Mean-field validity in a dissipative spin model

“Mean-field validity in a dissipative critical system:
Liouvillian gap, PT-symmetric antigap,
and permutational symmetry in the XYZ model”

https://arxiv.org/abs/1912.07570

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** RIKEN, Japan

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RIKEN, Saitama, Japan

AQM – 4th Meeting
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Milan, Italy

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日本学術振興会 Japan Society for the Promotion of Science

JST Japan Science and Technology Agency

fwo

VLAAMS SUPERCOMPUTER CENTRUM Vlaanderen is supercomputing

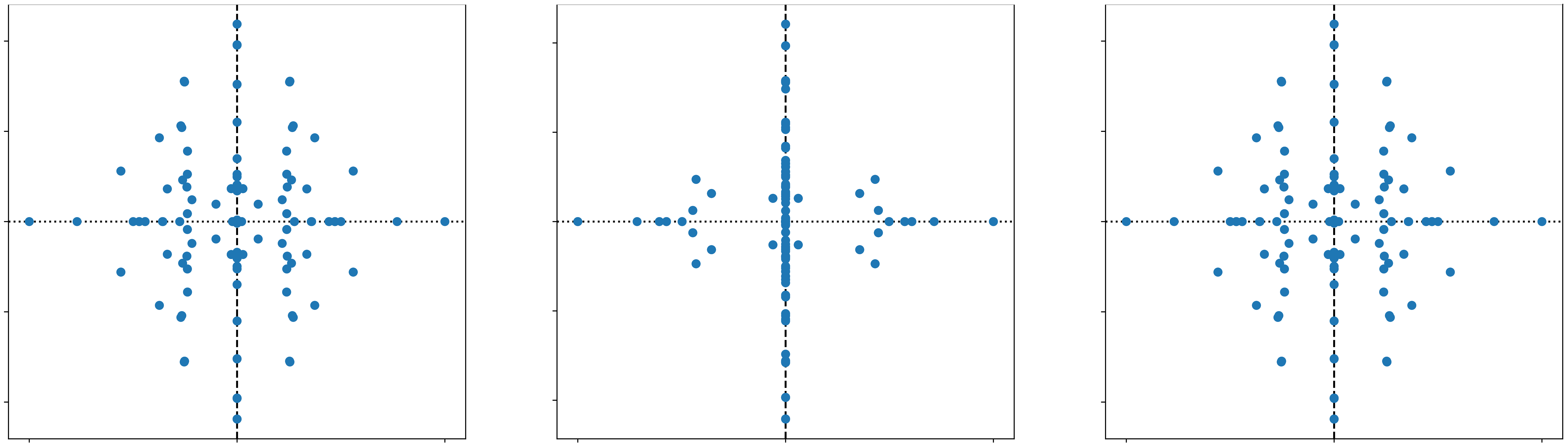
NTT Research

Outline

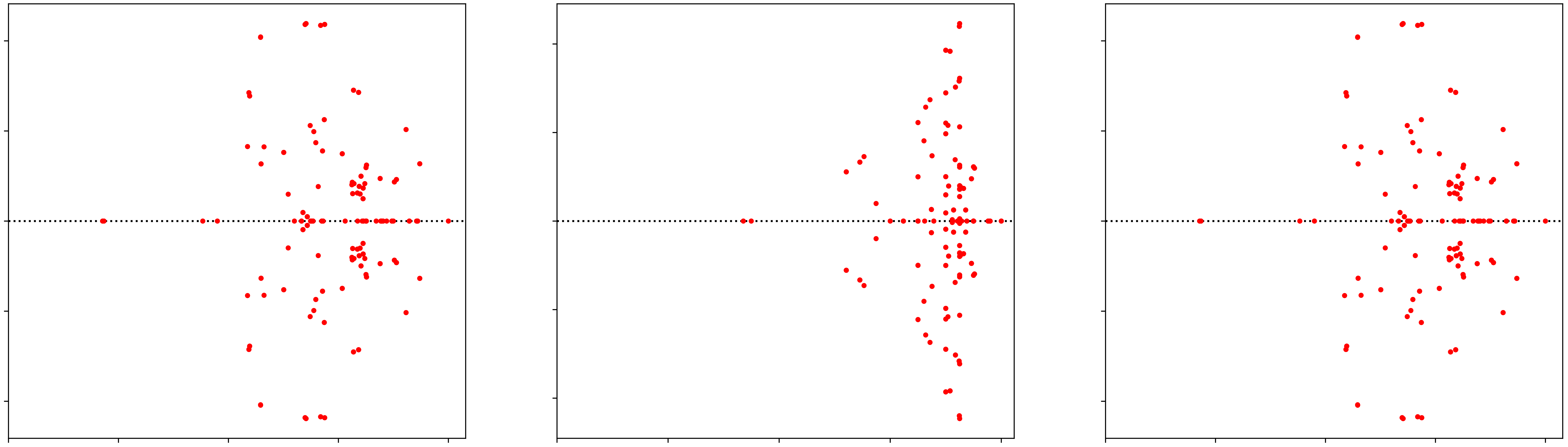
This talk

- **Introduction: code + physics**
- **XYZ model study** (most of the talk)
- **QuTiP updates**

Rorschach Test for Quantum Opticians



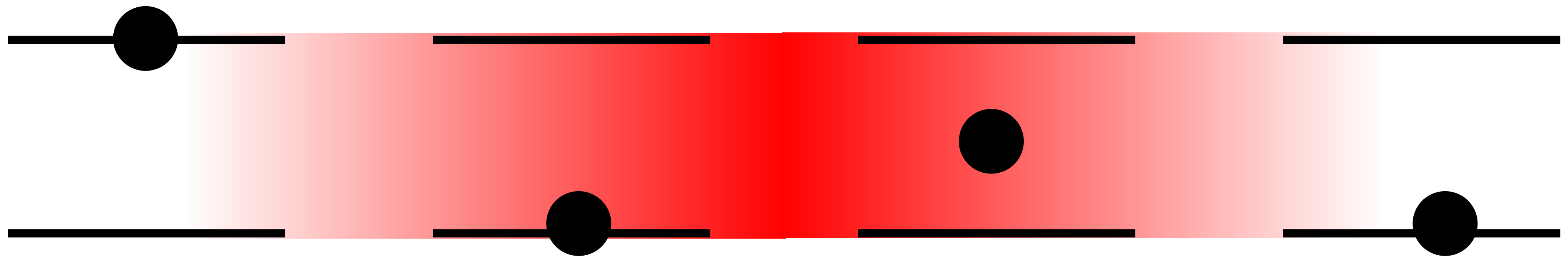
What do you see?



My research

Studying and enabling cooperative processes

Cooperative phenomena in quantum physics
– A common thread of my research interests

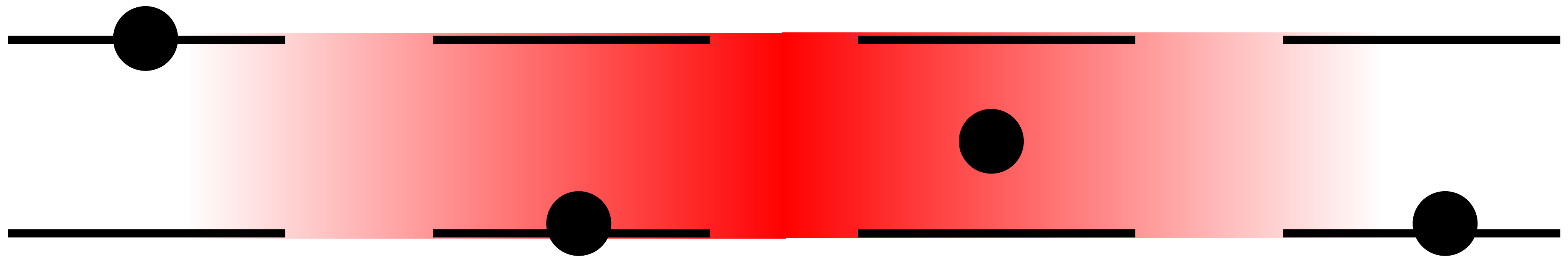


Cooperative behavior in scientific research
– My engagement with quantum open-source development

My research

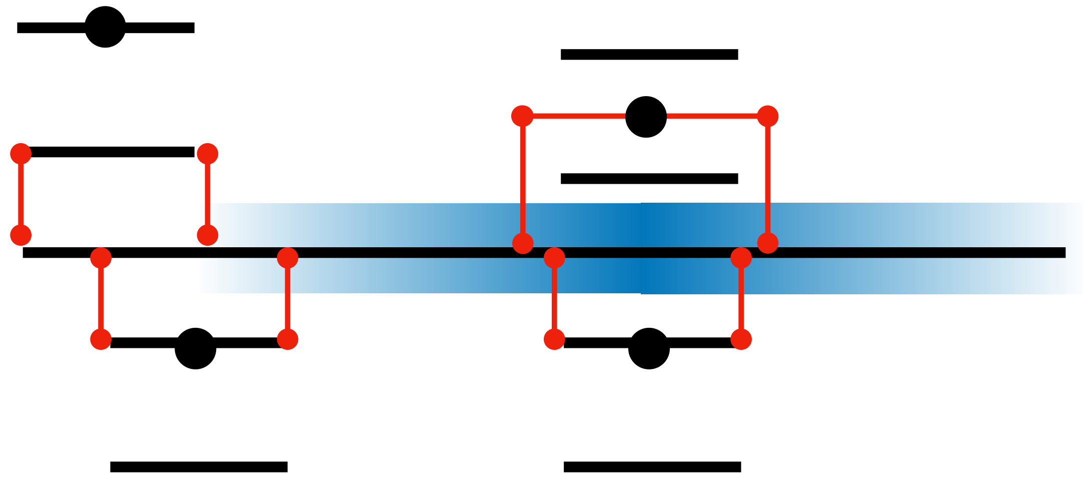
Studying and enabling cooperative processes

Cooperative phenomena in quantum physics
– A common thread of my research interests



Intersubband Transitions
Polaritons

Giant Artificial Atoms

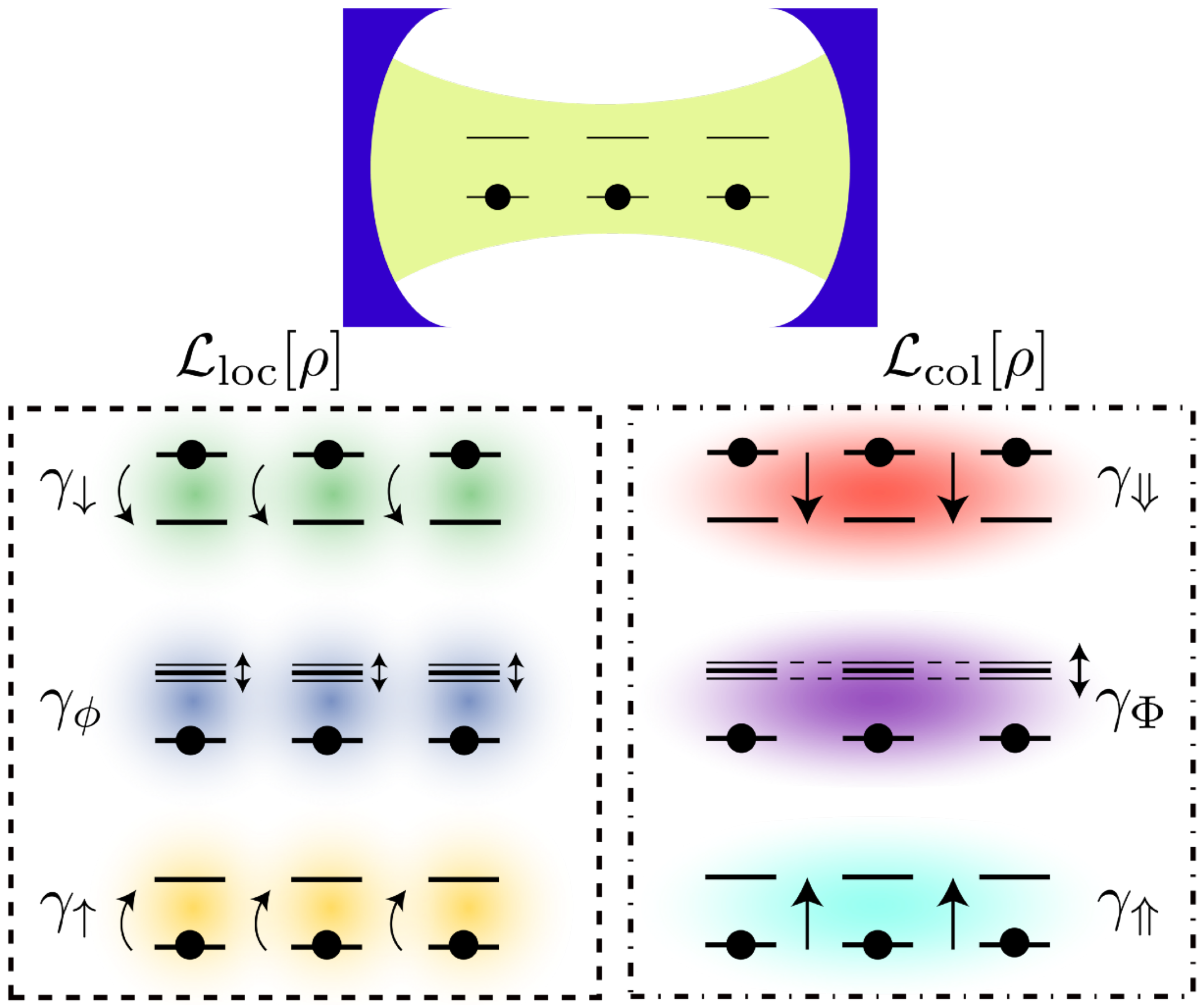


Two-Level Systems
Spins

PIQS: Driven-dissipative two-level system ensembles

The Permutational Invariant Quantum Solver

$$i\hbar\frac{d}{dt}\rho = [H,\rho] + \gamma_\alpha \sum_i^N \mathscr{D}_{L_i}[\rho]$$



$L_i = \hat{\sigma}_i^-$ $\qquad L_i = \sum_i^N \hat{\sigma}_i^-$

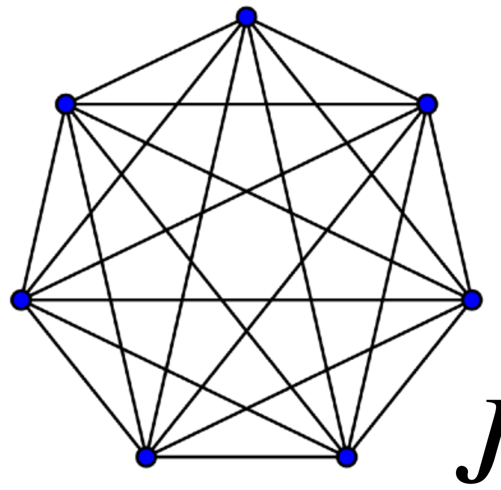
$L_i = \hat{\sigma}_i^z$ $\qquad L_i = \sum_i^N \hat{\sigma}_i^z$

$L_i = \hat{\sigma}_i^+$ $\qquad L_i = \sum_i^N \hat{\sigma}_i^+$

N. Shammah, S Ahmed, N. Lambert, S. De Liberato and F. Nori,
Phys Rev A **98**, 063815 (2018)

Code: Nathan Shammah and Shahnawaz Ahmed

Hamiltonian



$$\hat{H} = \sum_{i,j} J_i^\alpha J_j^\beta \hat{\sigma}_i^\alpha \hat{\sigma}_j^\alpha$$

$$J_i^\alpha \equiv J^\alpha \ \forall i$$

Lindblad dissipation

$$\mathscr{D}_{L_i}[\rho] = L_i\rho L_i^\dagger - \frac{1}{2}(L_i^\dagger L_i\rho + \rho L_i^\dagger L_i)$$

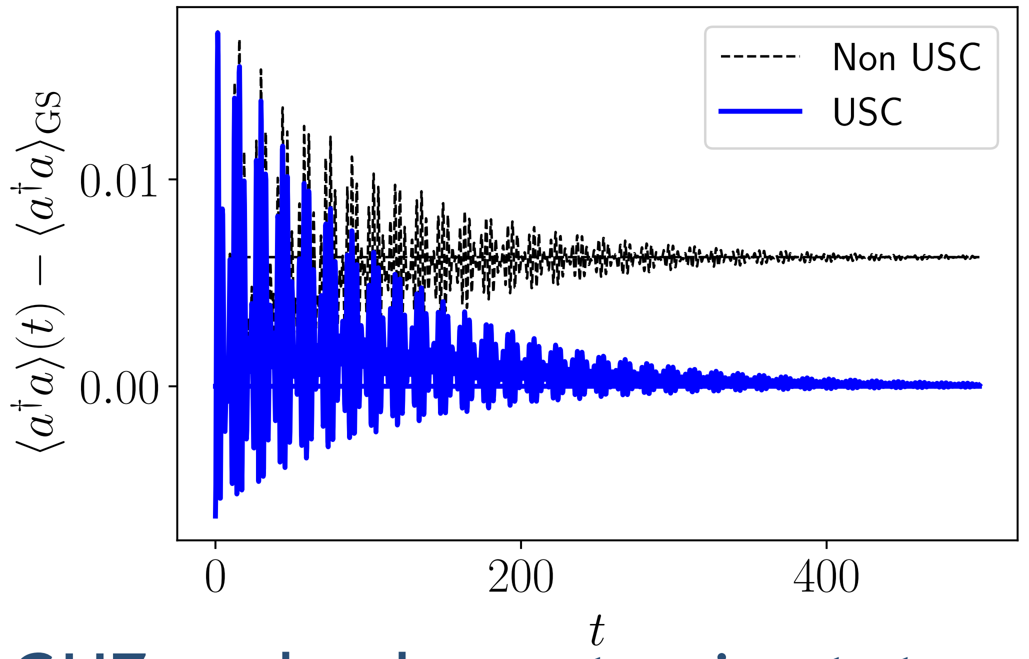
PIQS: Driven-dissipative two-level system ensembles

The Permutational Invariant Quantum Solver

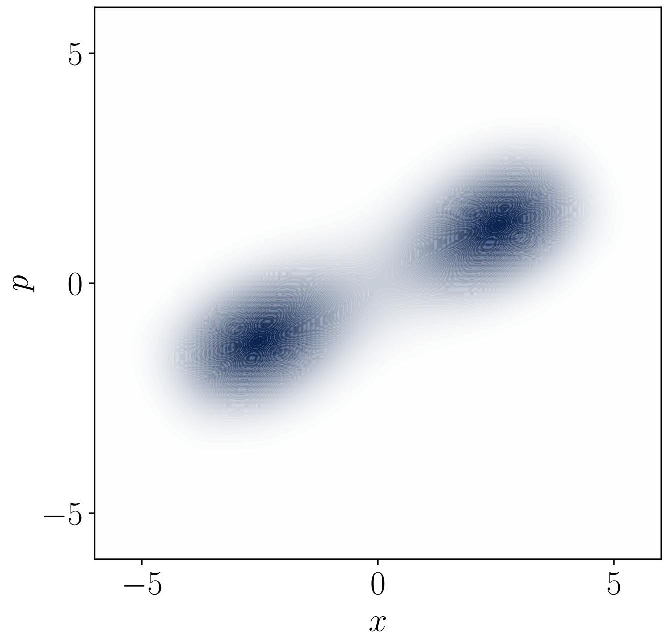
$$i\hbar\frac{d}{dt}\rho = [H,\rho] + \gamma_\alpha \sum_i^N \mathscr{D}_{L_i}[\rho]$$

PRA 98, 063815 (2018)

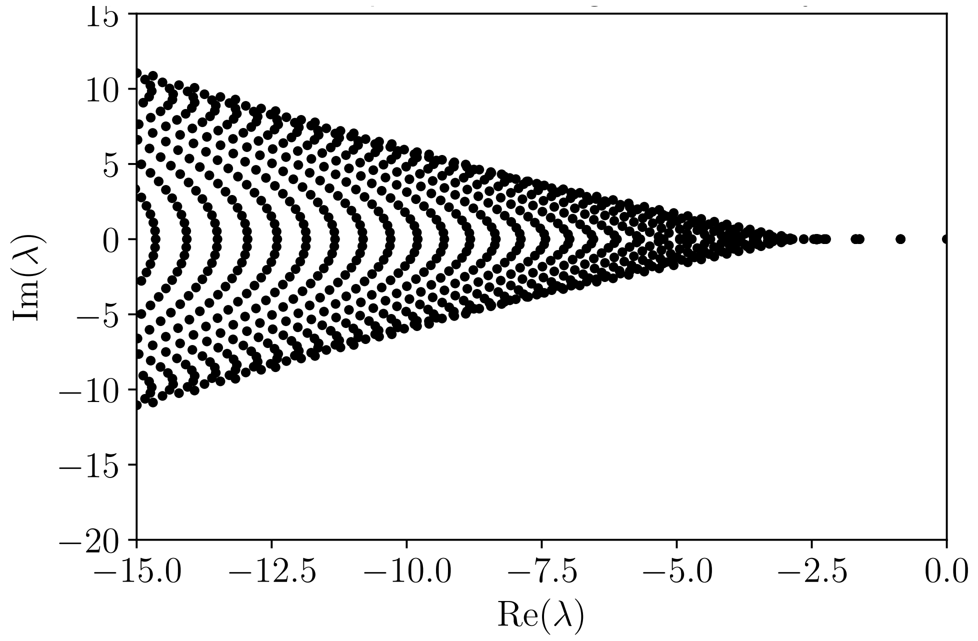
Ultrastrong Coupling (USC)



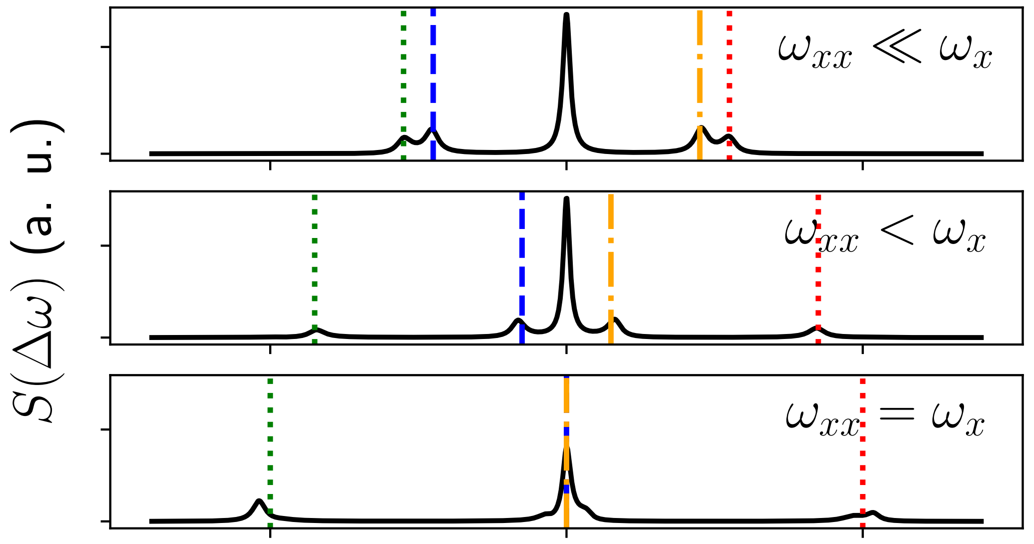
Superradiant PT



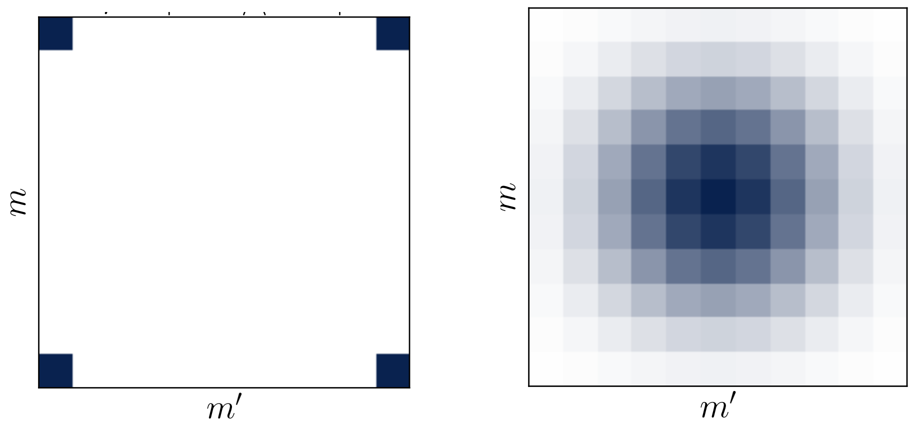
Boundary Time Crystals



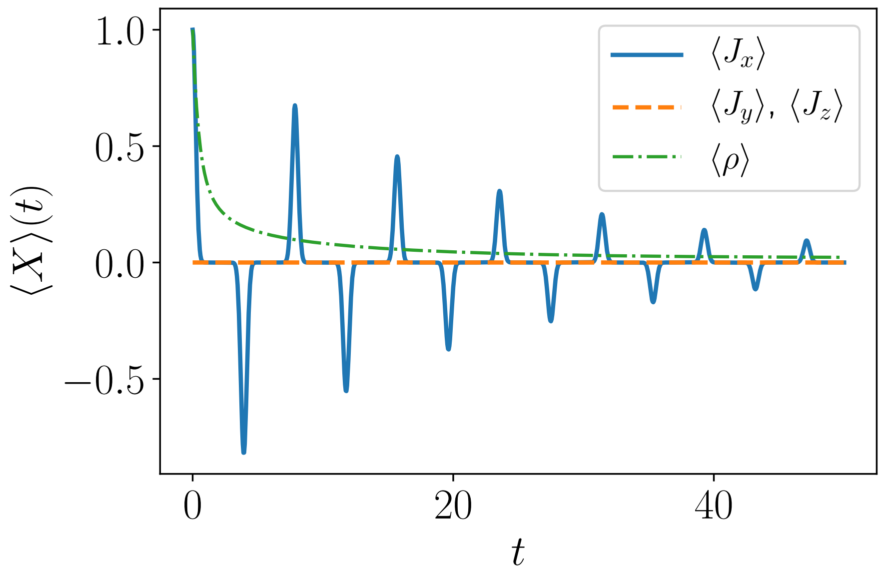
Resonance Fluorescence



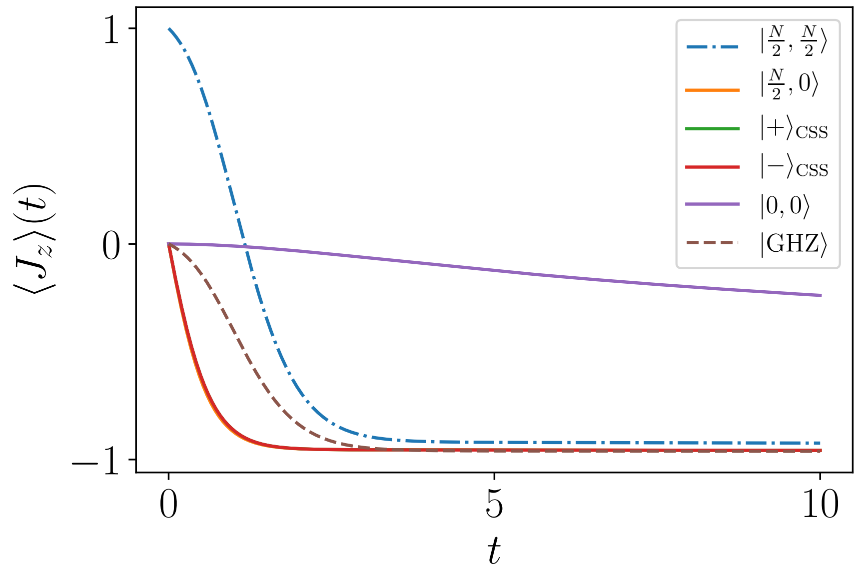
GHZ and coherent spin states



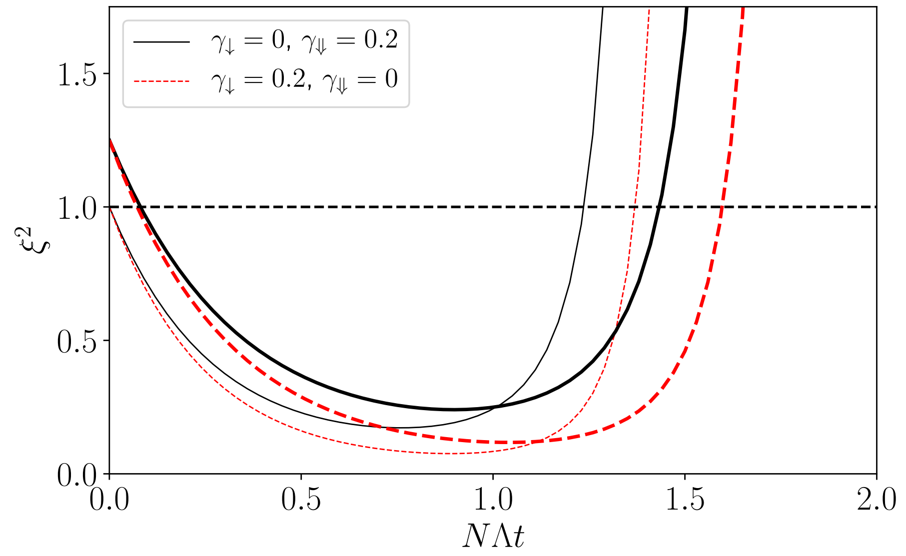
Noisy Heisenberg Model



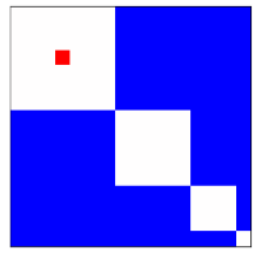
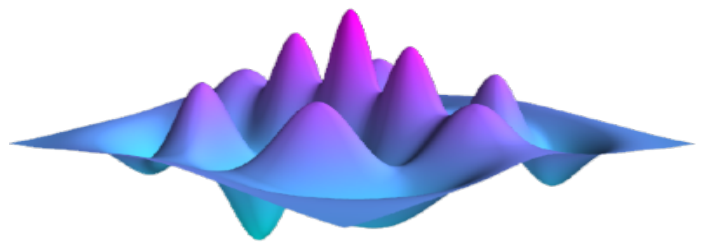
Dicke Superradiance



Spin Squeezing



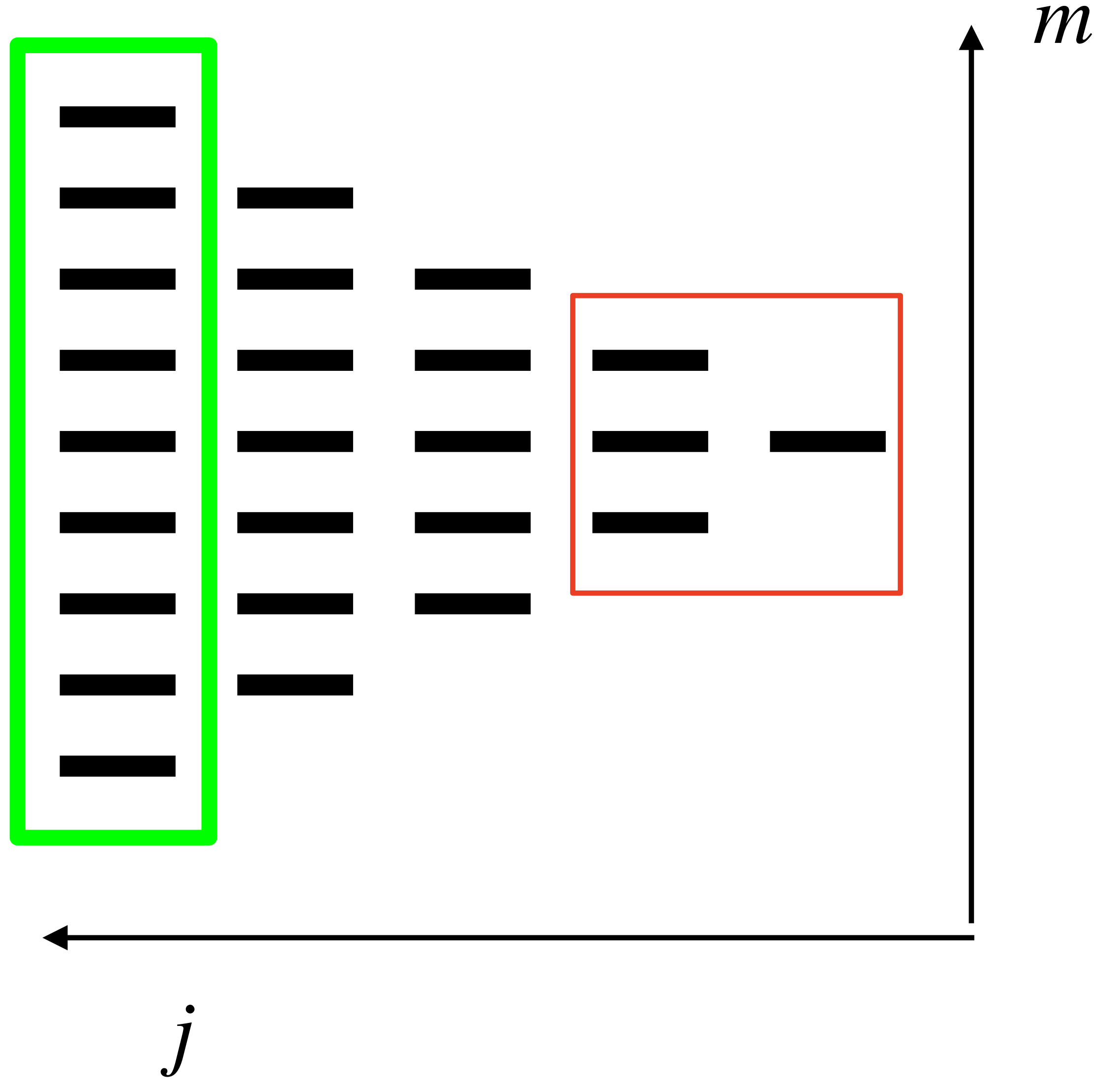
N. Shammah, S. Ahmed, N. Lambert, S. De Liberato, and F. Nori, PRA 98, 063815 (2018) arXiv:1805.05129

