Quantum Impurities Coupled to Markovian and Non-Markovian Environments

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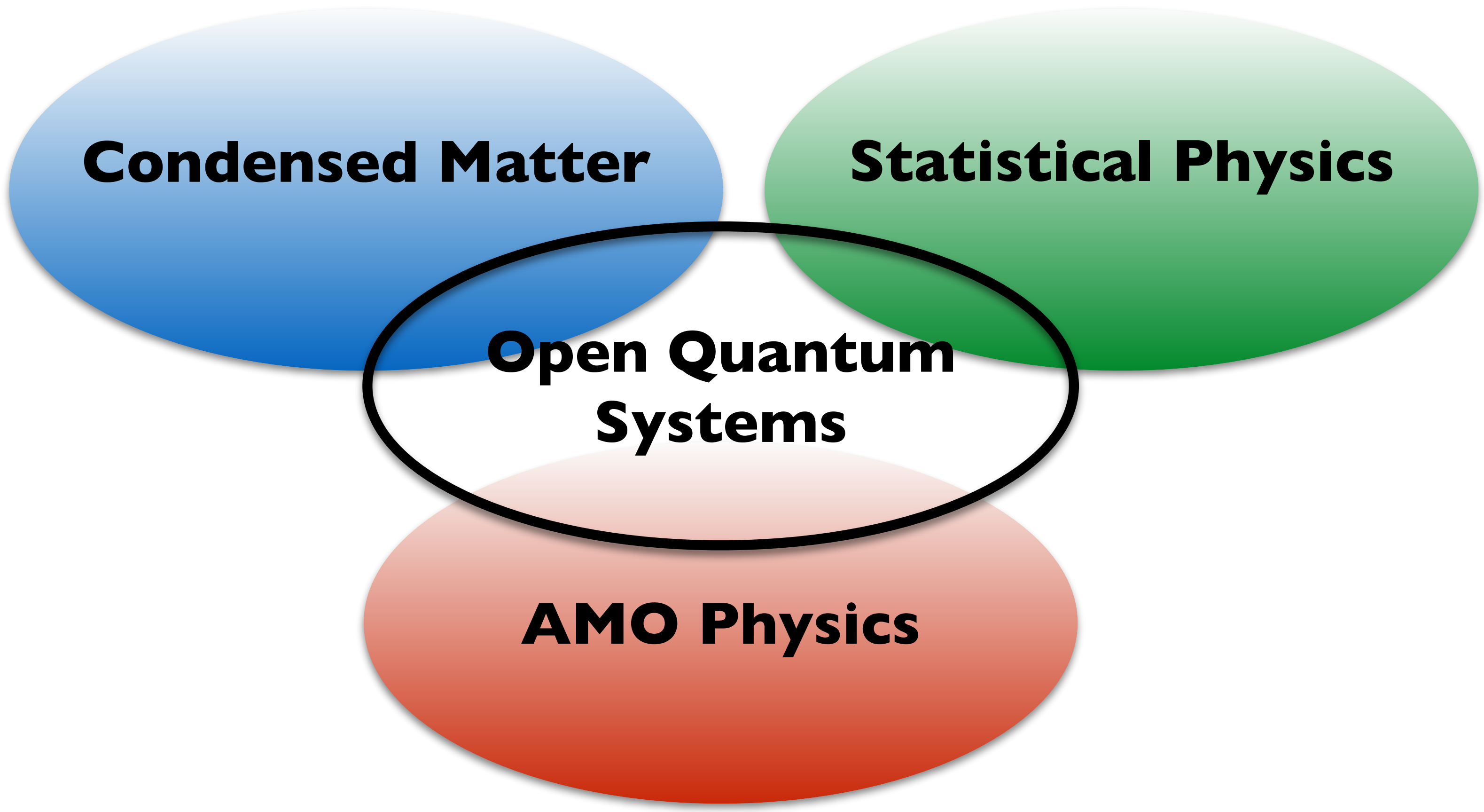
Quantum2021, *Dynamics and local control of impurities in complex quantum environments*, Institut Pascal, September 1st 2021

Outline

- Two Paradigms of Open Quantum Systems:
  Quantum Impurity Models vs Markovian Quantum Systems

- <u>Markovian Quantum Impurity Models</u>:
  Examples, Motivations, Theoretical Approaches

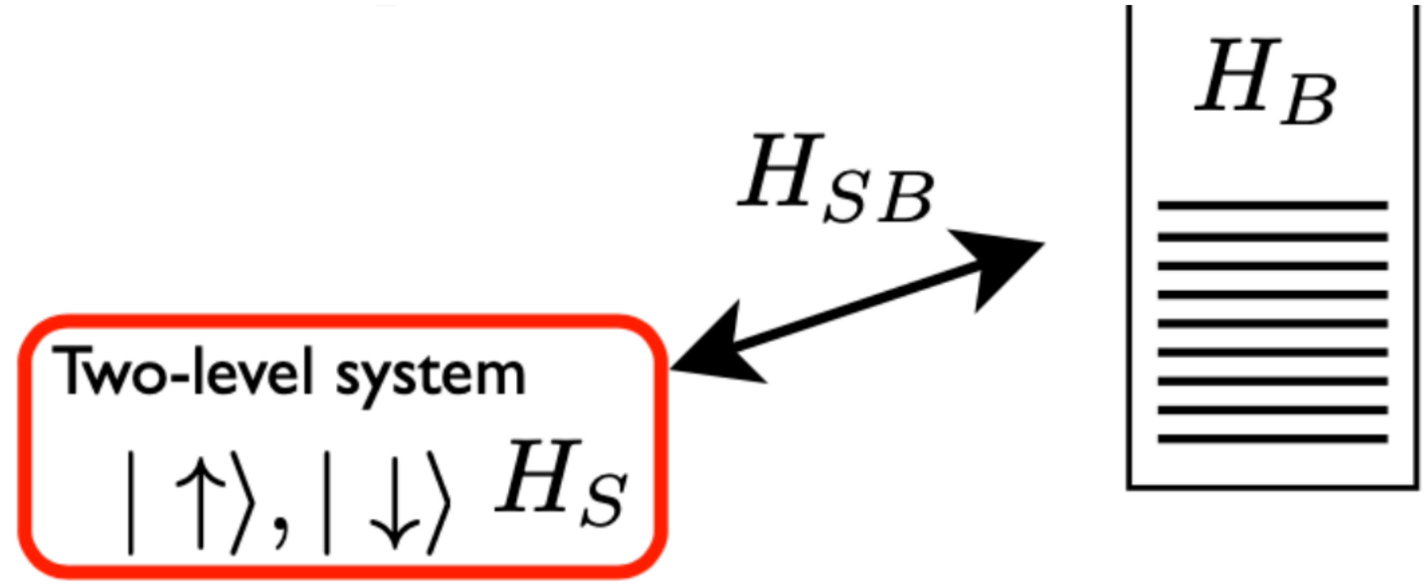
- Applications: Fermionic and Bosonic Markovian Impurities


Condensed Matter
Statistical Physics
Open Quantum
Systems
AMO Physics

Open Quantum Systems

- System+Bath Picture

$$H = H_S + H_B + H_{SB}$$

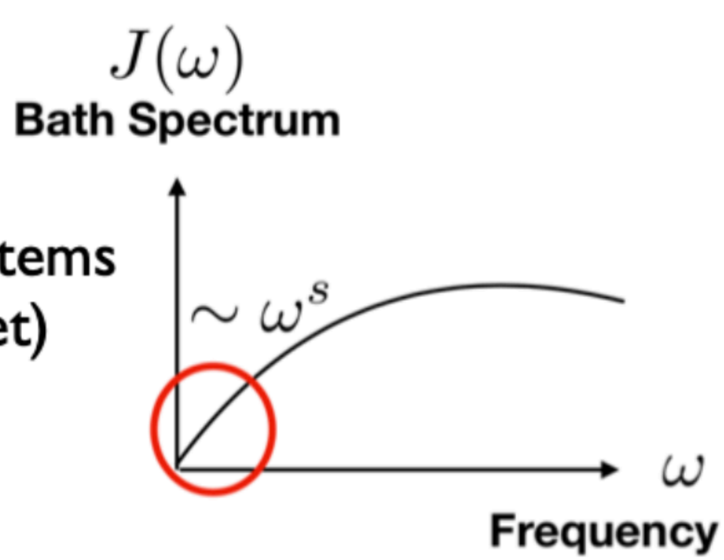


- <u>Examples:</u> Impurity in Metals, Quantum Dots, Photons in a Cavity, Atoms under spontaneous decay, Qubits,…

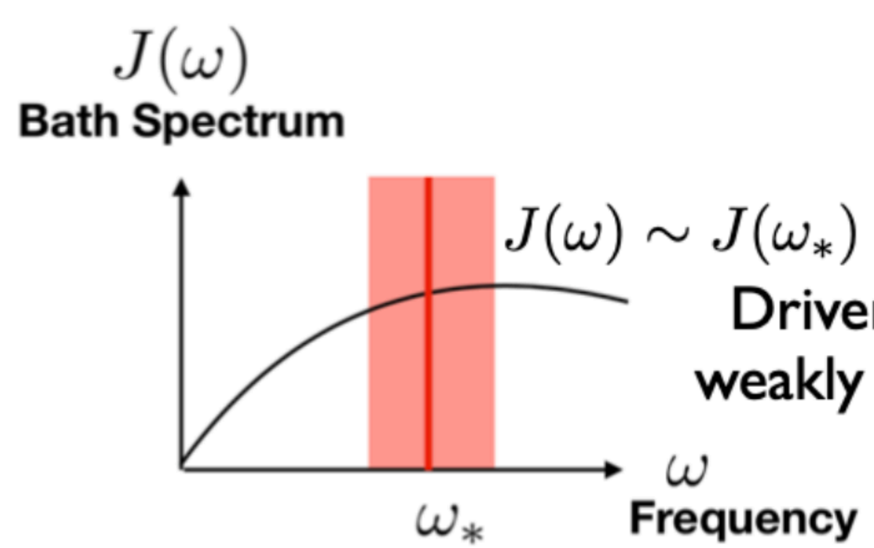
- System Dynamics affected by the bath: retardation/memory effects

- Slow vs Fast Baths

Equilibrium Open Systems
(e.g. Caldeira-Legget)



