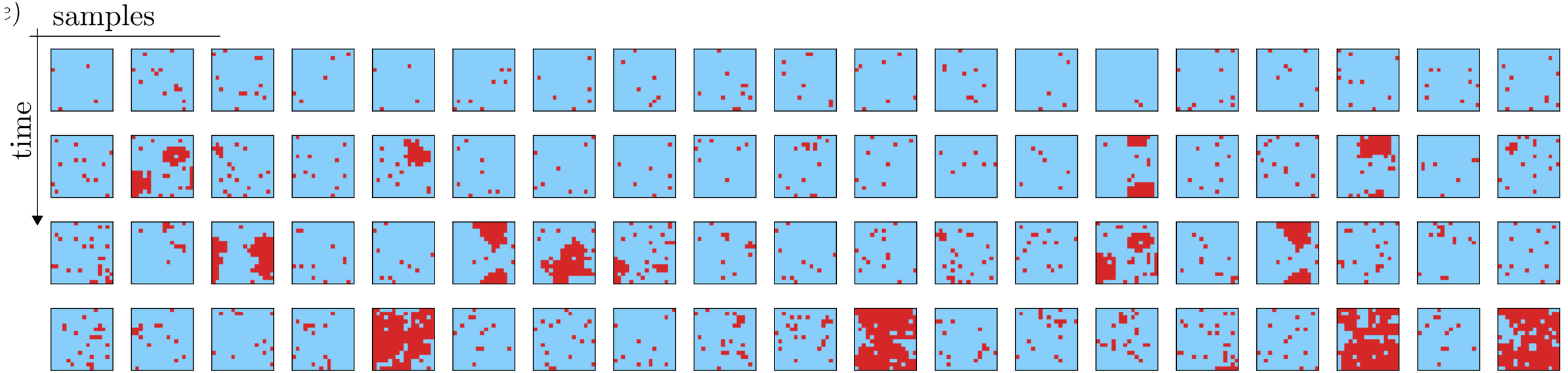




What does the state look like?



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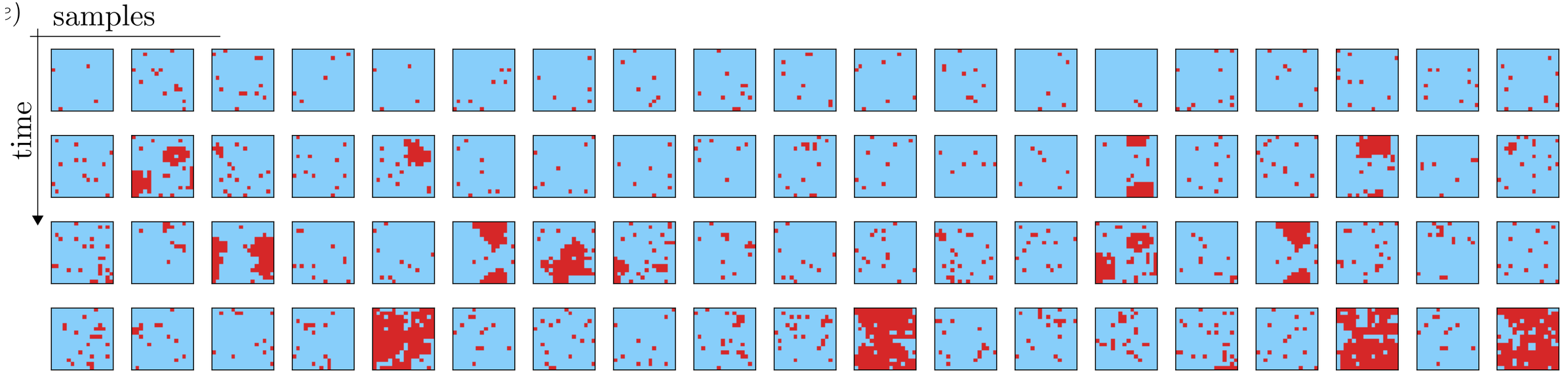
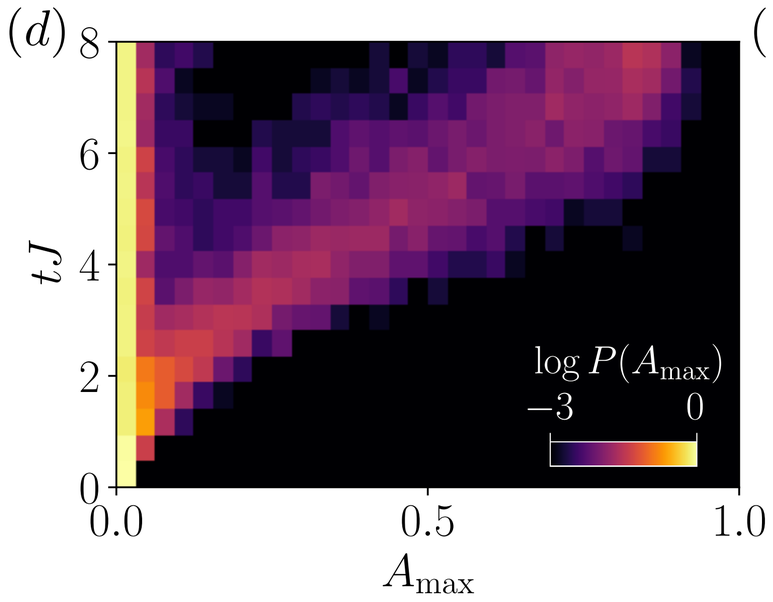




area of the biggest bubble in the snapshot

Where to next?

a) Better classification of the bubbles’ shapes and sizes

b) Beyond the assumptions of Coleman’s theory

Where to next?

a) Better classification of the bubbles' shapes and sizes

How do lattice effects affect them?

This probably requires ***deterministic*** nucleation.

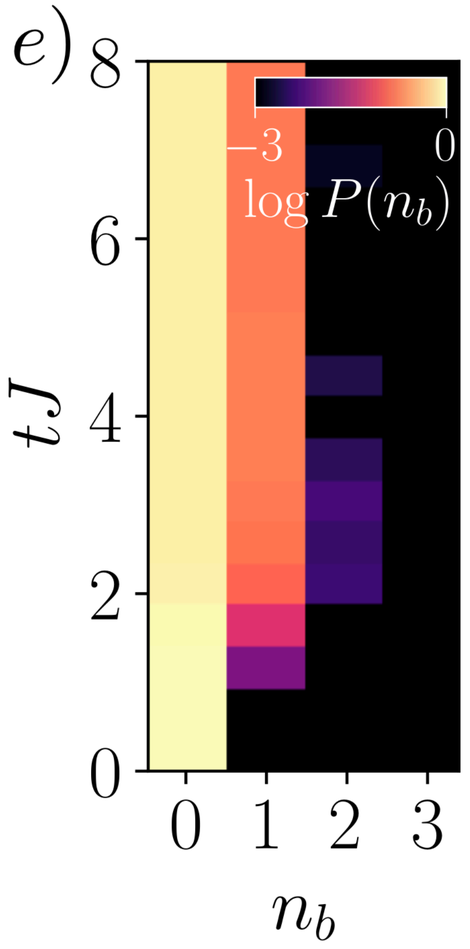
b) Beyond the assumptions of Coleman's theory

Where to next?

b) Beyond the assumptions of Coleman's theory

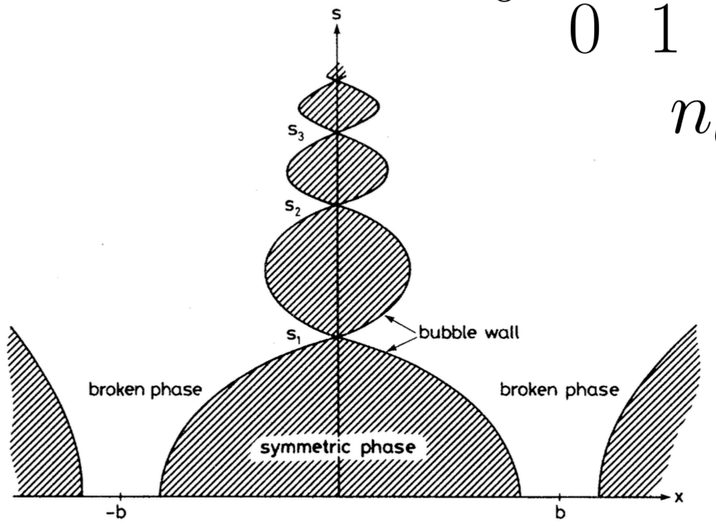
Multiple bubbles:

- Are nucleation events correlated? Anti-correlated?
- What happens when the bubbles collide?



Bubble collisions in the very early universe

S. W. Hawking, I. G. Moss, and J. M. Stewart
D.A.M.T.P. Silver Street, Cambridge CB3 9EW, U. K.
(Received 30 November 1981)



over

Backup slides

The critical bubble theory, but actually

(applied to Ising-type spin systems)

The quantum Ising model can be reformulated as a classical Ising in D+1 dimensions, with the *+1* being the imaginary time.

The evolution in the path-integral formalism is: $A = \int e^{iS[\phi]} \mathscr{D}\phi$

The action of a configuration ***x***: $S_E[\mathbf{x}] = \int \sigma(\mathbf{n}) dA - 2h \int dV$

The semiclassical solution to ***A*** is obtained by extremizing the action (*saddle-point approximation*), yielding the ***instanton*** solution. It implies a relation between the surface and volume terms:

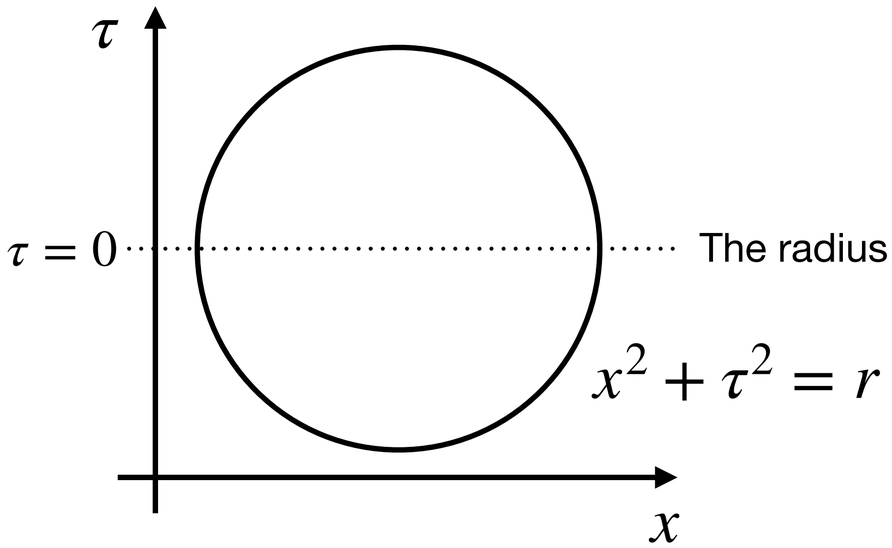
$$S_E[\alpha\mathbf{x}] = \alpha^2 \int \sigma(\mathbf{n}) dA - 2h\alpha^3 \int dV \qquad \text{thus} \qquad S_E[\mathbf{x}_b] = h \int dV$$

Additionally (dimensional analysis shows) that for the instanton solution, each coordinate scales as h^{-1}

The instanton action (=***the decay rate***) scales as $\frac{q}{h^2}$

More critical bubble theory

The instanton solution maximizes the *volume* term for a given *interface*:
it is a **sphere** in the (x, tau) plane.



The radius at 0 determines the critical bubble size.

Rotating back to $\tau \to it$ gives an expanding solution:

$$x = \pm\sqrt{r + t}$$