 +  = **import** qutip.piqs

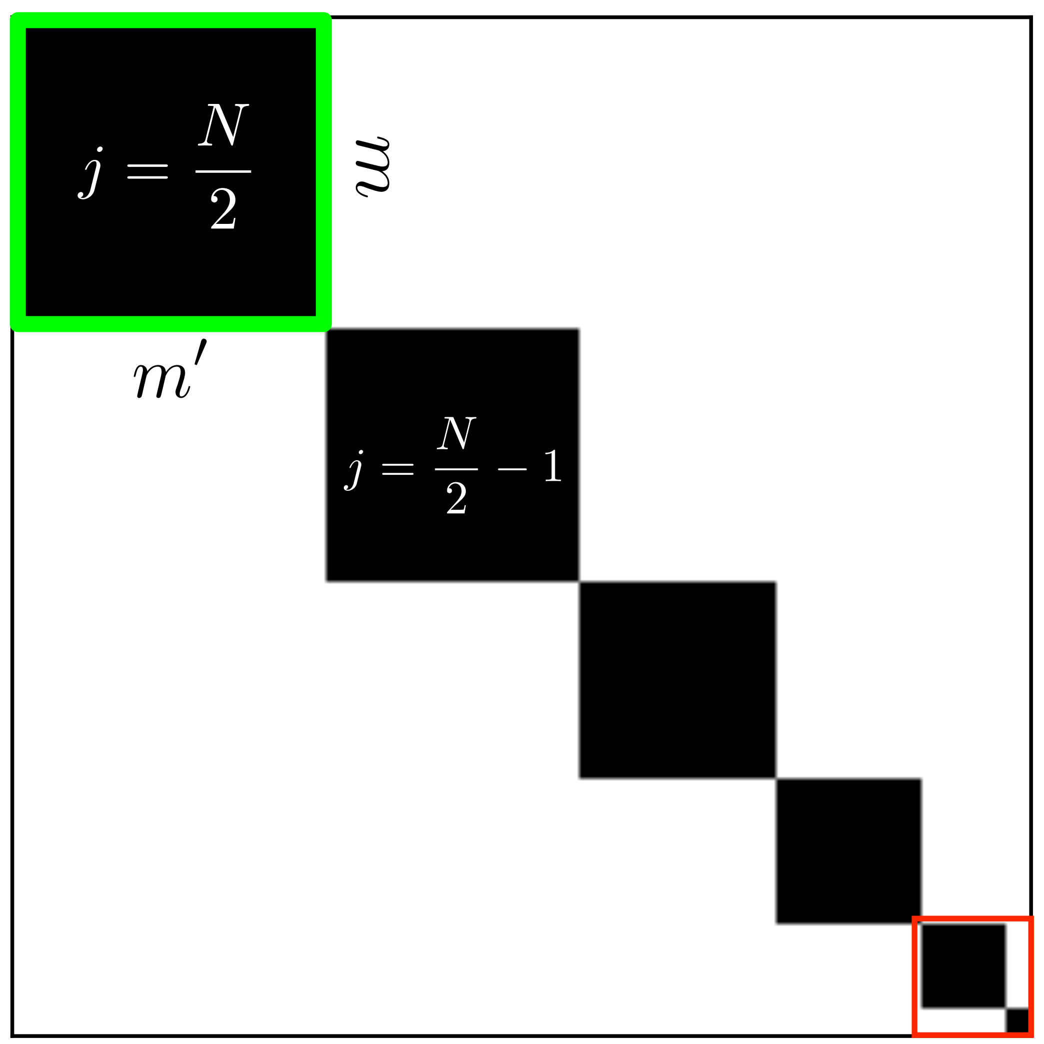
Permutational symmetric method in the Dicke space

Homogeneous local dissipation can be included in the dynamical model

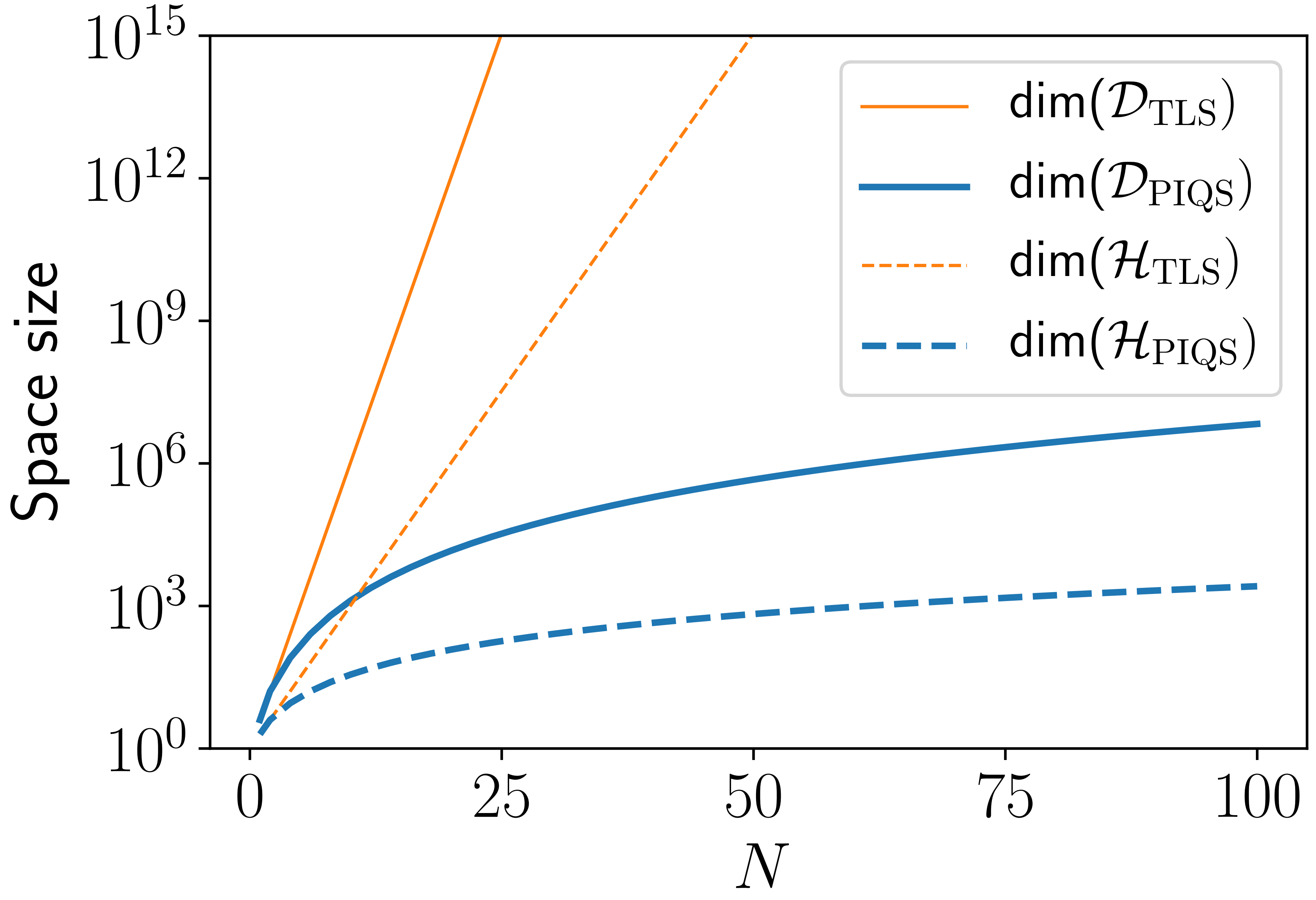
Dicke space visualization



Block-Diagonal Density Matrix



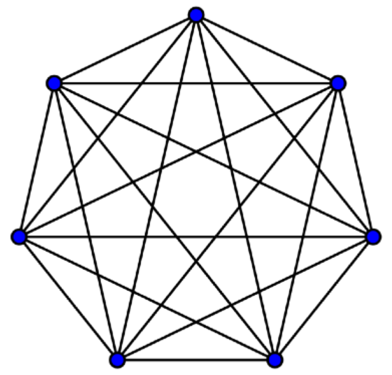
Exponential Space Reduction



Number of Dicke States

$$n_{\mathrm{DS}}(N) = \sum_{j=0}^{N/2}(2j+1) = \left(\frac{N}{2}+1\right)^2$$

B. A. Chase and J. M. Geremia, Phys. Rev. A **78**, 052101 (2008)
F. Damanet, D. Braun, and J. Martin, Rev. A **94**, 033838 (2016)
N. Shammah et al. Phys. Rev. A (2017)



Hamiltonian
Collective spin operators only
Complete graph (fully connected).
Constant edges weight: no lattice distance.

Dissipation
Homogeneous local couplings.

$$i\hbar\frac{d}{dt}\rho = [H,\rho] + \gamma_\alpha \sum_i^N \mathscr{D}_{L_i}[\rho]$$

States
Limited to identical qubit states.

N. Shammah, S. Ahmed, N. Lambert, S. De Liberato, and F. Nori, PRA 98, 063815 (2018) arXiv:1805.05129

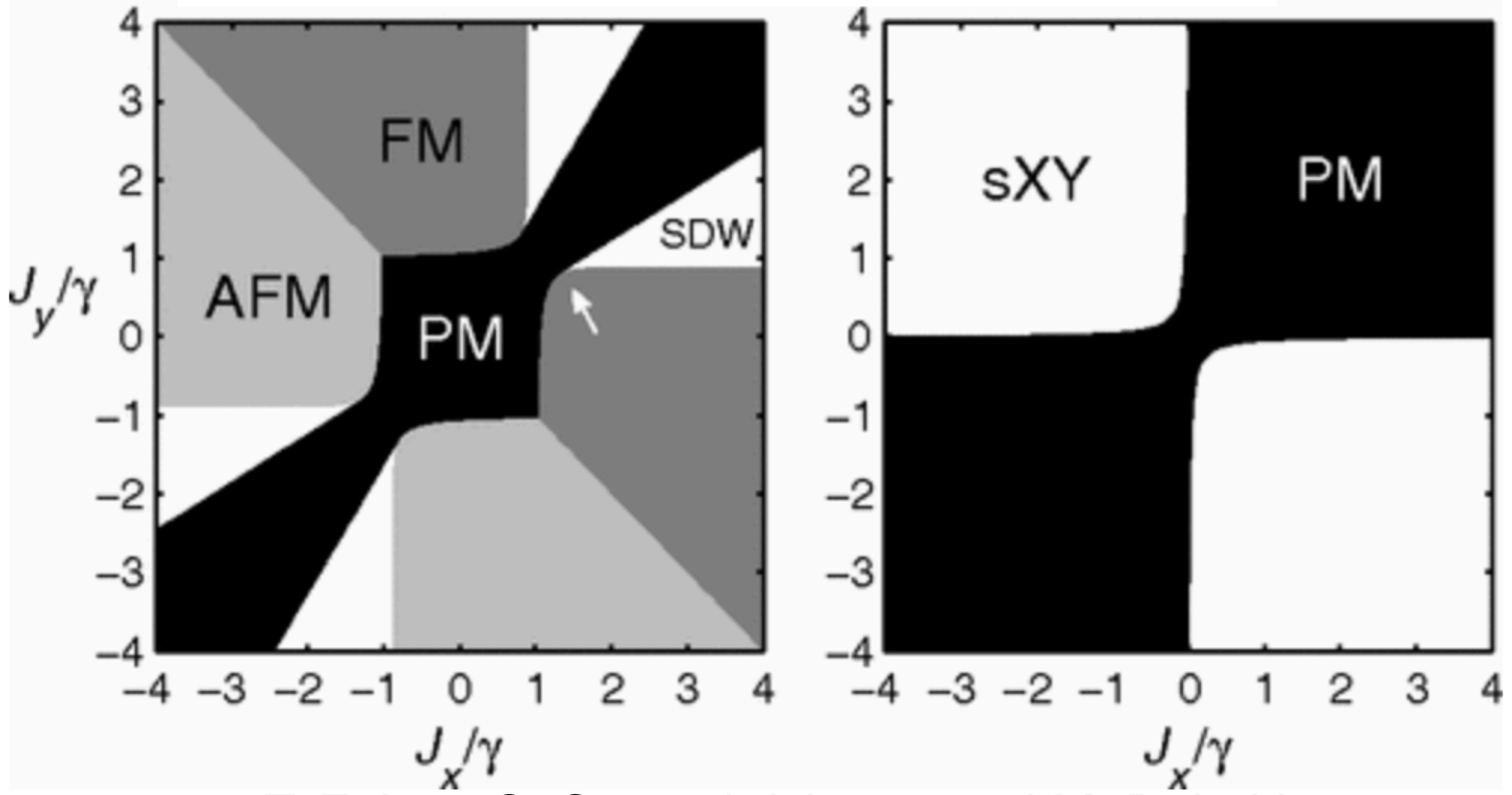
XYZ spin Model: Benchmark for Mean Field (MF)

$$\hat{H} = \frac{1}{Z}\sum_{\langle i,j\rangle}\left(J_x\hat{\sigma}_i^x\hat{\sigma}_j^x + J_y\hat{\sigma}_i^y\hat{\sigma}_i^y + J_z\hat{\sigma}_i^z\hat{\sigma}_j^z\right) \qquad \frac{\partial\hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H},\hat{\rho}(t)\right] + \gamma\sum_{j=1}^{N}\mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t)$$

AFM: Antiferromagnetic; PM: Paramagnetic; FM: Ferromagnetic

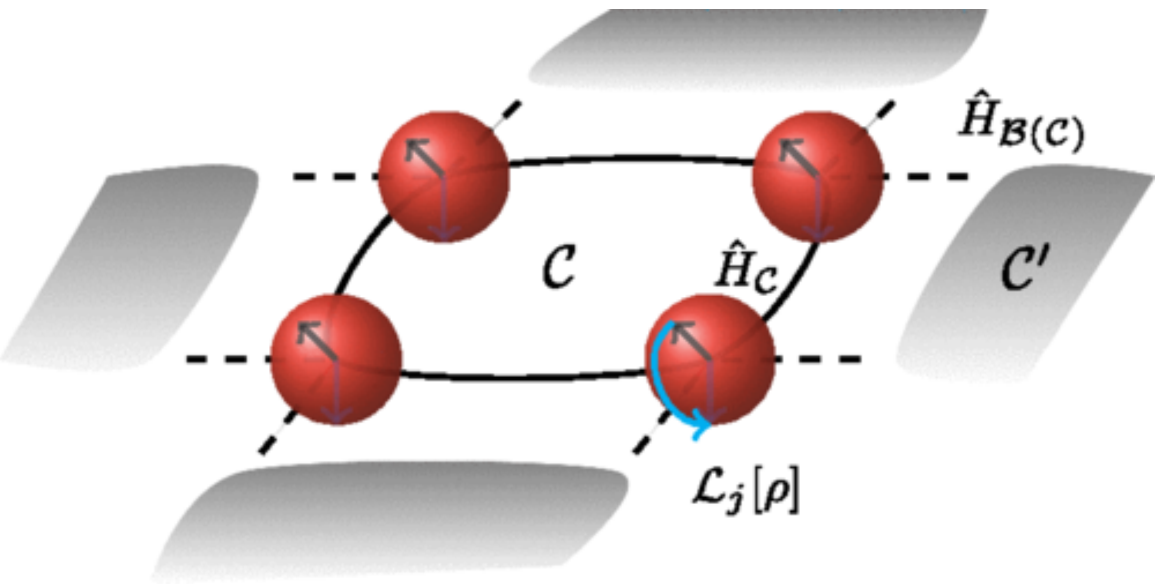
Gutzwiller MF

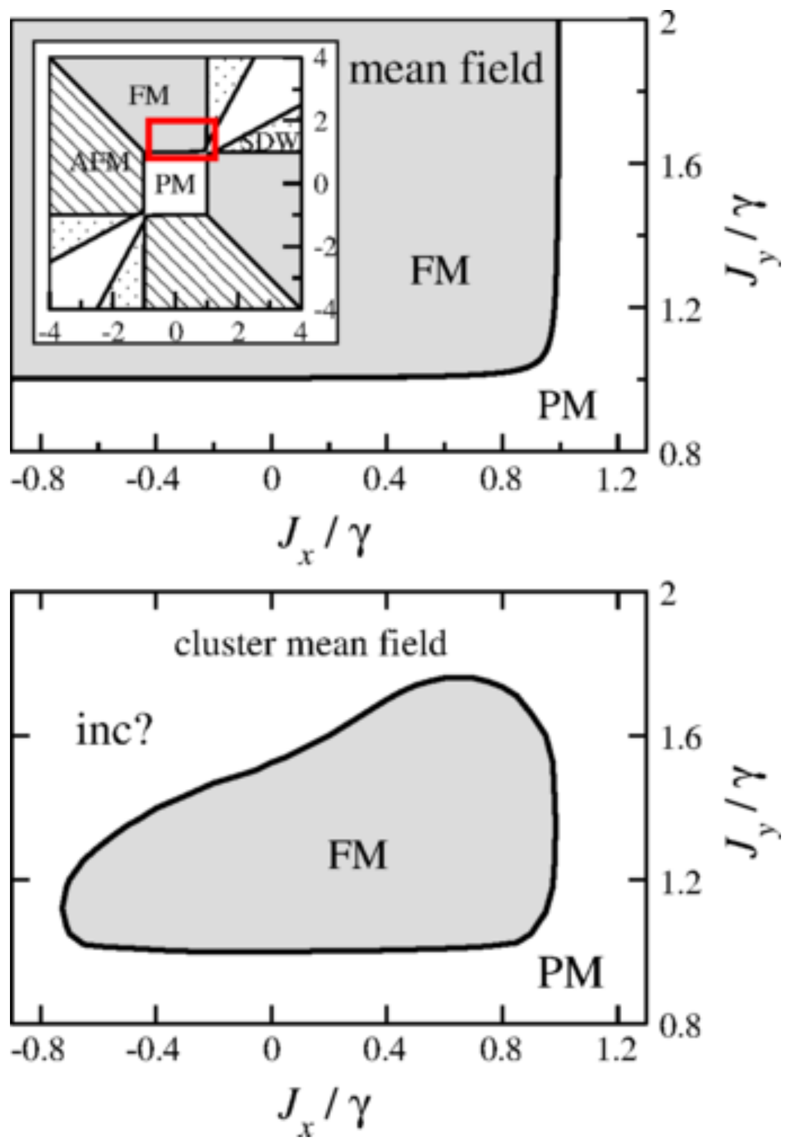
Local Dissipation: AFM phase



T. E. Lee, S. Gopalakrishnan, and M. D. Lukin
Phys. Rev. Lett. **110**, 257204 (2013)

Cluster MF



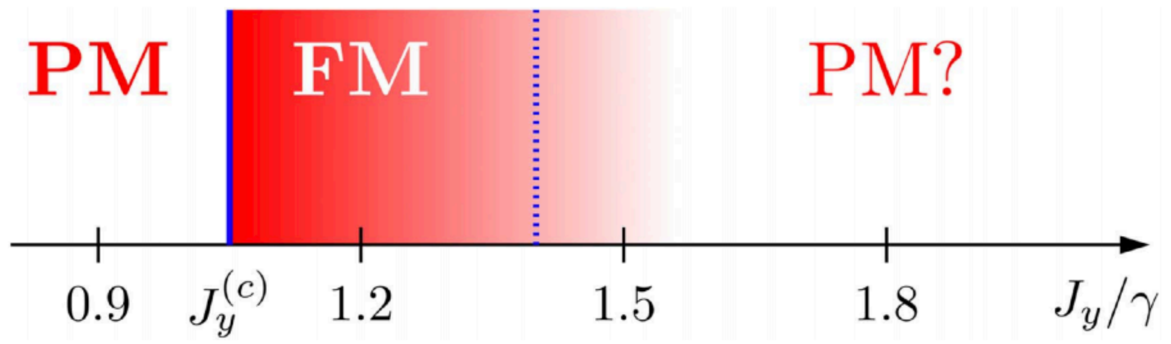


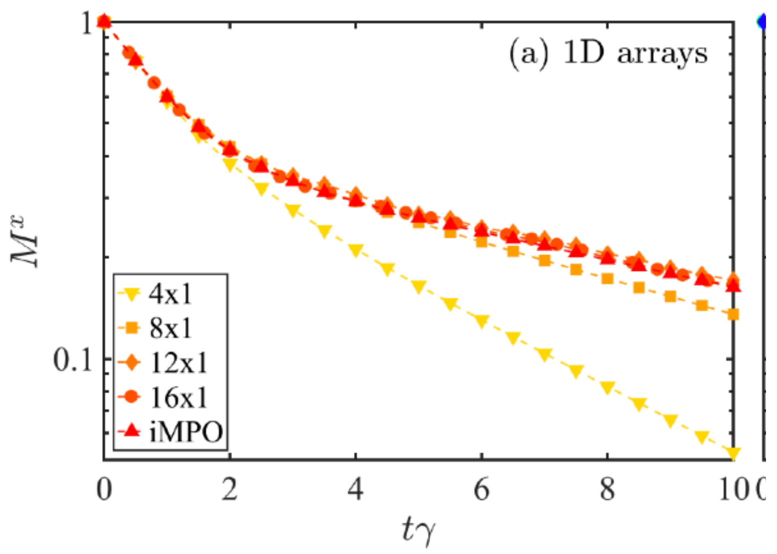
J. Jin,…, and D. Rossini,
Phys.Rev.X **6**, 031011 (2016)

Cluster MF

Quantum Trajectories

Corner Space

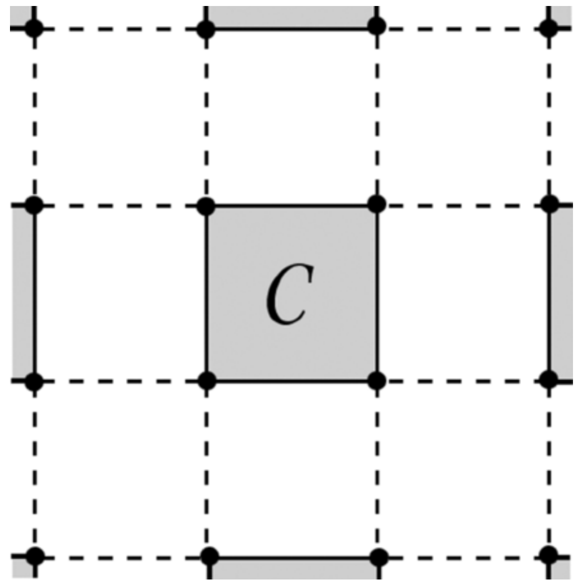


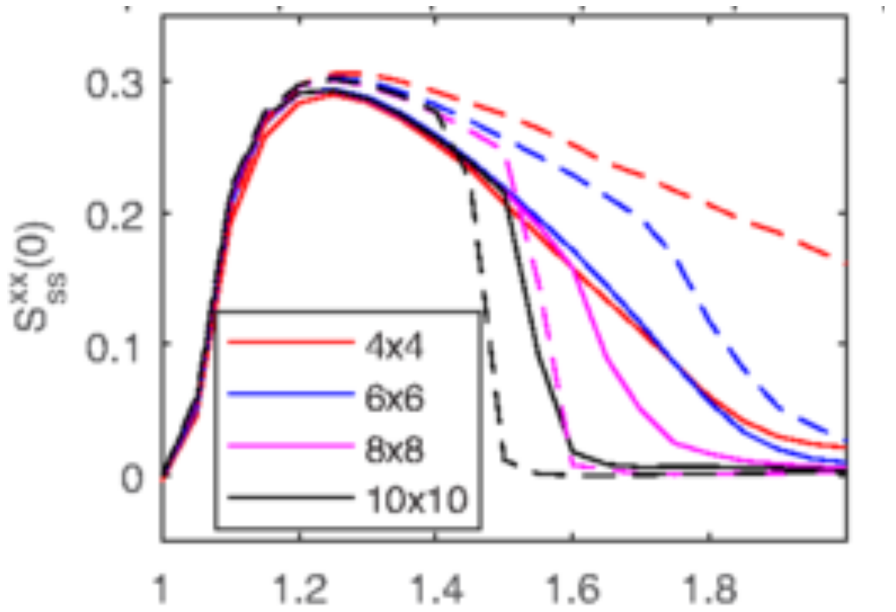


R. Rota, …, and C. Ciuti,
Phys. Rev. B **95**, 134431 (2017).

R. Rota, F. Minganti, A. Biella, and C. Ciuti
New J. Phys. **20** 045003 (2018)

Gutzwiller Montecarlo





D. Huybrechts and M. Wouters,
Phys. Rev. A **99**, 043841 (2019)

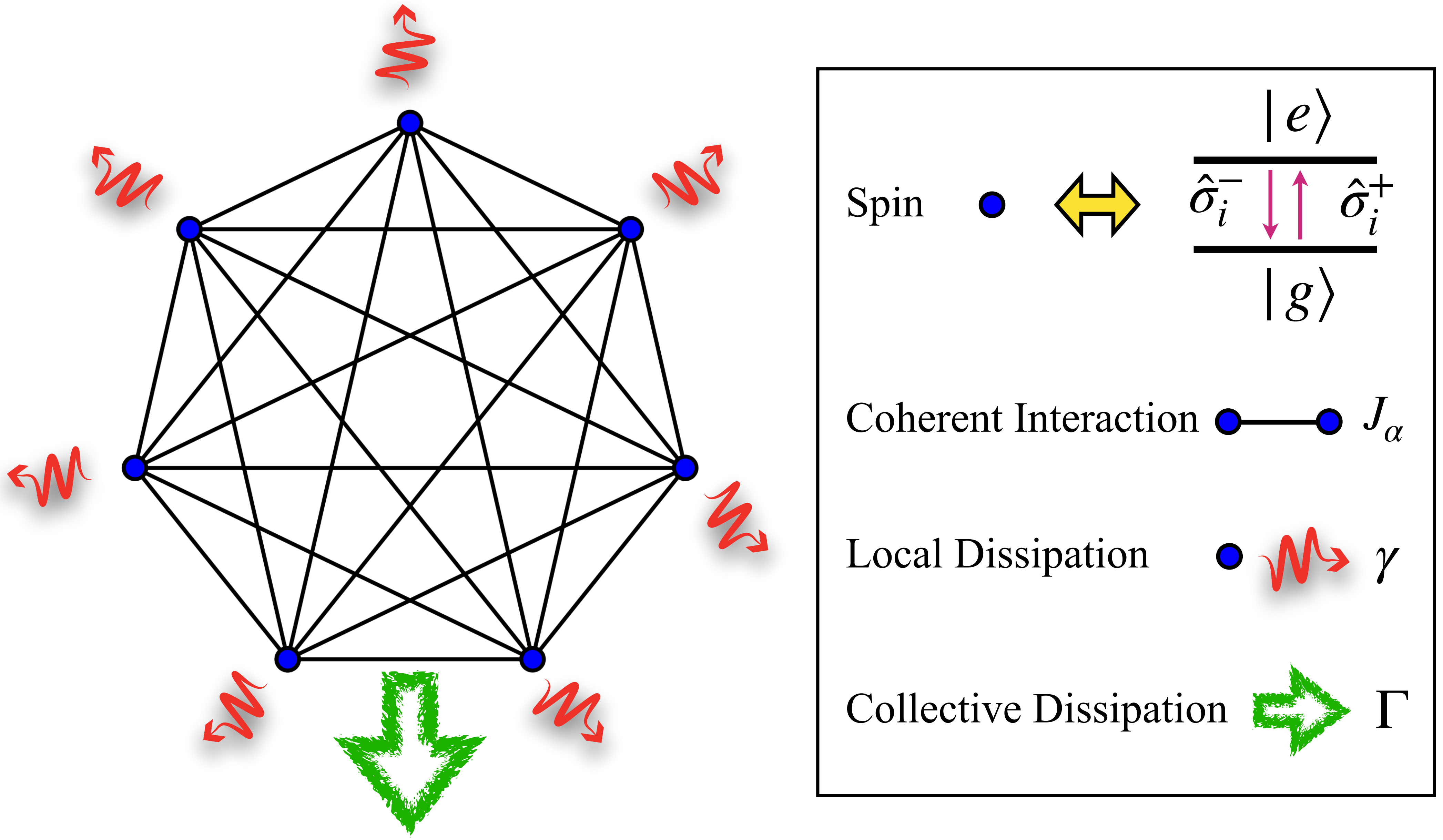
W. Casteels, R. M. Wilson, and M. Wouters,
Phys. Rev. A **97**, 062107 (2018)

A study of the dissipative Heisenberg model

XYZ model

$$\hat{H} = \frac{1}{Z}\sum_{\langle i,j\rangle}\left(J_x\hat{\sigma}_i^x\hat{\sigma}_j^x + J_y\hat{\sigma}_i^y\hat{\sigma}_i^y + J_z\hat{\sigma}_i^z\hat{\sigma}_j^z\right) \rightarrow \hat{H} = \frac{1}{2(N-1)}\left[J_x\left(\hat{S}^x\right)^2 + J_y\left(\hat{S}^y\right)^2 + J_z\left(\hat{S}^z\right)^2\right] \quad \hat{S}^z = \sum_i^N \hat{\sigma}_z$$

$$\frac{\partial\hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H},\hat{\rho}(t)\right] + \gamma\sum_{j=1}^{N}\mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t) + \frac{\Gamma}{N-1}\mathscr{D}[\sum_{j=1}^{N}\hat{\sigma}_j^-]\hat{\rho}(t)$$



- Anisotropic *XYZ* model
- All-to-all connection
- Local dissipation
- Local and collective dissipation

$$\mathscr{D}[A]\cdot = A\cdot A^\dagger - \frac{1}{2}\left(A^\dagger A\cdot + \cdot A^\dagger A\right)$$

Local vs. collective dissipation: Superradiant Systems

$$\frac{\partial \hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H}, \hat{\rho}(t)\right] + \gamma \sum_{j=1}^{N} \mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t) + \frac{\Gamma}{N-1}\mathscr{D}[\sum_{j=1}^{N} \hat{\sigma}_j^-]\hat{\rho}(t)$$

Local **Collective**

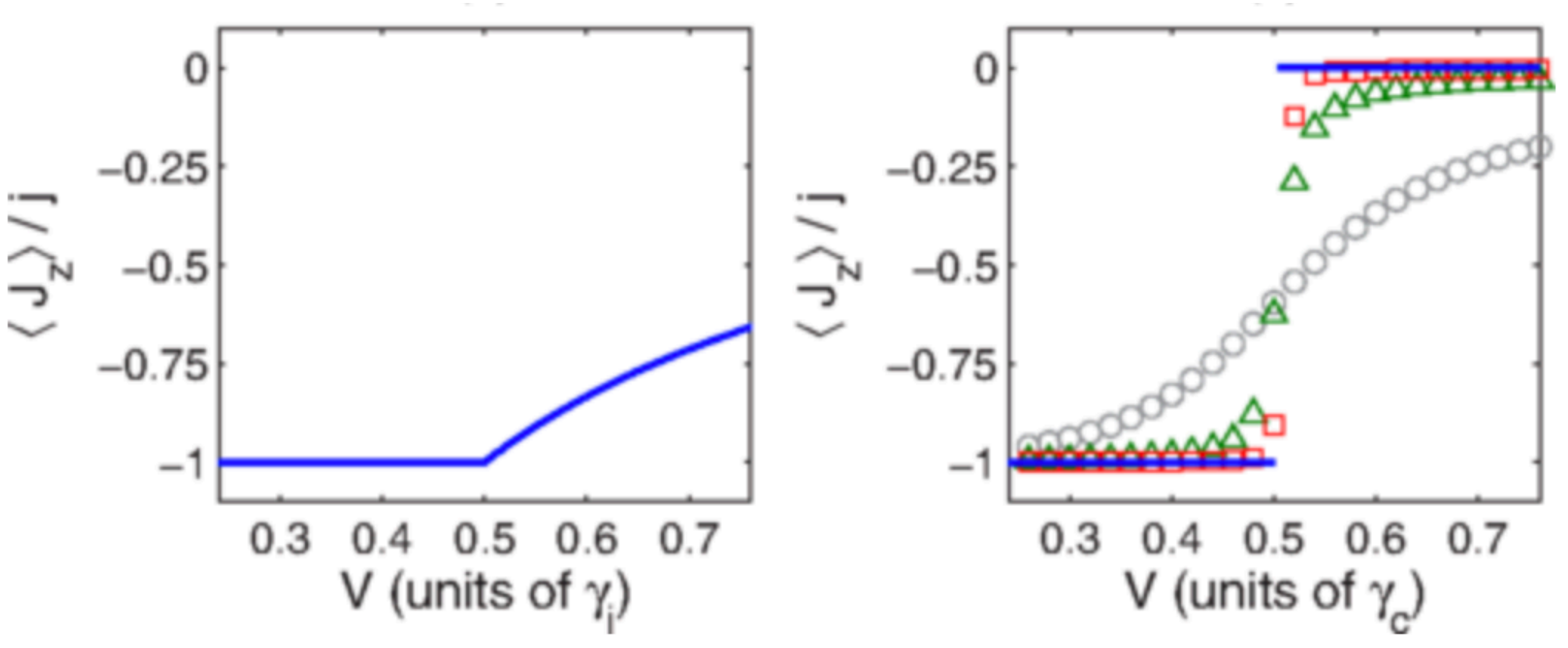
$$S^- = \sum_i \hat{\sigma}_i^-$$

$$\hat{H} = \frac{1}{Z}\sum_{i,j}\left(J_x\hat{\sigma}_i^x\hat{\sigma}_j^x + J_y\hat{\sigma}_i^y\hat{\sigma}_i^y + J_z\hat{\sigma}_i^z\hat{\sigma}_j^z\right)$$

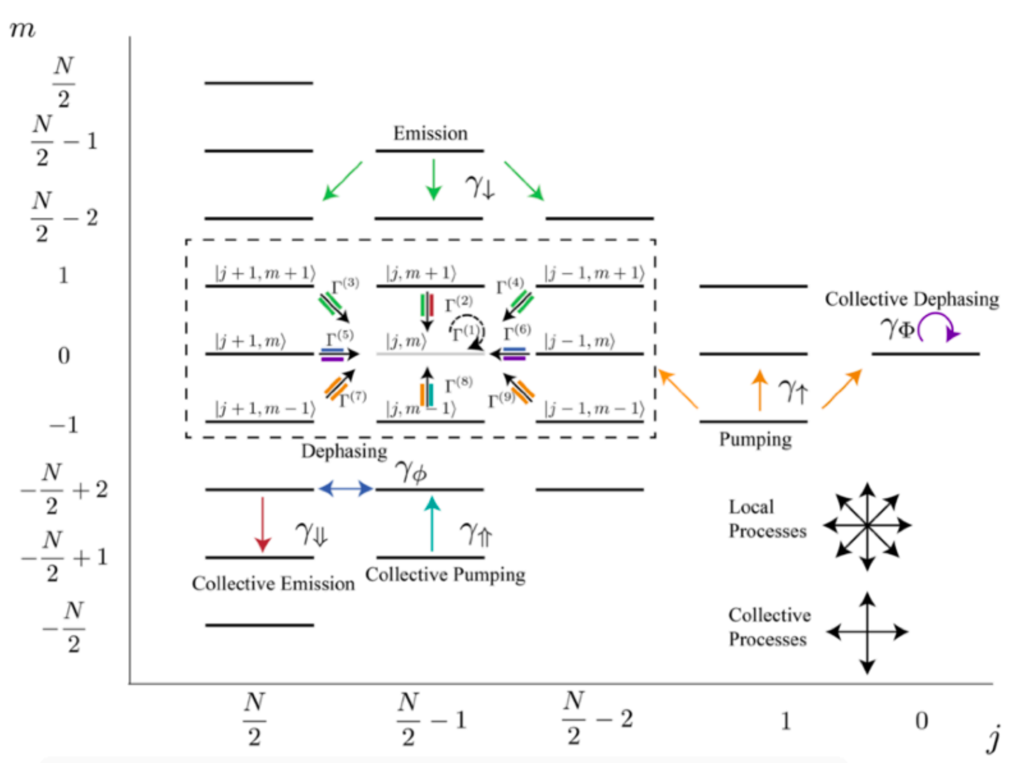
$$\hat{H} = \frac{1}{Z}\sum_i J_z\hat{\sigma}_i^z$$

2nd Order Phase Tr. **1st Order Phase Tr.** **Superradiant Systems (Transient)**

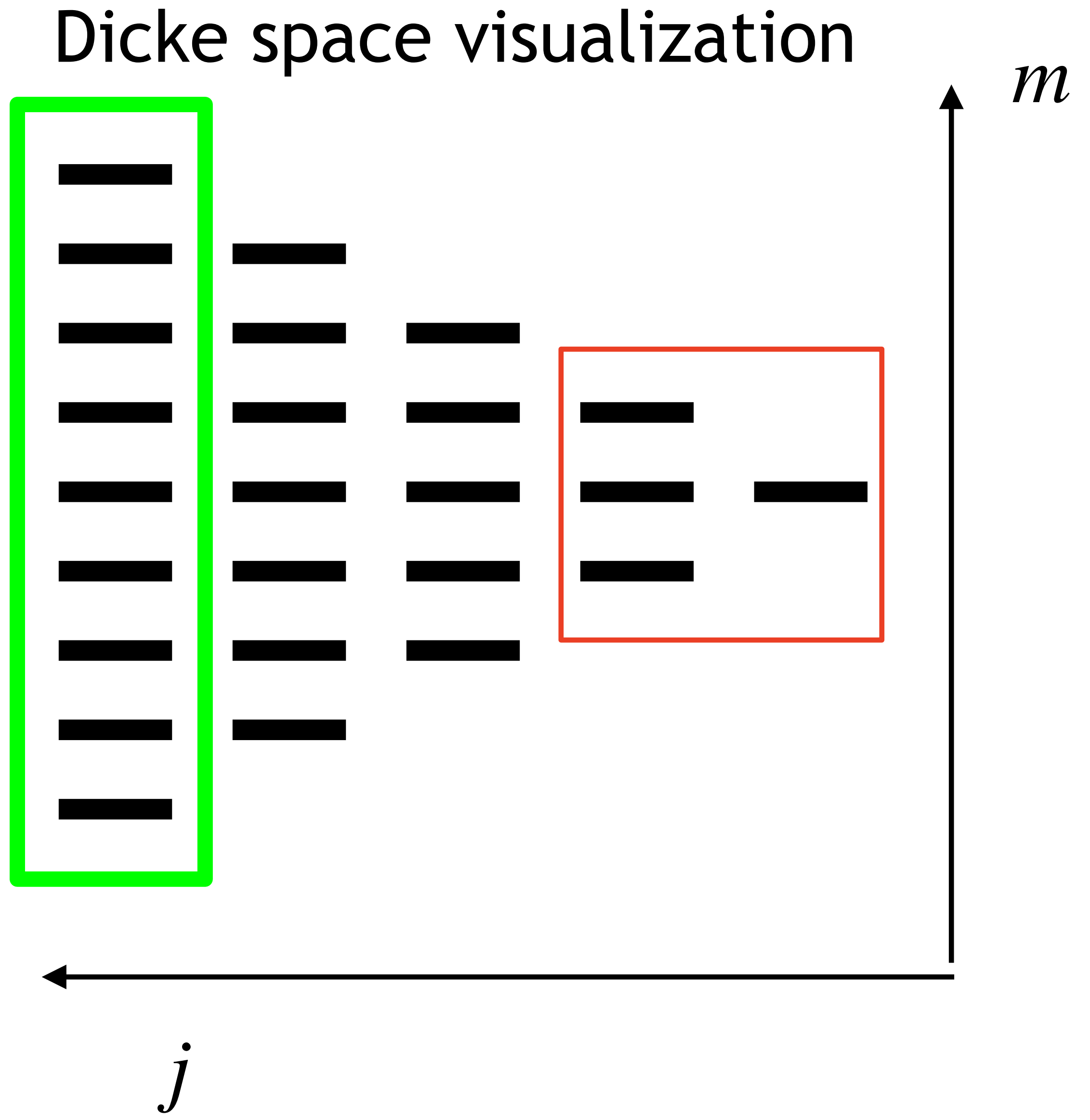
Local Dissipation **Collective Dissipation**



T. E. Lee, C.-K. Chan, and S. F. Yelin
Phys. Rev. A **90**, 052109 (2014)



N. Shammah, …., and S. De Liberato
Phys. Rev. A **96**, 023863 (2017)
N. Shammah, …., and F. Nori
Phys. Rev. A **98**, 06385 (2018)



Collective Dissipation $[\hat{H}, \hat{S}^2] = 0,\ [\hat{S}^-, \hat{S}^2] = 0$ **Spin length is conserved**

Local Dissipation $[\hat{H}, \hat{S}^2] = 0,\ [\hat{\sigma}_i^-, \hat{S}^2] \neq 0$ **Spin length is not conserved**

Local vs. collective dissipation: Superradiant Systems

$$\frac{\partial\hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H},\hat{\rho}(t)\right] + \gamma\sum_{j=1}^{N}\mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t) + \frac{\Gamma}{N-1}\mathscr{D}[\sum_{j=1}^{N}\hat{\sigma}_j^-]\hat{\rho}(t)$$

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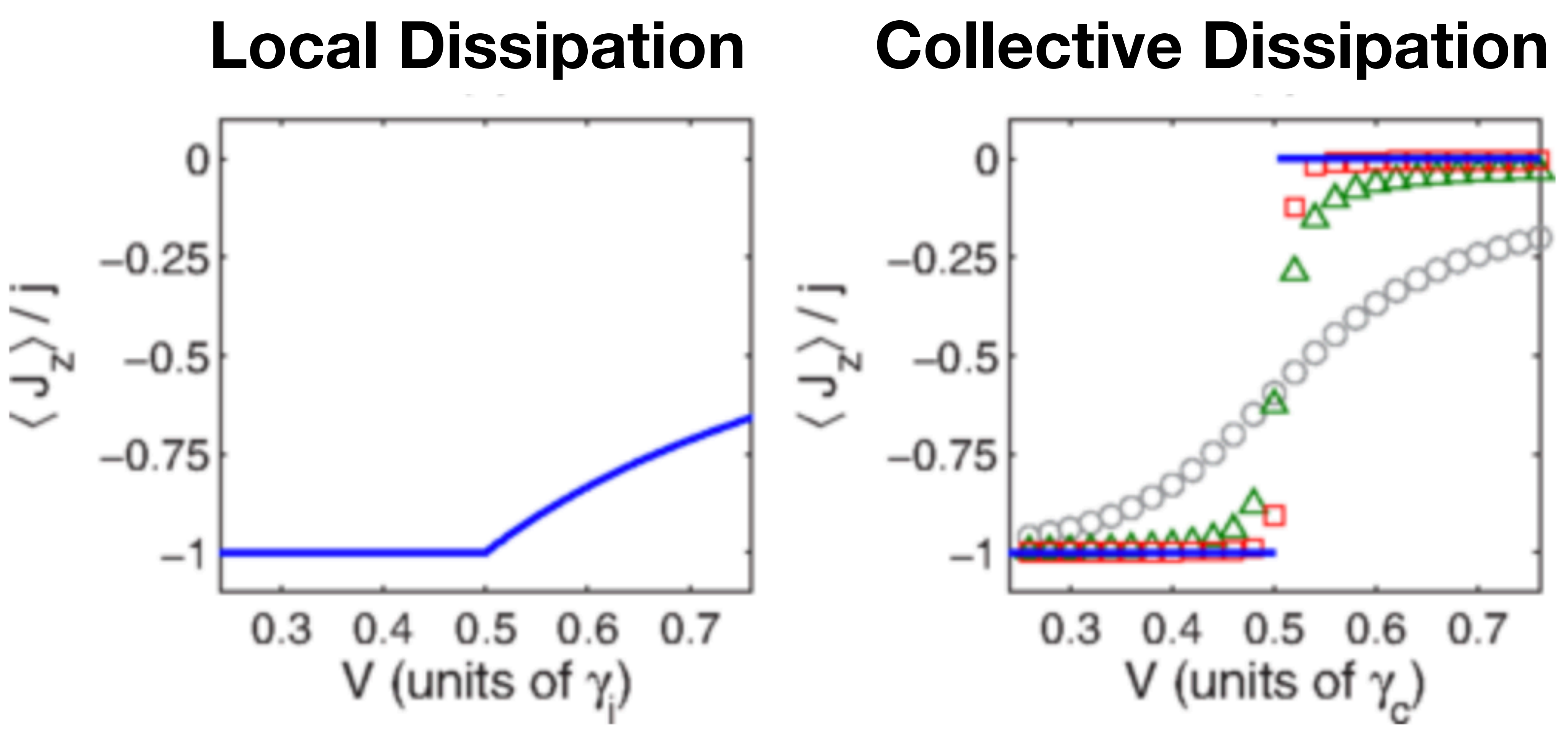
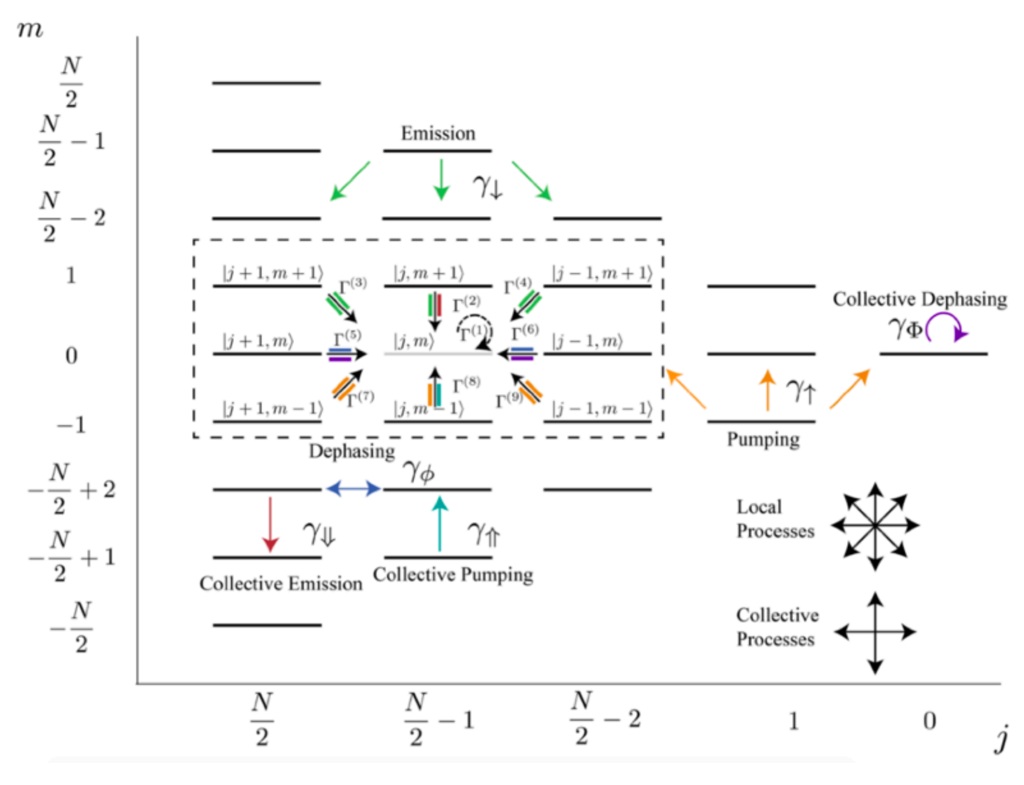
$$\hat{H} = \frac{1}{Z}\sum_i J_z\hat{\sigma}_i^z$$

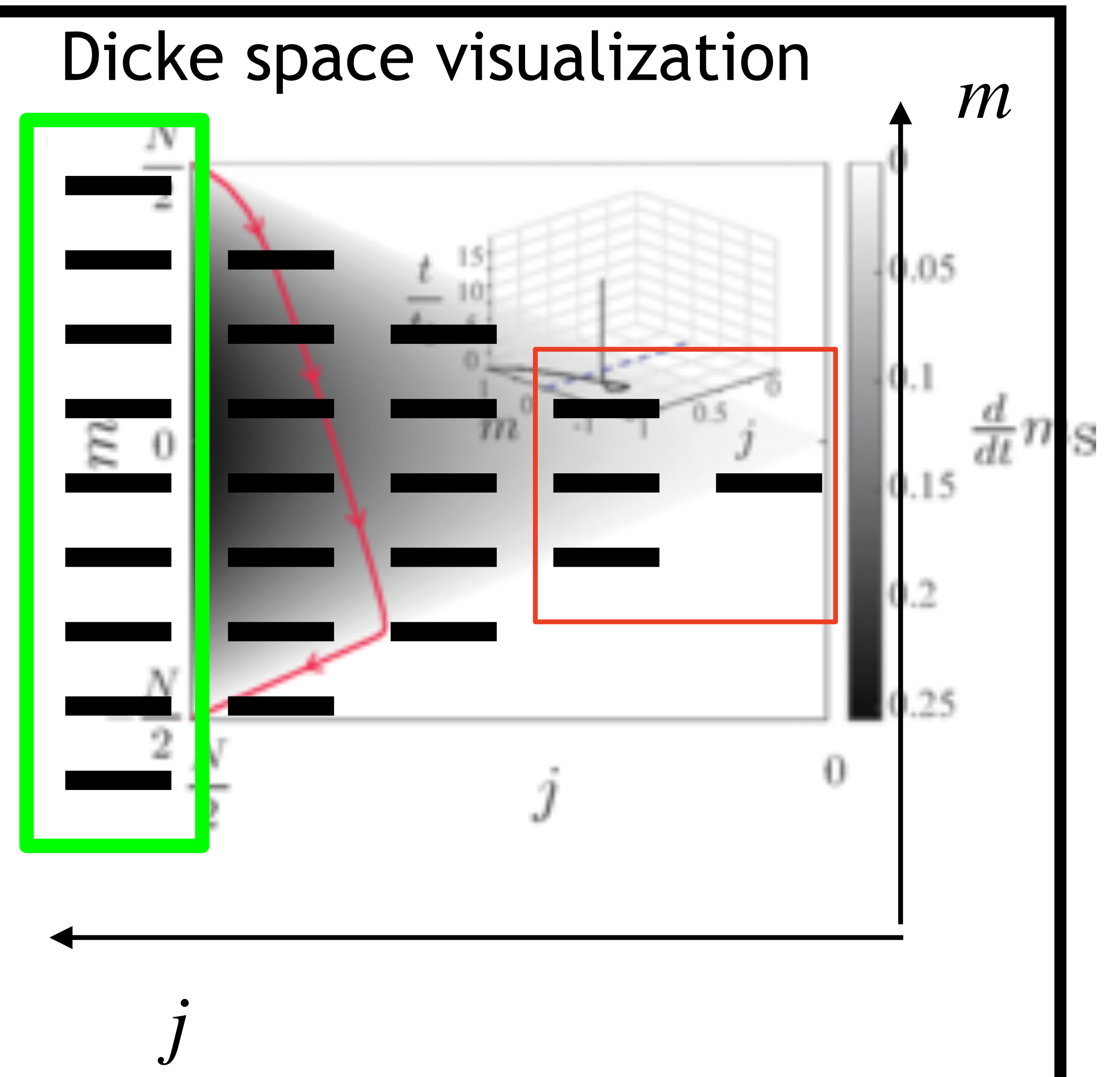
2nd Order Phase Tr. **1st Order Phase Tr.** **Superradiant Systems (Transient)**



T. E. Lee, C.-K. Chan, and S. F. Yelin
Phys. Rev. A **90**, 052109 (2014)



N. Shammah, …., and S. De Liberato
Phys. Rev. A **96**, 023863 (2017)
N. Shammah, …., and F. Nori
Phys. Rev. A **98**, 06385 (2018)



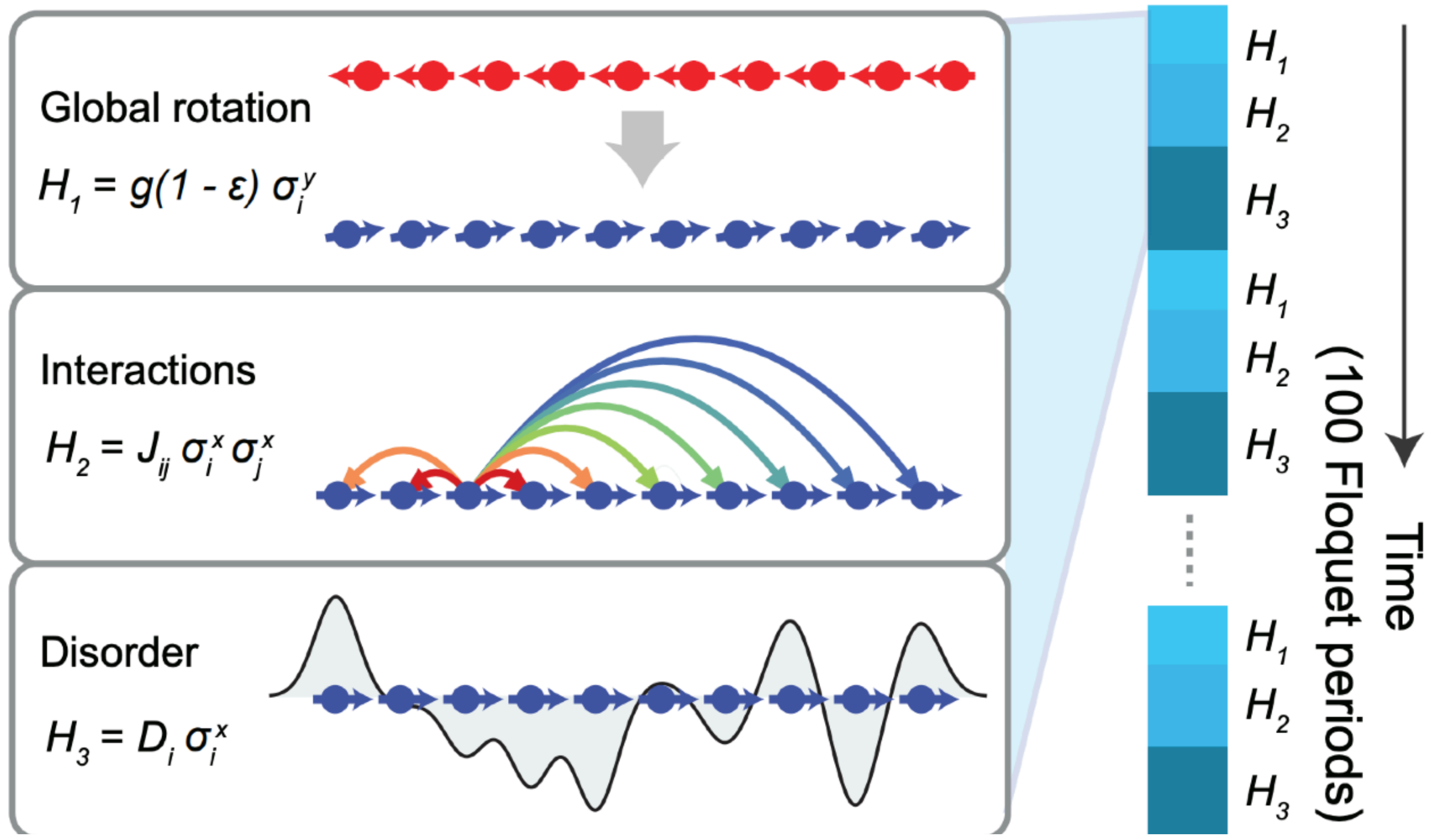
Collective Dissipation $[\hat{H},\hat{S}^2] = 0,\ [\hat{S}^-,\hat{S}^2] = 0$ **Spin length is conserved**

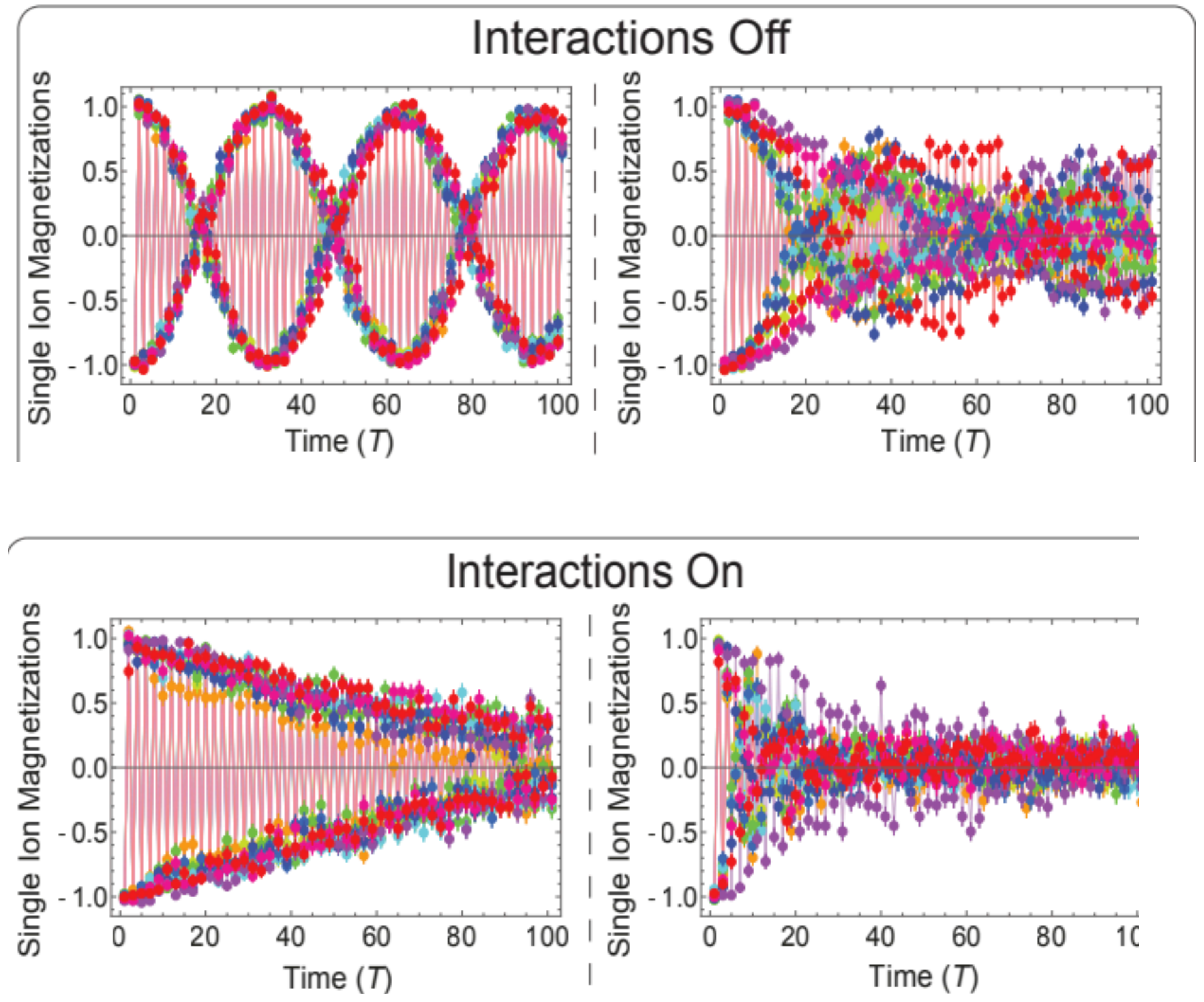
Local Dissipation $[\hat{H},\hat{S}^2] = 0,\ [\hat{\sigma}_i^-,\hat{S}^2] \neq 0$ **Spin length is not conserved**

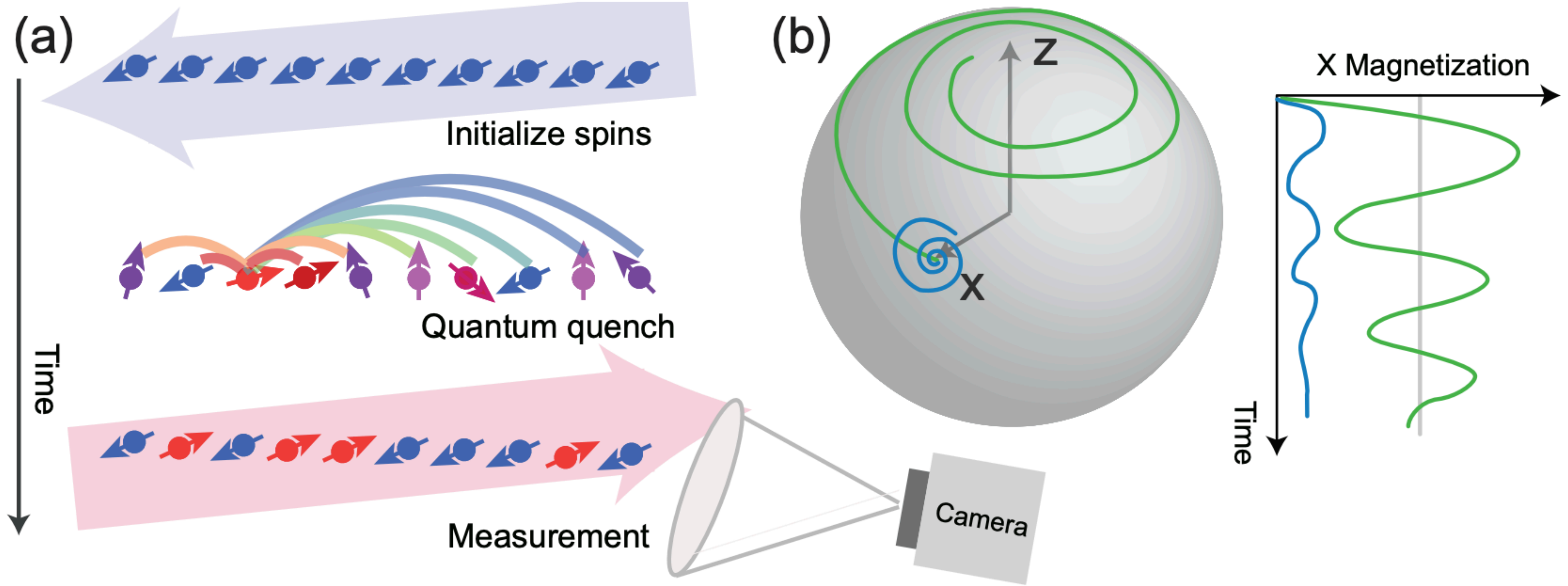
Any Dissipation $[\mathscr{L},\mathscr{Z}_2] = 0$ $\hat{\sigma}_i^x \to -\hat{\sigma}_i^x,\ \hat{\sigma}_i^y \to -\hat{\sigma}_i^y,$

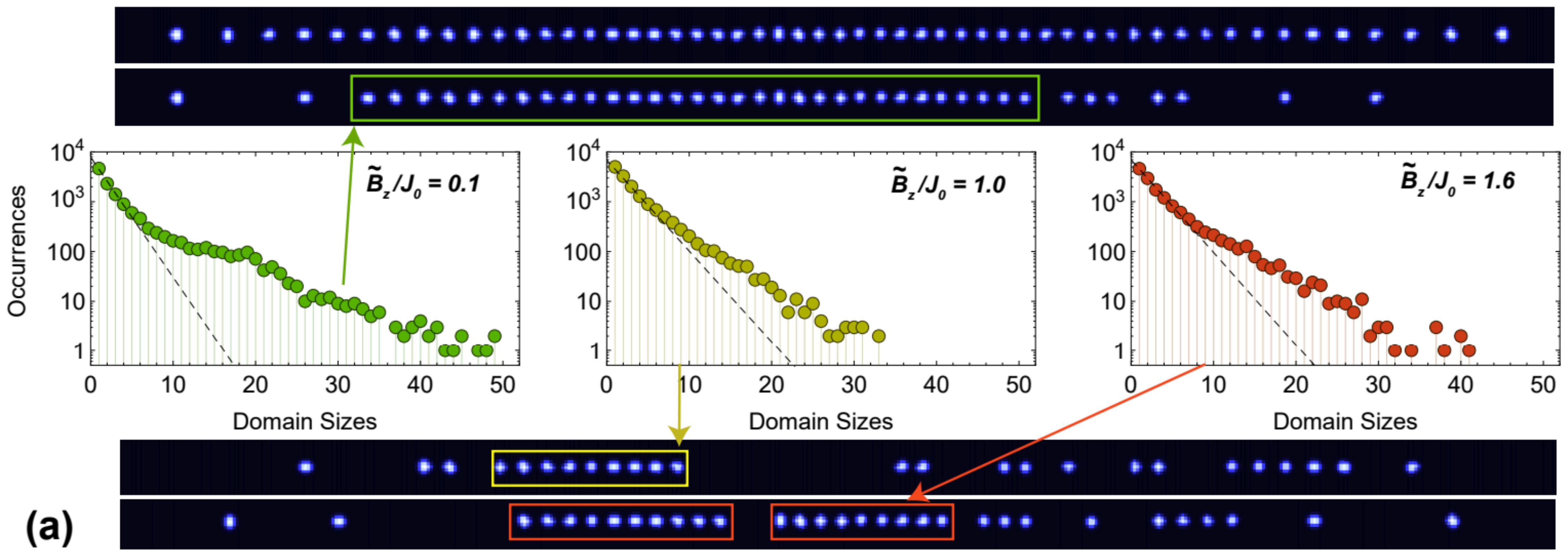
Spin models in experiments: Long-range interactions

Trapped Ions







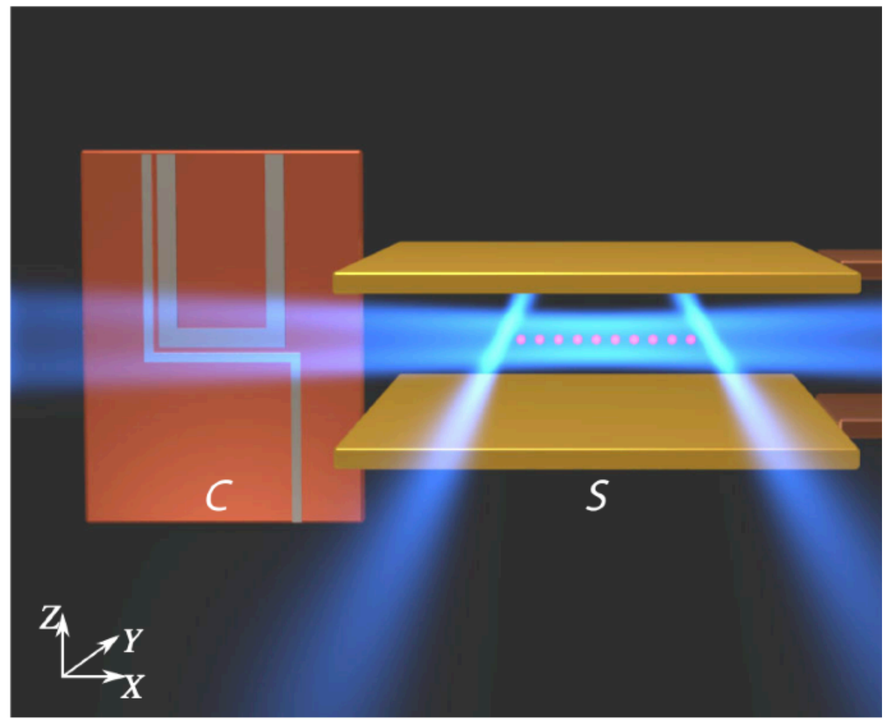


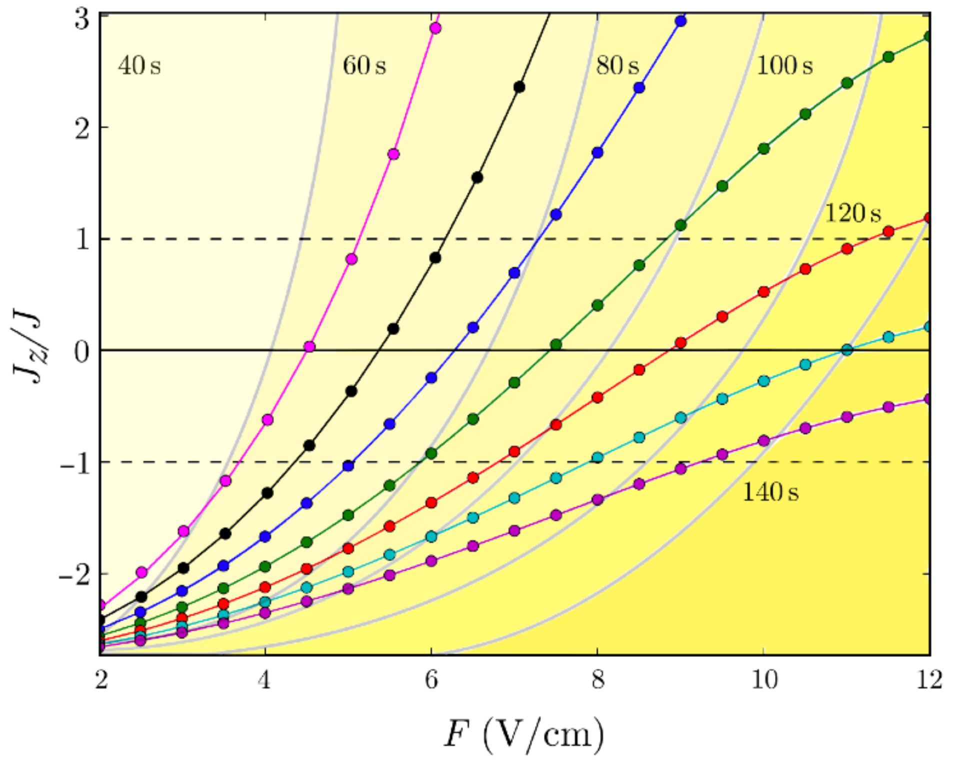
J. Zhang, …, C. Monroe
Nature **543**, 217 (2017)

J. Zhang, …, C. Monroe
Nature **551**, 601 (2017)

Experiments: Long-range interactions and dissipation

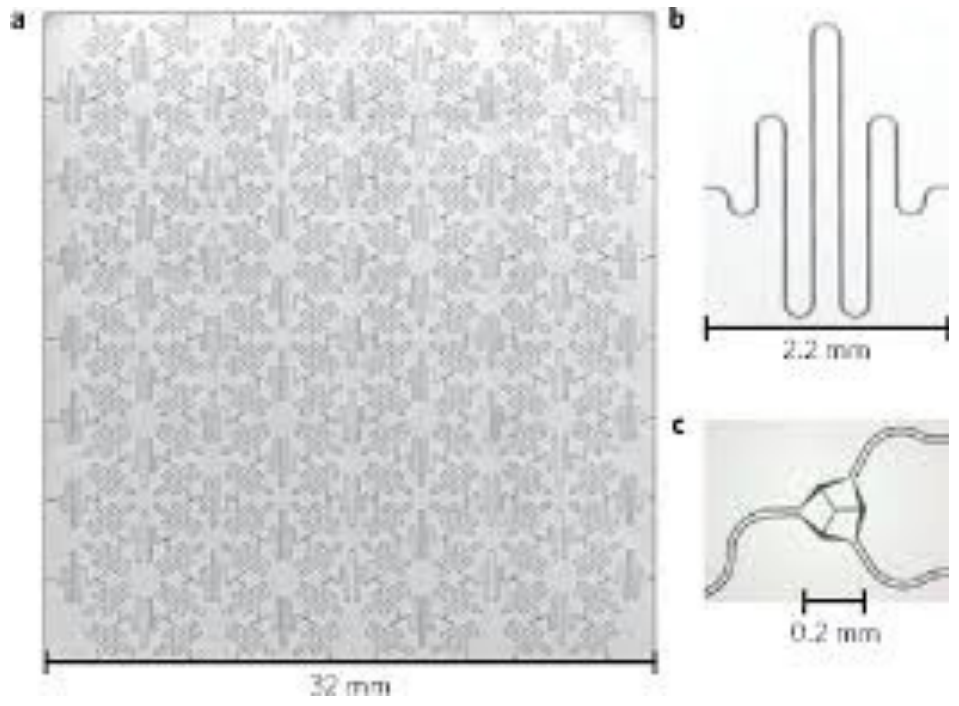
Rydberg Atoms

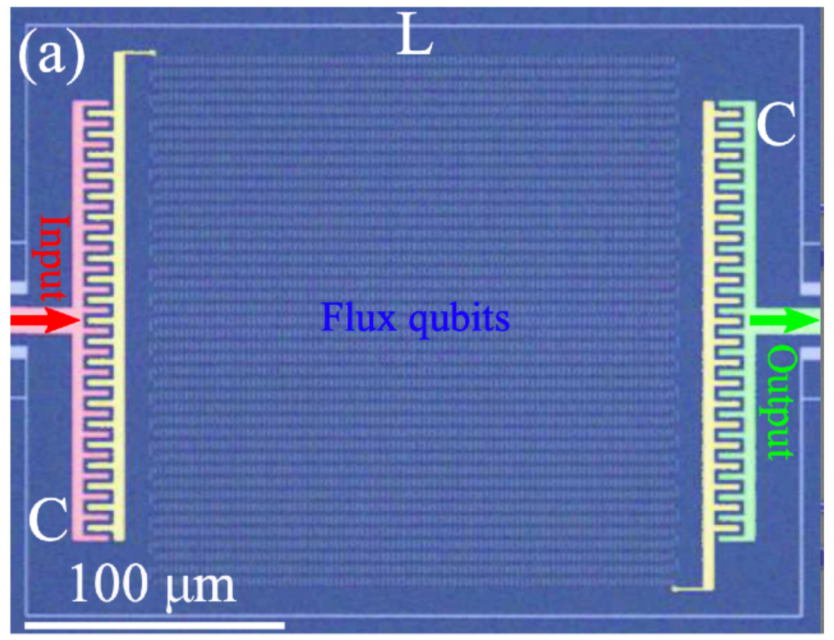




T.L. Nguyen, …, and M. Brune,
Phys. Rev. X **8**, 011032 (2018)

Superconducting Circuits

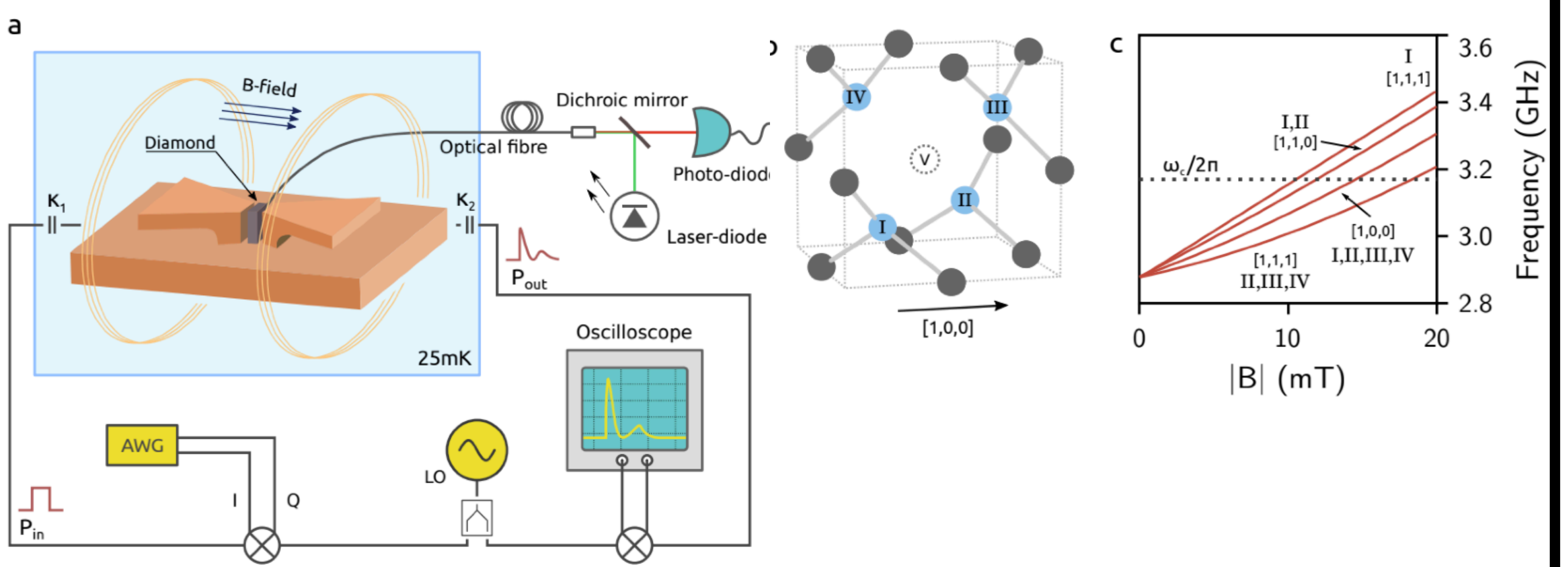


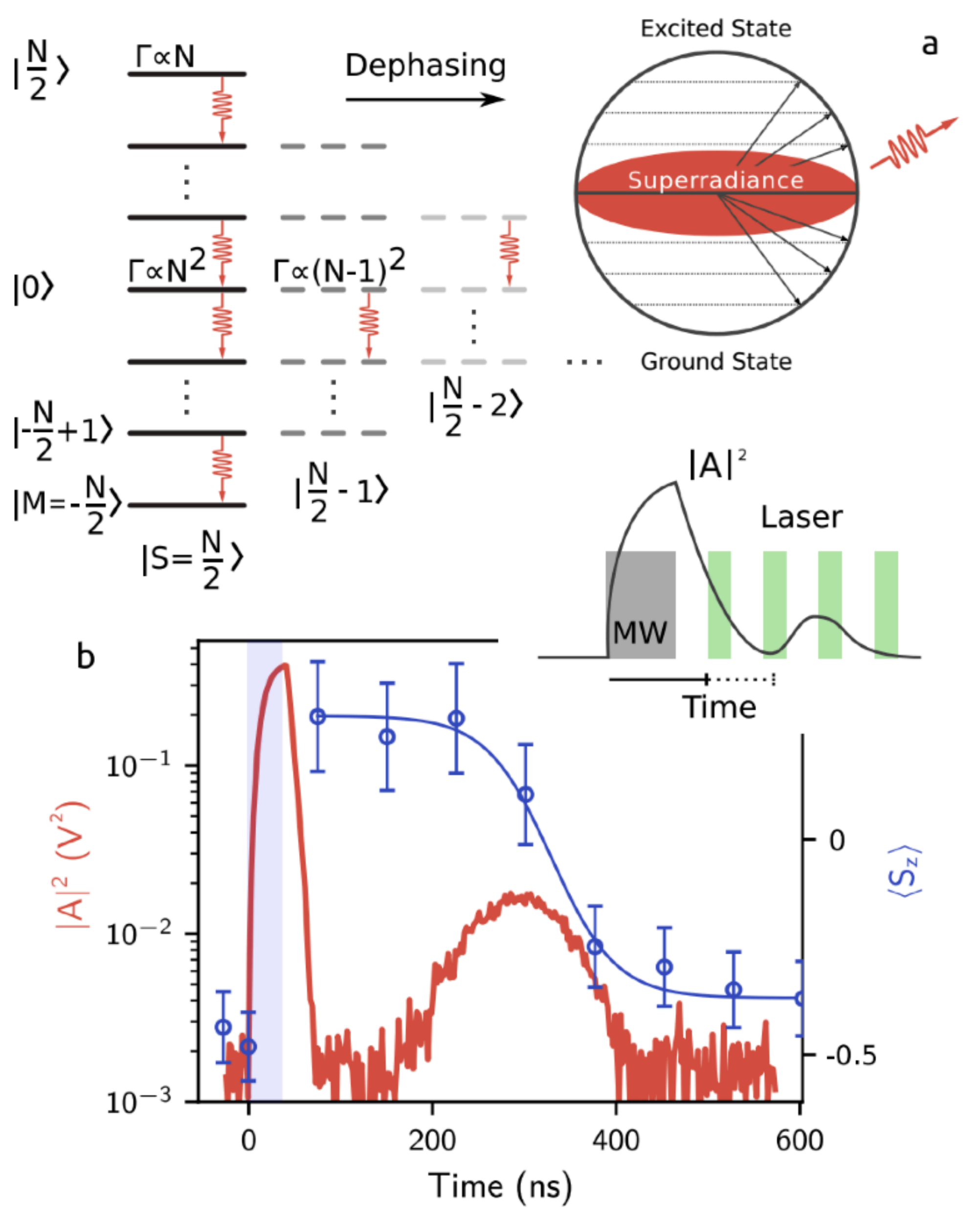


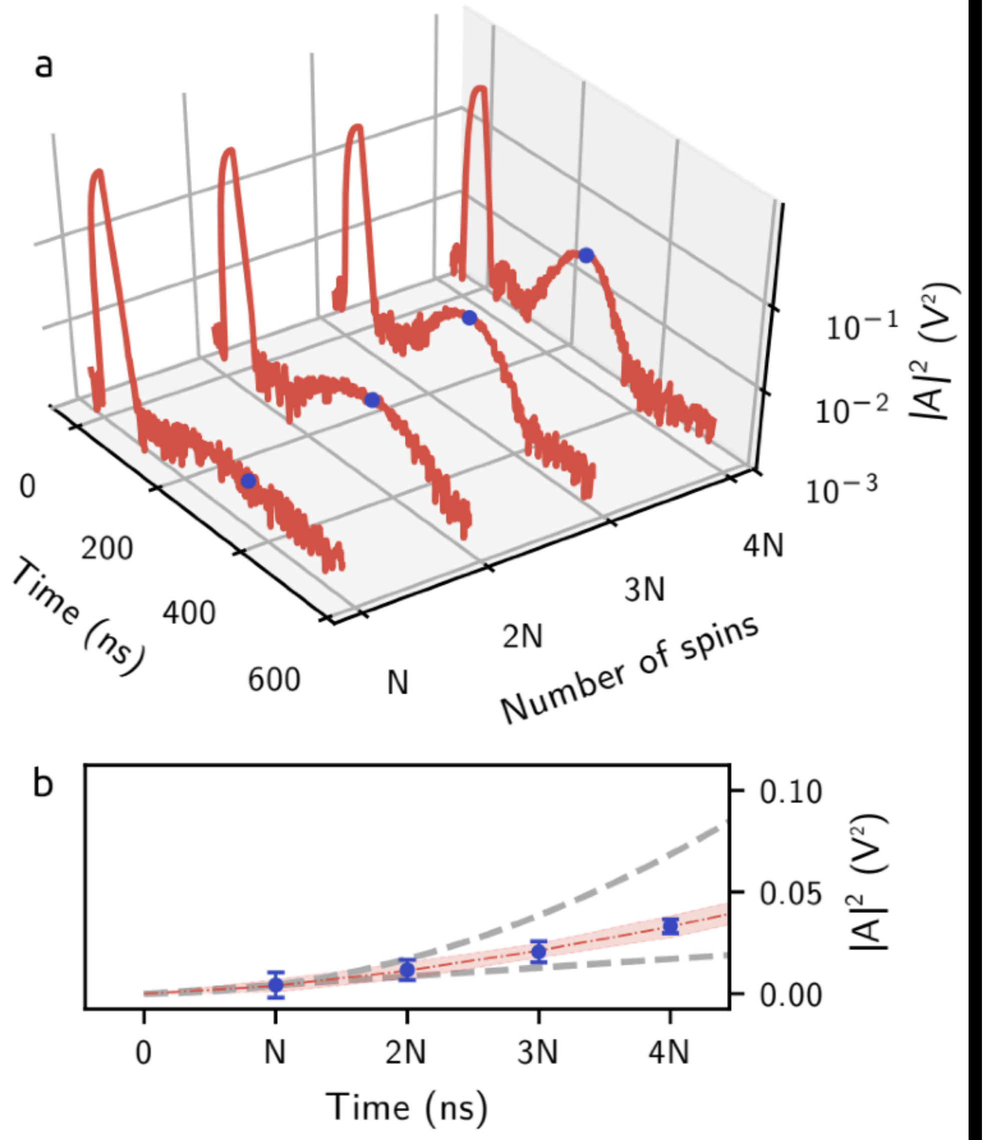
A. Houck, H. E. Türeci, and J. Koch,
Nature Physics **8** 292 (2012)

K. Kakuyanagi, …, and S. Saito,
Phys. Rev. Lett. **117**, 210503 (2016)

Hybrid Systems







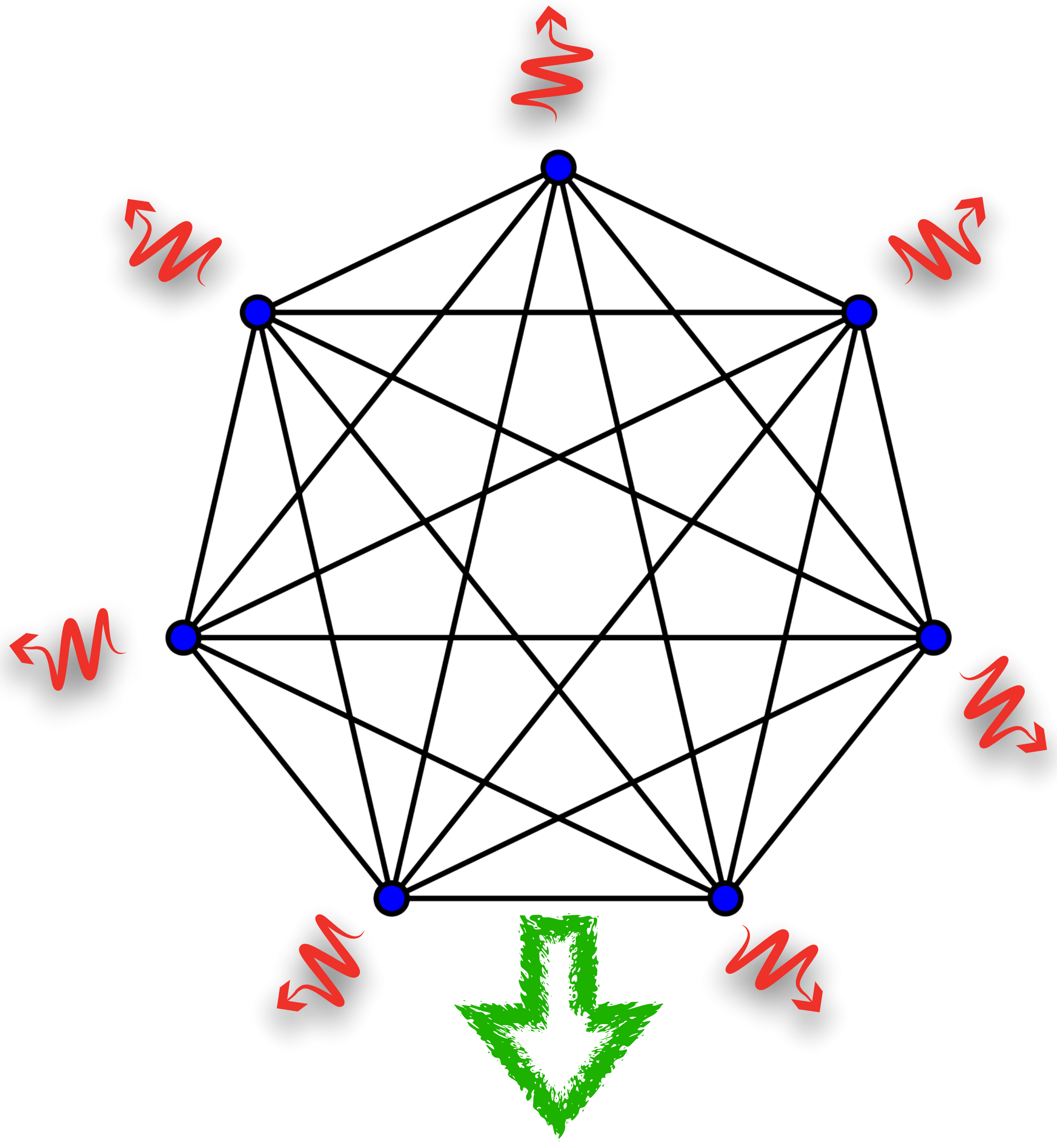
A. Angerer, …, and J. Majer,
Nature Physics **14**, 1168 (2018)

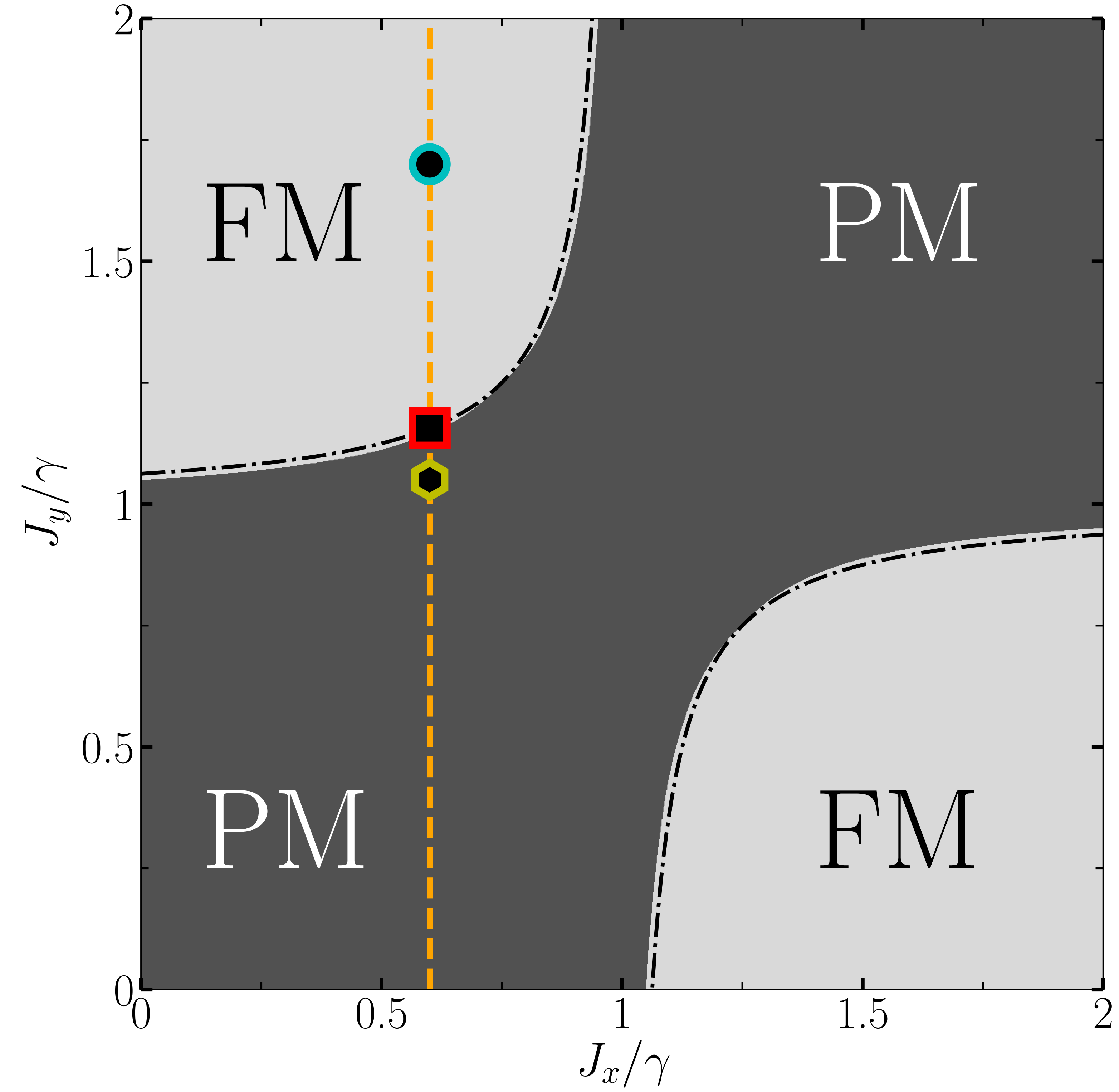
Gutzwiller Mean-Field Study

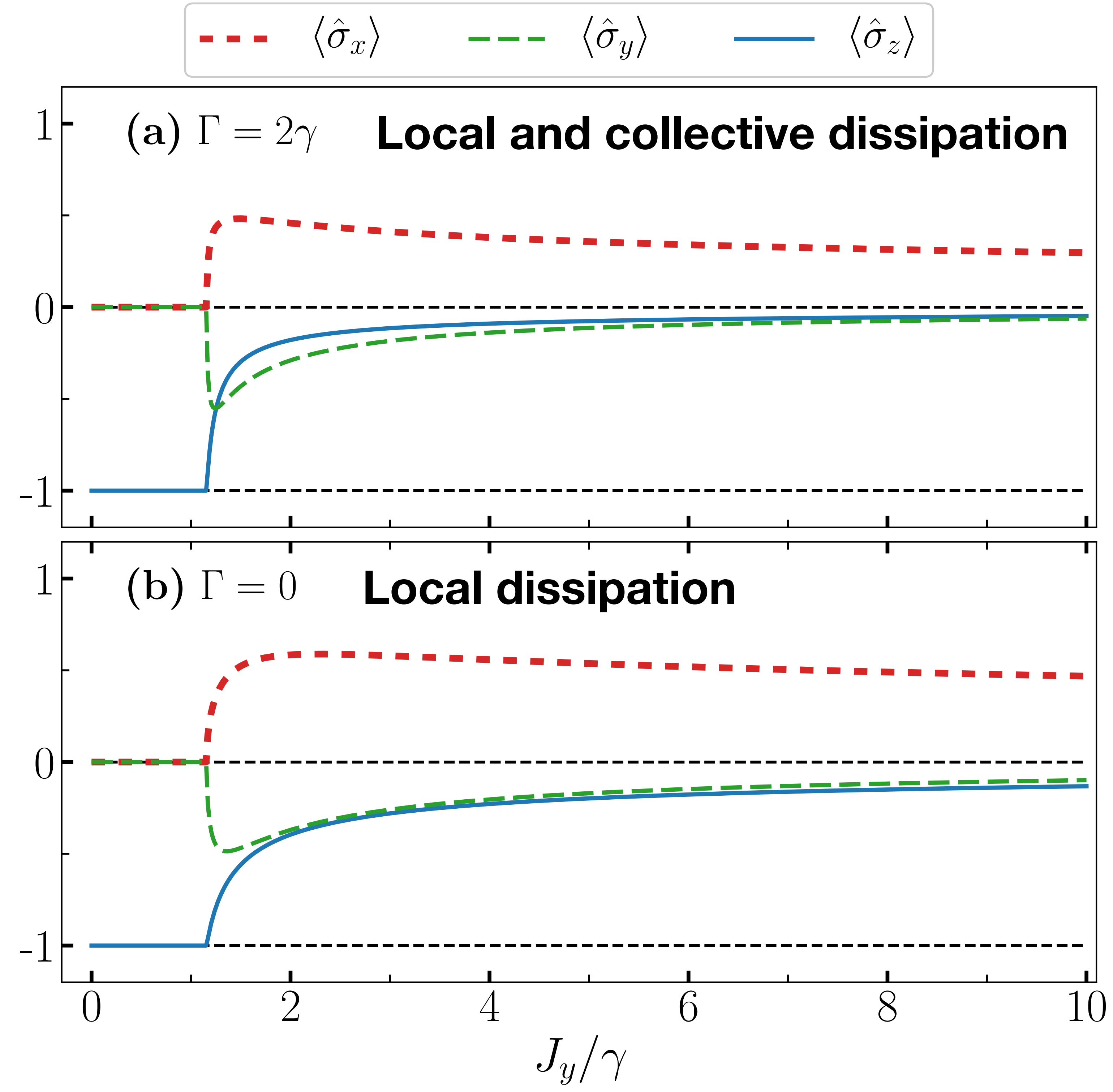
XYZ model

$$\hat{H} = \frac{1}{2(N-1)}\left[J_x\left(\hat{S}^x\right)^2 + J_y\left(\hat{S}^y\right)^2 + J_z\left(\hat{S}^z\right)^2\right] \qquad \hat{S}^z = \sum_i^N \hat{\sigma}_z$$

$$\frac{\partial \hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H}, \hat{\rho}(t)\right] + \gamma \sum_{j=1}^{N} \mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t) + \frac{\Gamma}{N-1}\mathscr{D}[\sum_{j=1}^{N} \hat{\sigma}_j^-]\hat{\rho}(t)$$







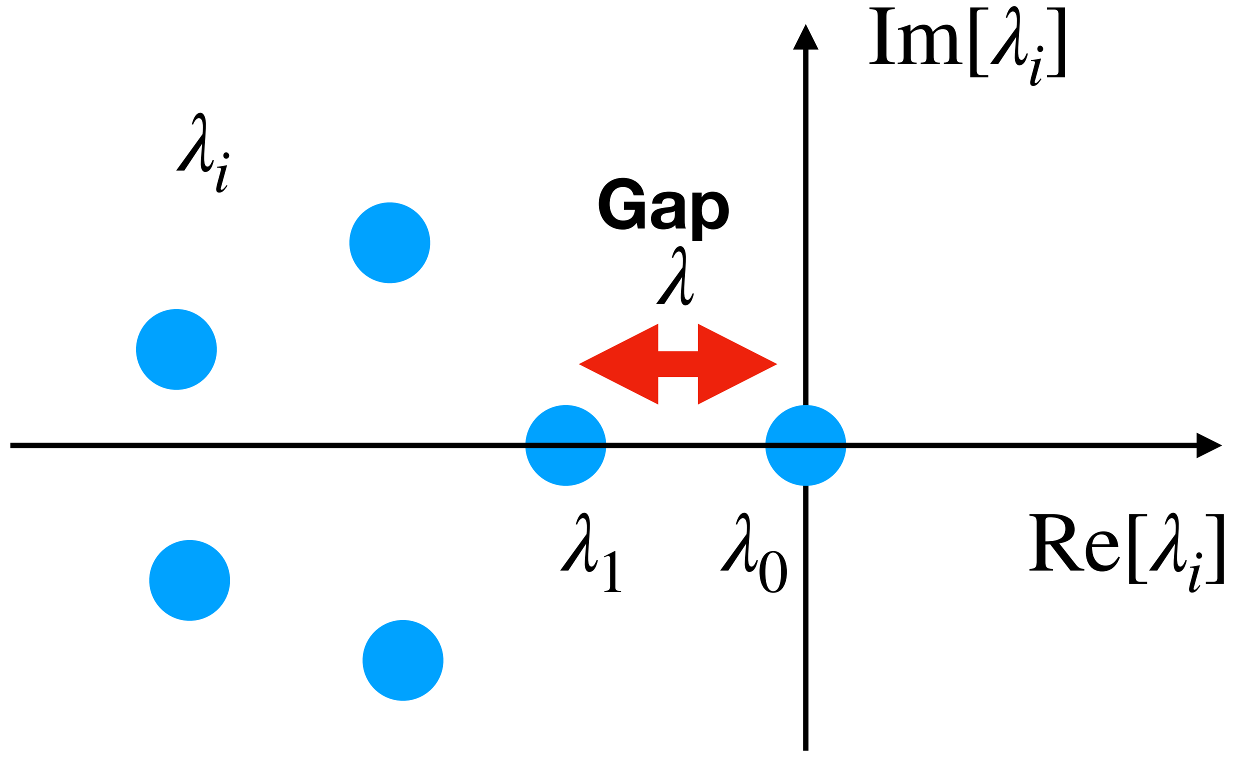
https://arxiv.org/abs/1912.07570

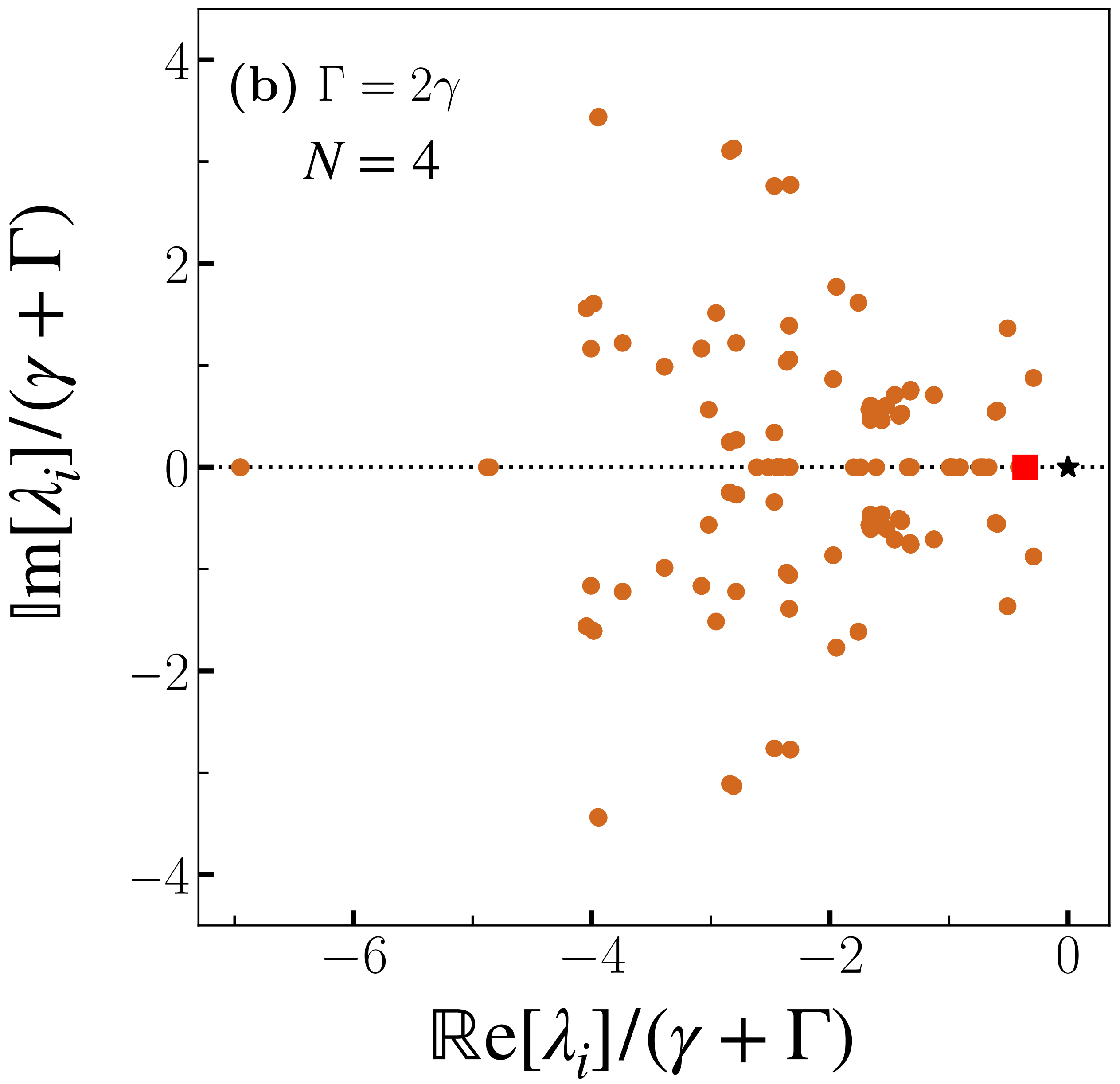
Study of the Liouvillian Gap

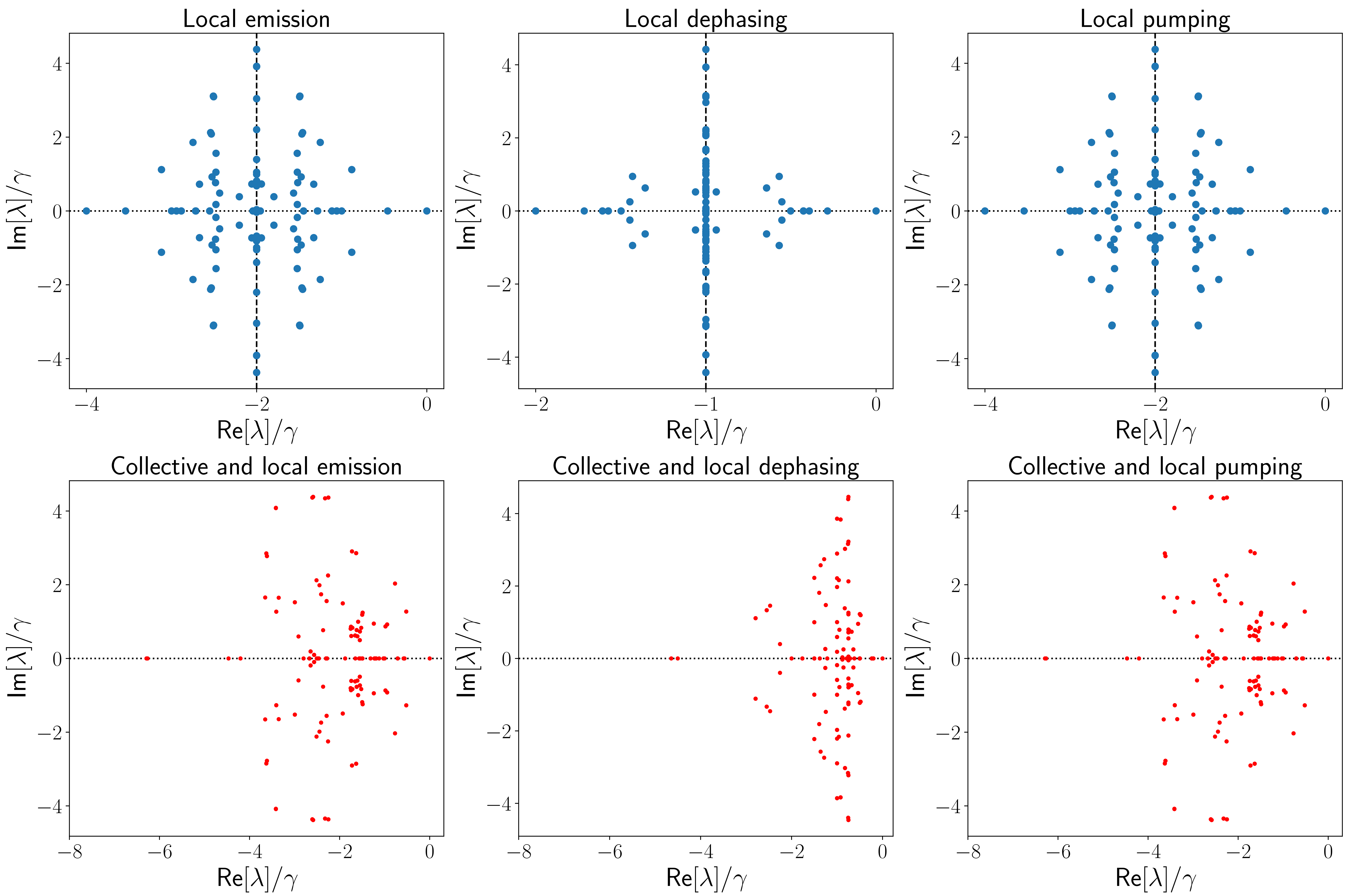
XYZ model at criticality

$$\frac{\partial \hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H}, \hat{\rho}(t)\right] + \gamma \sum_{j=1}^{N} \mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t) + \frac{\Gamma}{N-1}\mathscr{D}[\sum_{j=1}^{N} \hat{\sigma}_j^-]\hat{\rho}(t)$$

$$\frac{\partial \hat{\rho}(t)}{\partial t} = 0 \qquad \mathscr{L}\hat{\rho}_{ss}(t) = 0$$







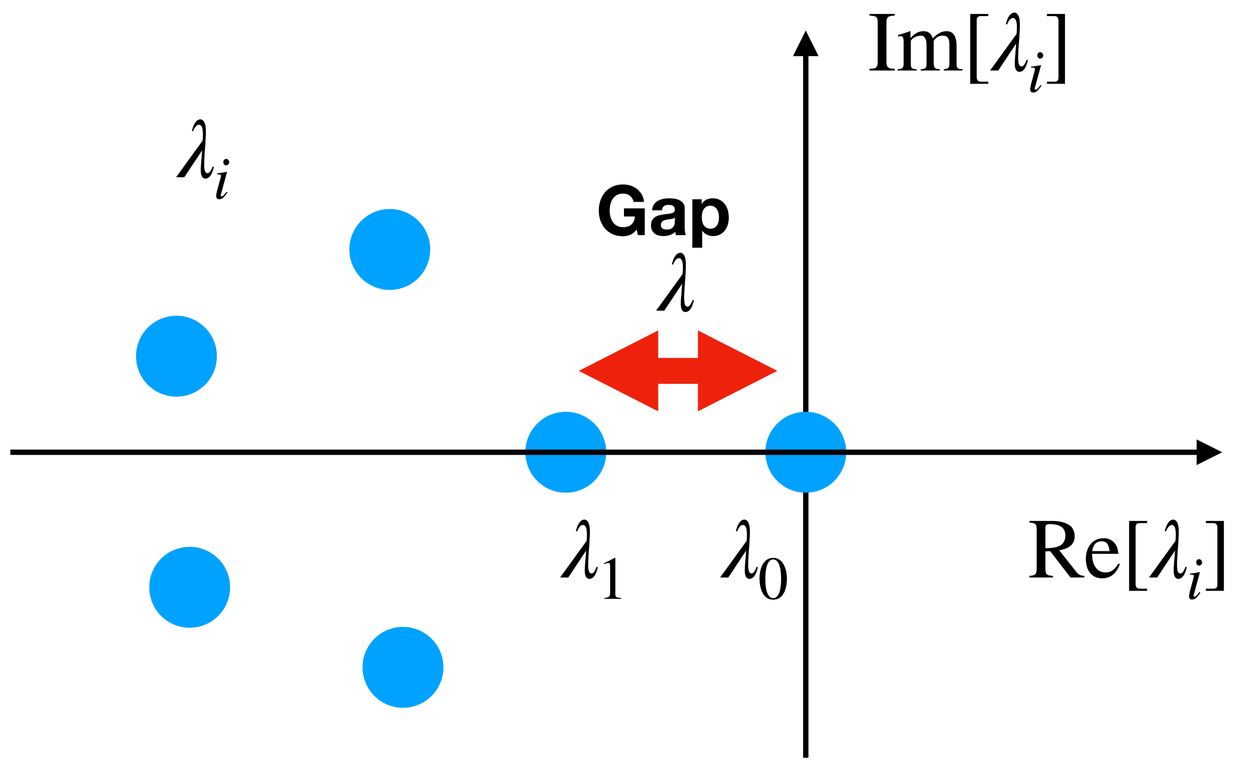
Local emission
Local dephasing
Local pumping
Collective and local emission
Collective and local dephasing
Collective and local pumping
Im[λ]/γ
Re[λ]/γ

Study of the Liouvillian Gap

XYZ model at criticality

$$\frac{\partial \hat{\rho}(t)}{\partial t} = \mathcal{L}\hat{\rho}(t) = -i\left[\hat{H}, \hat{\rho}(t)\right] + \gamma \sum_{j=1}^{N} \mathcal{D}[\hat{\sigma}_j^-]\hat{\rho}(t)$$

Steady state $\frac{\partial \hat{\rho}(t)}{\partial t} = 0$ $\mathcal{L}\hat{\rho}_{ss}(t) = 0$

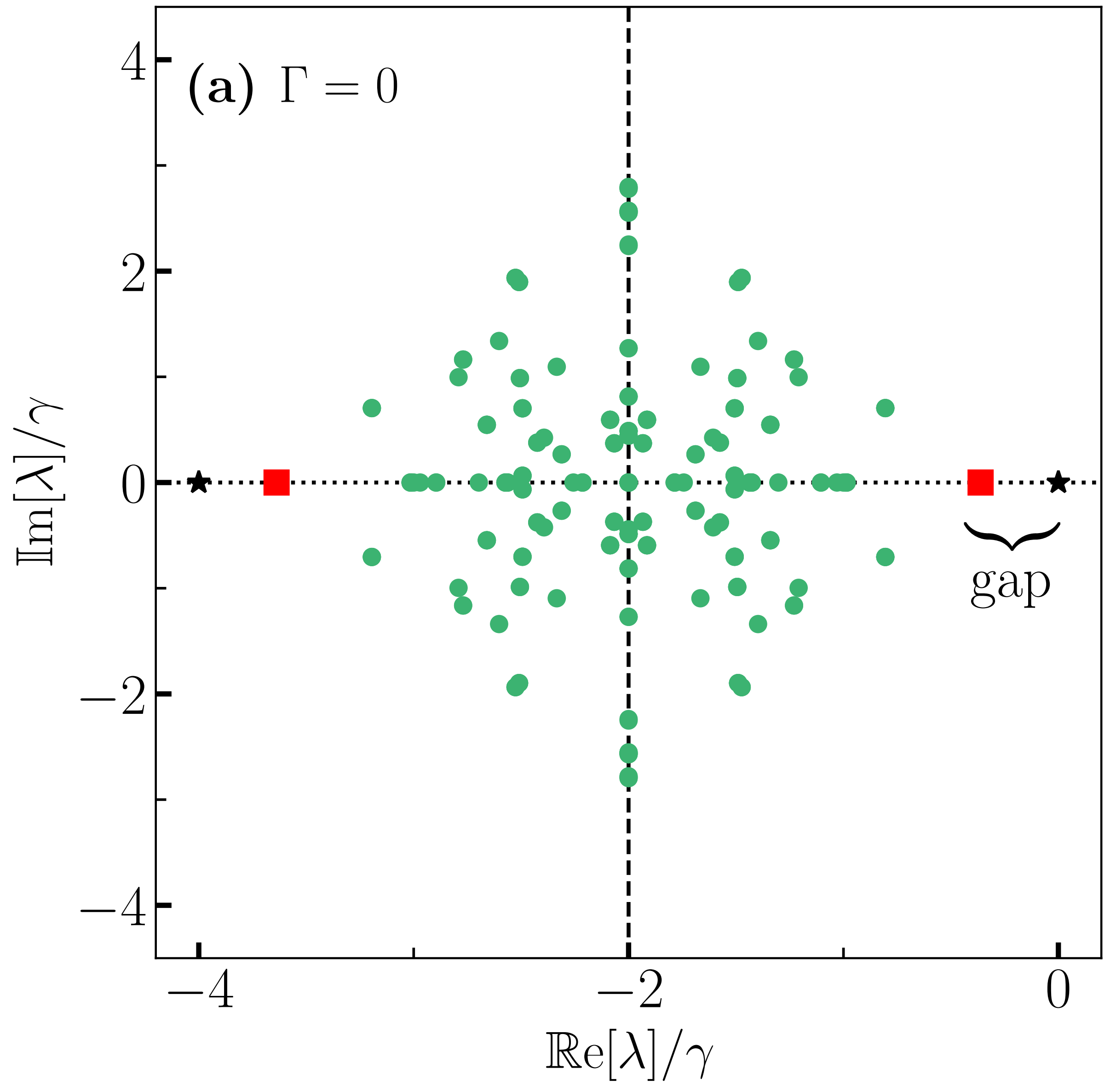


PT-symmetric Liouvillian

T. Prosen,
Phys. Rev. Lett. **109**, 090404 (2012)

$$(\mathbb{PT} \neq \mathcal{PT})$$

Weak symmetry
Not at superoperator level



Study of the Liouvillian Gap

XYZ model at criticality

$$\frac{\partial \hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H}, \hat{\rho}(t)\right] + \gamma \sum_{j=1}^{N} \mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t)$$

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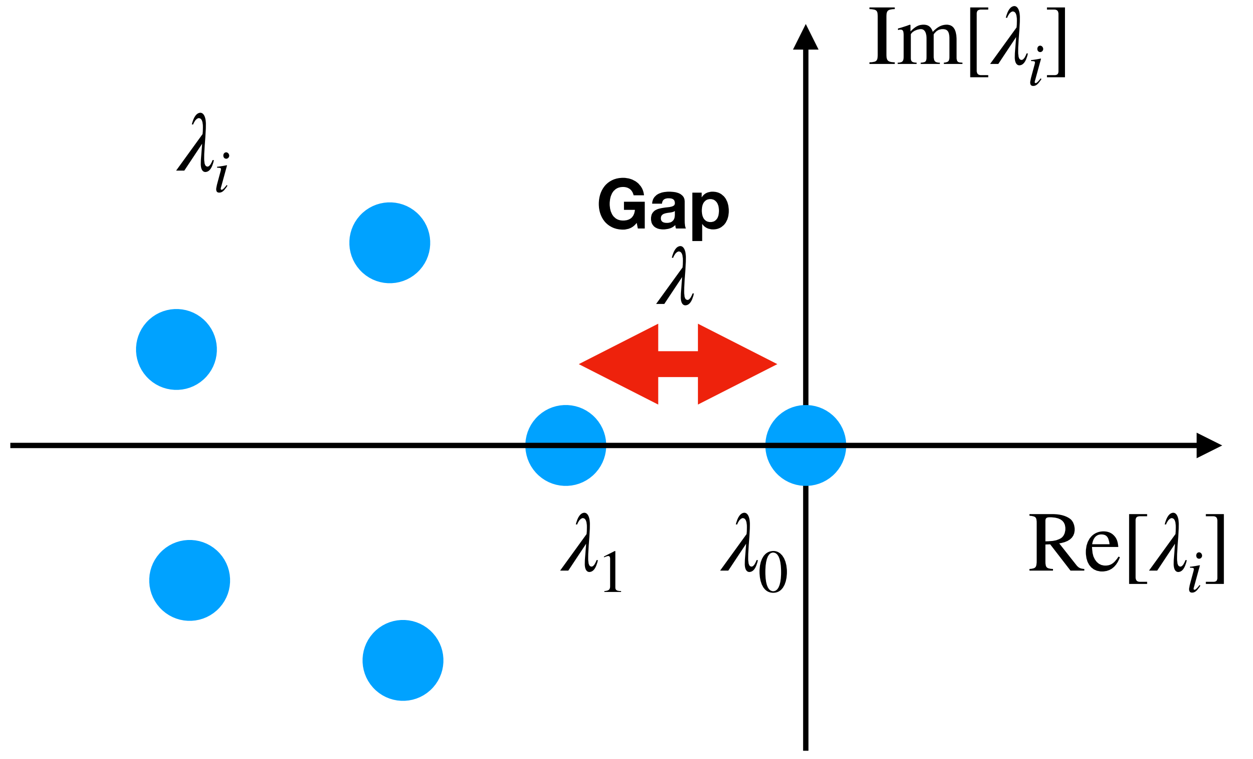

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Phys. Rev. Lett. **109**, 090404 (2012)

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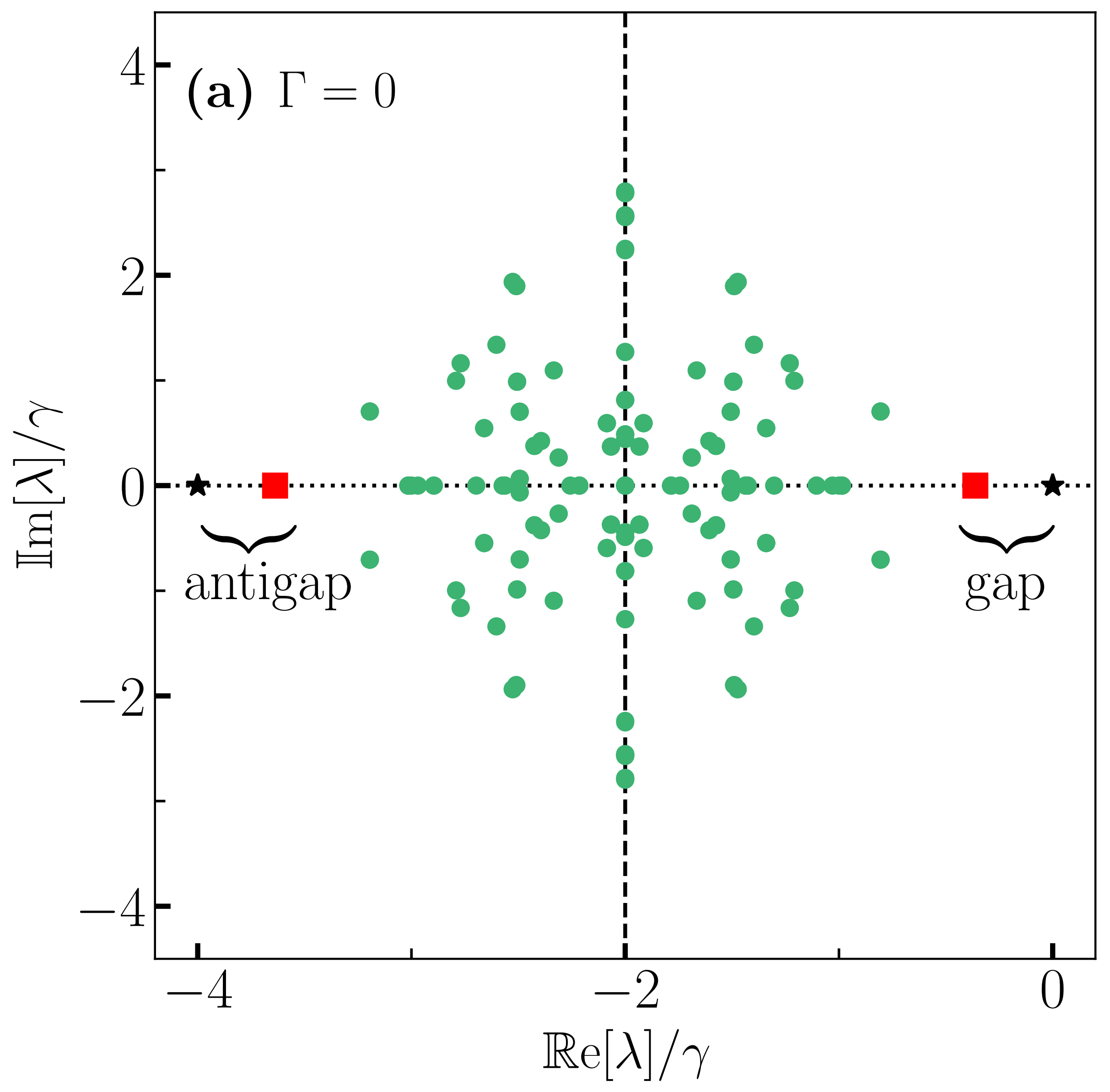


Efficient gap calculation using Krylov subspaces

https://arxiv.org/abs/1912.07570

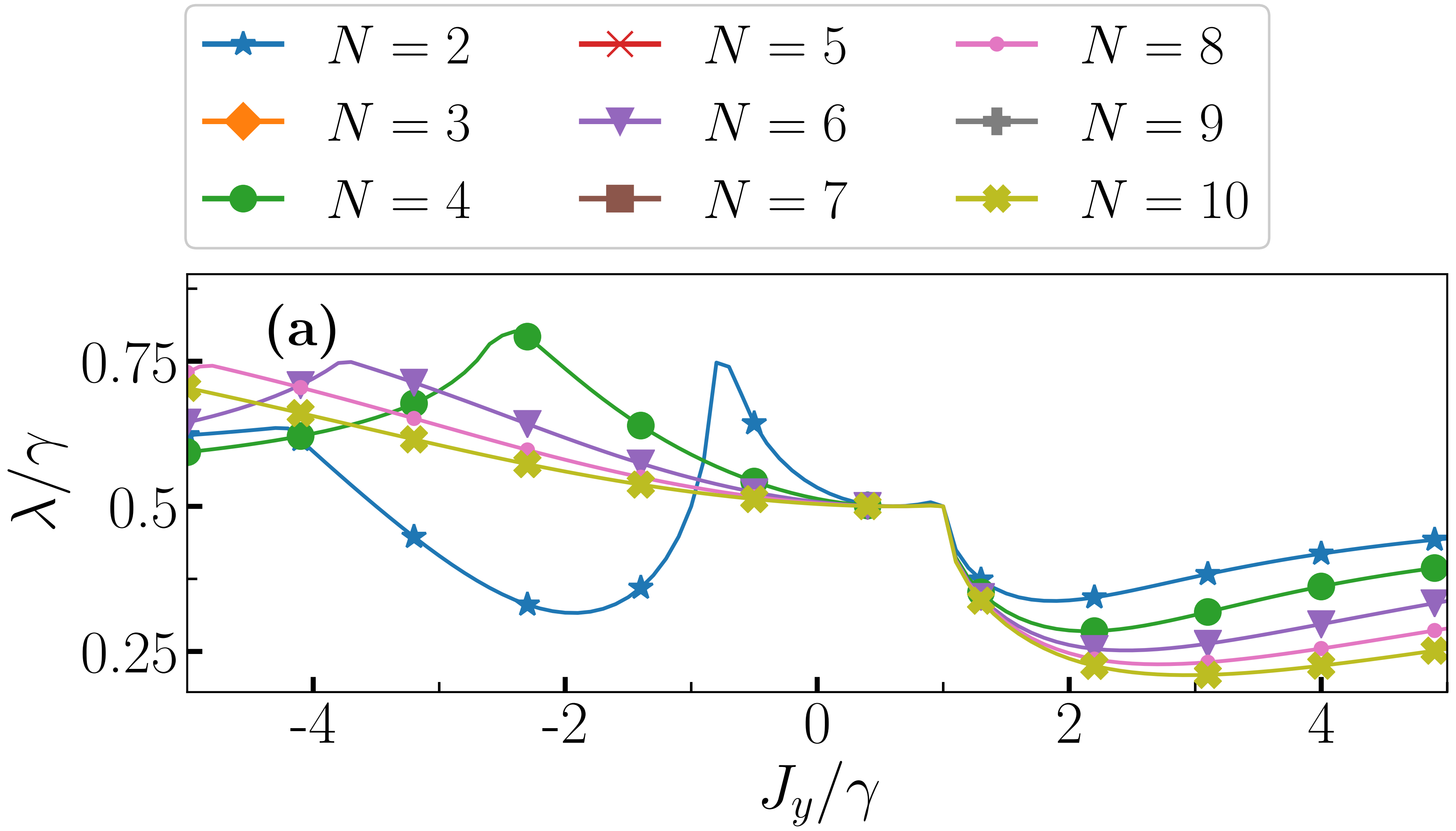
Study of the Liouvillian *anti*Gap

XYZ model

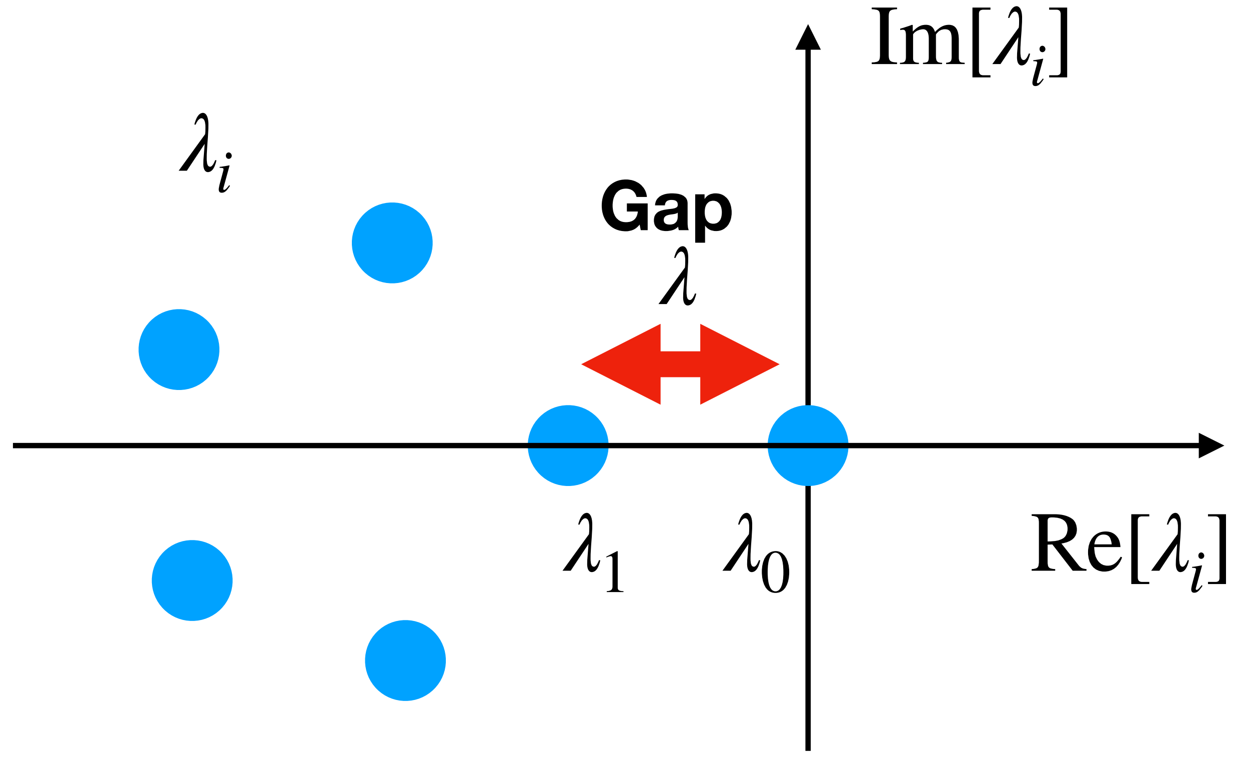
$$\hat{H} = \frac{1}{Z}\sum_{\langle i,j\rangle}\left(J_x\hat{\sigma}_i^x\hat{\sigma}_j^x + J_y\hat{\sigma}_i^y\hat{\sigma}_i^y + J_z\hat{\sigma}_i^z\hat{\sigma}_j^z\right)$$

$$\frac{\partial\hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H},\hat{\rho}(t)\right] + \gamma\sum_{j=1}^{N}\mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t)$$

Gap



$$\frac{\partial\hat{\rho}(t)}{\partial t} = 0 \qquad \mathscr{L}\hat{\rho}_{ss}(t) = 0$$



Study of the Liouvillian *anti*Gap

XYZ model

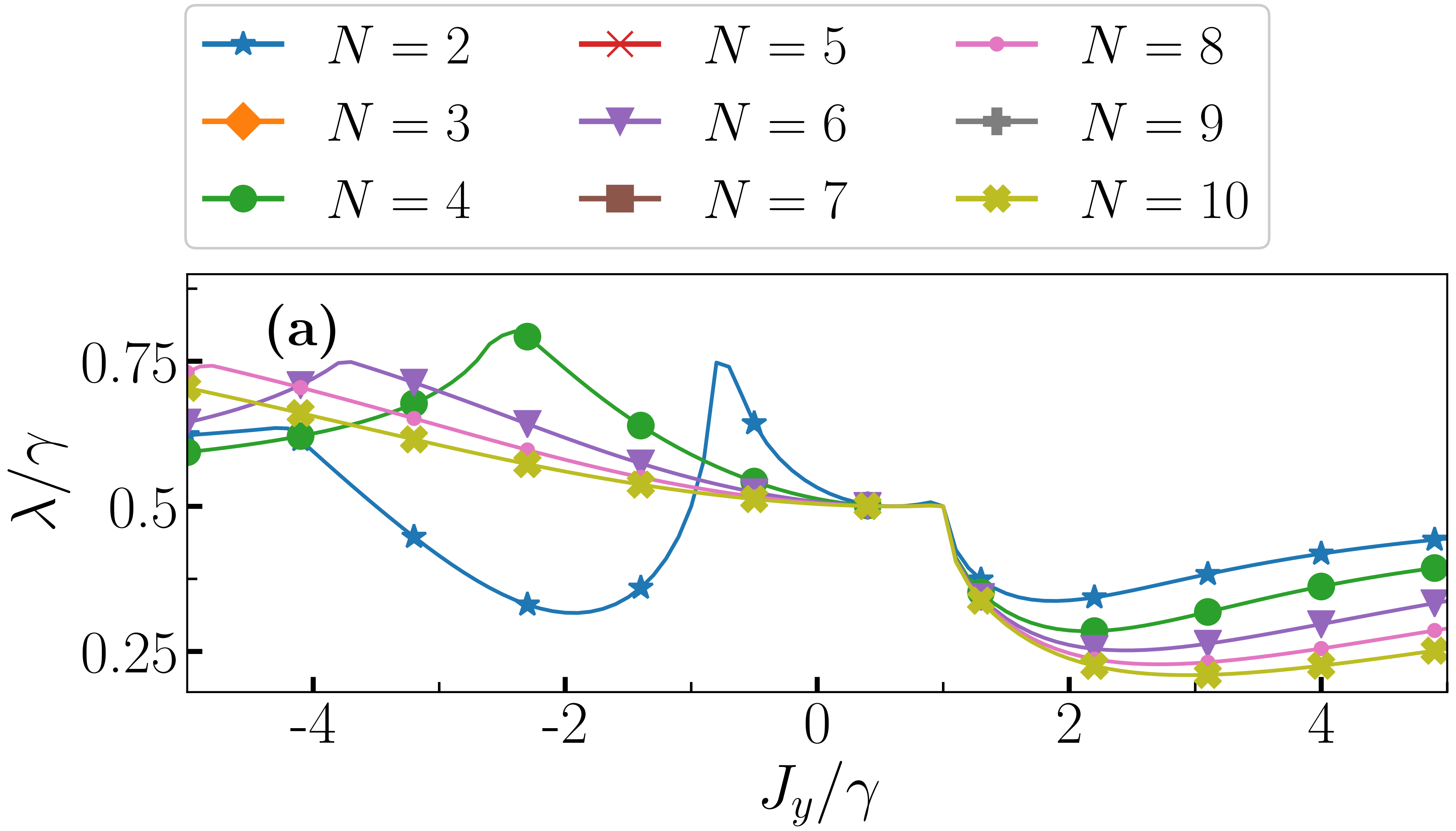
$$\hat{H} = \frac{1}{Z}\sum_{\langle i,j\rangle}\left(J_x\hat{\sigma}_i^x\hat{\sigma}_j^x + J_y\hat{\sigma}_i^y\hat{\sigma}_i^y + J_z\hat{\sigma}_i^z\hat{\sigma}_j^z\right)$$

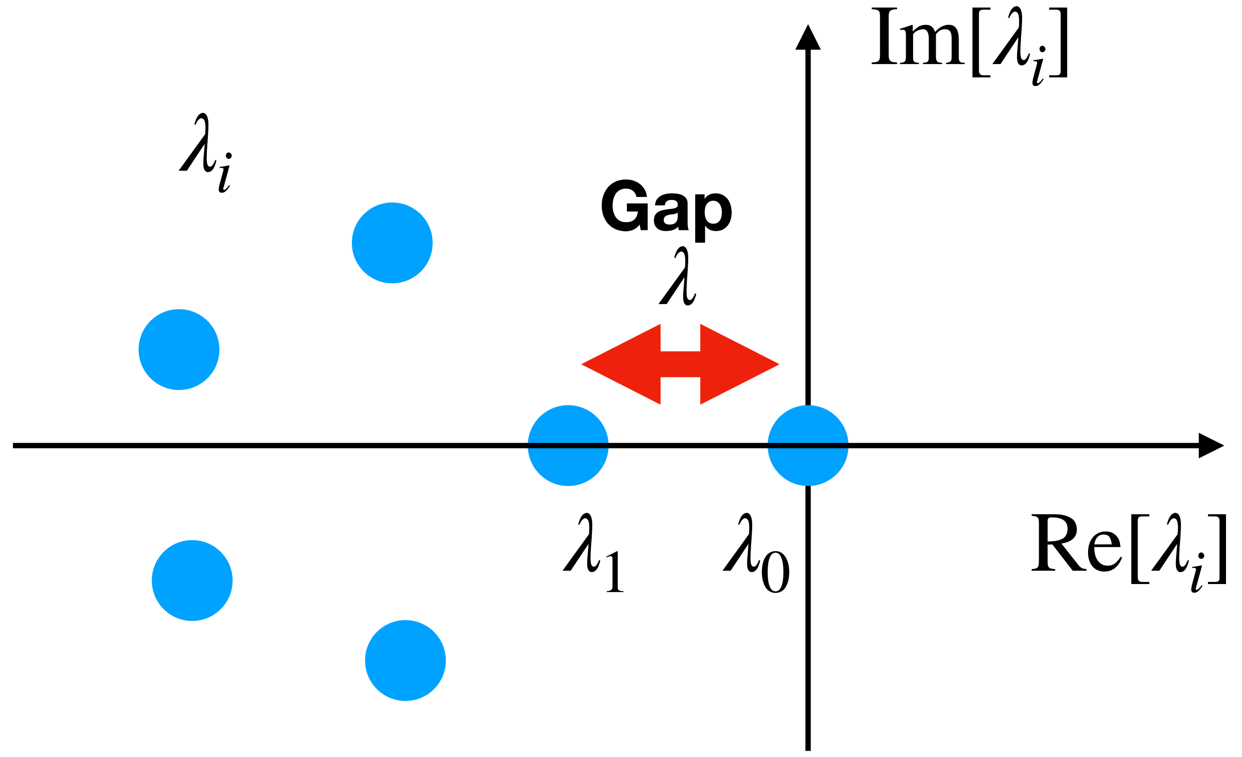
$$J_x = 0.6\gamma,\ J_z = \gamma$$

$$\frac{\partial\hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H},\hat{\rho}(t)\right] + \gamma\sum_{j=1}^{N}\mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t)$$

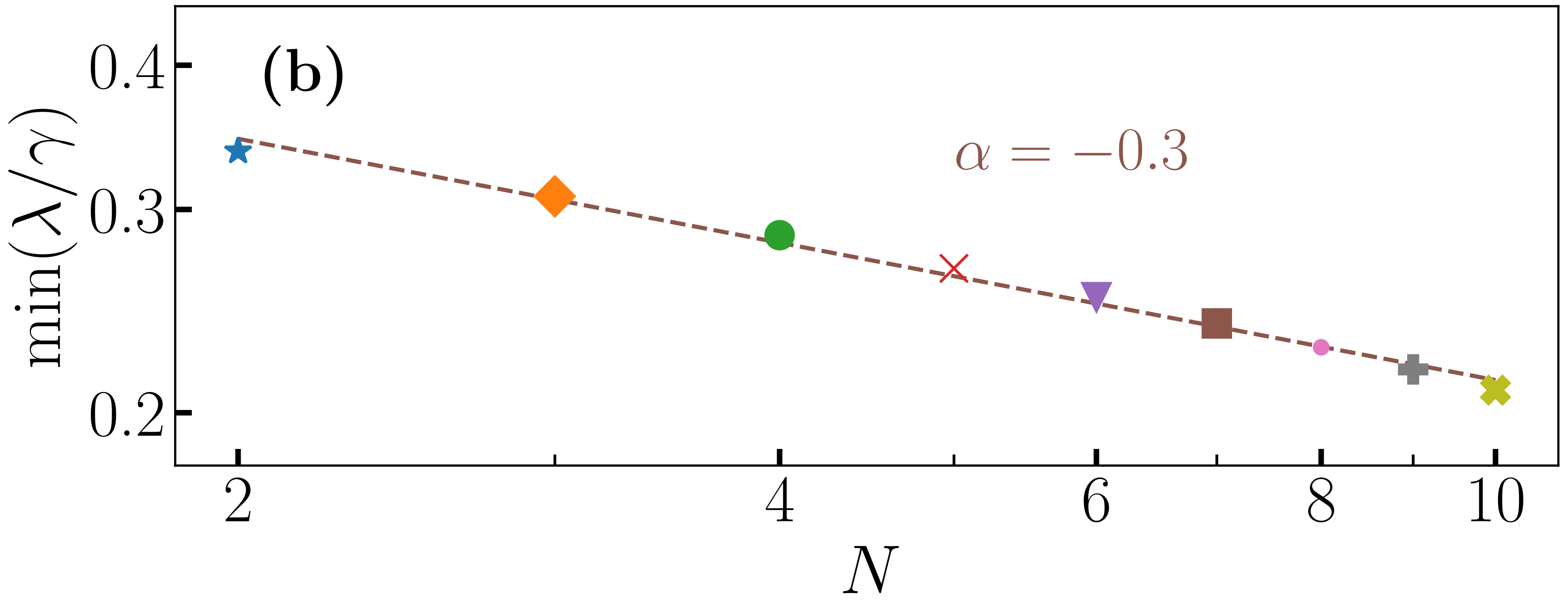
$$\frac{\partial\hat{\rho}(t)}{\partial t} = 0 \qquad \mathscr{L}\hat{\rho}_{ss}(t) = 0$$

Gap



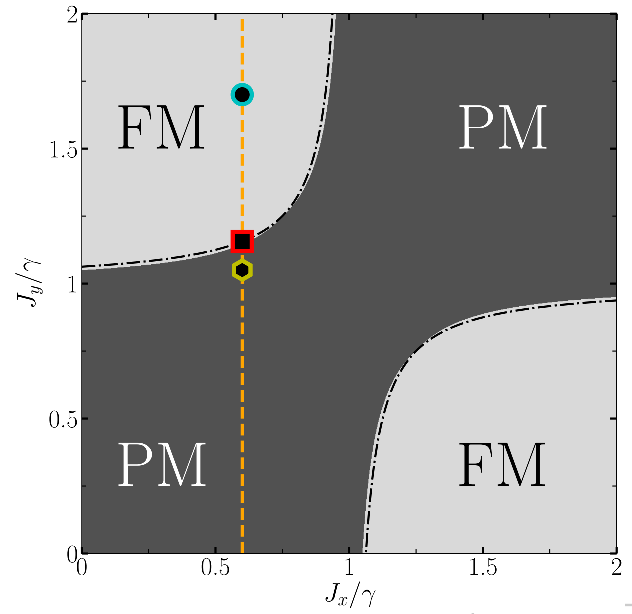


Log-Log Scaling of the Gap



https://arxiv.org/abs/1912.07570

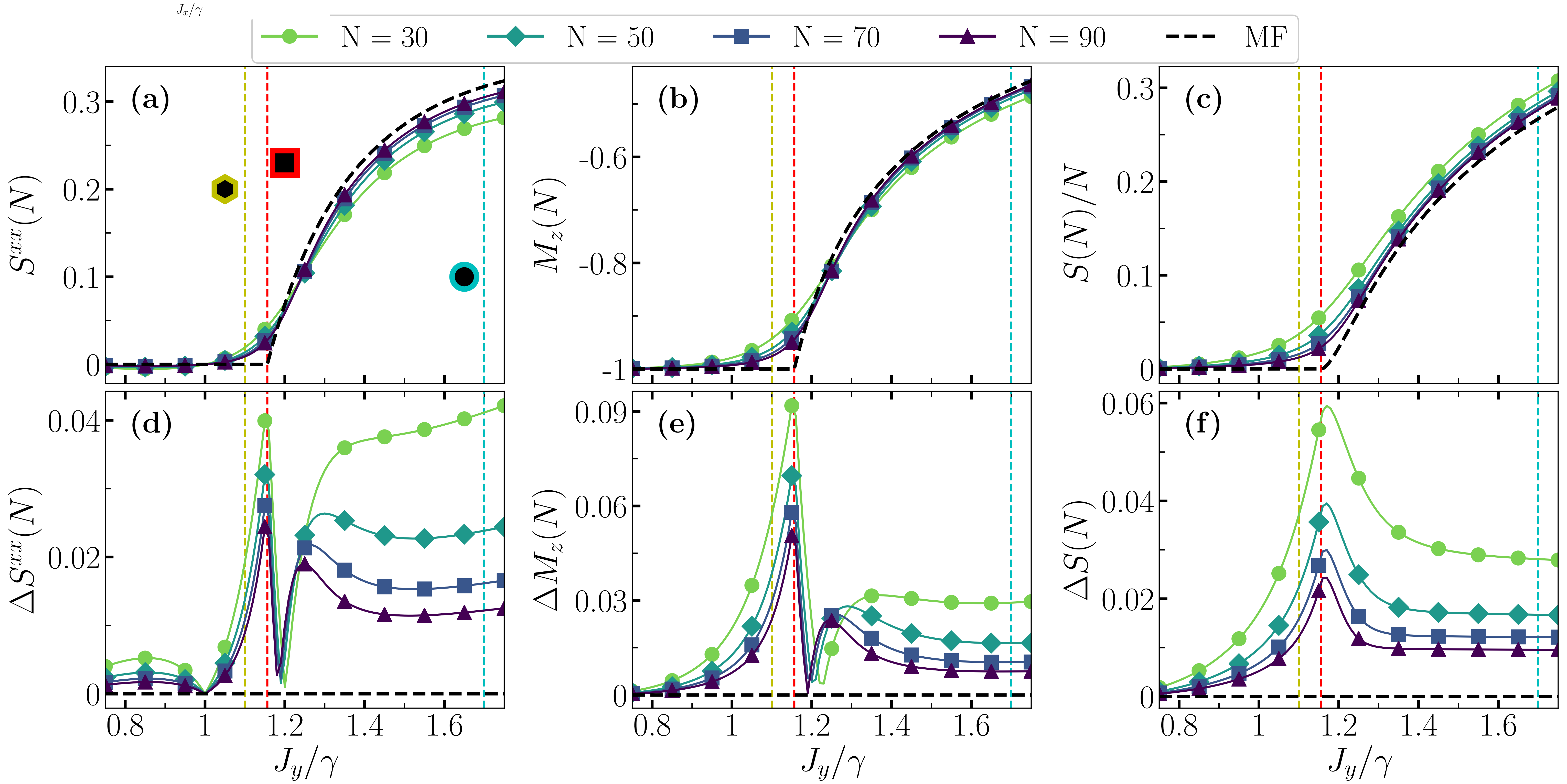
Steady-state behavior: Local dissipation



$$\hat{H} = \frac{1}{Z}\sum_{\langle i,j \rangle}\left(J_x\hat{\sigma}_i^x\hat{\sigma}_j^x + J_y\hat{\sigma}_i^y\hat{\sigma}_i^y + J_z\hat{\sigma}_i^z\hat{\sigma}_j^z\right)$$

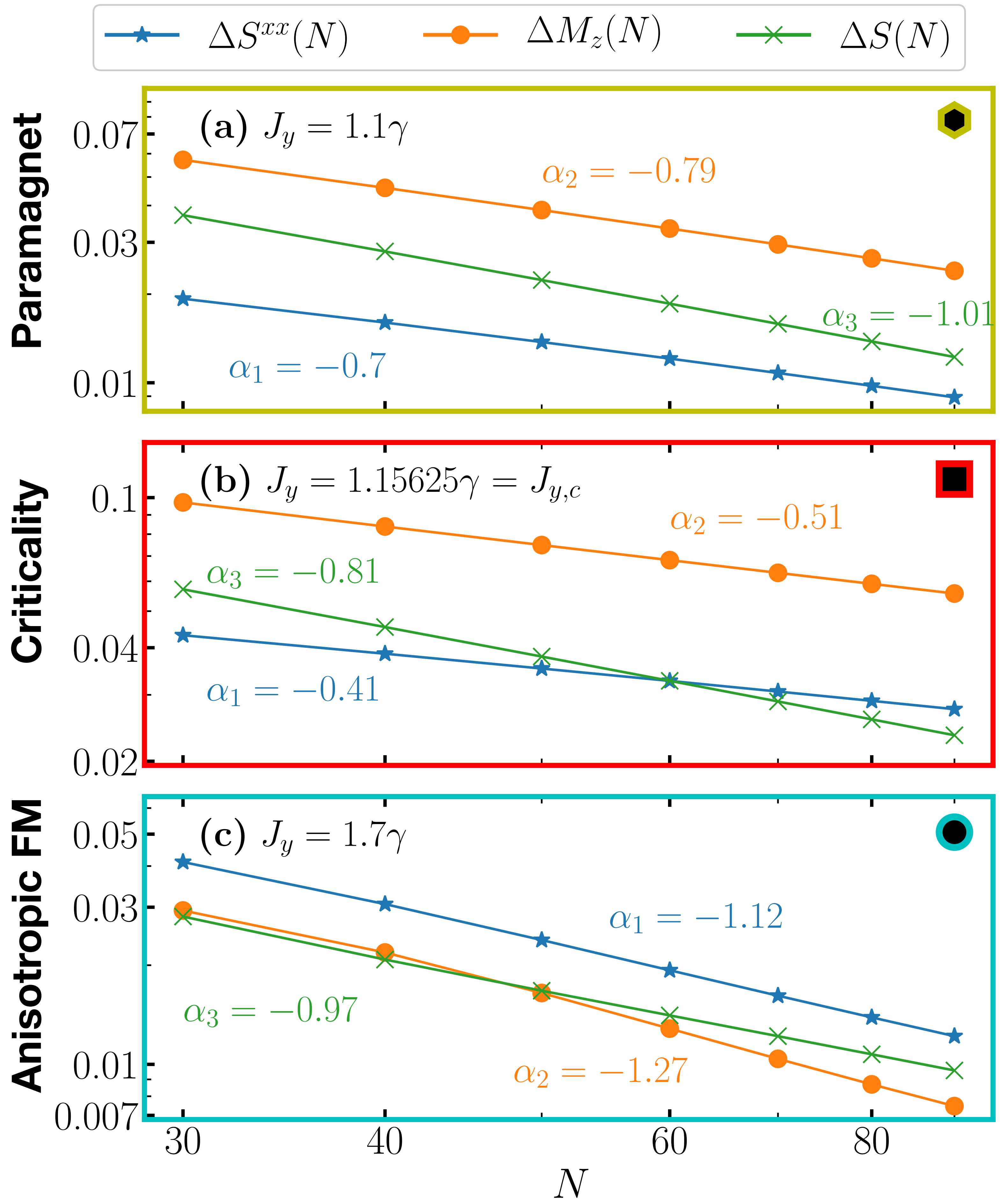
$$\frac{\partial\hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H},\hat{\rho}(t)\right] + \gamma\sum_{j=1}^{N}\mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t)$$

Study across the Phase Transition $\frac{\partial\hat{\rho}(t)}{\partial t} = 0$



Spin-Structure Factor **Magnetization** **Von Neumann Entropy**

Scaling in different points



$J_x = 0.6\gamma,\ J_z = \gamma$

https://arxiv.org/abs/1912.07570

Regime of High Anisotropy

Dissipative XYZ model

$$S^{\alpha\beta}(\mathbf{k}) = \frac{1}{N(N-1)} \sum_{j \neq l} e^{i\mathbf{k}\cdot(\mathbf{j}-\mathbf{l})} \langle \hat{\sigma}_j^{\alpha} \hat{\sigma}_l \rangle, \quad \mathbf{k} = 0$$

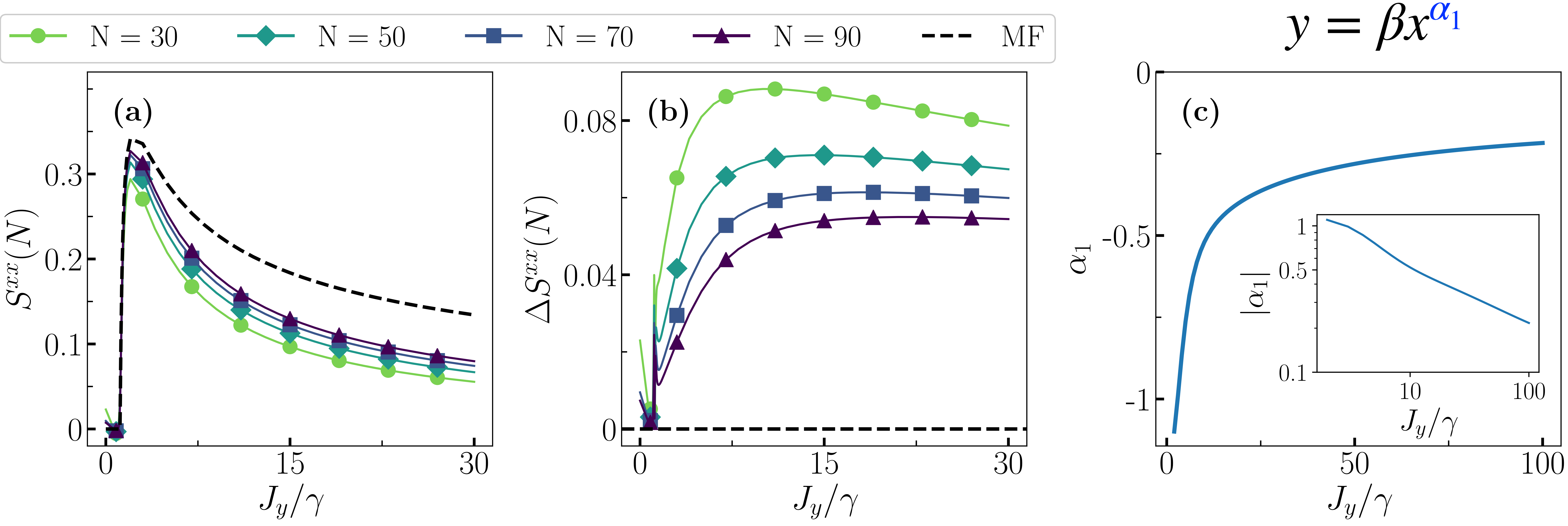
$$\frac{\partial \hat{\rho}(t)}{\partial t} = 0$$

Spin-structure Factor

Spin-structure Factor (MF difference)

Log-log scaling

$$y = \beta x^{\alpha_1}$$



$J_x = 0.6\gamma,\ J_z = \gamma$

https://arxiv.org/abs/1912.07570

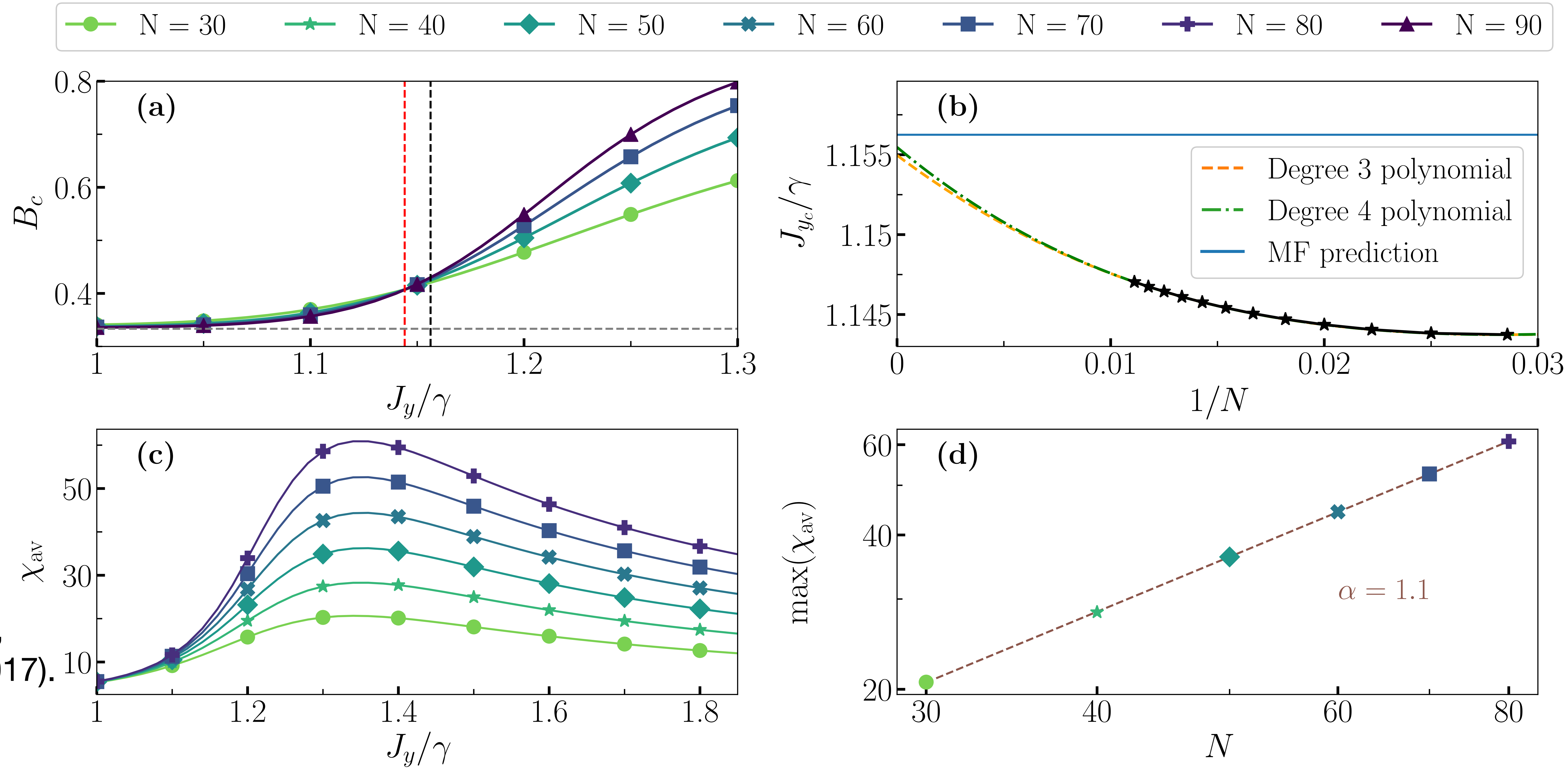
Pinpointing the phase transition

Dissipative XYZ model

$J_x = 0.6\gamma,\ J_z = \gamma$

Bimodality Coefficient

$$B_c = \frac{\langle \hat{S}_x^2 \rangle_{ss}^2}{\langle \hat{S}_x^4 \rangle_{ss}}$$



Fairly **Good**

Angular Average Susceptibility

χ_{av}

R. Rota, …, and C. Ciuti,
Phys. Rev. B **95**, 134431 (2017).

Non-predictive!

https://arxiv.org/abs/1912.07570

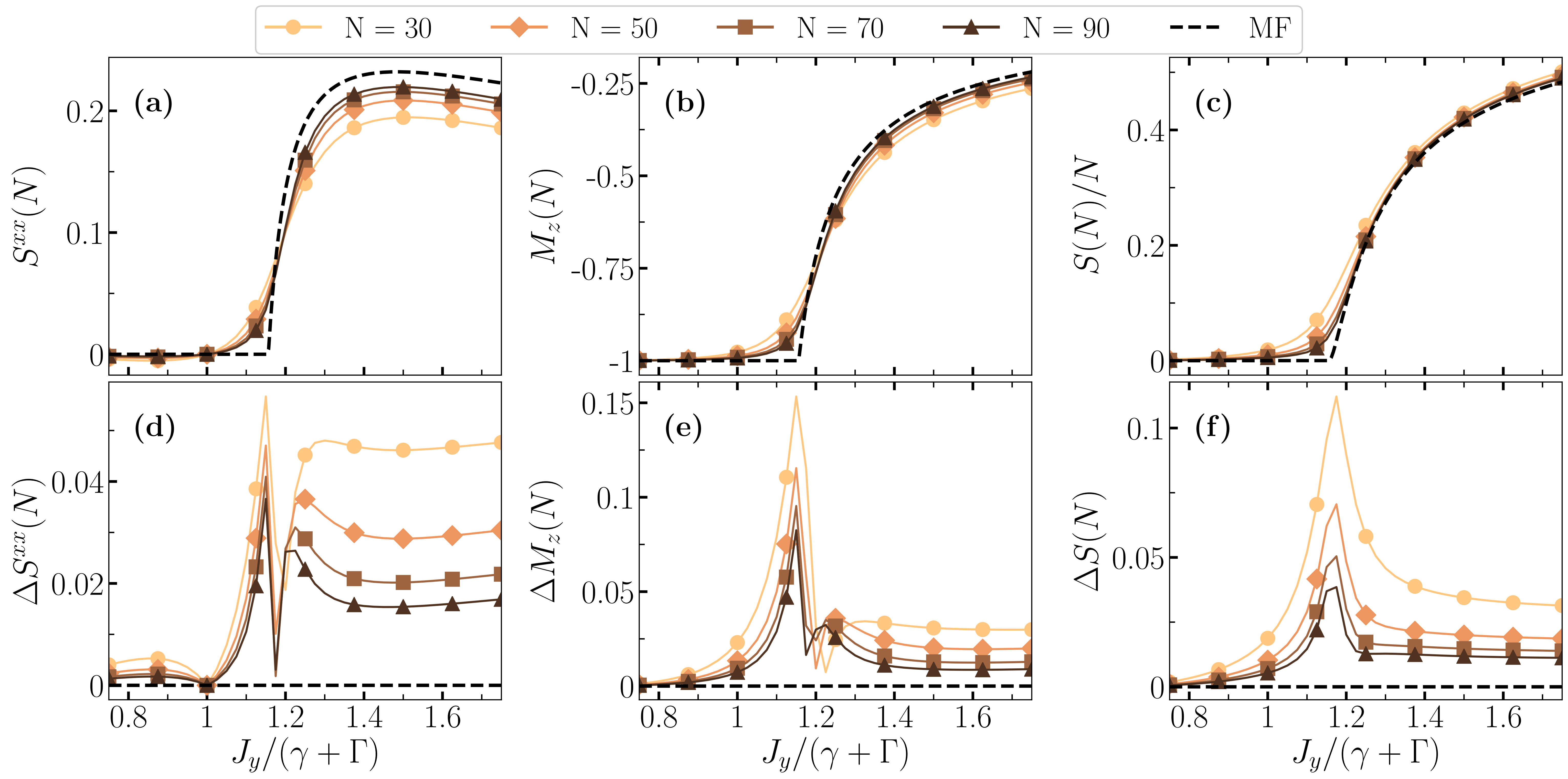
Local and collective dissipation

XYZ model

$$\hat{H} = \frac{1}{Z}\sum_{\langle i,j\rangle}\left(J_x\hat{\sigma}_i^x\hat{\sigma}_j^x + J_y\hat{\sigma}_i^y\hat{\sigma}_i^y + J_z\hat{\sigma}_i^z\hat{\sigma}_j^z\right)$$

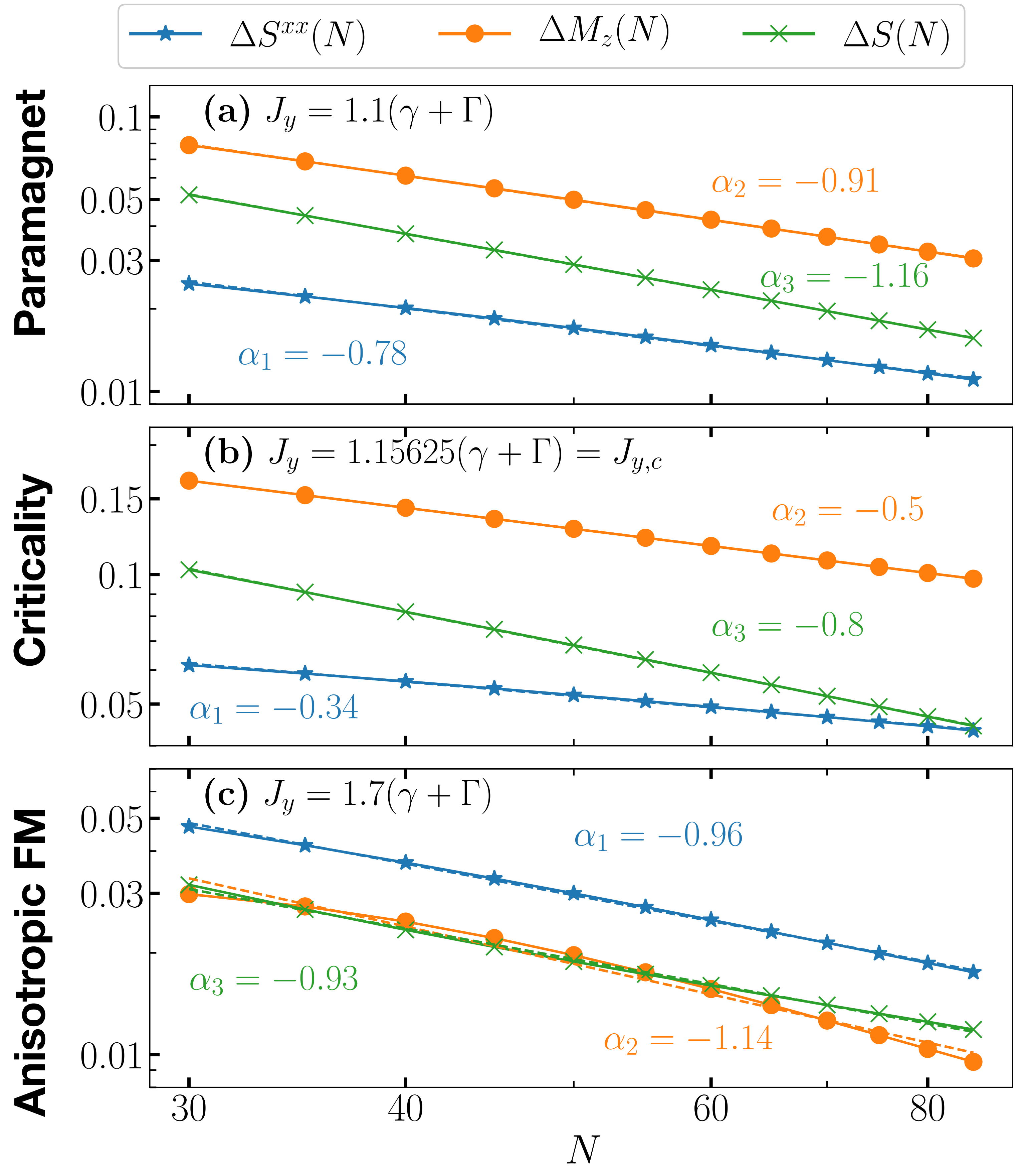
$$\frac{\partial\hat{\rho}(t)}{\partial t} = \mathscr{L}\hat{\rho}(t) = -i\left[\hat{H},\hat{\rho}(t)\right] + \gamma\sum_{j=1}^{N}\mathscr{D}[\hat{\sigma}_j^-]\hat{\rho}(t) + \frac{\Gamma}{N-1}\mathscr{D}[\sum_{j=1}^{N}\hat{\sigma}_j^-]\hat{\rho}(t)$$

Study across the Phase Transition $J_x = 0.6\gamma,\ J_z = \gamma$



Spin-Structure Factor **Magnetization** **Von Neumann Entropy**

Scaling in different points



https://arxiv.org/abs/1912.07570

Conclusions

All-to-all dissipative XYZ model

- **Mean Field performs worse than expected. Relevant for experiments**

- **Evidence of a highly entropic ferromagnetic phase**

- **No antiferromagnetic phase**

- **Local and collective dissipation: 2nd order transition**

- **PT-symmetric Liouvillian spectra: gap from the *anti*gap**

- **Open questions:**
  - **Quenches**
  - **Chaotic Dynamics and Quantum measures**
  - **Exploit other symmetries**

QuTiP

qutip.org

QuTiP: The Quantum *Physics* Simulator

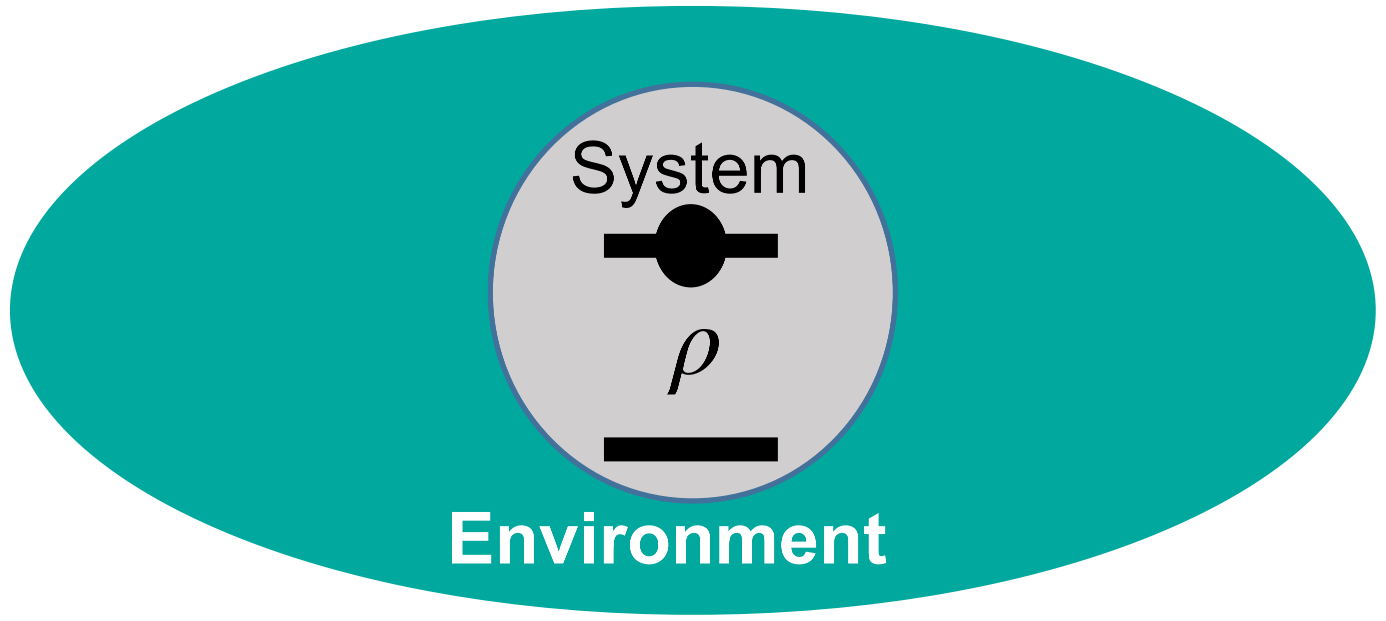
The **Qu**antum **T**oolbox **i**n **P**ython

QuTiP

Quantum Toolbox in Python

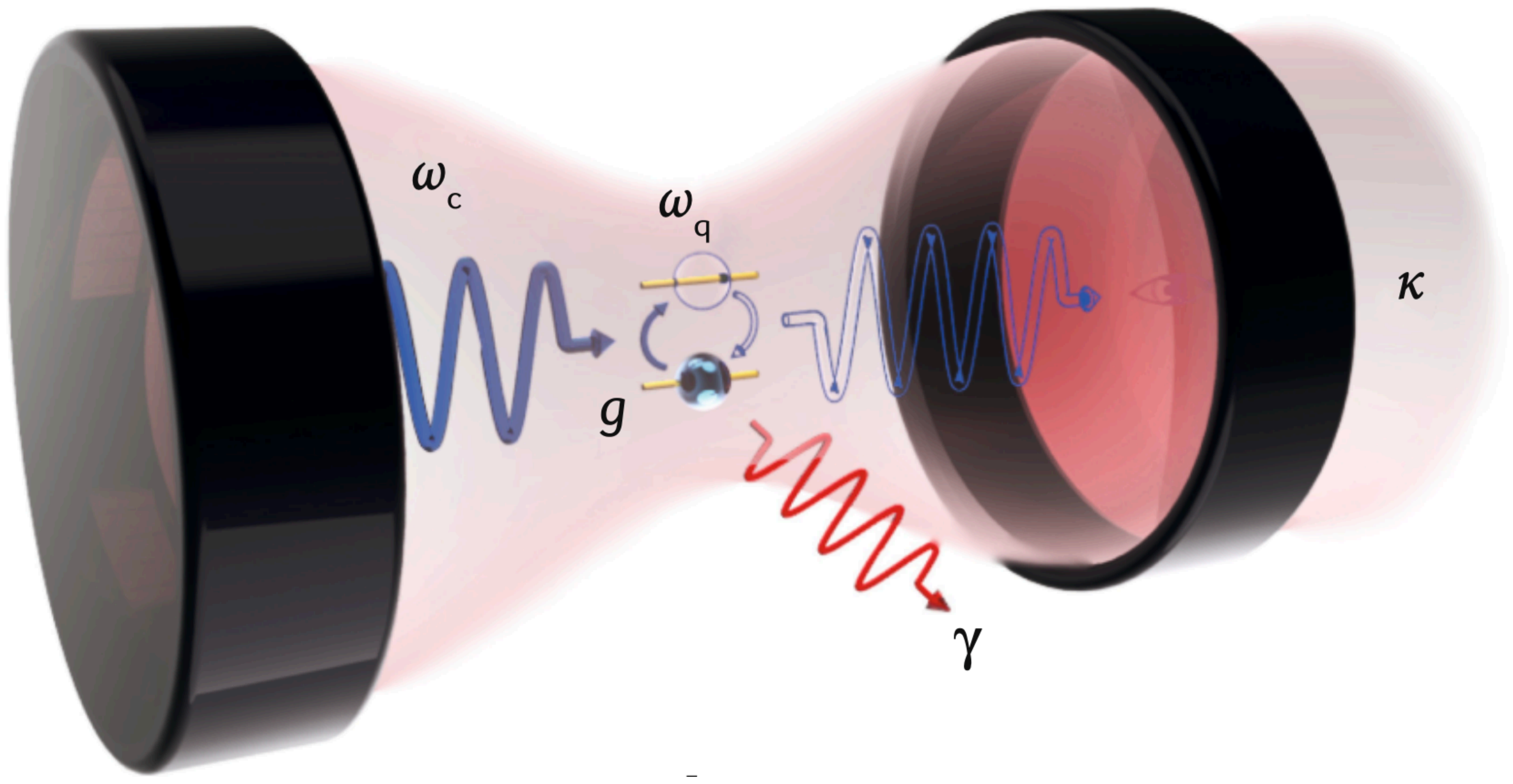
qutip.org

A toolbox to study the **open** quantum dynamics of real physical systems.



Cavity Quantum Electrodynamics (Cavity QED)

Using the **Qu**antum **T**oolbox **in** **P**ython to study physics

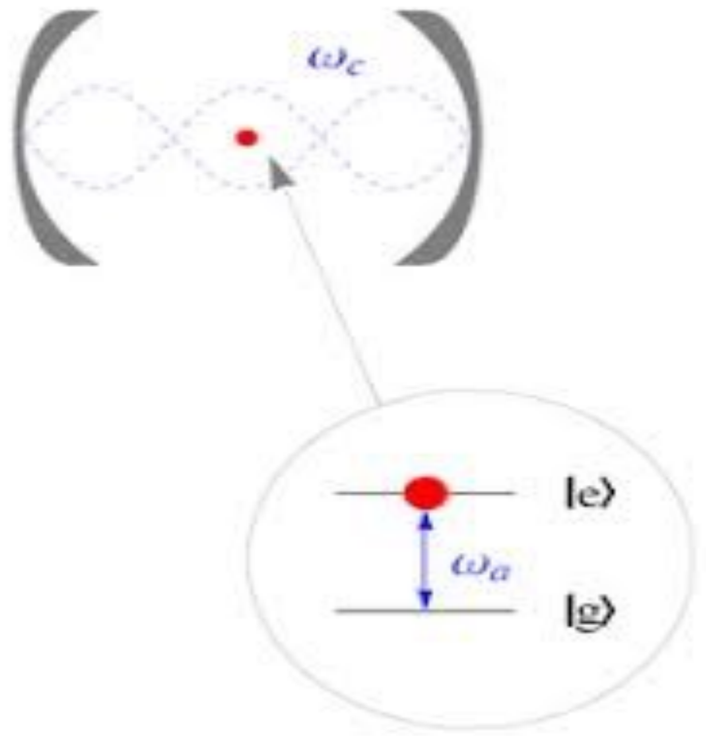


A. F. Kockum, A. Miranowicz, S. De Liberato, S. Savasta & Franco Nori, Nature Reviews Physics, **1** 19 (2019)

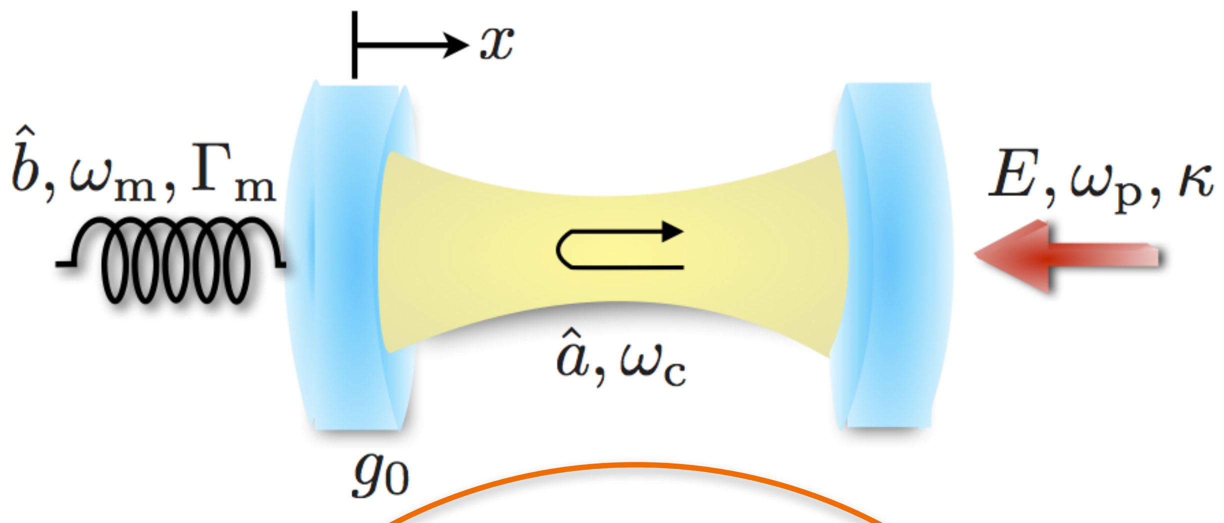
QuTiP: The Quantum *Physics* Simulator

The **Qu**antum **T**oolbox **i**n **P**ython

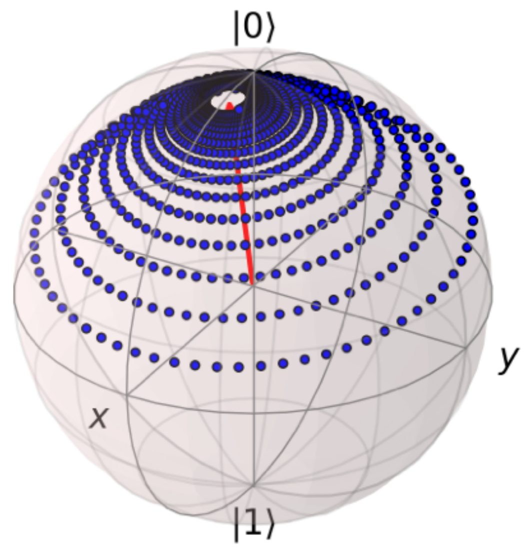
Cavity QED



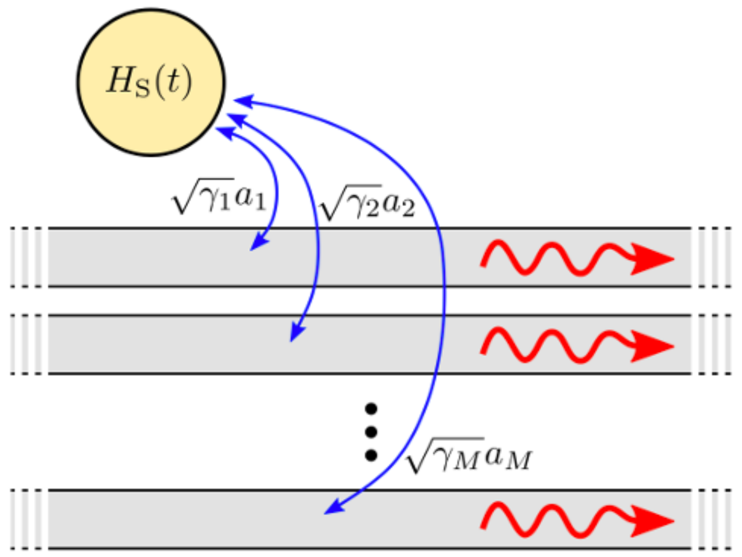
Optomechanics



Quantum Optics, QIP



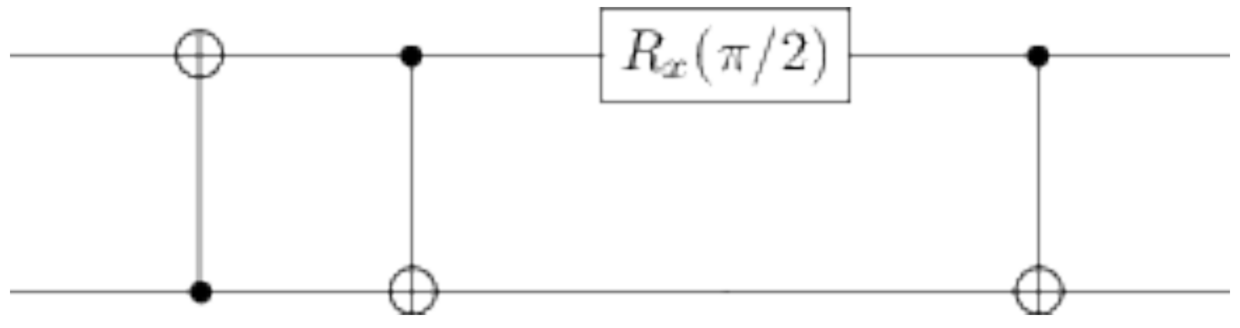
Waveguide QED



QuTiP

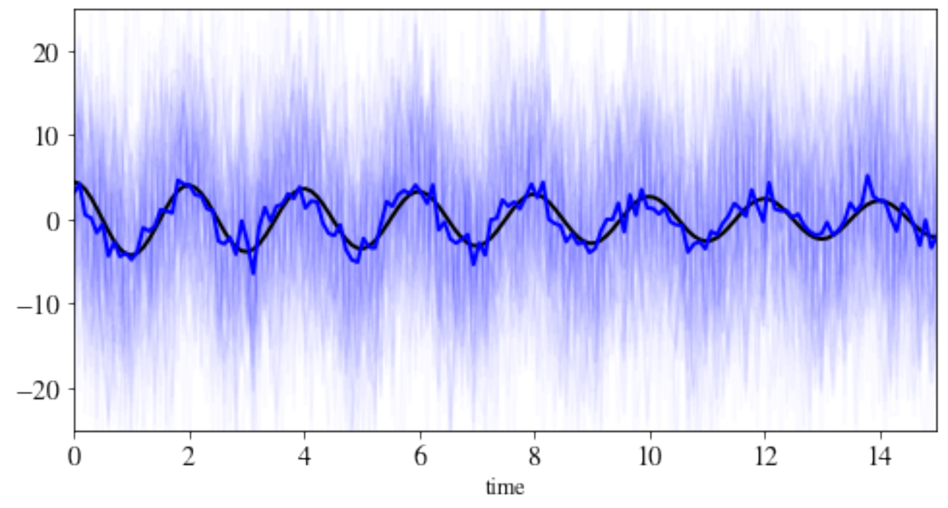
qutip.org

Quantum Circuits

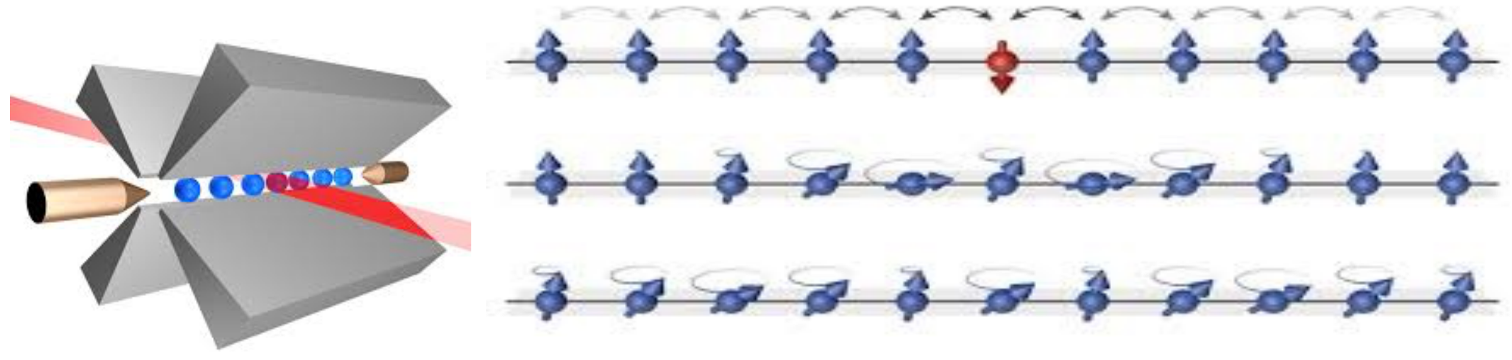


Quantum Optimal Control

Stochastic Dynamics



Spin Lattice Dynamics



Cloud-based Notebooks on Open Quantum Systems

The **Qu**antum **T**oolbox **i**n **P**ython

You can find an interactive notebook at

https://github.com/nathanshammah/interactive-notebooks

Take a snapshot

Repository: interactive-notebooks

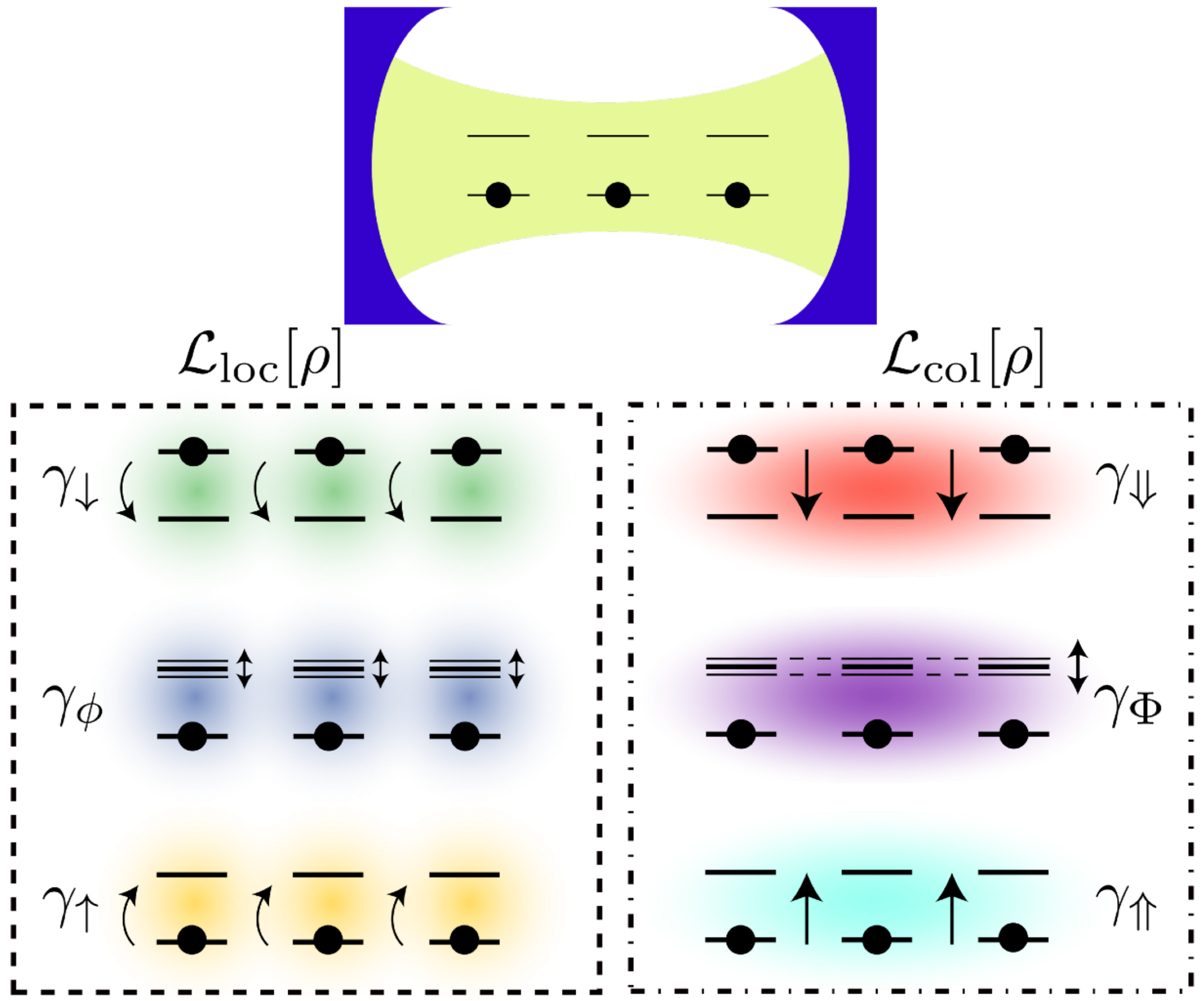
You can run the notebooks live

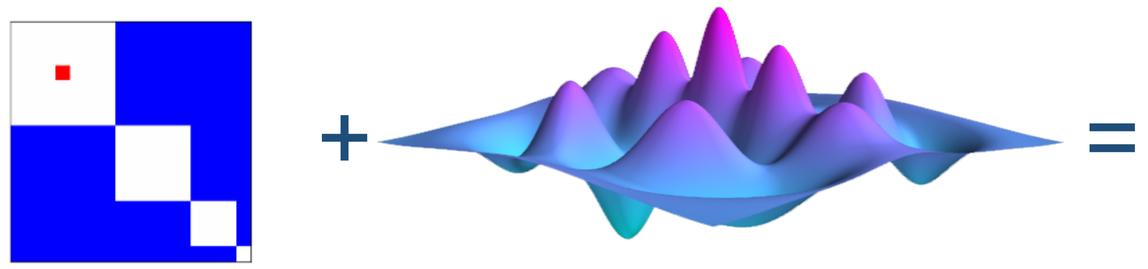
launch binder

Abdus Salam ICTP
UNESCO, AIEA
Trieste, Italy
July-August 2019

Efficiently studying out-of-equilibrium systems

What's going on





import qutip.piqs

piqs.readthedocs.io

qutip.org/tutorials#piqs

Efficiently model local dissipation

Collective dissipation

vs. Local dissipation

vs. Coherent coupling

N. Shammah *et al.*,
***Phys Rev A* 98**, 063815 (2018)

Code: Nathan Shammah and Shahnawaz Ahmed

piqs
QuTiP library
Now a qutip module

krotov
QuTiP-based quantum optimal control library

matsubara
A qutip plugin for non-Markovian dynamics

qutip.noise
Noisy quantum circuits using QuTiP solvers

QuTiP ecosystem: Like AstroPy, but for Quantum

Engineering Quantum Optimal Control

What's going on

Examples

render on nbviewer | launch binder

- Optimization of a State-to-State Transfer in a Two-Level-System
- Optimization of a state-to-state transfer in a lambda system with RWA
- Optimization of a dissipative state-to-state transfer in a Lambda system
- Optimization of Dissipative Qubit Reset
- Optimization of an X-Gate for a Transmon Qubit
- Optimization of a Dissipative Quantum Gate
- Optimization towards a Perfect Entangler

krotov.readthedocs.io

3 How to use the krotov package

3.1 Overview

To use Krotov's method for quantum optimal control in a Python script or Jupyter notebook, start by importing the package, as well as QuTiP [24].

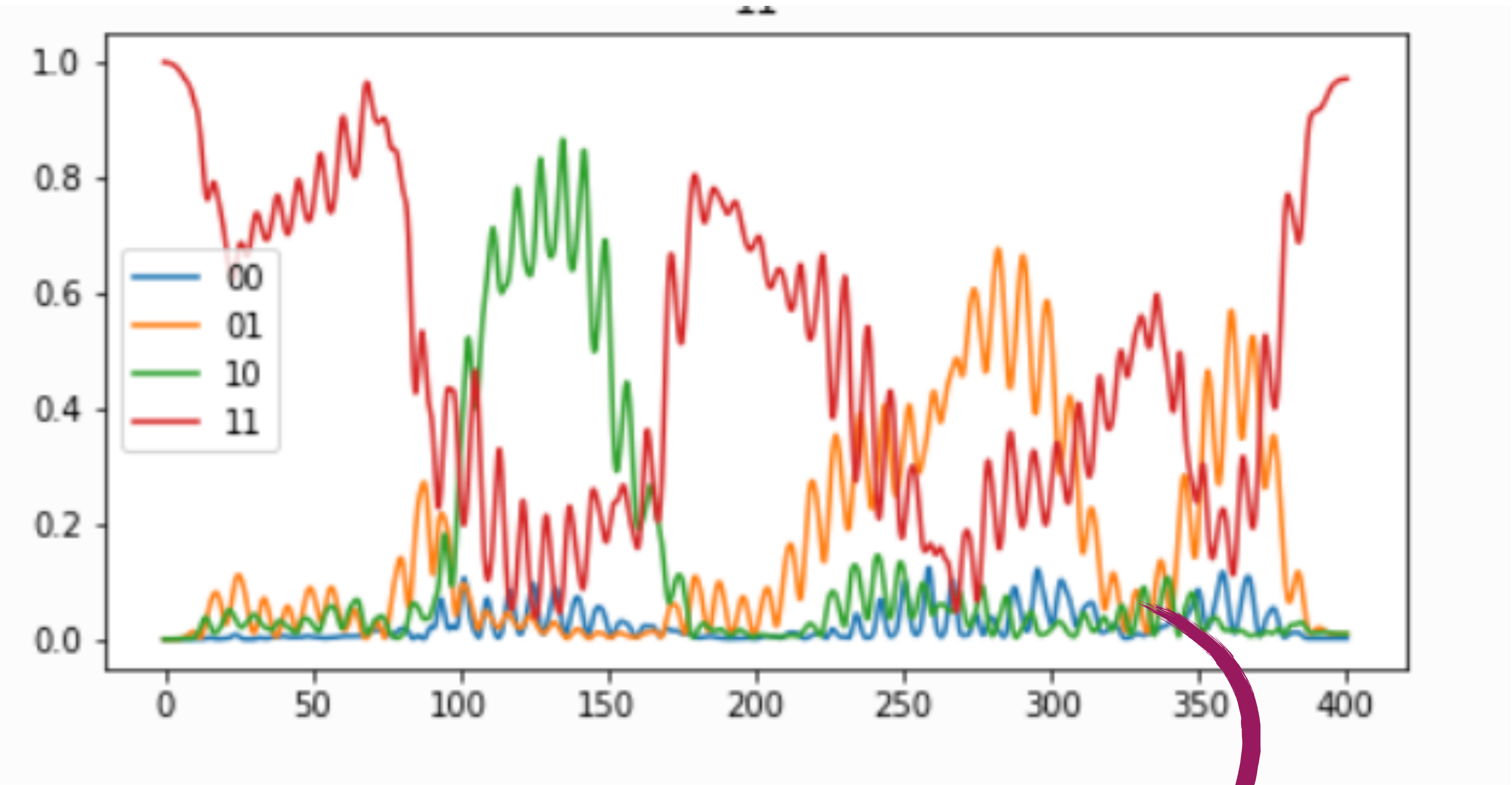
```
import krotov
import qutip
```

Then,

- define the necessary quantum operators and states using QuTiP objects,
- create a list of optimization objectives, as instances of `krotov.Objective`,
- call `krotov.optimize_pulses` to perform an optimization of an arbitrary number of control fields over all the objectives.

The integration of the `krotov` package with QuTiP is central: All operators and states are expressed as `qutip.Qobj` quantum objects. Moreover, the `optimize_pulses` interface for

Population evolutions for a gate (iSWAP)



Krotov: A Python implementation of Krotov's method for quantum optimal control
M. H. Goerz *et al.*, ***SciPost Phys.* 7**, 080 (2019)

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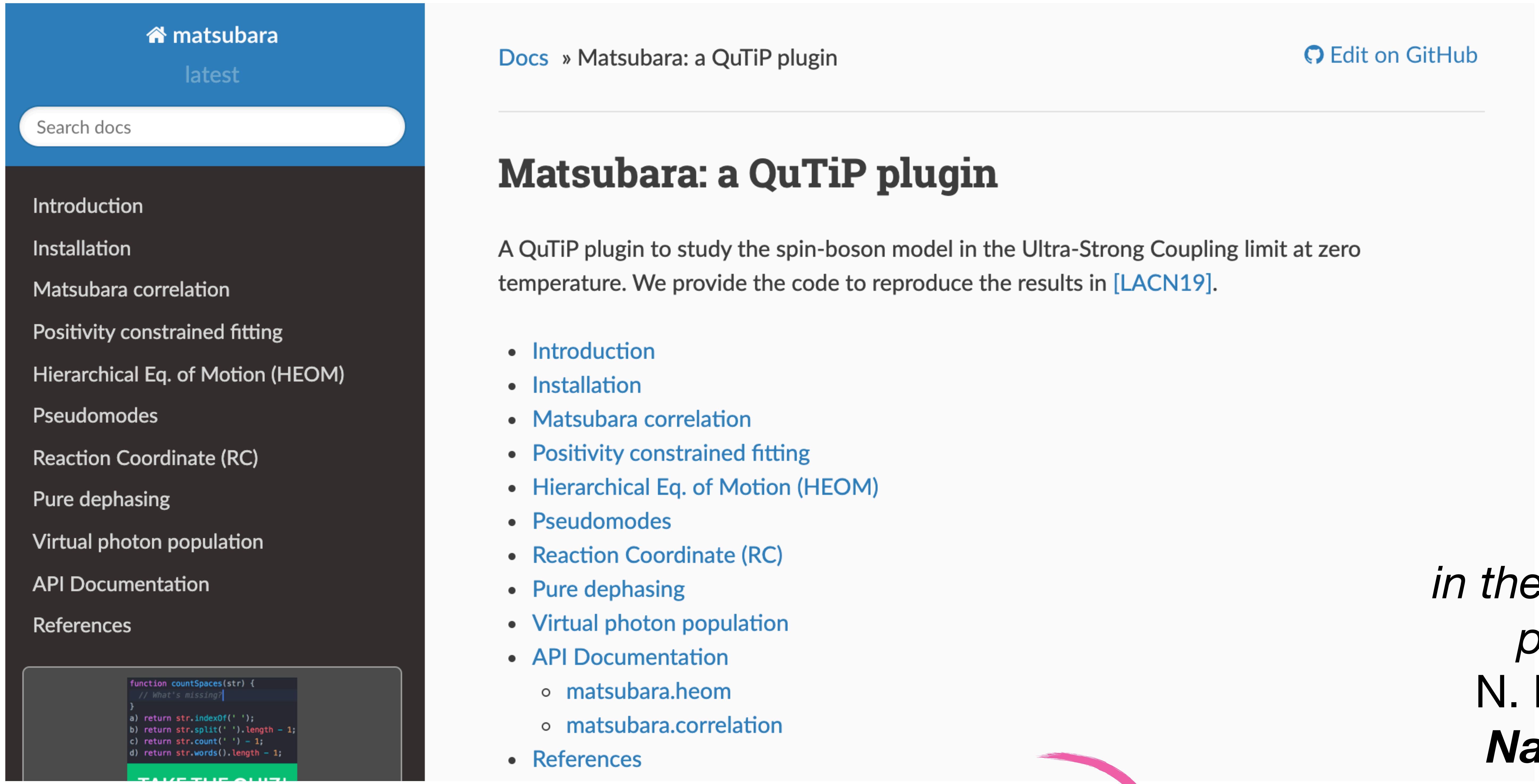
QuTiP ecosystem: Like AstroPy, but for Quantum

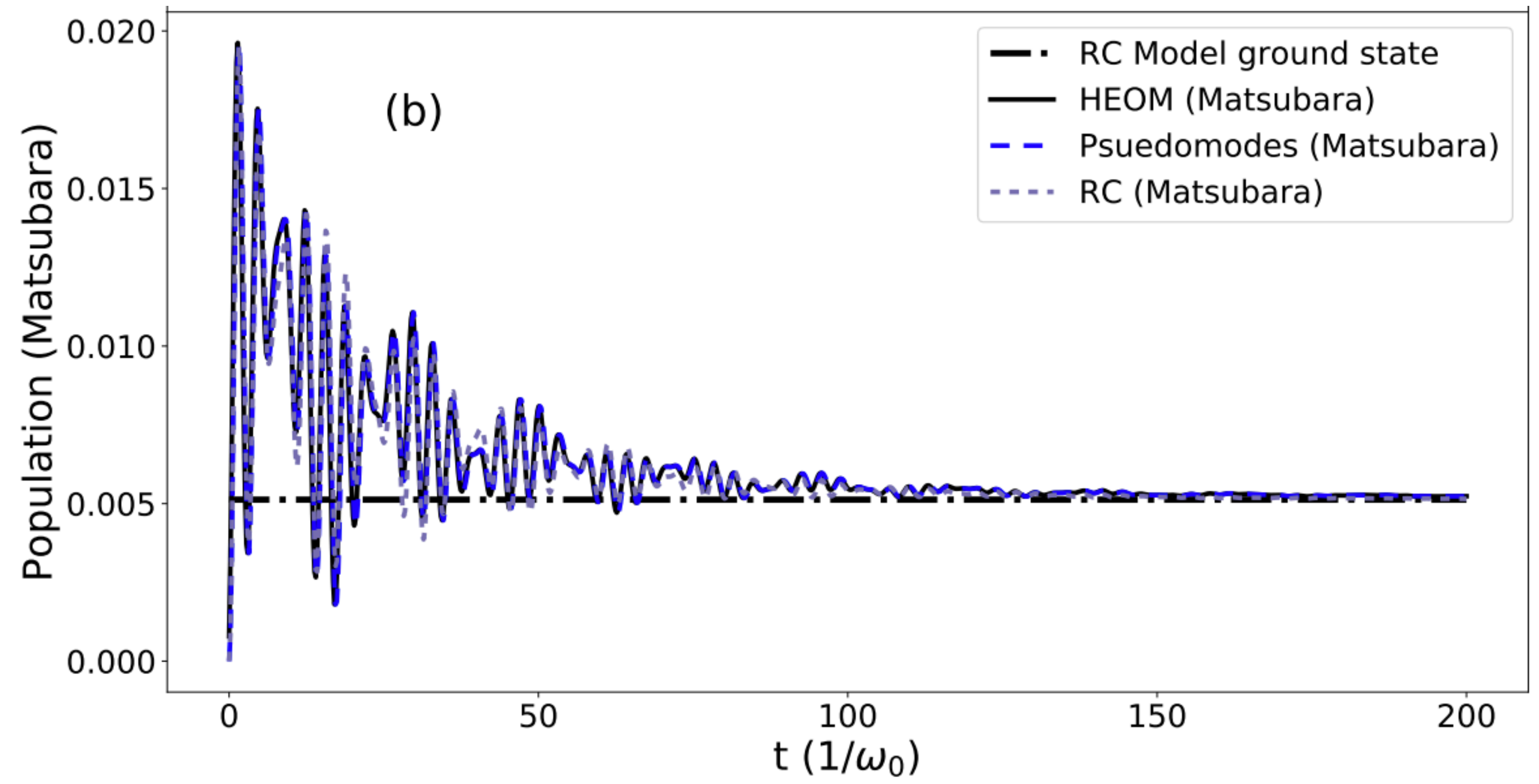
QuTiP plugin: The environment is watching

What's going on

matsubara.readthedocs.io



Comparison of open system models



Virtual excitations
in the ultra-strongly-coupled spin-boson model:
physical results from unphysical modes
N. Lambert, S. Ahmed, M. Cirio, and F. Nori
Nature Communications **10**, 3721 (2019)

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QuTiP ecosystem: Like AstroPy, but for Quantum

New in QuTiP *dev* version (Nov 2019)

qutip.nisq

Model noise in quantum information processing (QIP)

QuTiP's QIP module represents ideal quantum circuits.

Student: Boxi Li (ETH Zurich)

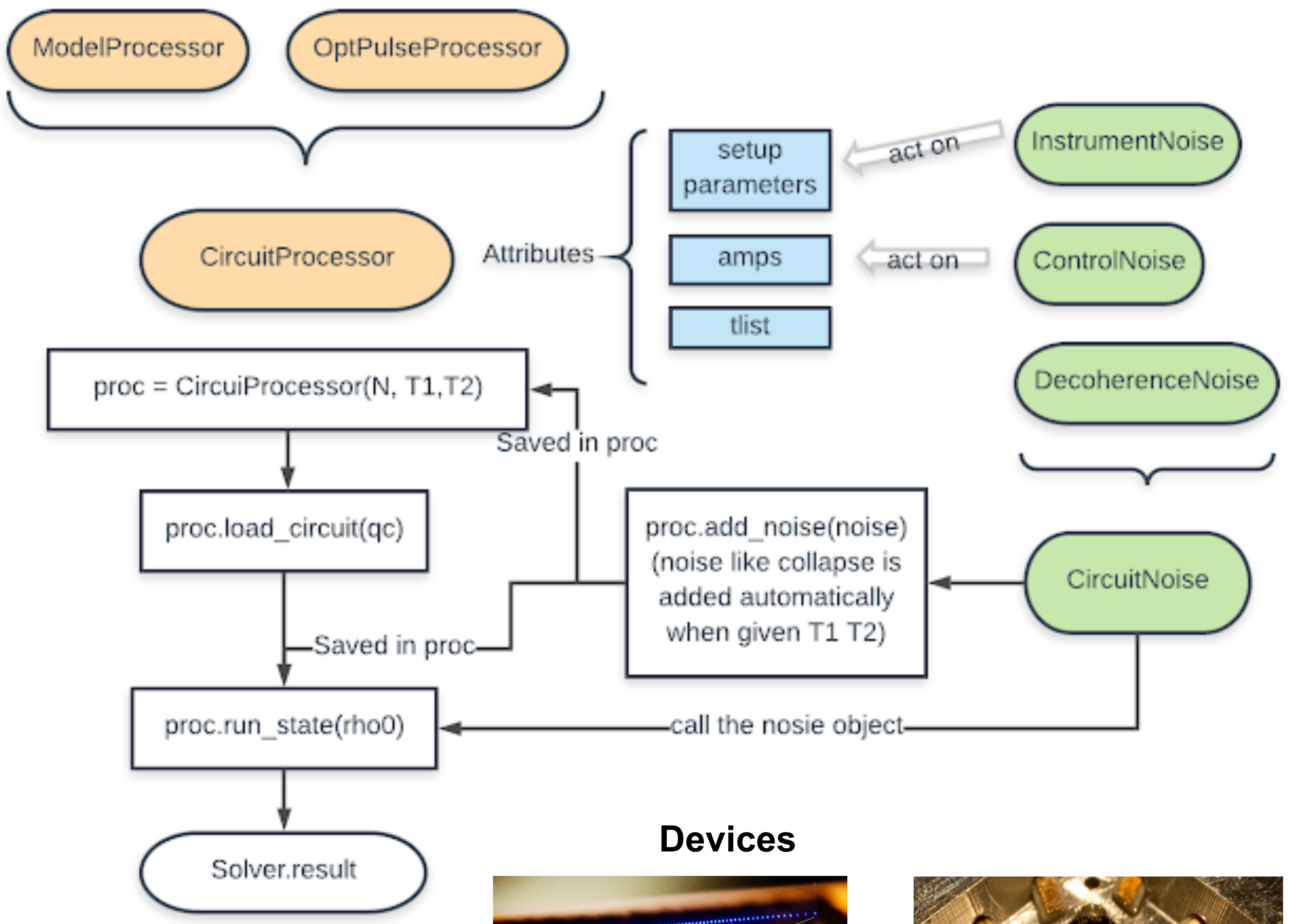
Objectives:
- Go beyond gates as instantaneous unitary transformation
- Noise model for realistic devices
- Noise model for dissipative dynamics

Deployed results:
- Added Mølmer-Sørensen gate
- Allowed user-defined gates
- Added optical pulses for gate shaping

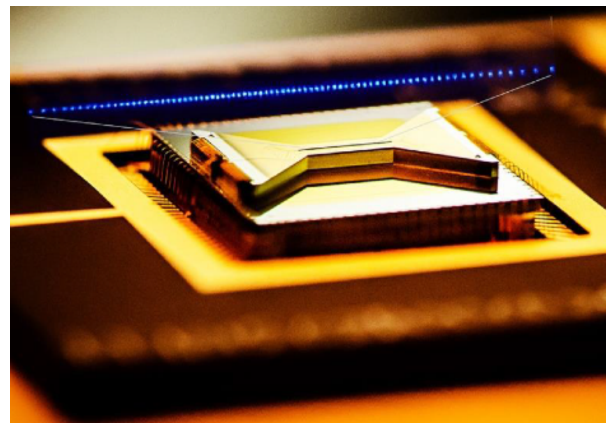
Code: Boxi Li. Github: BoxiLi
Mentors: Alex Pitchford,
Neill Lambert,
Shahnawaz Ahmed,
Nathan Shammah

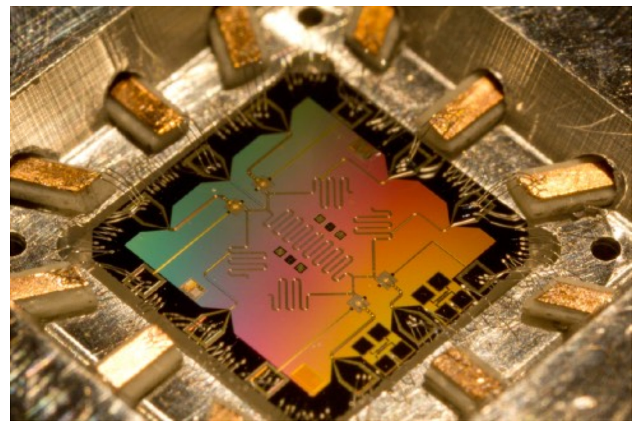
Google Summer of Code

https://gsoc2019-boxili.blogspot.com

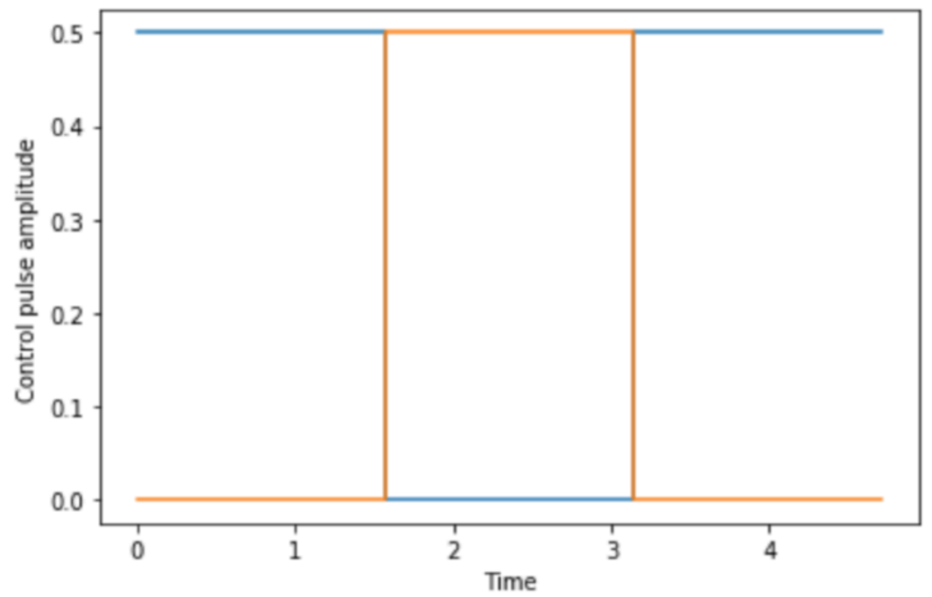


Devices

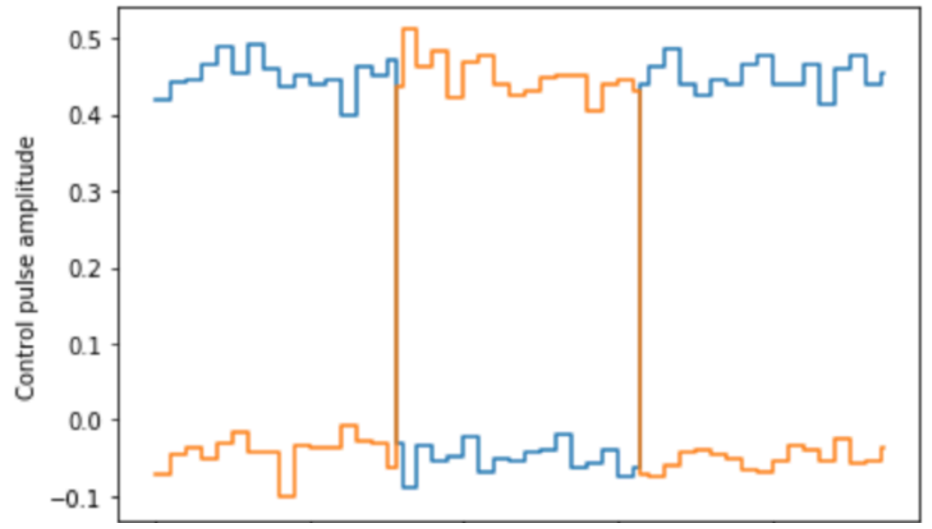




Perfect Unitary




```
[20]: processor_white.plot_pulses(noisy=True)
[20]: (<Figure size 432x288 with 1 Axes>,
       <matplotlib.axes._subplots.AxesSubplot at 0x269999bb710>)
```



Noisy pulses

piqs
QuTiP library
Now a qutip module

krotov
QuTiP-based quantum optimal control library

matsubara
A qutip plugin for non-Markovian dynamics

qutip.noise
Noisy quantum circuits using QuTiP solvers

...

QuTiP ongoing expansion (2019)

qutip.qip.noise

Model noise in quantum information processing (QIP)

QuTiP's QIP module represents ideal quantum circuits.

Student: Boxi Li (ETH Zurich)

Objectives:
- Go beyond gates as instantaneous unitary transformation
- Noise model for realistic devices
- Noise model for dissipative dynamics

First results:
- Added Mølmer-Sørensen gate
- Allowed user-defined gates
- Added optical pulses for gate shaping

Code: Boxi Li. Github: BoxiLi
Mentors: Alex Pitchford,
Neill Lambert,
Shahnawaz Ahmed,
Nathan Shammah

Google Summer of Code

https://gsoc2019-boxili.blogspot.com

qutip.lattice

Model lattices in QuTiP

A qutip.lattice module implementing Hamiltonians for paradigmatic 1D lattice models.

Student: Saumya Biswas (U. Oregon)

Objectives:
Single particle picture,
- SSH model (topological properties)
Spin chains and bosonic lattices
- Bose-Hubbard model

Complement existing libraries:
- QuSpin
- pythontb

Code: Saumya Biswas
Mentors: Clemens Gneiting,
Eric Giguere,
Shahnawaz Ahmed,
Nathan Shammah

Google Summer of Code

https://latticemodelfunctions.blogspot.com

qutip.tiqs

Translational invariant Lindblad dynamics

Driven-dissipative systems
Liouvillian spectrum

Idea
Exploit the symmetries of the dynamics
Spin chains and bosonic lattices
Liouvillian spectrum

$$\dot{\rho} = \mathscr{L}\rho$$

$$[\mathscr{L}, S] = 0$$

F. Minganti, *et.al.* Phys. Rev. A 98, 042118 (2018)

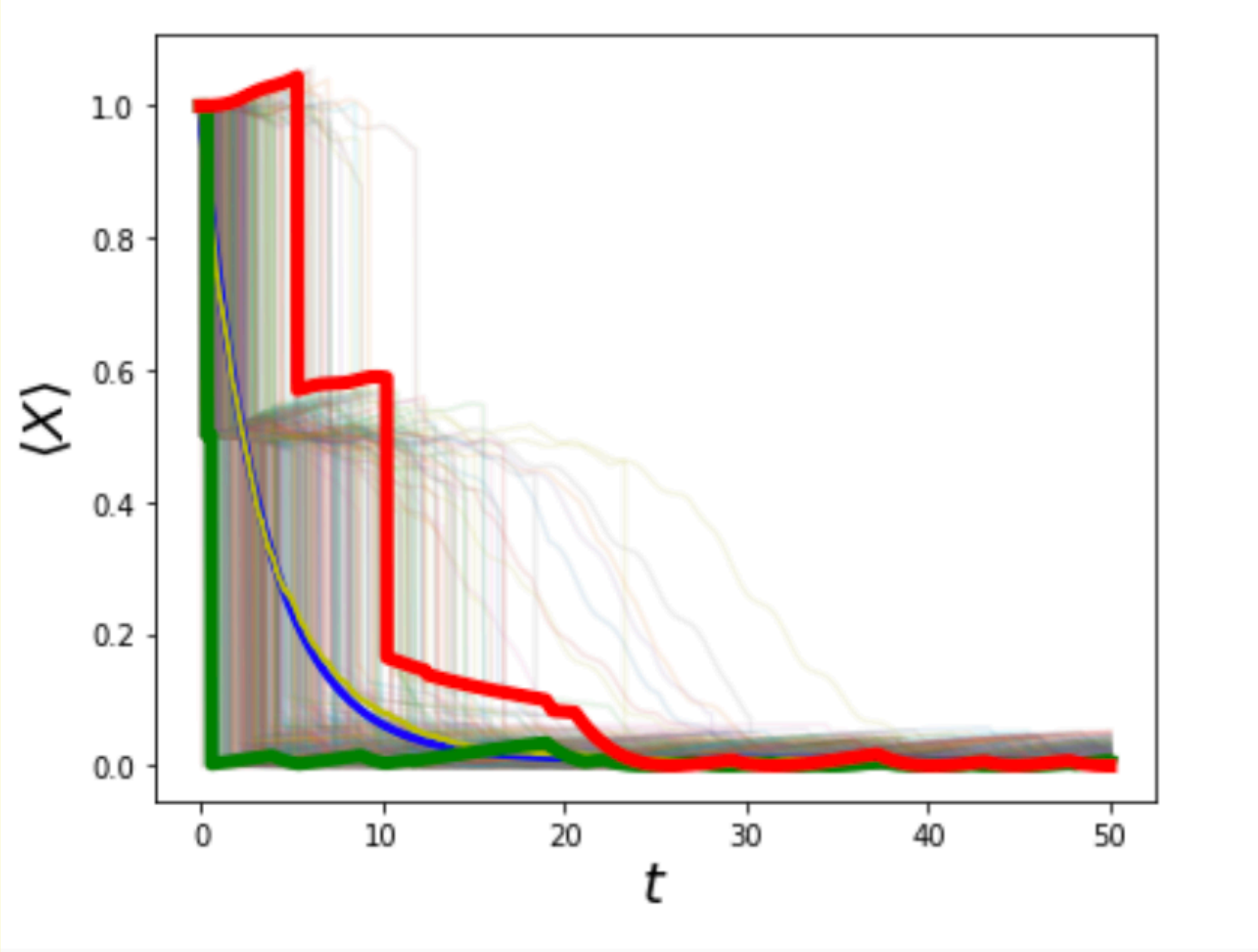
Code: Fabrizio Minganti. Github: fminga

Partly Deployed → **In Deployment** → **In Development**

QuTiP 4.4: Major updates

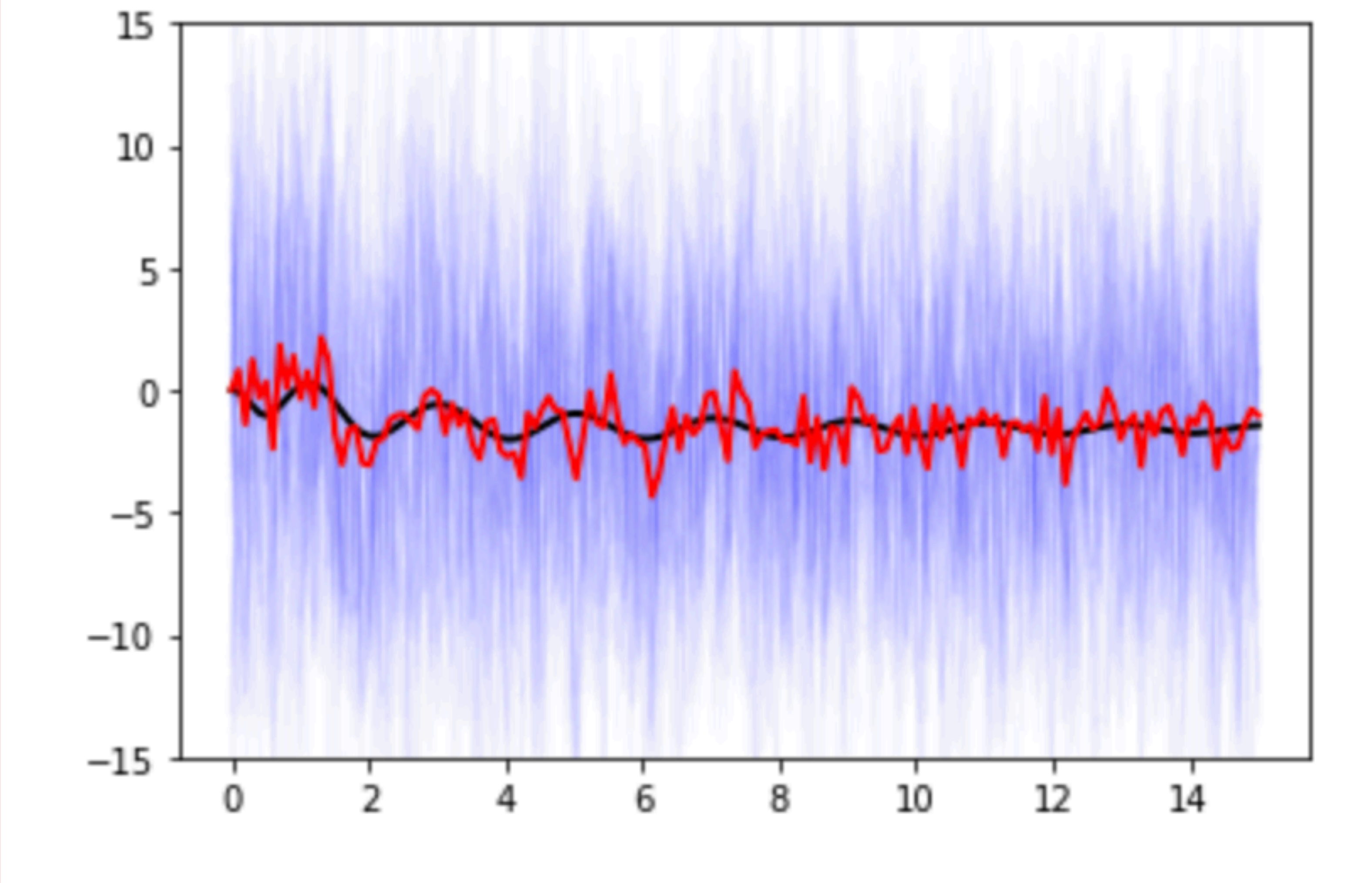
The **Qu**antum **T**oolbox **i**n **P**ython

Monte Carlo Quantum Trajectories
`mcsolve`



50x faster
Time-dependent jumps

Stochastic Master Equations
`smesolve`



More general
More integration methods
Benchmarked solvers

Quantum Information Processing

User-defined Quantum Gates

`molmer_sorensen`

Quantum Hellinger distance

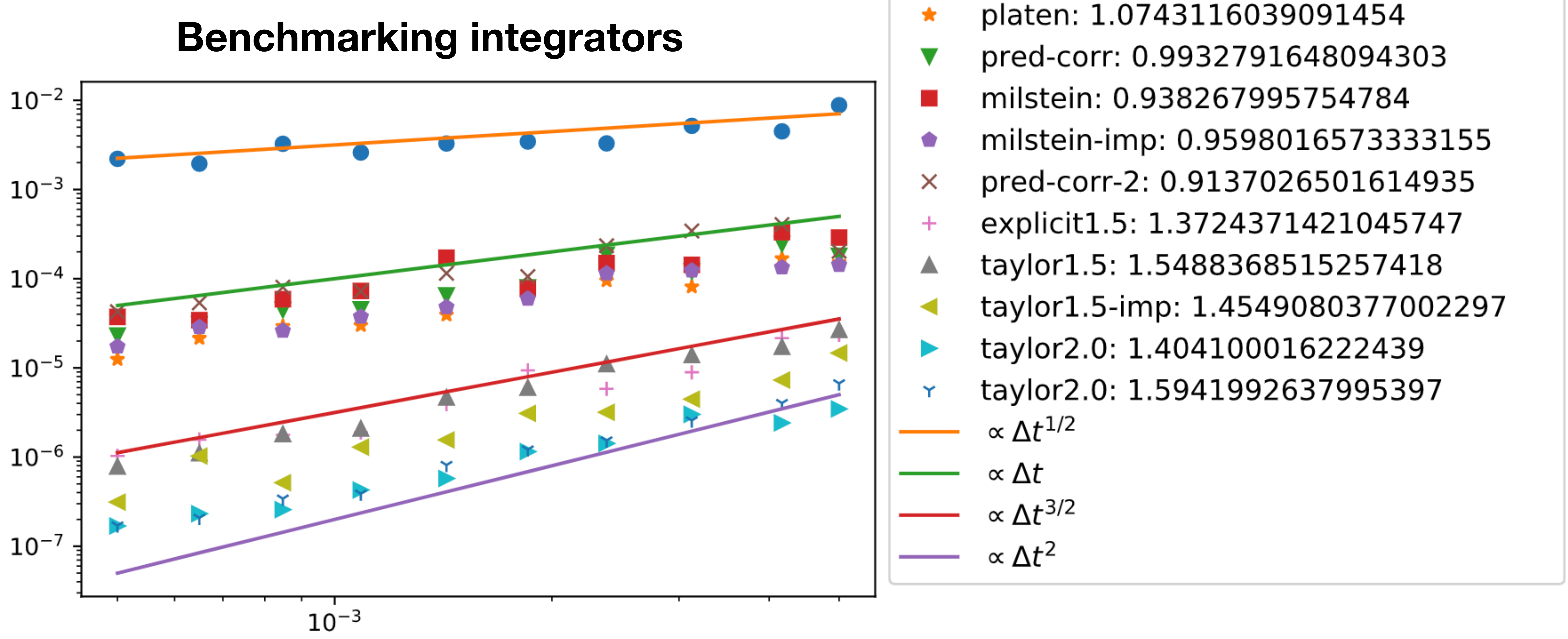
Bug Fixes

More info: qutip.org
July 2019: 4.4.0
August 2019: 4.4.1
4.5 (March 2020)

QuTiP: Numerical Stochastic Solvers

The **Qu**antum **T**oolbox **i**n **P**ython

Method: extracted scaling




```
solution = ssesolve([H, c_ops = c_ops , fock(N), tlist, sc_op_td, e_op, **kwargs)
```

- `ssesolve`: Stochastic Schrödinger equation `result = ssesolve(H, rho0, times, [], c_ops, e_ops)`

- `smesolve`: Stochastic master equations `result = smesolve(H, rho0, times, [], c_ops, e_ops)`

How to interact with the QuTiP project

Multiple interaction channels

http://qutip.org/tutorials.html

Website:
Tutorials

http://qutip.org/docs/latest/

Documentation User Guide
Documentation API: docstring comments
Documentation API: source code

https://groups.google.com/forum/#!forum/qutip

Help Group:
Ask questions (installation, physics)
Find *already answered* questions

https://github.com/qutip/qutip

GitHub:
Found a bug?
- Search answer in *already closed* issue
- Search *an open (unsolved)* issue on same topic
- Unknown? Open an Issue

Have a solution? Open a Pull Request (proposal for code modification of the official project source code)

https://gitter.im/qutip

Gitter Chat:
Join the conversation if you have other question

Thank you

@NathanShammah

GitHub: nathanshammah

Ideas and Goals for 2020

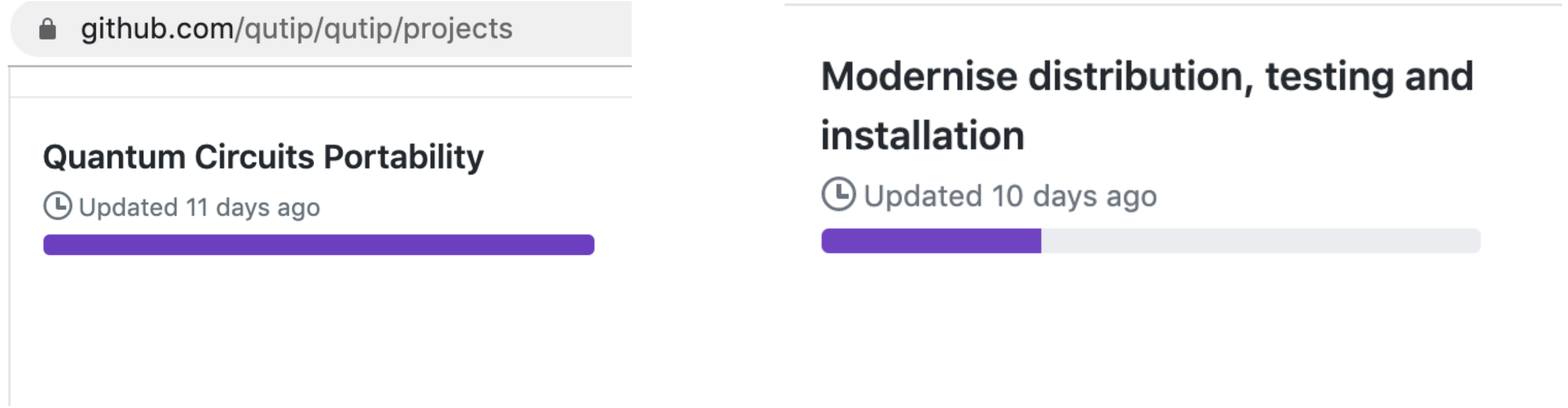
What’s next

Code: C++ and GPU-accelerated Non-Markovian Dynamics

Code: More flexible time-dependance

Community: KWoC 2020 (IIT Kharagpur); Google SoC 2020

Community: qutip/qutip-community: Projects from researchers



Contact me:
nathan.shammah@gmail.com

Devs: 2nd QuTiP dev Workshop (RIKEN, Spring 2020)

Project: QuTiP fiscally sponsored project of NumFOCUS

scikit-project: Easy steps to open-source a science project

The tools of open source make your code count

https://github.com/nathanshammah/scikit-project

A Guide to Building Your Open-Source Science Library

A cheatsheet to develop a scientific open-source library from scratch.

Zero to Library

Here you will find information to design, build, and release an open-source library to perform scientific research in Python from scratch to finish.

Code & Testing

GitHub

Travis CI

Documentation

SPHINX Python Documentation Generator

Read the Docs

Publication

python Package Index

CONDA

zenodo

binder

Mean-field validity in a dissipative spin model

"Mean-field validity in a dissipative critical system:
Liouvillian gap, PT-symmetric antigap,
and permutational symmetry in the XYZ model"

https://arxiv.org/abs/1912.07570

Dolf Huybrechts*, Fabrizio Minganti**, Franco Nori**, Michiel Wouters*, Nathan Shammah**

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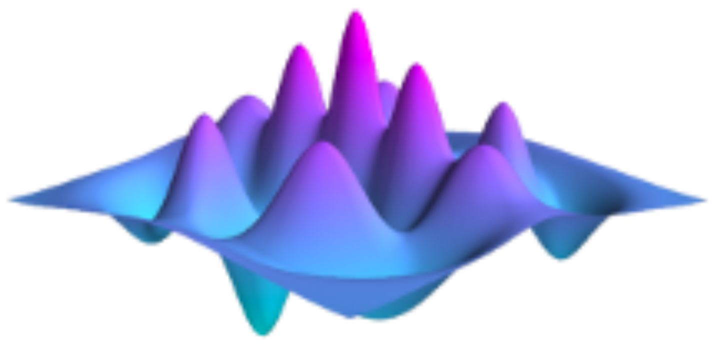


December 19th, 2019
University of Milan,
Milan, Italy

Thank You

Some ideas on QuTiP

Multiple directions: some details

Nathan Shammah
September 14th, 2018

Update: September 24th, 2019

Governance & Funding

Foundation
Sponsorships
Roles and acknowledgements

NUMFOCUS
OPEN CODE = BETTER SCIENCE

Updated qutip.org/devs:
- **Current / Former Lead Developers**
- **Original Designers / Supervisor**

Coders & Development

Internship programs (Google SoC)
Developers workshops
Strategy

Google Summer of Code

1st [QuTiP Devs] Workshop (RIKEN)

Over 10 talks:
- **Universities (Caltech, Stanford)**
- **R&D (Rigetti, Google)**
- **Conferences (Berkeley, IQIS)**

Education & Research

More modules, tutorials, info
try.qutip.org
Marketing (social, website, confs)

jupyter
binder

Prompted new notebooks:
- **Von Neumann entropy (Shammah)**
- **Q. trajectories (Minganti)**
- **Lecture on measurement (Cross)**

qutip.org/news
Monthly updates

Vision & Outlook

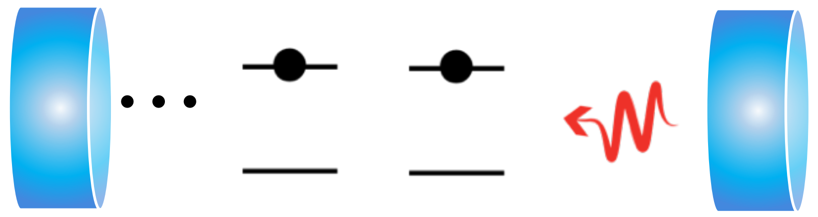
Quantum tech open source: QuPy
Actuators and control software
Libraries integration

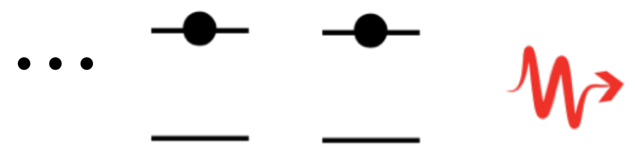
Discussions on development lines
Cython > Numba; GPU;
Cirq/qiskit/pennylane integrations

EuroSciPy 2019

Superradiance: phase transition vs. light emission

Two kinds of superradiance





	SUPERRADIANT PHASE TRANSITION (SR PT)	SUPERRADIANT LIGHT EMISSION (SR LE)
Requirements	*N* two-level systems in a **cavity (cQED)** Typically strong coupling or beyond	*N* two-level systems, do not require a cavity Fast system initialization
Types	Order parameters: Temperature Light-matter coupling	Initially: Fully-excited → Superfluorescence (SF) Half-excited → Superradiance (SR) One-excitation → Single-photon SR
Quantities	Phase transition: Ground/Thermal state properties Entanglement	Peak delay time, height, width Cooperativity
Features Related Phenomena	Ultrastrong regime, No-go theorems (A^2 term) Light-matter quasiparticles Chaos	Subradiance, Dark states 'Superabsorption' Optical bistability
Experiments	- Bose-Einstein condensate (Dicke model) - Superconducting (SC) flux qubits coupled to a microwave waveguide (N=10^3) - Quantum well (QW) exciton-polariton quasiparticles in a microcavity	• SF: - ^{87}Rb cold atom Raman laser (N=10^6) - SC transmon qubits (small N, e.g., N<3) - QW exciton magnetoplasma (N>10^6) • Single-photon SR: - QW intersubband plasmon - Quantum dot exciton

F. Dimer, *et al.*, Phys. Rev. A **75**, 013804 (2007)

Analytical approach

Hierarchy Truncation: Higher-moment correlations are neglected

Mean-field approximation $N \gg 2$

Factorization

$$\langle \dot{J}_z^2 \rangle = \gamma_S \left(\langle J^2 \rangle + \langle J_z \rangle - 3\langle J_z^2 \rangle + 2\langle J_z \rangle \langle J_z^2 \rangle - 2\langle J_z \rangle \langle J^2 \rangle \right)$$

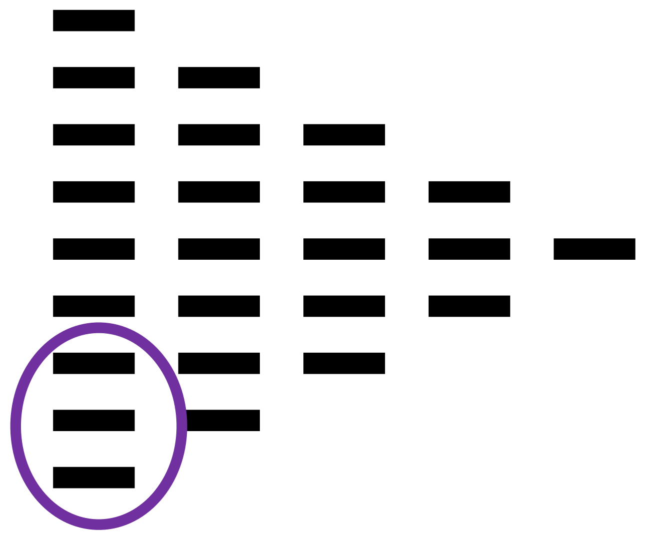
$$\langle J_z^3 \rangle \simeq \langle J_z^2 \rangle \langle J_z \rangle \qquad \langle J_z J^2 \rangle \simeq \langle J_z \rangle \langle J^2 \rangle$$

Bosonic approximation: Holstein-Primakoff (not suitable for local processes)

I Holstein-Primakoff

$$H_{\text{int}} = g(J_+ + J_-)(a + a^\dagger) \approx \sqrt{2j}\, g(b + b^\dagger)(a + a^\dagger)$$

$$J_z = b^\dagger b - j \qquad J_- = \sqrt{2j}\sqrt{1 - \frac{b^\dagger b}{2j}}\, b \qquad [b, b^\dagger] = 1 \qquad \frac{\langle b^\dagger b \rangle}{2j} \ll 1$$

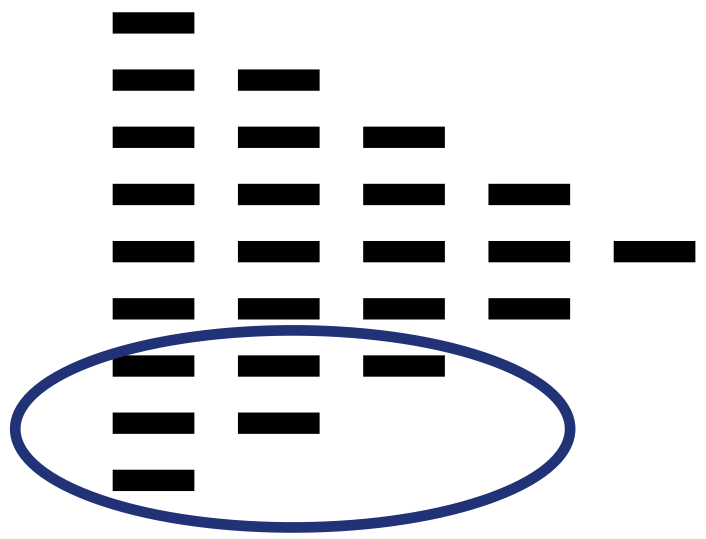


Bosonic approximation: Polariton Modes valid in the dilute regime

II Dilute regime without cooperative number conservation

$$H_{\text{int}} = \sqrt{N}\mathbf{d} \cdot \mathbf{E}(b_0 + b_0^\dagger)$$

$$b_p^\dagger = \frac{1}{\sqrt{N}} \sum_n f_n^p J_{+,n}, \quad p \in [1, N \qquad [b_p, b_q^\dagger] = \delta_{p,q}$$



N Shammah *et al.*, Superradiance with local phase-breaking mechanisms, Phys. Rev. A 2017, arXiv 1704.07066

PIQS: Driven-dissipative *spin* ensembles

Ongoing projects

$$i\hbar\frac{d}{dt}\rho = [H,\rho] + \gamma_\alpha \sum_i^N \mathscr{L}_{L_i}[\rho] + \gamma_\beta \mathscr{L}_L[\rho]$$

Model	XYZ Model	Generalized Lipkin-Meshkov-Glick Model	Kicked-Top
Features	Testbed Many-Body Physics Phase Diagram vs Mean Field PT-Symmetric Liouvillian Von Neumann Entropy	Dynamical Phase Transitions	Chaos and Scrambling Out-of-time-order-correlators
With	D. Huybrechts (Antwerp) M. Wouters (Antwerp) F. Minganti (RIKEN) F. Nori (RIKEN)	M. Wauters (SISSA) G. Piccitto (SISSA) G. Santoro (SISSA) F. Nori (RIKEN)	J. R. Gonzales (Chapman) J. Dressel (Chapman) S. Ahmed (Chalmers) F. Nori (RIKEN)

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Nathan Shammah
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Neill Lambert
RIKEN, Japan

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U. of Michigan (USA)

日本学術振興会
Japan Society for the Promotion of Science

Japan Science and Technology Agency

RIKEN

JOHN TEMPLETON FOUNDATION

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Google Summer of Code

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quantika.co