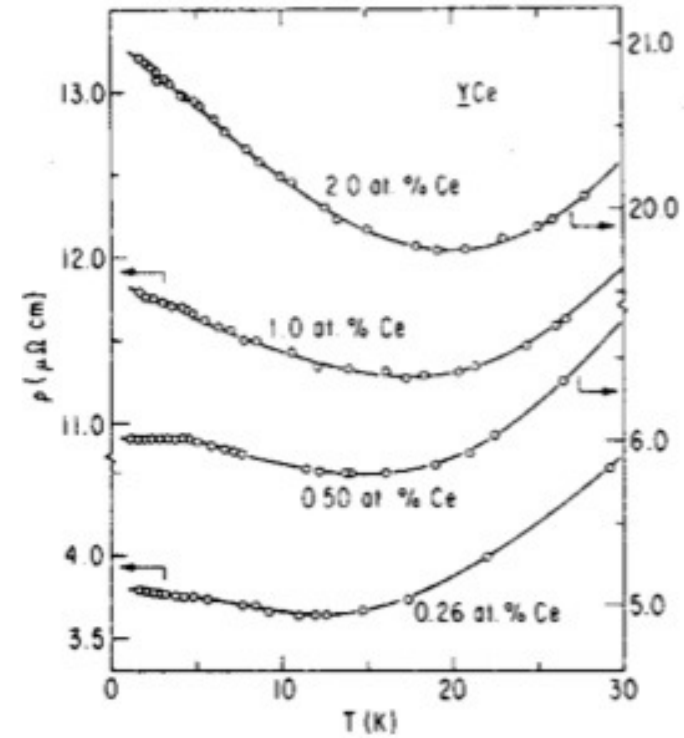
Quantum Impurity Physics



Driven Open Systems,
weakly coupled to a bath

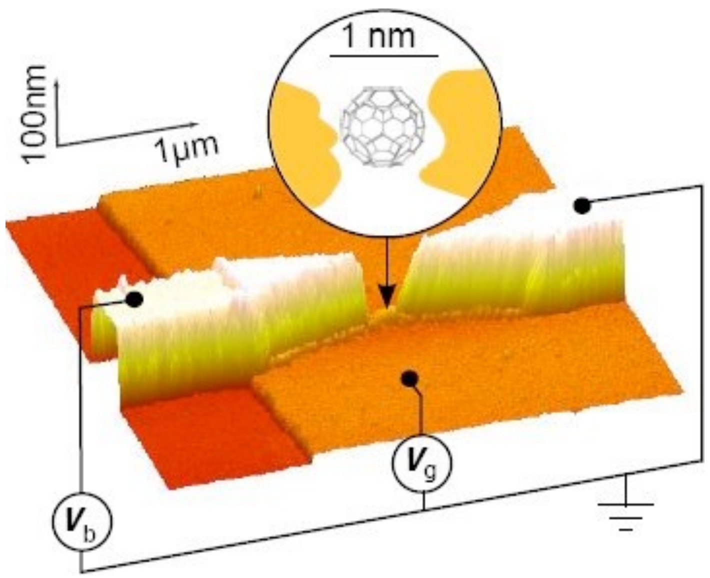
Markovian Open Systems

Quantum Impurity Physics



Experimental Motivations

- Diluted Magnetic Impurities in Metals and Kondo Effect



- Quantum Dots and Single Molecule Devices

- Light Control of Quantum Dots

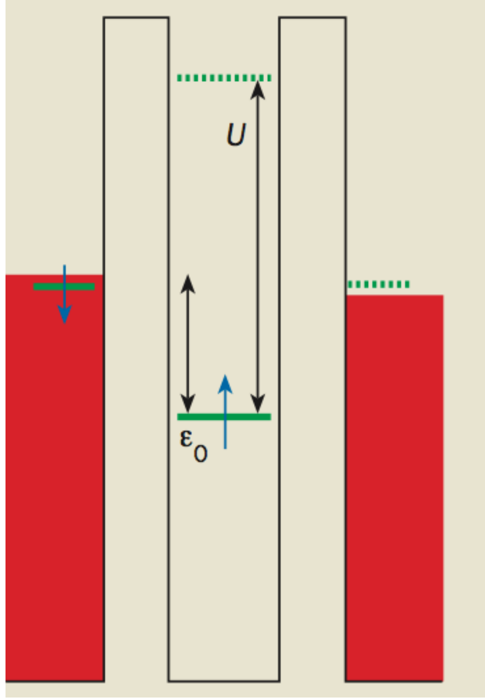
- Impurity in Cold Atomic Gases

- ……

Example: Anderson Impurity model

$$H = \frac{U}{2}(n-1)^2 + \sum_{k\sigma} \epsilon_k \, f^\dagger_{k\sigma} \, f_{k\sigma} + \sum_{k\sigma} V_k \, \left(c^\dagger_\sigma \, f_{k\sigma} + h.c.\right)$$

Anderson, Kondo, Haldane, Nozieres, Wilson,...(~1960-1975)



T

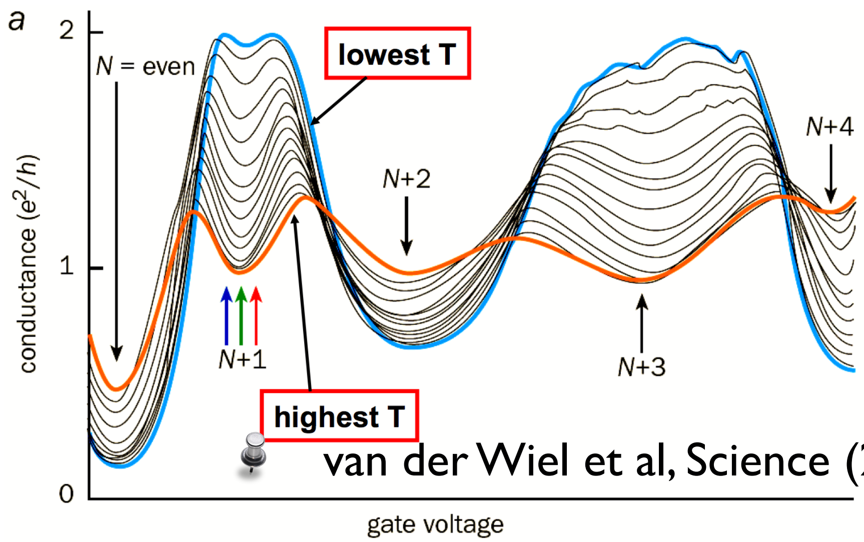
$|0\rangle, |\uparrow\rangle, |\downarrow\rangle, |\uparrow\downarrow\rangle$ — Free Orbital Regime: Charge Fluctuations

U

$|\uparrow\rangle, |\downarrow\rangle$ — Local Moment Regime: Spin Fluctuations

$T_K \sim e^{-U/\Gamma}$

$(|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle)/\sqrt{2}$ — Strong Couplig Regime: Kondo "Screening"



van der Wiel et al, Science (2000)

- Collective Many Body State (Impurity+Bath) available for resonant transport

- Paradigm for Strong Correlation Physics (Dynamical Mean-Field Theory)

Open Markovian Quantum Systems

- *Breuer, Petruccione, Open Quantum Systems*

- Dynamics for the system reduced Density Matrix $\rho(t)$ is <u>local in time</u> and <u>linear</u>

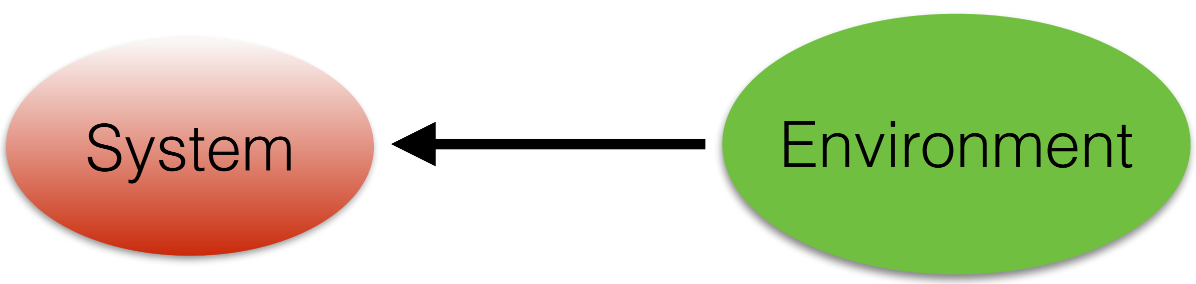
Markov **Born**

- Lindblad Form:

$$\frac{d\rho}{dt} = -i[H, \rho(t)] + \sum_\alpha \left(L_\alpha \rho(t) L_\alpha^\dagger - \frac{1}{2}\left\{ L_\alpha^\dagger L_\alpha, \rho(t) \right\} \right)$$

Coherent (Unitary) Evolution

Environment Effects described by a set of "Jump Operators"



- <u>Idealisation</u>: no memory effects from the environment, no system-bath entanglement

- …but a useful one! Theoretical Insights, Experimentally relevant

- Diagrammatic Derivation of Lindblad? Scarlatella, Schiro, arXiv:2107.05553

Spectral Properties of Lindblad Superoperator

$$\partial_t \rho = \mathcal{L}\rho$$

- Linear Equation in terms of a Lindbladian "Superoperator"
- Well defined dynamical map (trace and complete positivity preserving)
- **Spectrum of Lindbladian** $\mathcal{L} r_\alpha = \lambda_\alpha r_\alpha \qquad \mathcal{L}^\dagger l_\alpha = \lambda_\alpha^* l_\alpha$

$$\partial_t \rho = \mathcal{L}\rho \qquad \rho(t) = \rho_{ss} + \sum_{\alpha\neq 0} c_\alpha e^{\lambda_\alpha t} r_\alpha \qquad c_\alpha = \mathrm{Tr}\left(l_\alpha^\dagger \rho(0)\right)$$

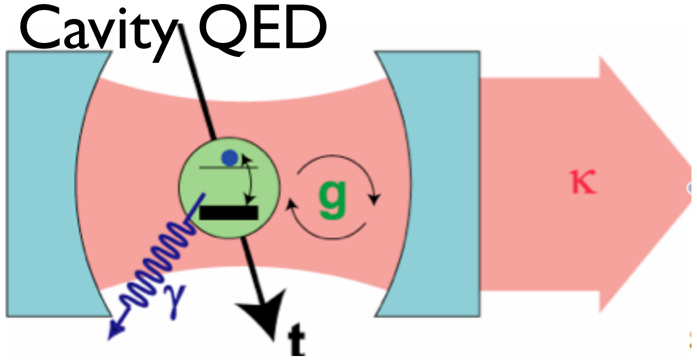
Stationary State $\lambda_0 = 0$

"Decay Modes"

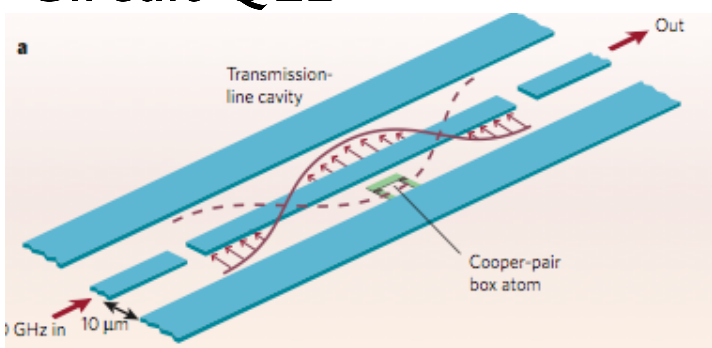
- In absence of specific symmetries and for finite-size systems the steady state is <u>unique</u> and <u>analytic, but not necessarily thermal!</u>

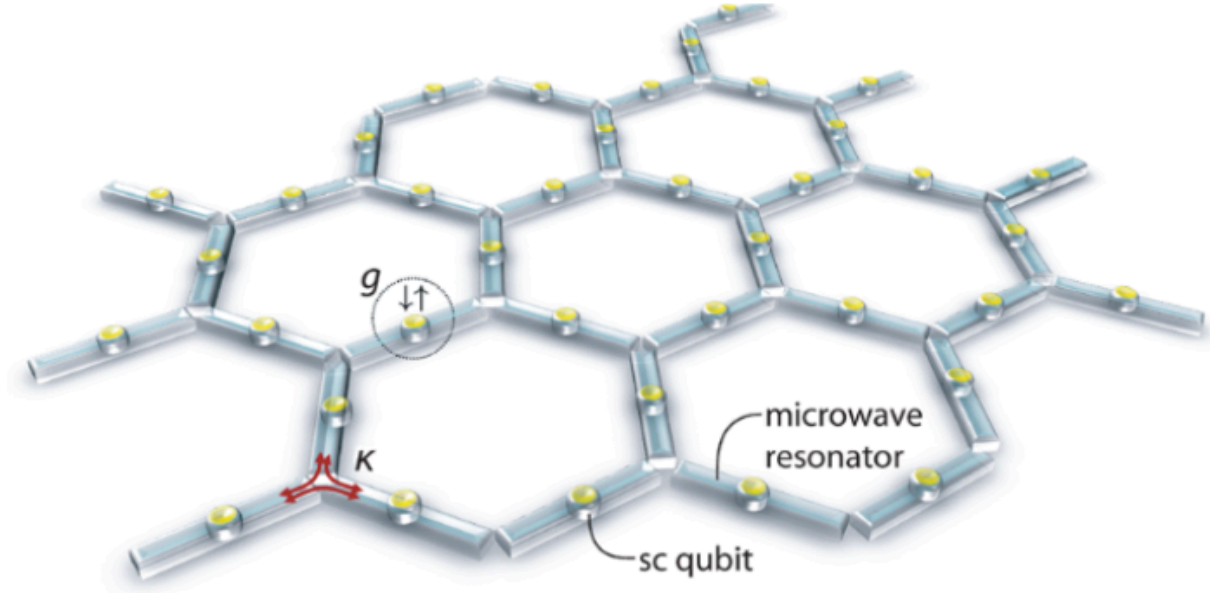
Cavity/Circuit QED Lattices: Many-Body Physics with "Photons"

Cavity QED



Circuit QED





- J. Koch, A. Houck and H. E. Tureci Nat. Phys. **8** 292 (2012)
- Le Hur, Henriet, Petrescu, Plekhanov, Roux, **MS**, CRAS (2015)
- I. Carusotto Et Al, Nat. Phys. 2020

- Exploring Light-Matter Interaction at the Quantum Level
- Fundamentally "Open" (leakage) - need refilling (pump&losses)
- Dissipative processes highly tunable (correlated losses, ..)

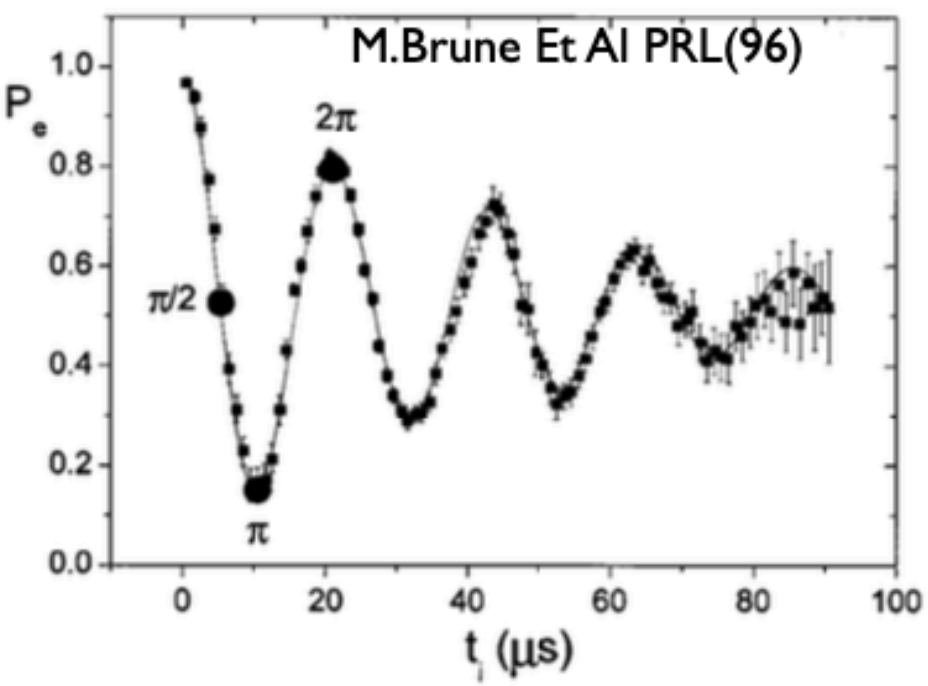
Environment Effects in CQED

- Photon Losses and Atomic Decay Rates (Dissipation) κ, γ

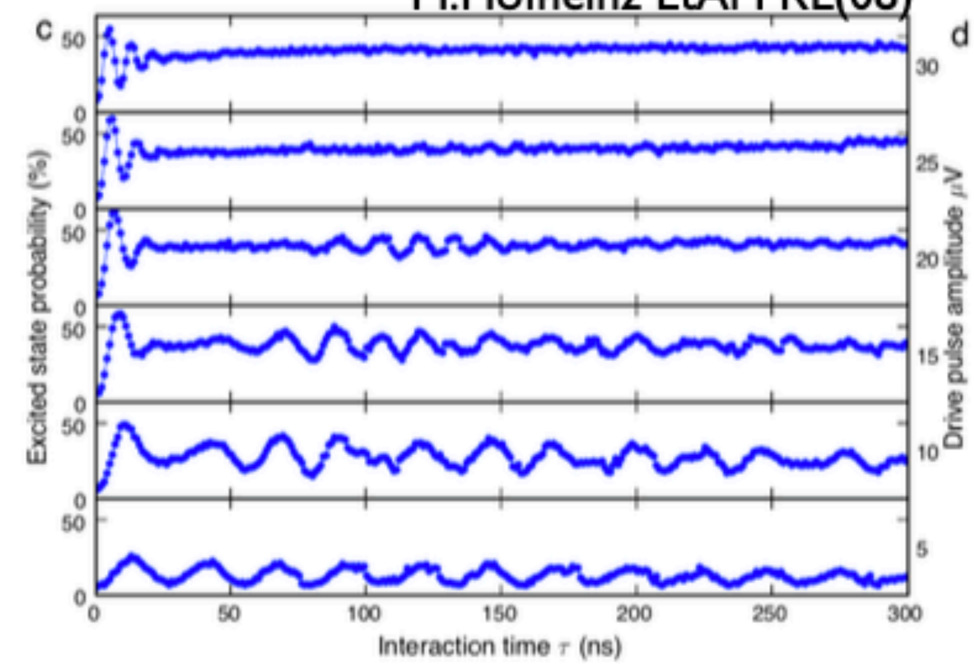
$$\partial_t \rho = -i[H, \rho] + \mathcal{D}[\rho]$$

$$\mathcal{D}[\rho] = \kappa \left(a\rho a^\dagger - \frac{1}{2}\left\{a^\dagger a, \rho\right\} \right) + \gamma \left(\sigma_- \rho \sigma_+ - \frac{1}{2}\left\{\sigma_+ \sigma_-, \rho\right\} \right)$$

- Rabi Oscillations in Cavity/Circuit QED



M.Hofheinz EtAl PRL(08)



Strong-Coupling Regime of cQED

$$g \gg \kappa, \gamma$$

- Typical Circuit QED:

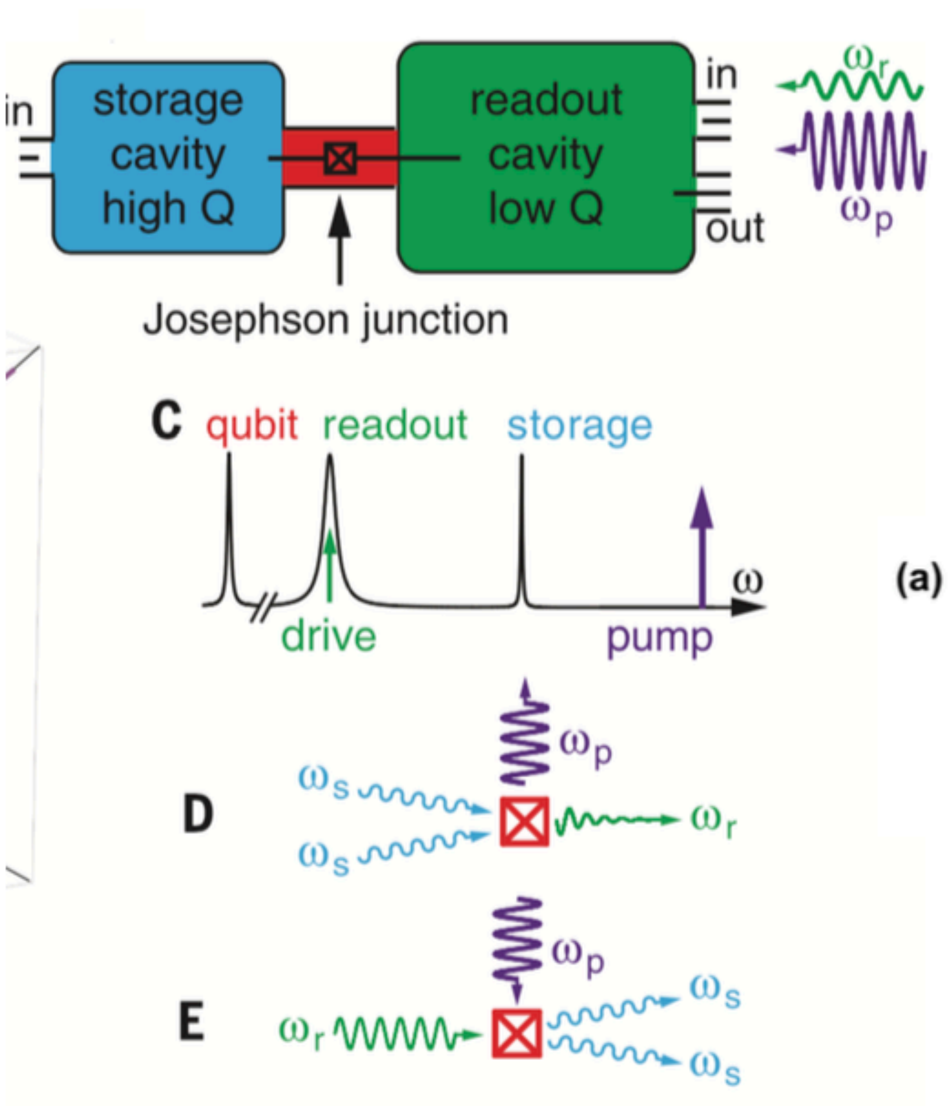
$$\omega_r \sim 10\,\mathrm{Ghz} \quad g \sim 1\mathrm{Ghz} \quad \kappa, \gamma \sim 500\,\mathrm{kHz}$$

Dissipation Engineering

- Use coupling to the environment to stabilise interesting target states (<u>often non-thermal!</u>)
  - S. Diehl et al, Nat. Phys (2008)
  - F.Verstraete et al, NatPys(2009)
  - C. Aron et al, PRX(2016)

- Incoherent pumping of photons/qubit $L_{ph} = a^\dagger \quad L_{qbit} = \sigma_+$

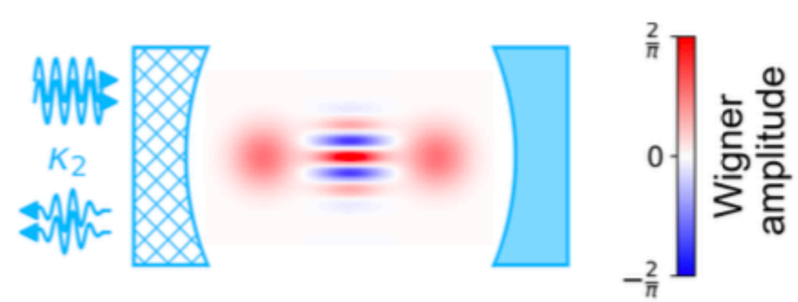
- Two-Photons Losses in Circuit QED
  - Z. Leghtas Et Al, Science(2015)

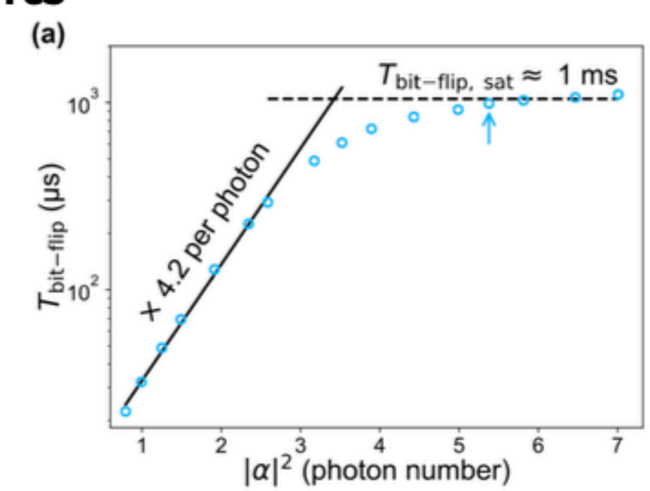


$$\partial_t \rho = -i[H, \rho] + \mathcal{D}[\rho]$$

$$\mathcal{D}[\rho] = \kappa_2 \left(a\, a \rho a^\dagger a^\dagger - \frac{1}{2} \left\{ \left(a^\dagger\right)^2 (a)^2, \rho \right\} \right)$$

- Route for robust Cat-Qubits



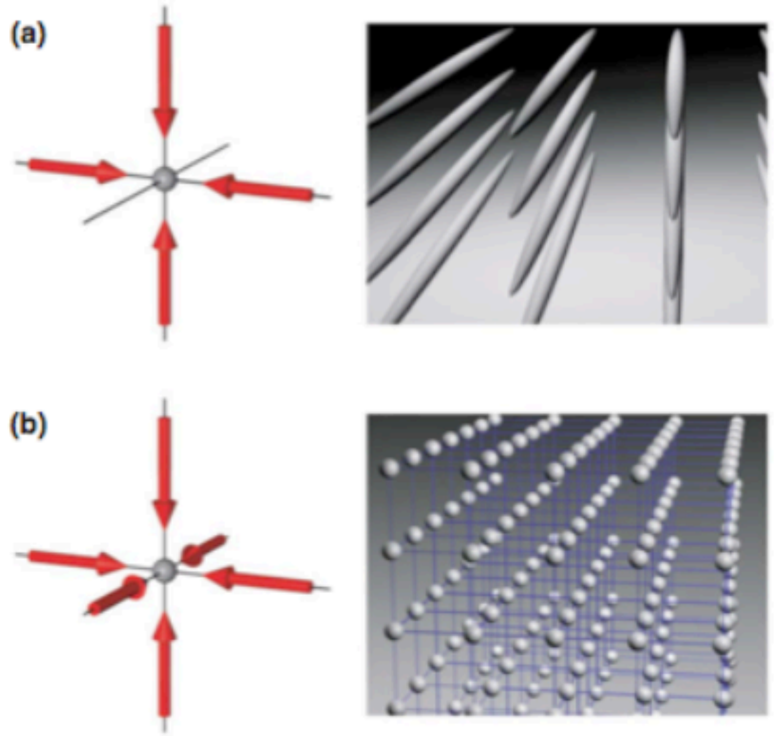


- R.Lescanne et al, NatPhys(2020)

- "Correlated" Dissipative Processes for Quantum Simulation

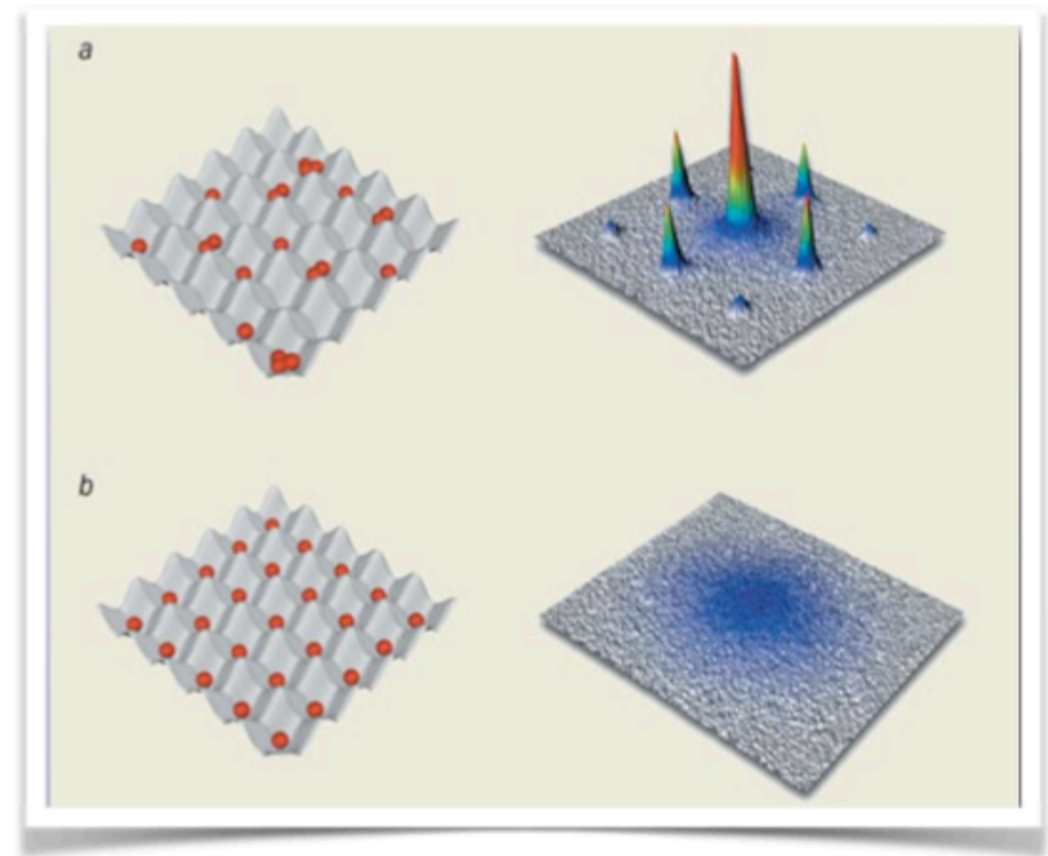
- J. Lebreuilly, C. Aron, C. Mora PRL(2019) Many-Body Cat States!

Ultracold Atoms in Optical Lattices



$$V(x,y,z) = V_0\,(sin^2\,kx + sin^2\,ky + sin^2\,kz)$$

- I.Bloch, et al, RMP (08)



- M. Greiner et al, Nature (2002)

- Ideal Platform for Quantum Simulations
- I.Bloch, J.Dalibard,S. Nascimbene NatPhys(2012)

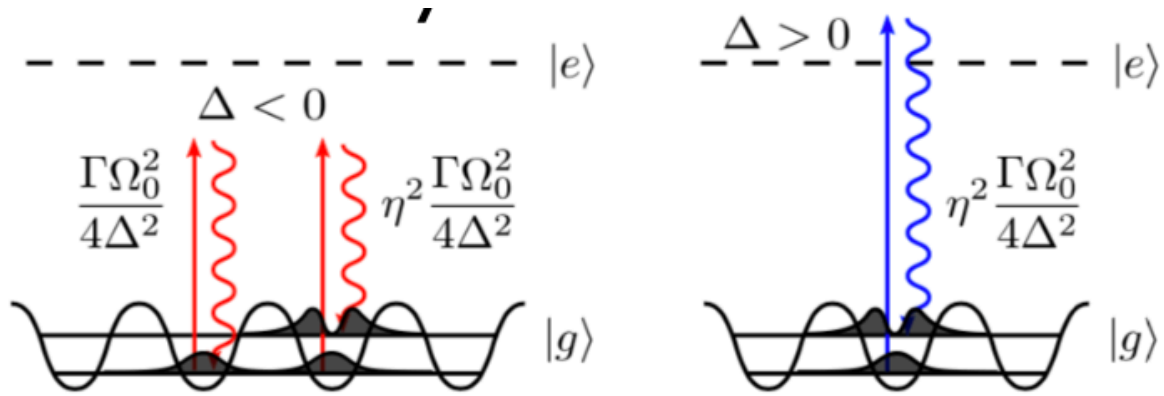
- Example: Superfluid to Mott Transition of bosons

$$H = \sum_{\langle ij \rangle} J_{ij}\left(a_i^\dagger a_j + hc\right) + \frac{U}{2}\sum_i n_i(n_i - 1) - \mu \sum_i n_i$$

- Dynamics of <u>**Almost**</u> Isolated Quantum Many Body States….

Dissipative Processes in Ultracold Gases

- Heating by Spontaneous Emission



- H. Pichler et al, PRA(2010);
- F. Gerbier, Y. Castin, PRA(2010

- Lindblad Dissipator

$$\mathcal{D}[\rho] = \gamma \sum_i \left(n_i \rho n_i - \frac{1}{2}\left\{ n_i^2, \rho \right\} \right)$$

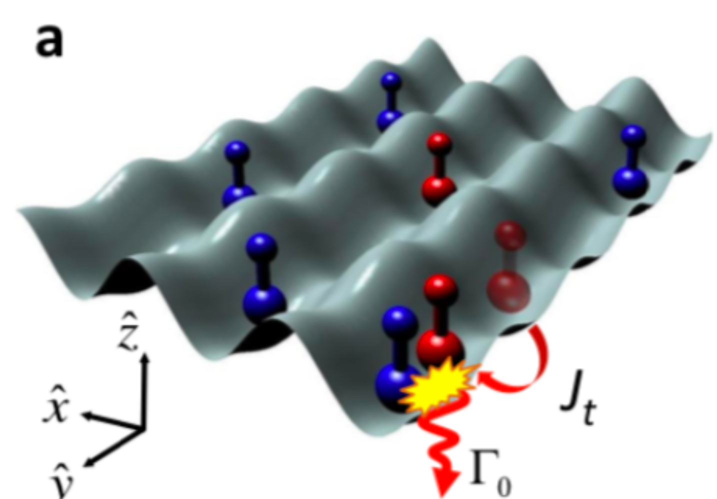
Experiment@CdF - Bouganne et al, Nature Physics (2019)

- Two-Particle Losses (inelastic scattering)

Syassen et al, Science (2008)

- Lindblad Dissipator

$$\mathcal{D}[\rho] = \Gamma_0 \sum_i \left(a_i^2 \rho \left(a_i^\dagger\right)^2 - \frac{1}{2}\left\{ \left(a_i^\dagger\right)^2 (a_i)^2, \rho \right\} \right)$$



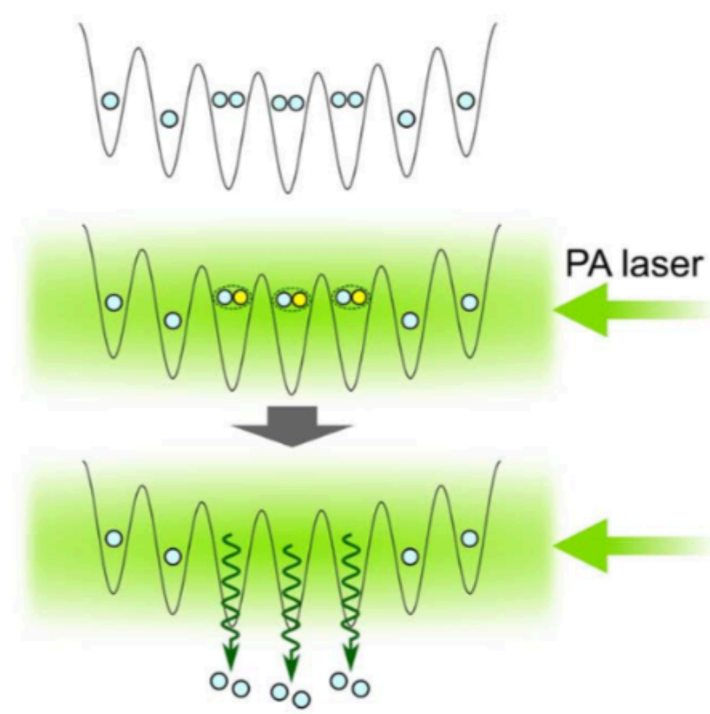
SCIENCE ADVANCES | RESEARCH ARTICLE

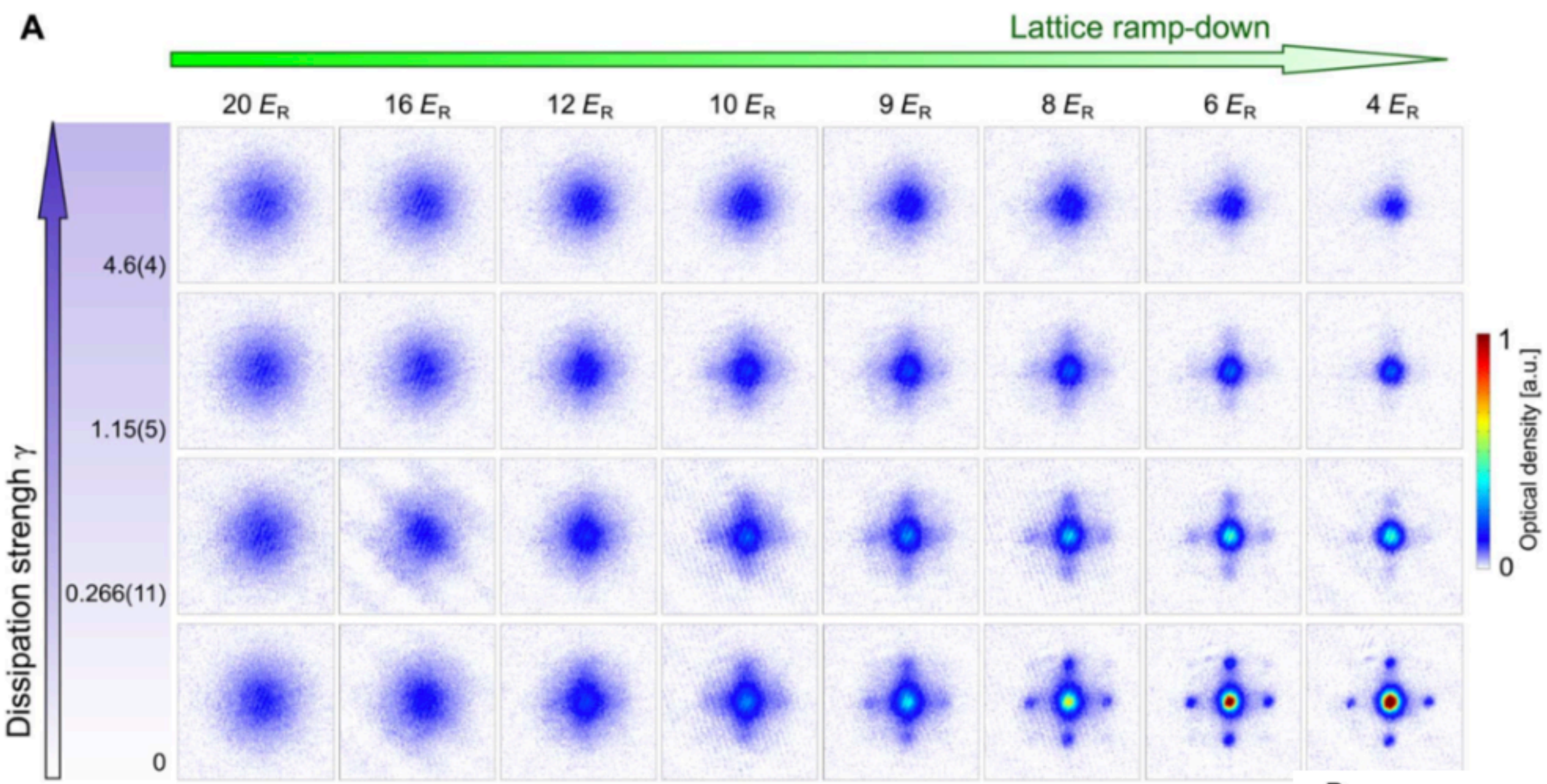
PHYSICS

Observation of the Mott insulator to superfluid crossover of a driven-dissipative Bose-Hubbard system

Takafumi Tomita,[1]* Shuta Nakajima,[1] Ippei Danshita,[2] Yosuke Takasu,[1] Yoshiro Takahashi[1]

A





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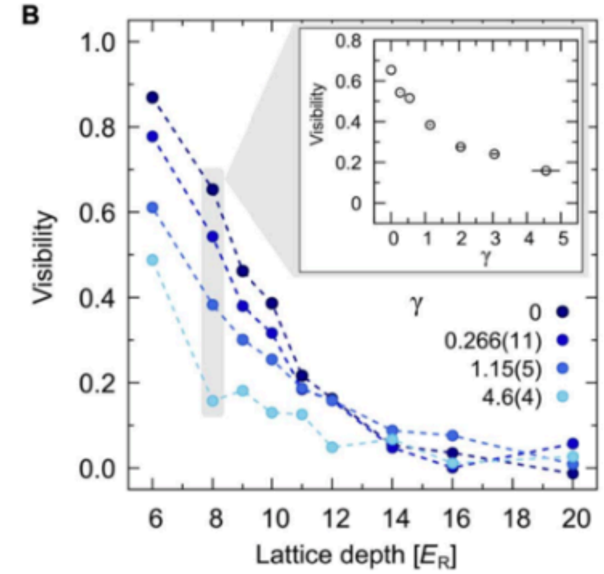

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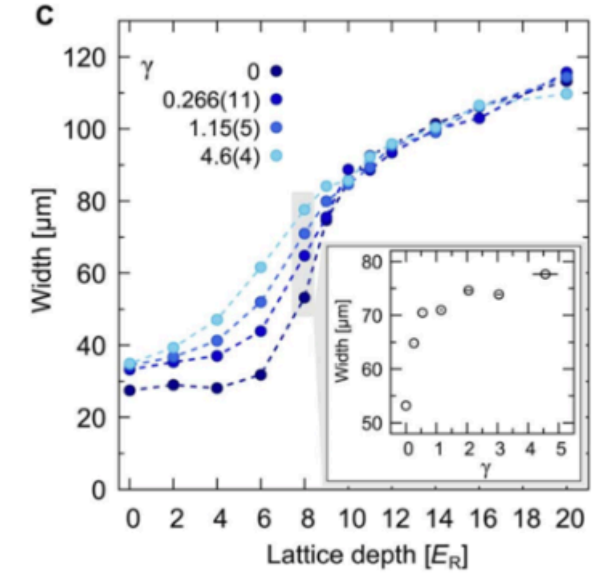


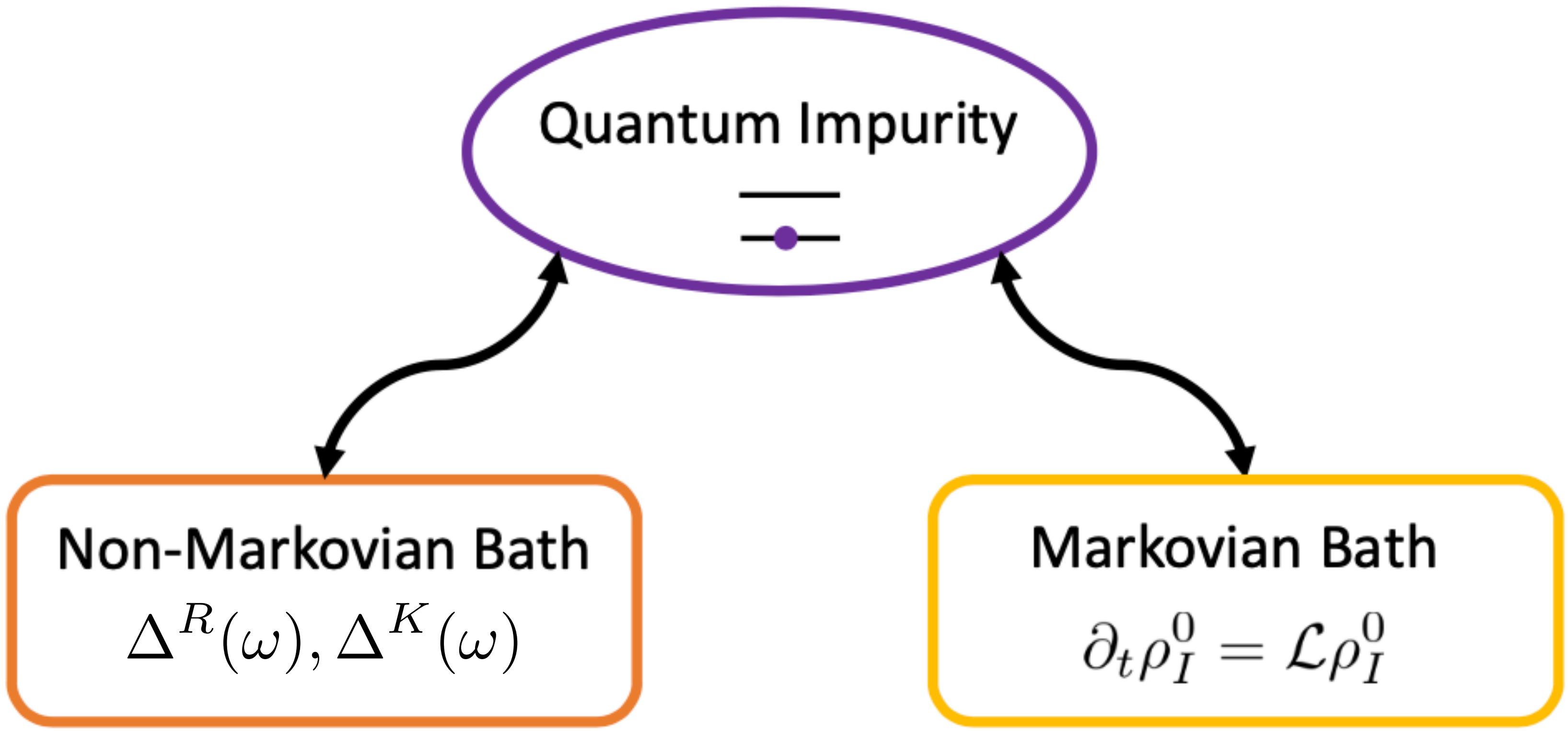
$$\partial_t \rho = -i[H, \rho] + \mathcal{D}[\rho]$$

$$\mathcal{D}[\rho] = \Gamma_0 \sum_i \left(a_i^2 \rho \left(a_i^\dagger\right)^2 - \frac{1}{2}\left\{ \left(a_i^\dagger\right)^2 (a_i)^2, \rho \right\} \right)$$

A new class of Quantum Impurity Models

“Markovian” Quantum Impurity Models

Few, interacting, quantum
degrees of freedom



Frequency-Dependent, out of equilibrium environment with gapless excitations

Dissipative environment described by a set of local (non-linear) jump operators/local lindbladian

Example I: Dissipative Kondo Effect

Nakagawa et al, PRL(2018)

Cold Atoms Experiment:Riegger et al PRL(2018)

- Interaction of a localised spin with a fermionic bath

$$H = \sum_{k,\sigma} \varepsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \frac{1}{N_s} \sum_{k,k',\sigma,\sigma'} c^\dagger_{k\sigma} c_{k'\sigma'} (v_r \delta_{\sigma\sigma'} - J_r \boldsymbol{\sigma}_{\sigma\sigma'} \cdot \boldsymbol{S}_{\text{imp}}).$$

Inelastic (2body) collision between impurity and bath

$$\frac{d\rho(t)}{dt} = -i[H,\rho] + \sum_{\alpha=+,-,\uparrow\uparrow,\downarrow\downarrow} \left(L_\alpha \rho L^\dagger_\alpha - \frac{1}{2}\{L^\dagger_\alpha L_\alpha, \rho\} \right)$$
$$= -i(H_{\text{eff}}\rho - \rho H^\dagger_{\text{eff}}) + \sum_\alpha L_\alpha \rho L^\dagger_\alpha,$$

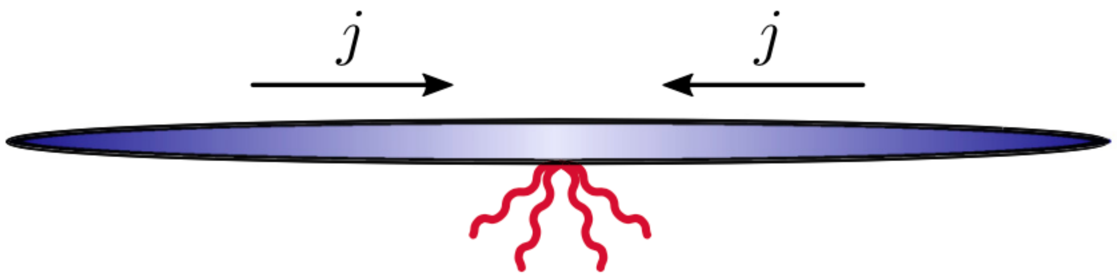
$$L_\pm = \sqrt{2\gamma^\mp_{eg}} \frac{1}{\sqrt{2}} (f_\downarrow c_\uparrow(0) \pm f_\uparrow c_\downarrow(0)),$$
$$L_{\uparrow\uparrow} = \sqrt{2\gamma^-_{eg}} f_\uparrow c_\uparrow(0),$$
$$L_{\downarrow\downarrow} = \sqrt{2\gamma^-_{eg}} f_\downarrow c_\downarrow(0),$$

Mapping to non-Hermitian Kondo problem, unusual RG flow!

Example II: Localized Losses in 1d wire

Experiments: Barontini et al PRL(2013); Labouvie et al PRL(2016)

Froml, Muckel, Kollath, Chiocchetta, Diehl PRL (2019); PRB(2020)

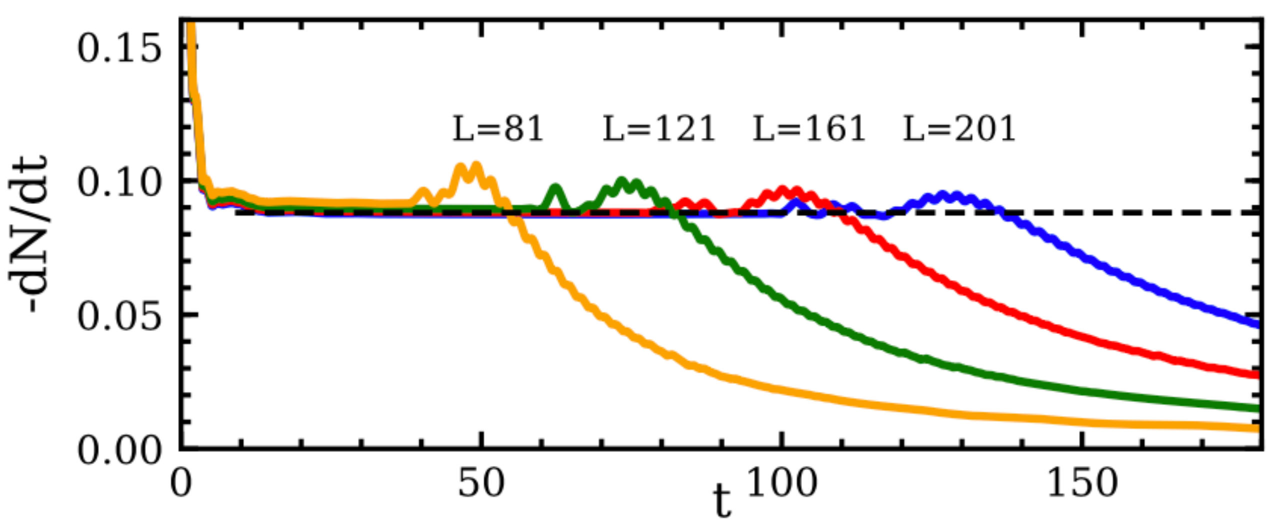


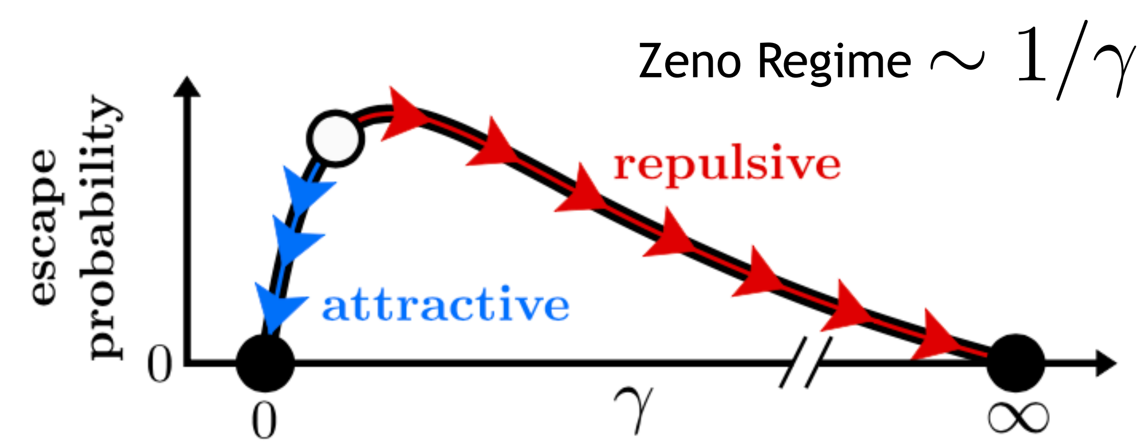
$$\partial_t \rho = -i[H,\rho] + \int_x \Gamma(x) \left[L\rho L^\dagger - \frac{1}{2}\{L^\dagger L, \rho\} \right]$$

$$H = -\int_x \psi^\dagger(x) \frac{\nabla^2}{2m} \psi(x) + \int_{x,y} V(x-y) n(x) n(y),$$

$$L(x) = \psi(x), \ \Gamma(x) = \gamma \delta(x)$$

- Dissipative version of Kane-Fisher Problem (Potential Barrier)
- Quasi-stationary current-carrying state formed





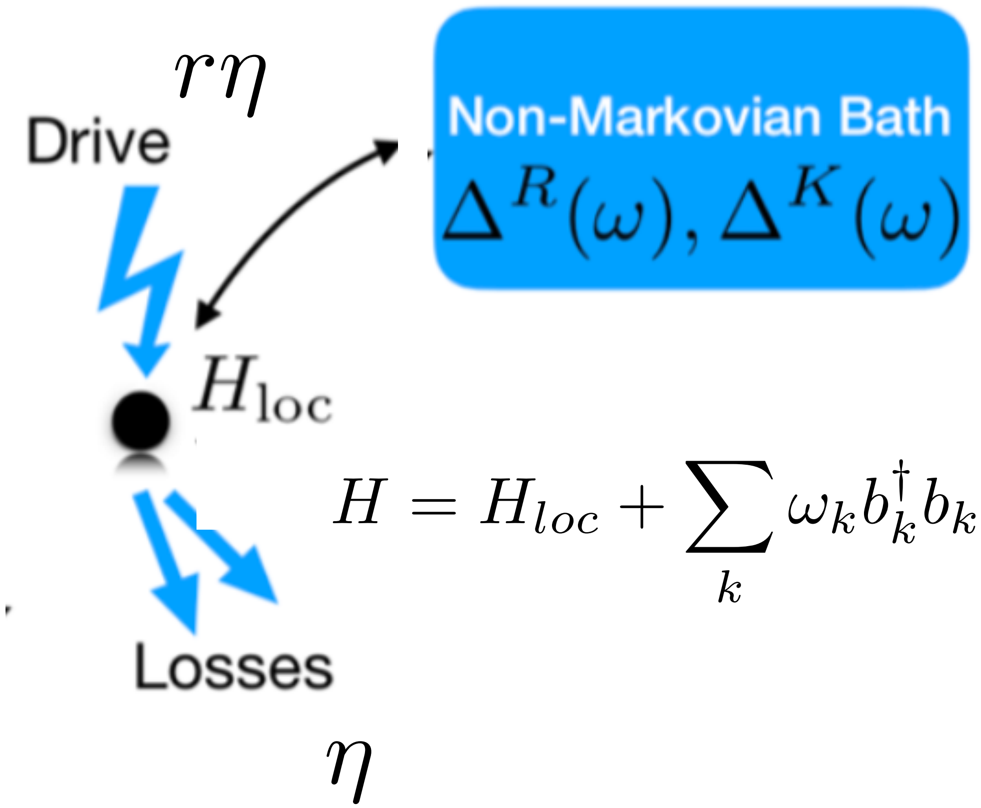
Example III: Bosonic Anderson Impurity Model with 2body Losses

$$H_{loc} = \omega_0 n + U n^2$$

- Single Particle Pump/2 Particle Losses

$$D_{pump}[\rho] = a^\dagger \rho a - \frac{1}{2}\{a a^\dagger, \rho\}$$

$$D_{losses}[\rho] = a a \rho a^\dagger a^\dagger - \frac{1}{2}\{a^\dagger a^\dagger a a, \rho\}$$



$$H = H_{loc} + \sum_k \omega_k b_k^\dagger b_k + \sum_k g_k \left(b_k^\dagger a + a^\dagger b\right)$$

Pump/Loss ratio: r

Experimental Motivation: Circuit QED (transmon qubit coupled to a transmission line), Atomic impurity in a BEC +plus inelastic collisions,..

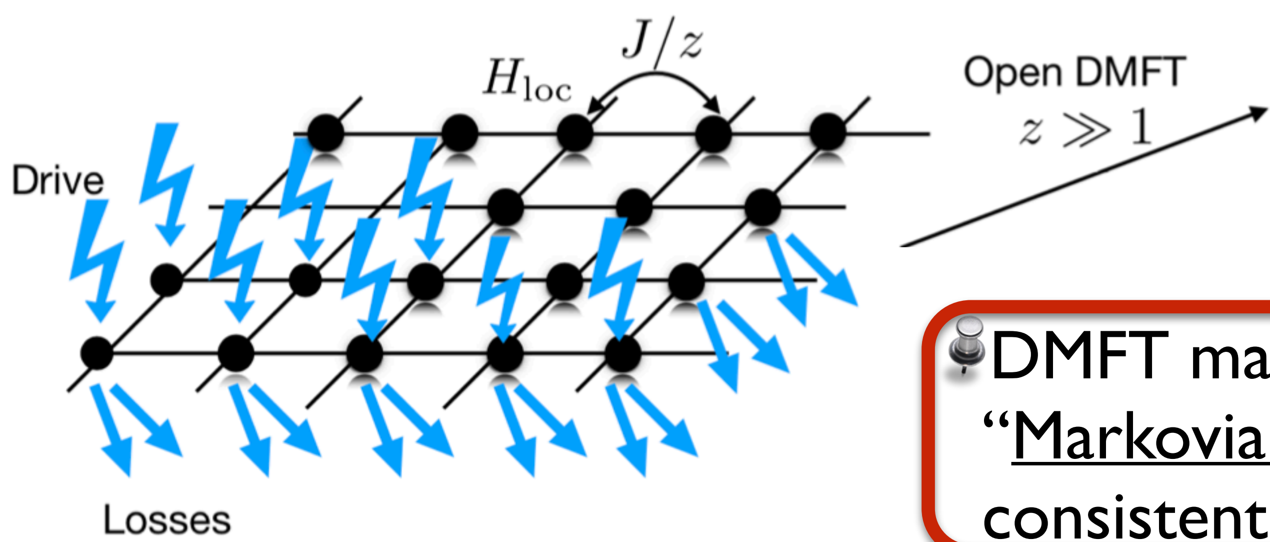
Theoretical Motivation: capture the local physics of open quantum many-body systems

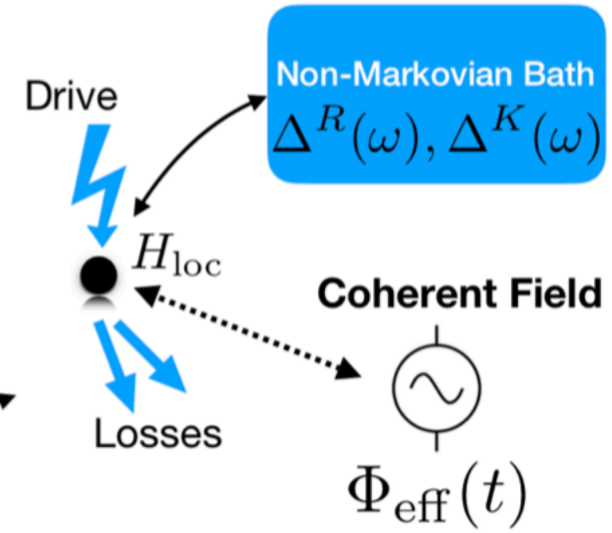
Dynamical Mean Field Theory for Markovian Lattice Systems

- O. Scarlatella, A. Clerk, R. Fazio, M. Schiro', PRX(2021)

- Large connectivity limit of open quantum many-body systems

$$\partial_t \rho = -i[H,\rho] + \mathcal{D}[\rho]$$





- DMFT maps the full master equation on a "<u>Markovian Quantum Impurity Model</u>" in a self-consistent environment!

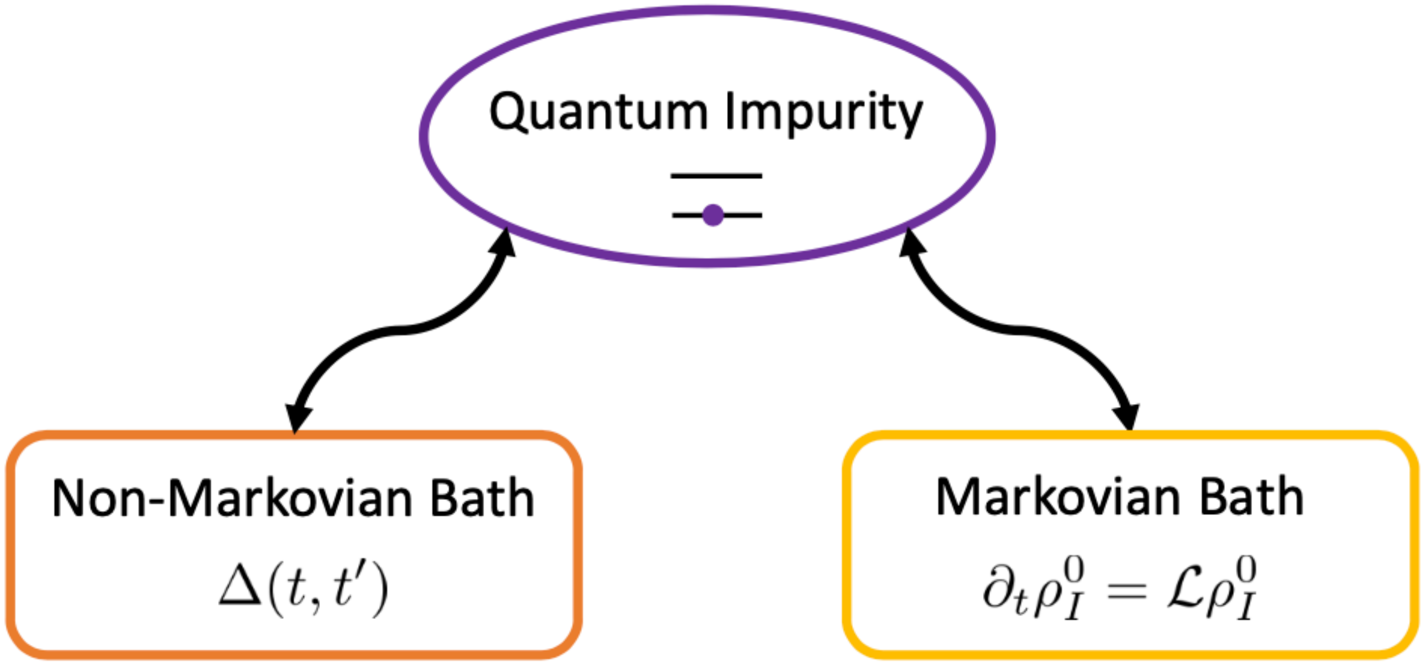
- Example: Driven-Dissipative Bose Hubbard Lattice….

$$H = -\frac{J}{z}\sum_{\langle ij\rangle} a_i^\dagger a_j + \sum_i \omega_0 n_i + \frac{U}{2} n_i^2 \qquad L_{i1} = \sqrt{r\eta}\, a_i^\dagger \qquad L_{i2} = \sqrt{\eta}\, a_i a_i$$

$$\mathcal{D}[\rho] = \sum_{i\mu}\left(L_{i\mu}\rho L_{i\mu}^\dagger - \frac{1}{2}\left\{L_{i\mu}^\dagger L_{i\mu}, \rho\right\}\right)$$

…Maps onto a Bosonic Anderson Impurity with drive and 2 body (impurity)losses

How to solve Markovian Quantum Impurities?



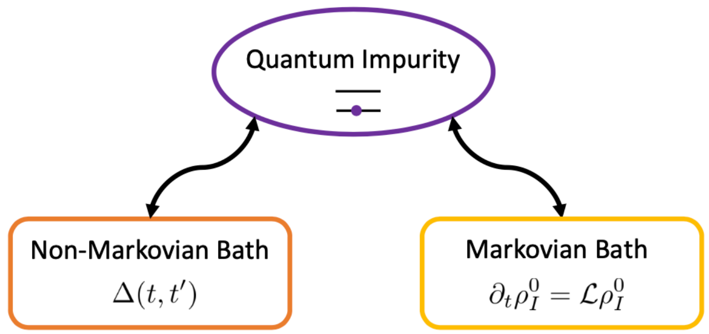
Methodological challenge for many existing methods (QMC/NRG/MPO..)!

Non-Markovian bath induces memory effects (long-range in time)

Markovian bath induces dissipative interactions

Superoperator Hybridization Expansions

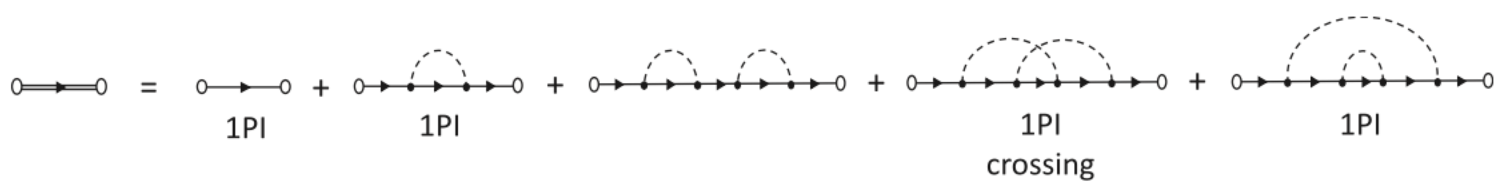
Scarlatella,Schiro JCP(2019);
Scarlatella et al PRX(2021)



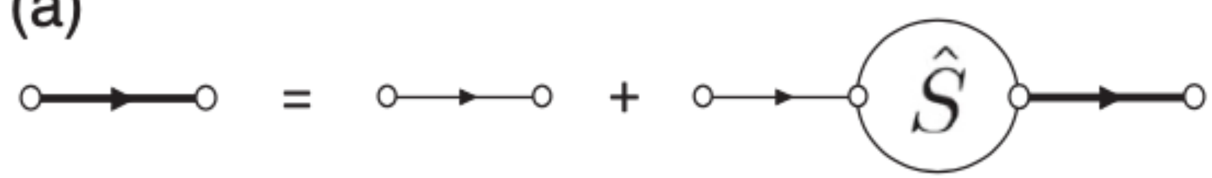
- Exact Evolution "Superoperator" for reduced impurity density matrix

$$\rho(t) = \hat{\mathcal{V}}(t,0)\rho(0)$$

- Diagrammatic Expansion of $\hat{\mathcal{V}}$ in the non-Markovian Bath Kernel Δ



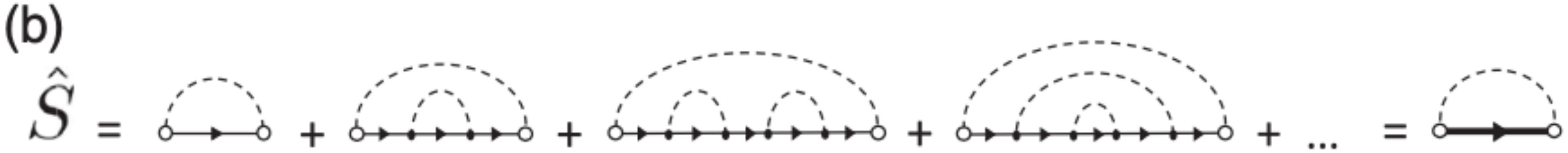
(a)



$$\hat{\mathcal{V}}(t,t') = \hat{\mathcal{V}}_0(t,t') + \int_{t'}^{t} dt_1 \int_{t'}^{t_1} dt_2 \hat{\mathcal{V}}_0(t,t_1)\hat{S}(t_1,t_2)\hat{\mathcal{V}}(t_2,t').$$

- Lowest-Order (Self-consistent) Diagrams: Non-Crossing Approximations (NCA)

(b)

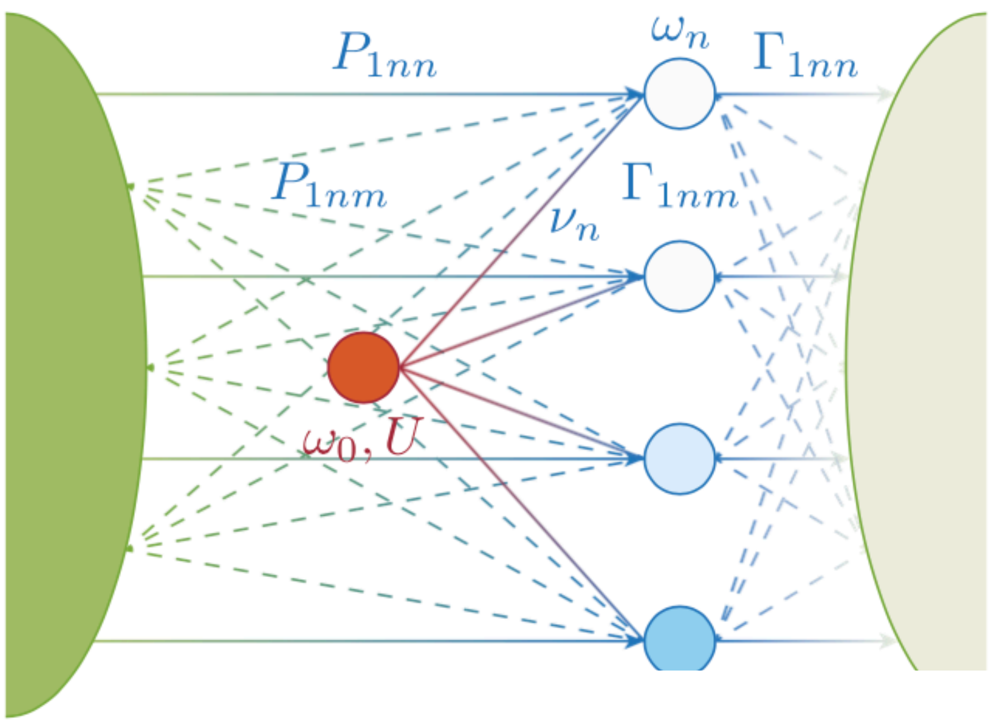


For Unitary QIM:Bickers,...Cohen&Gull, Eckstein&Werner, ..

Exact Diagonalization of Lindblad Superoperator

Secli, Capone, Schiro NJP (2021)

- Discretization of the non-Markovian bath in a finite number of (dissipative) levels



$$\dot{\rho} = \mathcal{L}\rho = \mathcal{L}_H\rho + \mathcal{L}_D\rho$$

$$\mathcal{L}_H\rho = -i\,[H,\rho]$$

$$H = \omega_0 a_0^\dagger a_0 + U a_0^\dagger a_0 a_0^\dagger a_0 + \sum_{n=1}^{N_B}\left\{\omega_n a_n^\dagger a_n + \nu_n a_n^\dagger a_0 + \nu_n^* a_0^\dagger a_n\right\}$$

$$\begin{aligned}\mathcal{L}_D\rho = 2\sum_{n,m=0}^{N_B}\Bigg\{&\Gamma_{1mn}\left(a_n\rho a_m^\dagger - \frac{1}{2}\left\{a_m^\dagger a_n,\rho\right\}\right)\\ &+P_{1mn}\left(a_m^\dagger\rho a_n - \frac{1}{2}\left\{a_n a_m^\dagger,\rho\right\}\right)\\ &+\Gamma_{2mn}\left(a_n a_n\rho a_m^\dagger a_m^\dagger - \frac{1}{2}\left\{a_m^\dagger a_m^\dagger a_n a_n,\rho\right\}\right)\Bigg\}\end{aligned}$$

- Diagonalization of the resulting (finite-sized) Lindblad super operator

Dissipative Flow-Equation

- Iterative "Diagonalization" of Lindblad Superoperator

$$\frac{d\rho}{dt} = \mathcal{L}\rho$$

$$\mathcal{L}(l) = S(l)\mathcal{L}(0)S^{-1}(l)$$

$$\frac{d\mathcal{L}}{dl} = [\eta(l), \mathcal{L}]$$

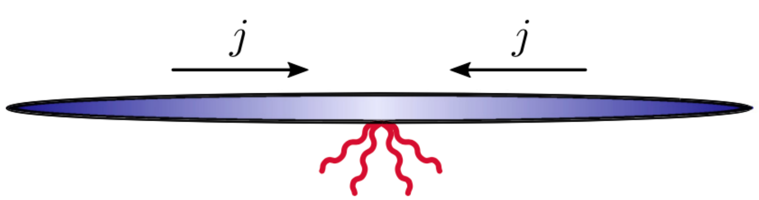
$$\partial_l S(l) = \eta(l)S(l)$$

- Different choices for the generator are possible

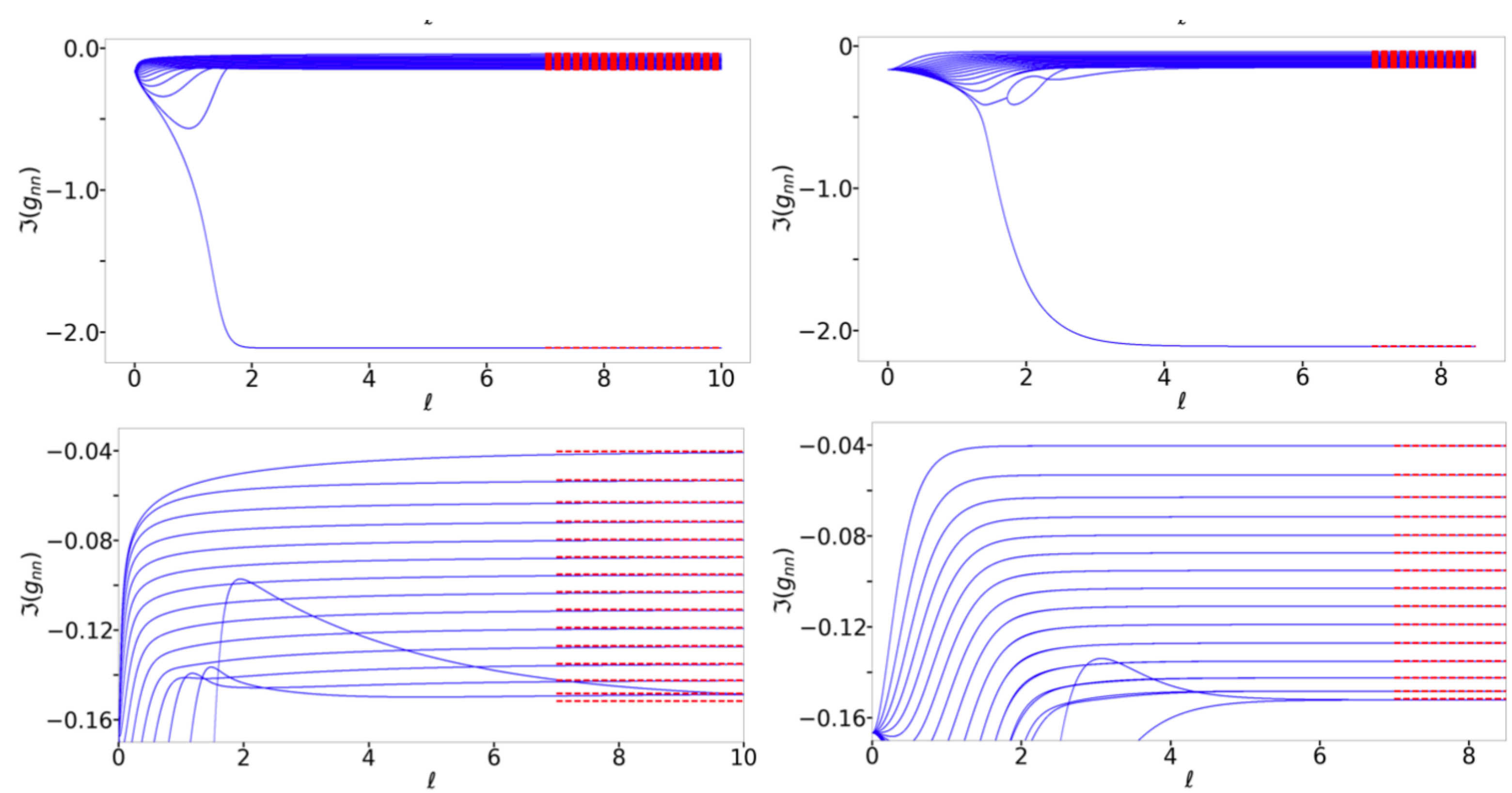
$$\eta(\ell) = [\mathcal{L}(\ell)^\dagger, \mathcal{V}(\ell)]. \qquad \eta(\ell) = [\mathcal{D}(\ell)^\dagger, \mathcal{V}(\ell)];$$

$$\eta_{nk}(\ell) = \begin{cases} \dfrac{\mathcal{V}_{nk}(\ell)}{\mathcal{D}_{nn}(\ell) - \mathcal{D}_{kk}(\ell)}, & \text{if } \mathcal{D}_{nn}(\ell) \neq \mathcal{D}_{kk}(\ell); \\ 0, & \text{if } \mathcal{D}_{nn}(\ell) = \mathcal{D}_{kk}(\ell). \end{cases}$$

- Application: 1d fermions with localised losses



$$\lambda = \Lambda \tan\left(\frac{\pi}{2}\left(\frac{4\nu}{\gamma} - 1\right)\right), \qquad \gamma > 4\nu$$

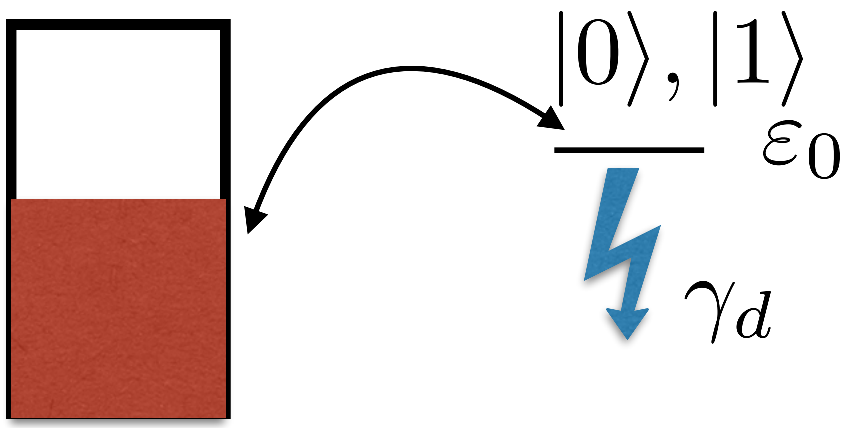


L. Rosso, F. Iemini, M. Schiro, L. Mazza, SciPost(2020)

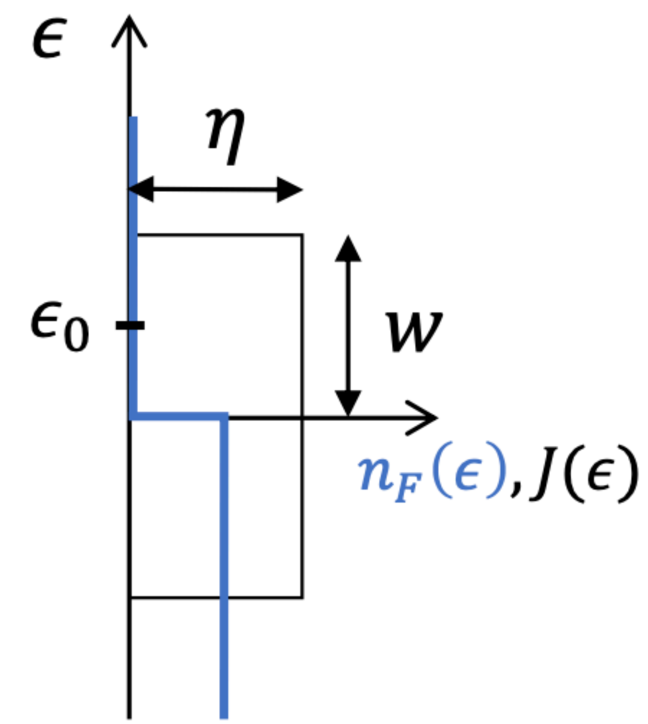
Applications

NCA Benchmark: Fermionic Resonant Level Model with Dephasing

Scarlatella, Schiro JCP(2019);



- Fermionic Bath at T=0



- Lindblad Master Equation

$$\partial_t \rho_I^0 = \mathcal{L}\rho_I^0,$$

$$\mathcal{L}\rho_I^0 = -i\left[H_I, \rho_I^0\right] + (\gamma_l \mathcal{D}_l + \gamma_p \mathcal{D}_p + \gamma_d \mathcal{D}_d)\rho_I^0,$$

$$H_I = \epsilon_0 d^\dagger d,$$

$$\mathcal{D}_l \rho_I^0 = d\rho_I^0 d^\dagger - \frac{1}{2}\{d^\dagger d, \rho_I^0\},$$

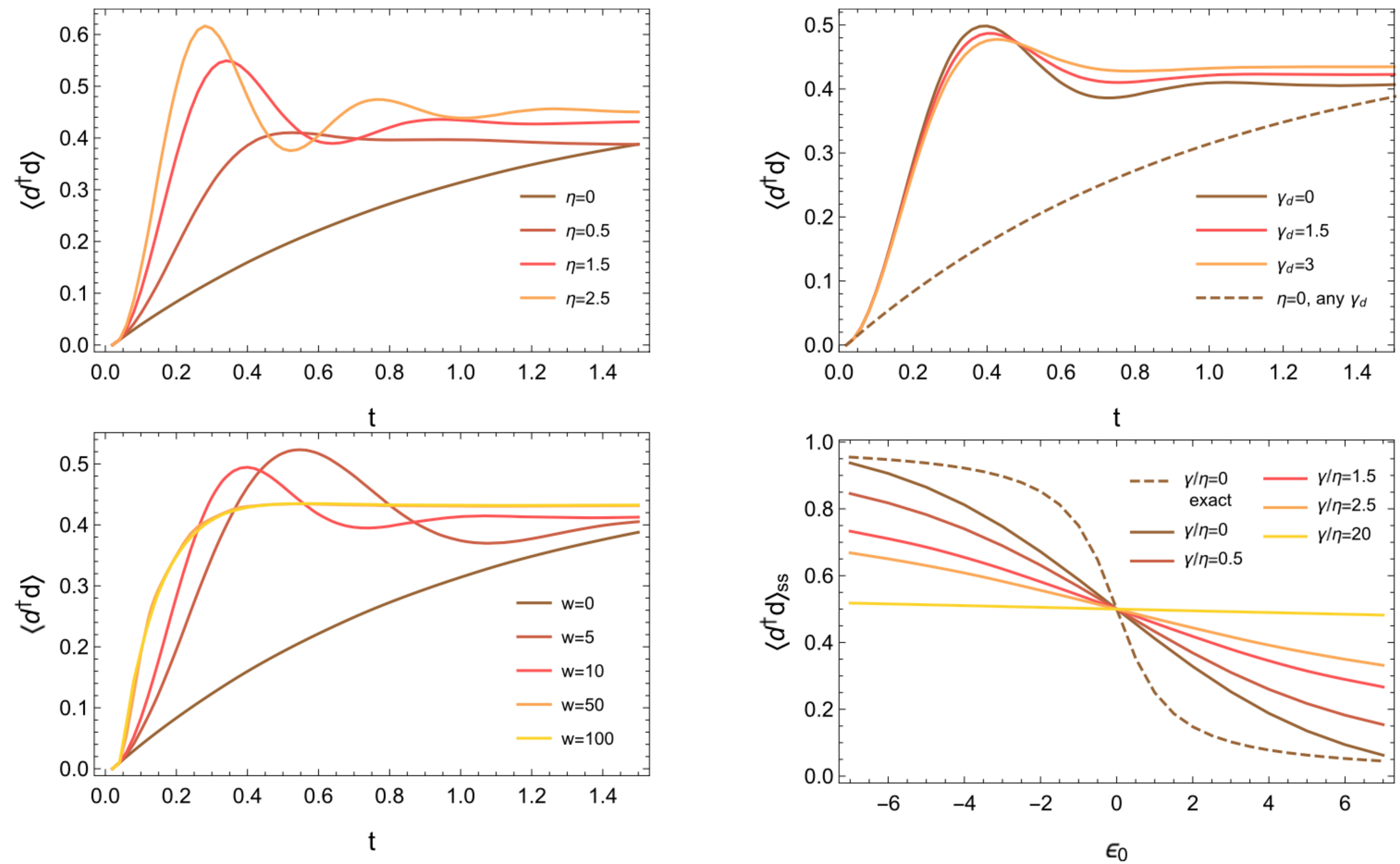
$$\mathcal{D}_p \rho_I^0 = d^\dagger \rho_I^0 d - \frac{1}{2}\{dd^\dagger, \rho_I^0\},$$

$$\mathcal{D}_d \rho_I^0 = d^\dagger d \rho_I^0 d^\dagger d - \frac{1}{2}\{d^\dagger d, \rho_I^0\},$$

- Local Dissipator includes: pump, losses and dephasing

Fermionic Resonant Level Model with Dephasing

Scarlatella,Schiro JCP(2019);

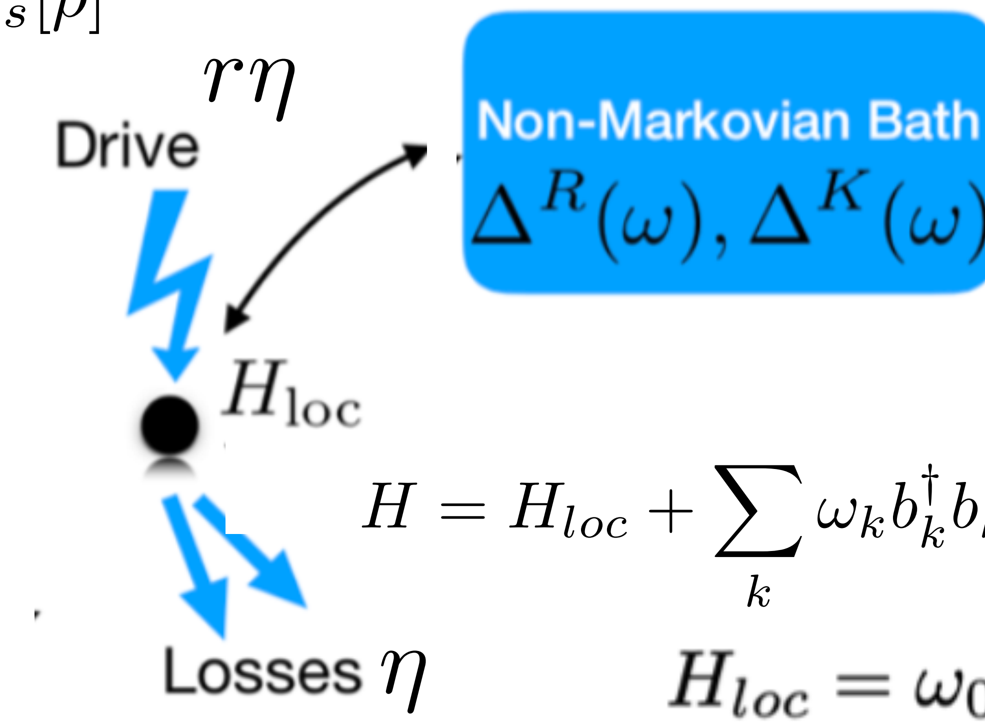


Crossover from Markovian to Non-Markovian Dynamics - Heating due to dephasing

Open Question: Role of impurity interactions?

Back to: Bosonic Anderson Impurity Model with 2body Losses

$$\partial_t \rho = -i[H,\rho] + D_{pump}[\rho] + D_{losses}[\rho]$$



- