Quantum physics out of equilibrium

Frederick del Pozo

1: Laboratoire Kastler Brossel, Sorbonne Universite, CNRS,
ENS-PSL Research University, College de France;
4 Place Jussieu, 75005 Paris, France

Jeudi Morning Session (3hrs)

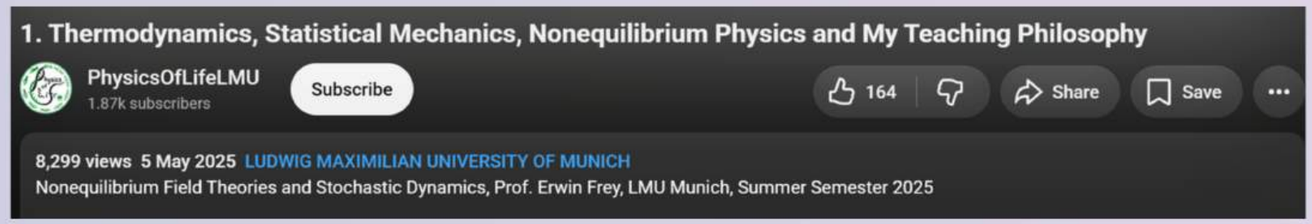
LES GUSTINES 2026 :)

> **Thermodynamics** is the study of how energy, heat, and work govern the macroscopic behavior of matter, including emergent phenomena like phase transitions, through universal laws that apply regardless of microscopic details.

Arrow of time: entropy cannot decrease (naturally)

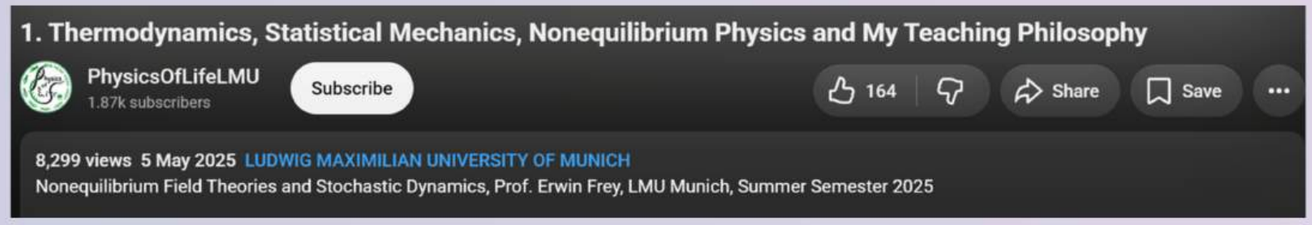
2nd Law of thermodynamics:
A generic system will always reach a maximal entropy state eventually (thermal equilibrium)

Talk by Anton Kapustin, California Institute of Technology
https://youtu.be/Qq-LzOPD5go?si=eDrivcO3jJ6Spx4l



> **Thermodynamics** is the study of how energy, heat, and work govern the macroscopic behavior of matter, including emergent phenomena like phase transitions, through universal laws that apply regardless of microscopic details.

> **Statistical physics** is the framework that explains how the macroscopic laws of thermodynamics and emergent collective behavior arise from the probabilistic dynamics of microscopic degrees of freedom, using ensembles, fluctuations, and coarse-graining to connect microstates to observable phenomena.



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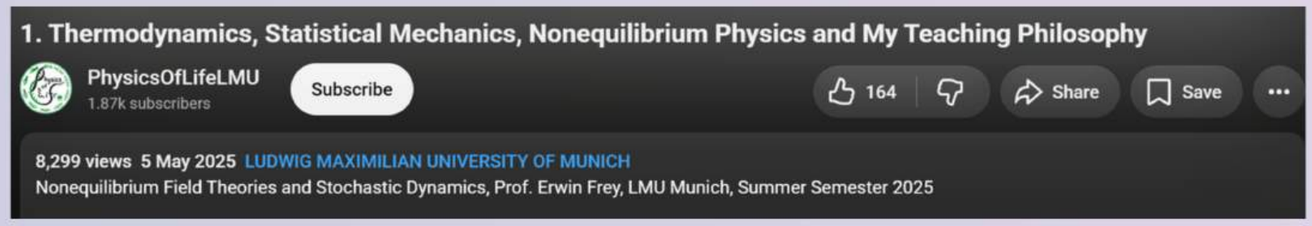
> **Statistical physics** is the framework that explains how the macroscopic laws of thermodynamics and emergent collective behavior arise from the probabilistic dynamics of microscopic degrees of freedom, using ensembles, fluctuations, and coarse-graining to connect microstates to observable phenomena.

> **Nonequilibrium physics** is the field that studies systems driven away from thermodynamic equilibrium, integrating macroscopic thermodynamic laws with microscopic statistical descriptions to understand transport, dissipation, fluctuations, and emergent behavior across scales.



My main references, *but there are of course more resources out there!*

The basis of the Second Law of thermodynamics in quantum field theory

D.W. Snoke [a], Gangqing Liu [a], S.M. Girvin [b]

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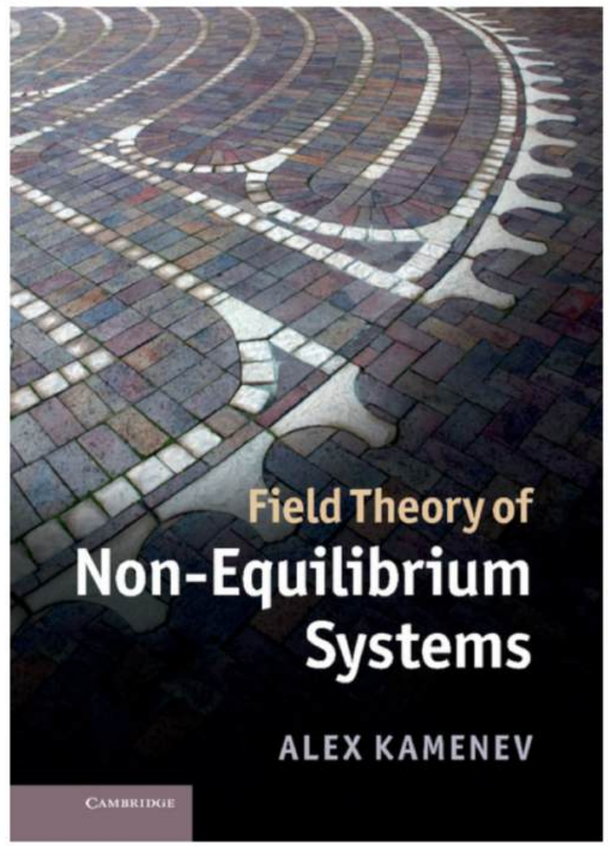
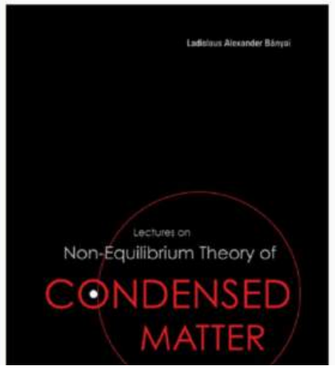
https://doi.org/10.1016/j.aop.2011.12.016 Get rights and content





Lectures on Non-Equilibrium Theory of Condensed Matter

https://doi.org/10.1142/6085 | August 2006

Pages: 248

By (author): Ladislaus Alexander Bányai (*J W Goethe Universität, Germany*)

View Full Book **Tools** **Share** **Recommend**

Outline, *but feel free to suggest changes!*

3hrs = 3 blocks + 2 pauses

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3hrs = 3 blocks + 2 pauses

Block A: Reversible physics of irreversible processes?

ca. 45-60min

Why classical or quantum physics in textbooks is usually not compatible with thermal equilibrium…

Outline, *but feel free to suggest changes!*

3hrs = 3 blocks + 2 pauses

Block A: Reversible physics of irreversible processes?

ca. 45-60min

Why classical or quantum physics in textbooks is usually not compatible with thermal equilibrium…

… and why actually it is, if we just use the right tools!

Focus: (Quantum) Boltzmann equations

Outline, *but feel free to suggest changes!*

3hrs = 3 blocks + 2 pauses

Block A: Reversible physics of irreversible processes?

ca. 45-60min

APRIL 1, 1933 PHYSICAL REVIEW VOLUME 43

Transport Phenomena in Einstein-Bose and Fermi-Dirac Gases. I

E. A. UEHLING AND G. E. UHLENBECK, *University of Michigan*

(Received February 13, 1933)

PHYSICAL REVIEW VOLUME 168, NUMBER 1 5 APRIL 1968

Many-Body Theory for Quantum Kinetic Equations*

BANDEL BEZZERIDES
Lawrence Radiation Laboratory, University of California, Livermore, California
AND
D. F. DUBOIS
Hughes Research Laboratories, Malibu, California

(Received 30 October 1967)

Outline, *but feel free to suggest changes!*

Block B: A humble introduction to Keldysh field theory

ca. 45-60min

A very old new way to look at quantum field theory…

that lets us derive in a consistent manner the kinetic equations to study non-equilibrium dynamics and thermalization!

Outline, *but feel free to suggest changes!*

Block B: A humble introduction to Keldysh field theory

ca. 45-60min

A very old new way to look at quantum field theory…

not just quantum!

Home › La Rivista del Nuovo Cimento › Article

Kinetic field theory for cosmic structure formation

Review Paper | Open access | Published: 08 August 2022

Volume 45, pages 737–799 (2022) Cite this article

Outline, *but feel free to suggest changes!*

3hrs = 3 blocks + 2 pauses

Last but not least, my own reseach:

Block C: Really cool physics really far away from equilibrium :)

ca. 45-60min

What happens when you drive a system
across a phase transition? Lets find out...

PHYSICAL REVIEW B VOLUME 44, NUMBER 7 15 AUGUST 1991-I

Carrier thermalization in Cu_2O: Phonon emission by excitons

D. W. Snoke, D. Braun, and M. Cardona
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 7000 Stuttgart 80, Germany
(Received 4 March 1991)

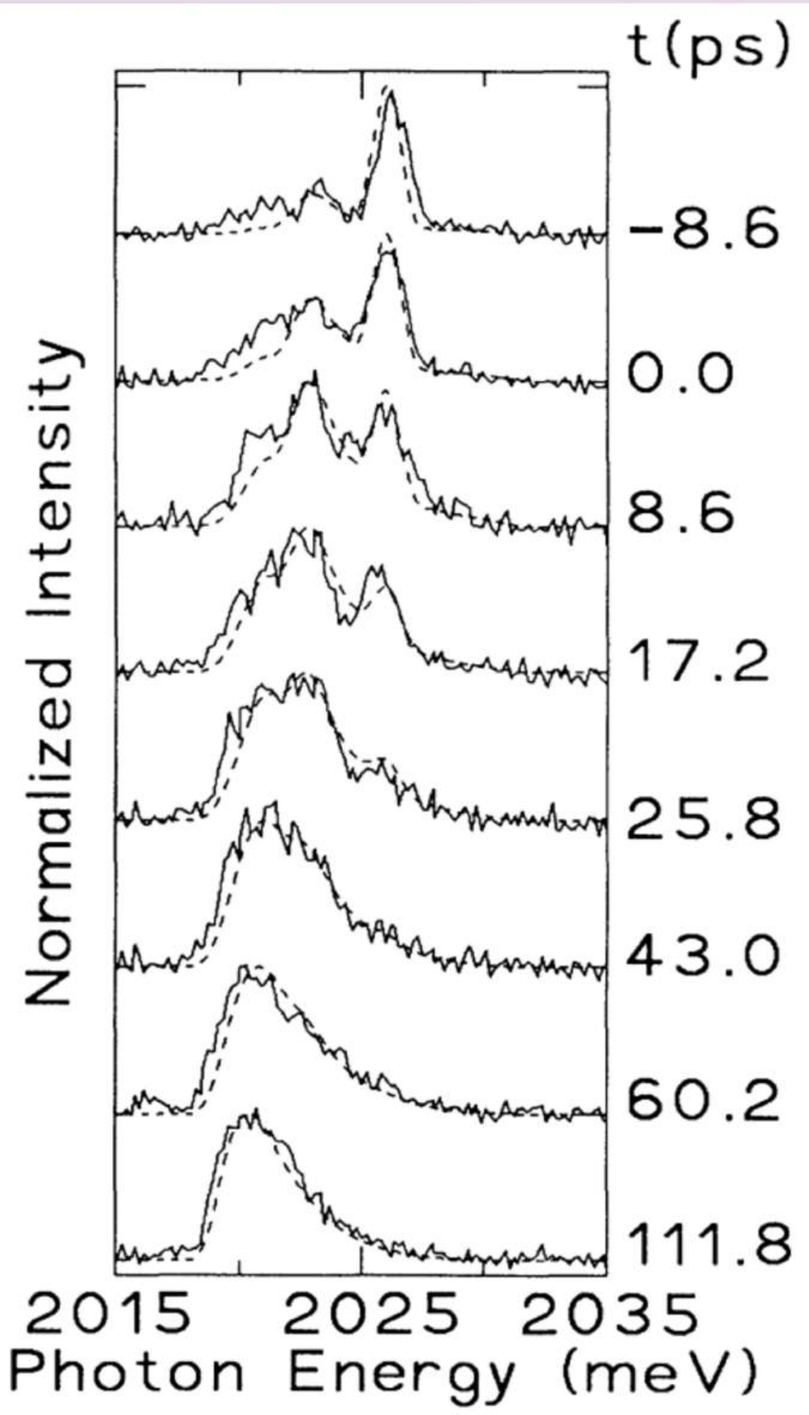


FIG. 2. Solid lines: the phonon-assisted luminescence of the orthoexcitons in Cu_2O at a lattice temperature of 16 K, at various delays after a synch-pumped dye laser pulse at photon energy 2.054 eV. The line shape gives the kinetic-energy distribution of the excitons directly. The excitons can only emit acoustic phonons to cool. Dashed lines: the prediction of the model of the energy distribution presented in the text. The entire series is fitted with variation of only one parameter, the deformation potential. The distribution at $t=111$ ps is within 5% of a Maxwell-Boltzmann distribution, $I(E) \propto E^{1/2} e^{-E/kT}$. The theory is convoluted with a triangle function of width 1.1 meV to account for the experimental spectral resolution. The laser generation function has the form $G(t) \propto e^{-(t/\gamma)^2}$, where $\gamma = 8$ ps.

Entanglement entropy across the dynamical phase transition in the quantum O(N) model

Frederick del Pozo[1], Tangi Morvan[2,3], Irenee Frerot[1] and Nicolas Cherroret[1]

recently finished and submitted.

arXiv:2605.23600 [quant-ph]

1: Laboratoire Kastler Brossel, Sorbonne Universite, CNRS, ENS-PSL Research University, College de France; 4 Place Jussieu, 75005 Paris, France

2: Laboratoire de Physique Theorique et Modeles Statistiques, Batiment 530, Rue Andre Riviere, 91405 Orsay, France

3: Ecole Normale Superieure de Lyon, 15 parvis Rene Descartes, 69342 Lyon, France

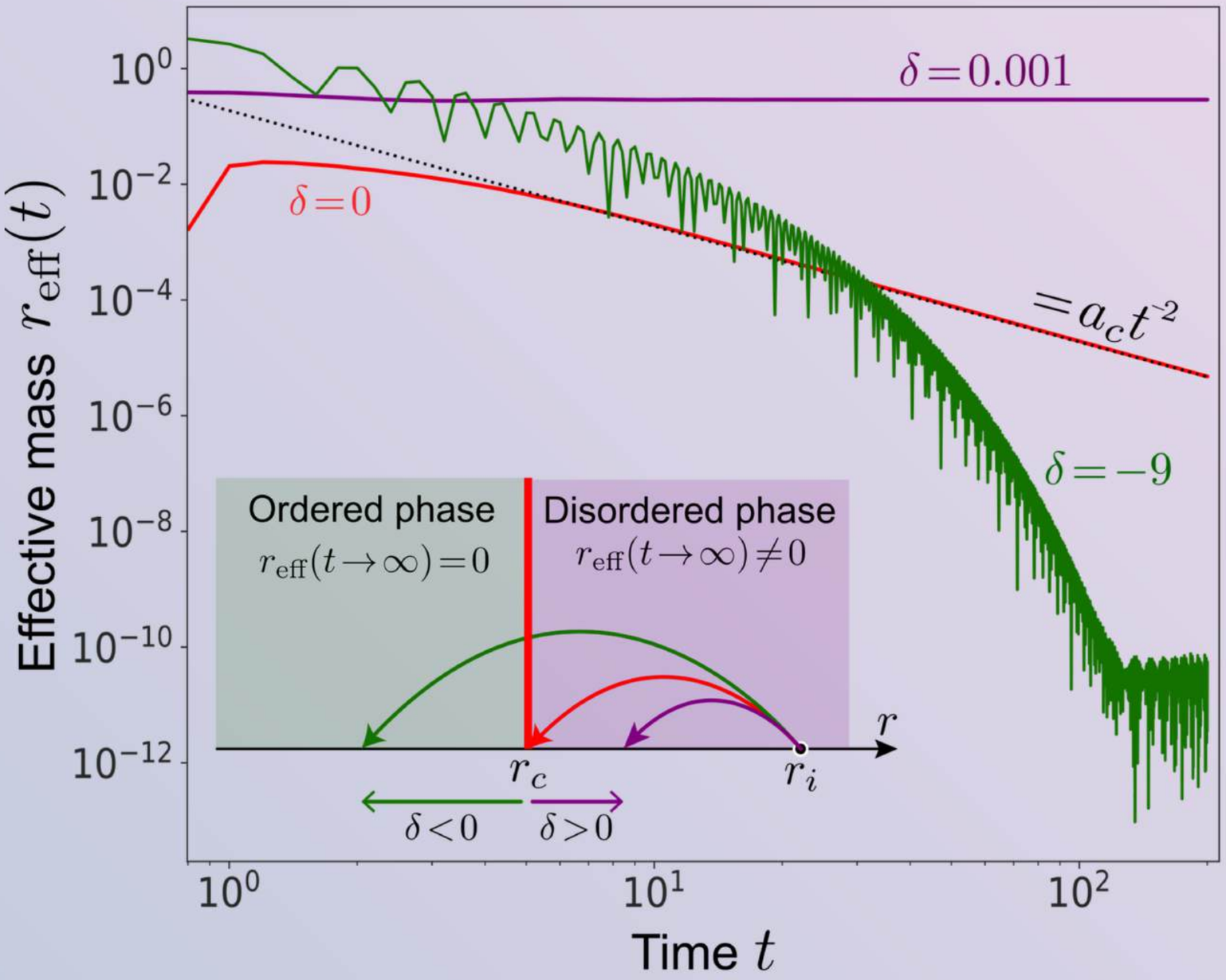
INVITED TALK

~~CONTRIBUTING~~ TALK

~~Session 3~~ **Non-equilibrium and Chaos**

CMQM 01-03rd of July, **2026**

$$r_{eff}(t) = r + \frac{u}{6}\langle\phi^\dagger\phi\rangle$$



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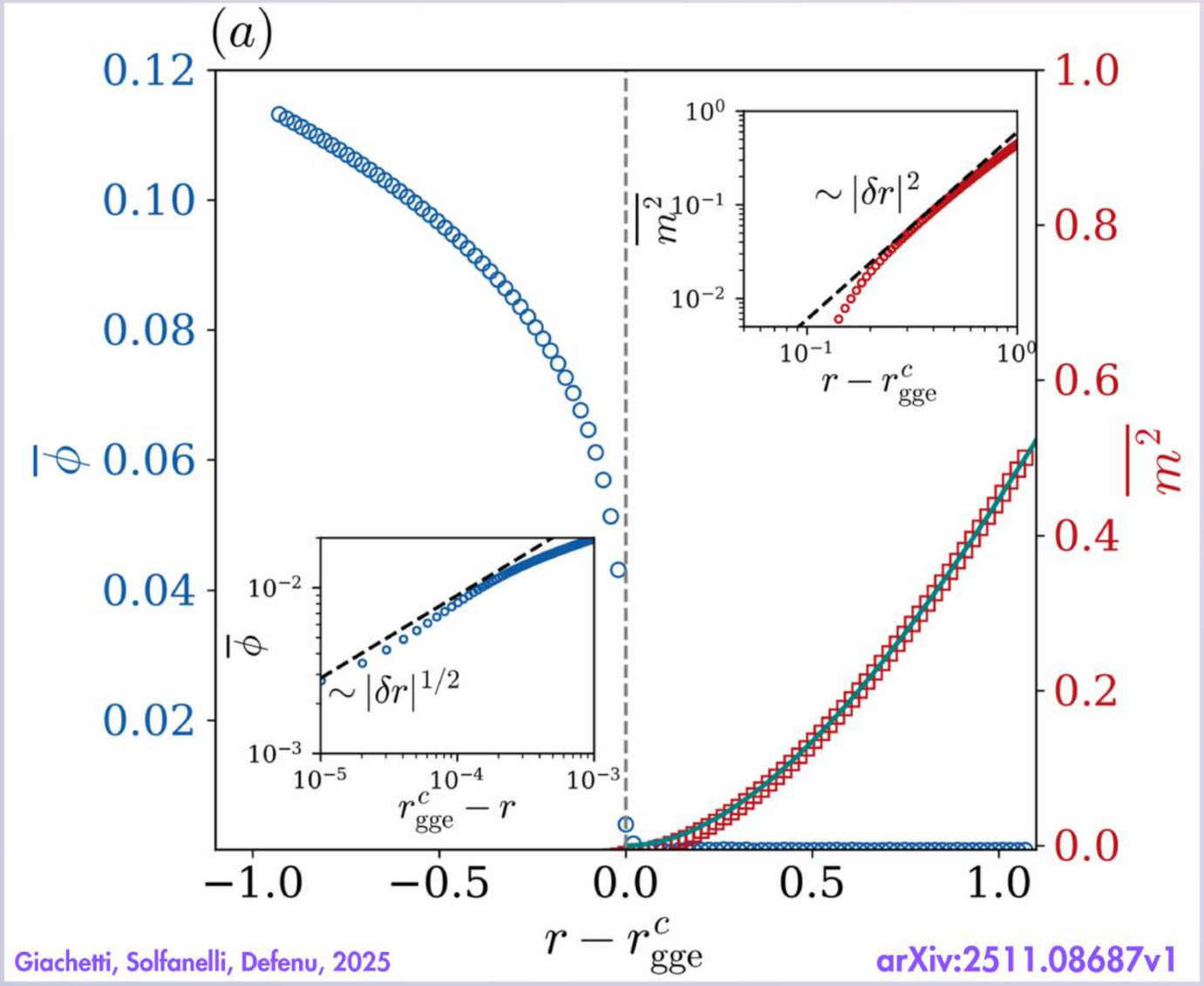

Giachetti, Solfanelli, Defenu, 2025 arXiv:2511.08687v1

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CMQM 01-03rd of July, **2026**

$$G_{\phi\phi}(k,t) = t^{2\alpha+1} f(kt^z)$$

Chandran, Nanduri, Gubser, Sondhi 2013

Maraga, Chiocchetta, Mitra, Gambassi 2015

Chiochetta, Gambassi, Diehl, Marino 2017

$$z=1 \text{ and } \begin{cases} \text{at:} & \alpha=(d-2)/4 \\ \text{bel.:} & \alpha=(d-2)/2 \end{cases}$$

Finite N: Gagel, Orth, Schmalian 2014

N=1 trans. field Ising
N=2 AFM in external field
N = 3 Q. dimer systems
and more...

Entanglement entropy across the dynamical phase transition in the quantum O(N) model

Frederick del Pozo

Lemonik, Mitra 2016

$$\rho_A = e^{-\mathcal{H}_A}/\mathrm{Z}$$
$$S_A = -\mathrm{tr}\left[\rho_A \log\left(\rho_A\right)\right]$$

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Lemonik, Mitra 2016

$$\rho_A = e^{-\mathcal{H}_A}/\mathrm{Z}$$
$$S_A = -\mathrm{tr}\left[\rho_A \log\left(\rho_A\right)\right]$$

$$\rightarrow \quad \mathrm{spec}\left[\mathcal{H}_A\right] = \{\omega_j\}_{j=0,1,\ldots}$$

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$$S \sim (1+n)\log(1+n) - n\log(n) \qquad n = \frac{1}{e^{+\omega}-1}$$

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Entanglement entropy across the dynamical phase transition in the quantum O(N) model

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$$\eta = (\phi, \Pi)$$
$$G \equiv \frac{1}{2}\mathrm{tr}_A\left(\{\eta, \eta^\dagger\}\rho_A\right)$$

Lemonik, Mitra 2016

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$$G \equiv \frac{1}{2}\mathrm{tr}_A\left(\{\eta, \eta^\dagger\}\rho_A\right)$$

$$\mathrm{spec}\left[(iGJ)^2\right] = \{\lambda_j\}_{j=0,1,\ldots}$$

$$n = \lambda - 1/2$$

Lemonik, Mitra 2016

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$$\mathrm{spec}\left[\mathcal{H}_A\right] = \{\omega_j\}_{j=0,1,\ldots}$$

$$\omega = \log\left(\frac{n+1}{n}\right)$$

$$n = \lambda - 1/2 \quad \Rightarrow \quad S \sim (1+n)\log(1+n) - n\log(n) \quad \Leftarrow \quad n = \frac{1}{e^{+\omega} - 1}$$

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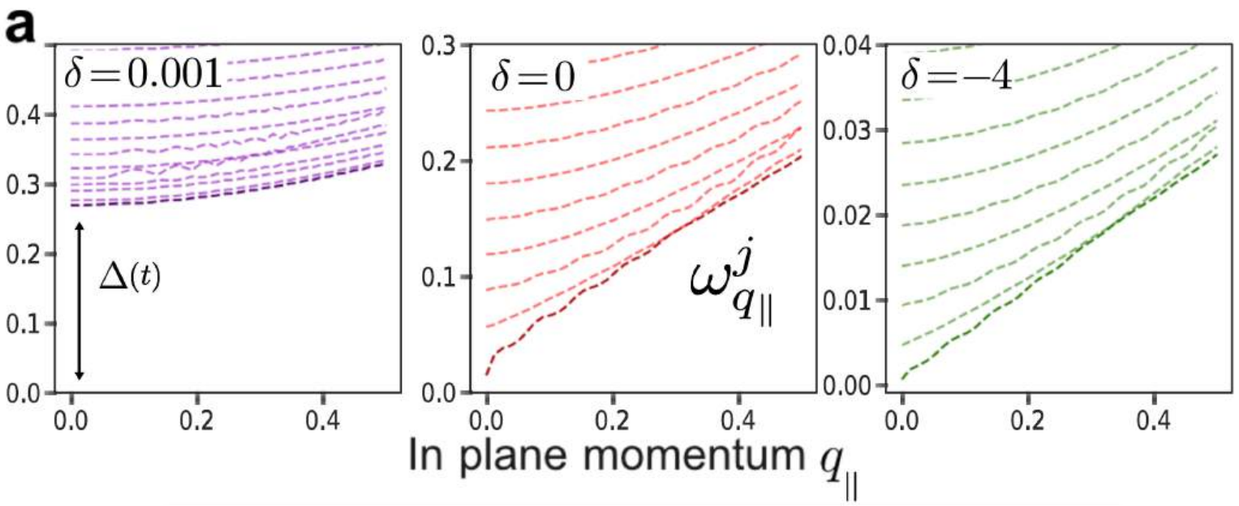
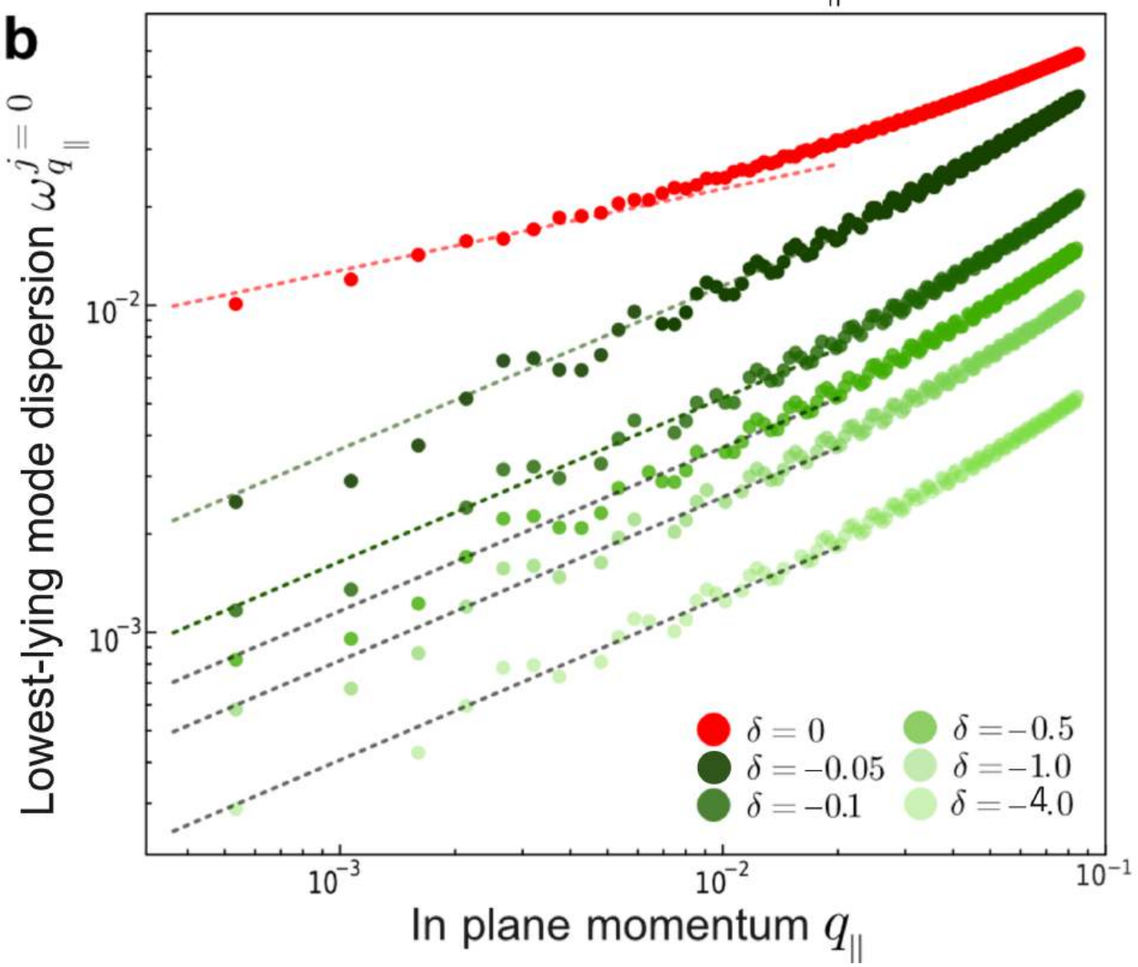
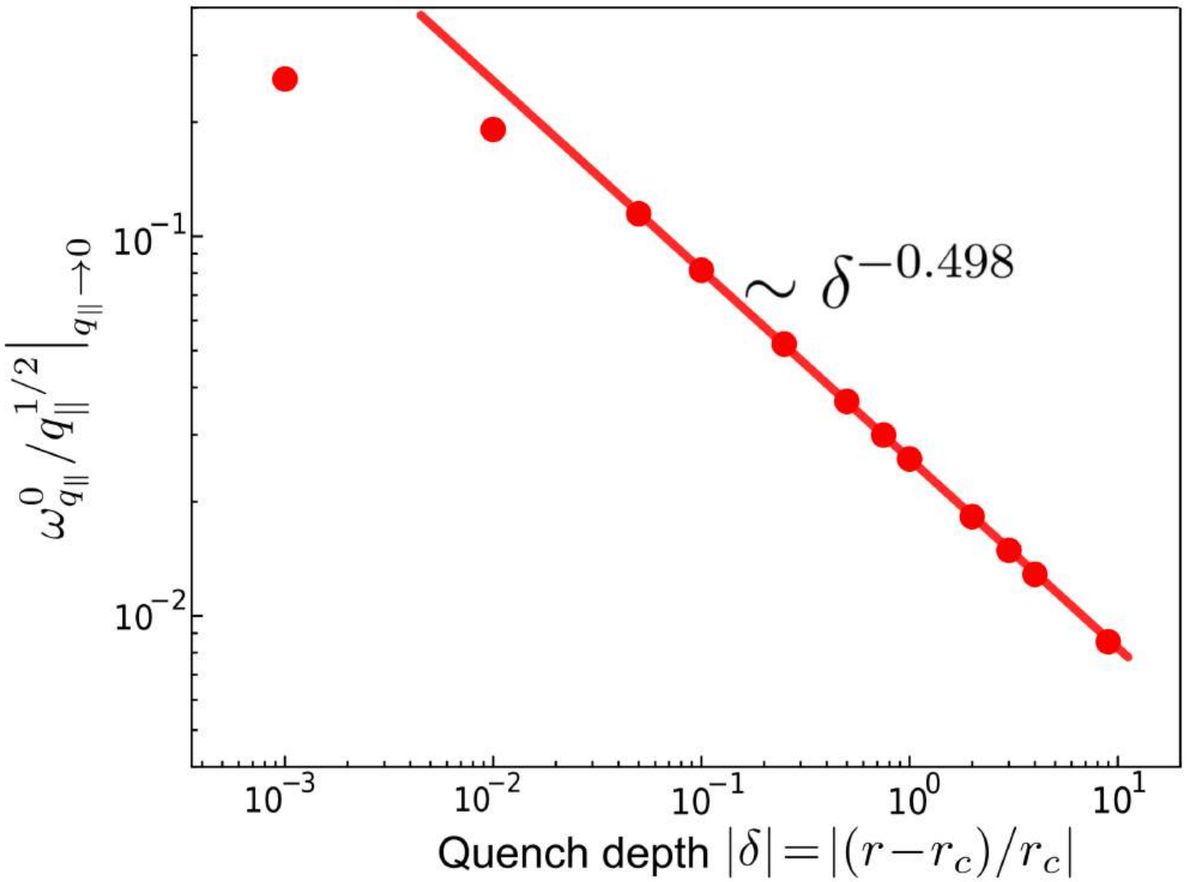
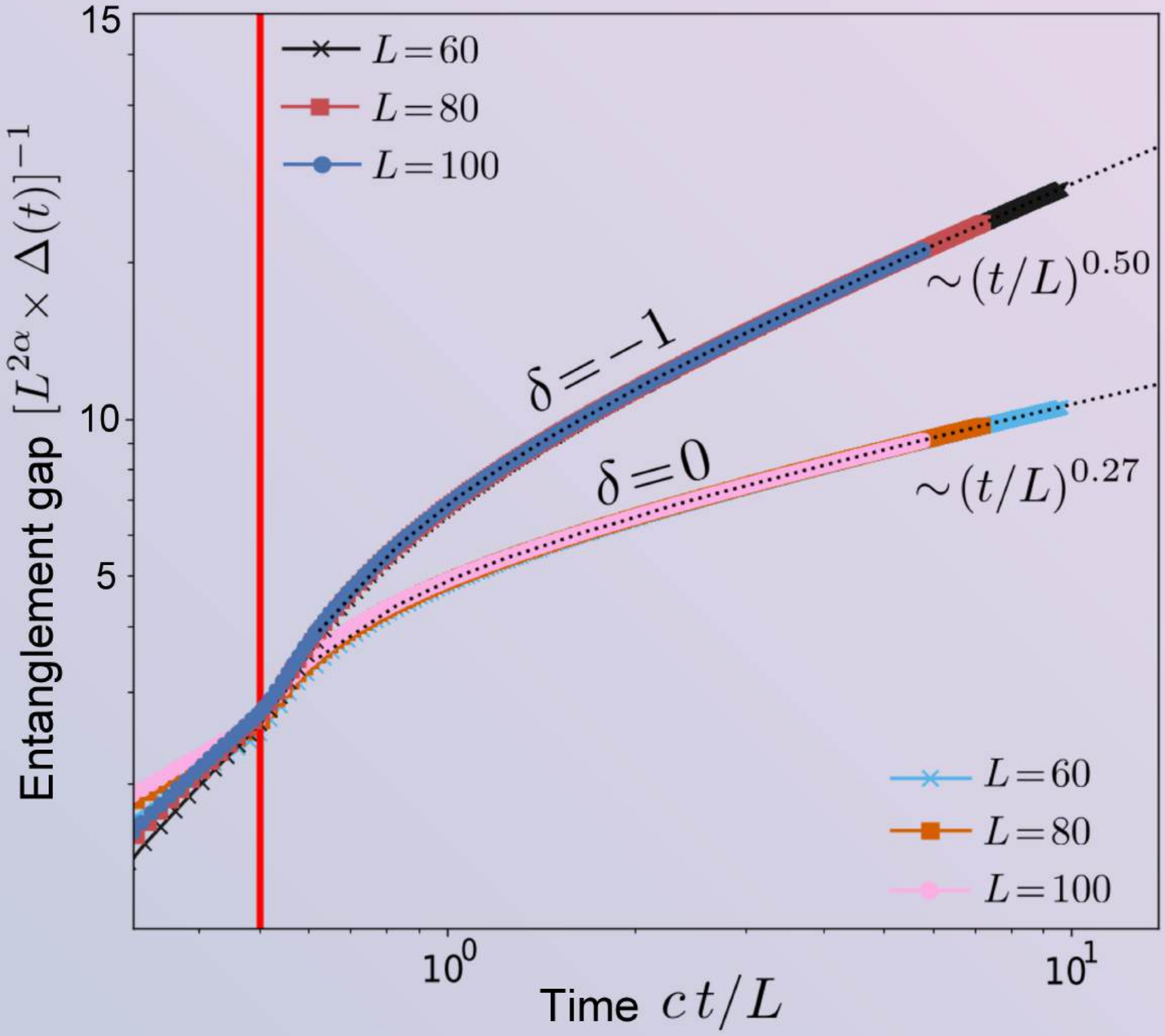

a
$\delta = 0.001$
$\Delta(t)$
$\delta = 0$
$\omega^j_{q_\parallel}$
$\delta = -4$
In plane momentum $q_\parallel$


b
Lowest-lying mode dispersion $\omega^{j=0}_{q_\parallel}$
$\delta = 0$
$\delta = -0.05$
$\delta = -0.1$
$\delta = -0.5$
$\delta = -1.0$
$\delta = -4.0$
In plane momentum $q_\parallel$


$\omega^0_{q_\parallel}/q^{1/2}_\parallel\Big|_{q_\parallel\to 0}$
$\sim \delta^{-0.498}$
Quench depth $|\delta| = |(r - r_c)/r_c|$


15
10
5
$L=60$
$L=80$
$L=100$
$\delta=-1$
$\delta=0$
$\sim(t/L)^{0.50}$
$\sim(t/L)^{0.27}$
Entanglement gap $[L^{2\alpha}\times\Delta(t)]^{-1}$
10^0
10^1
Time ct/L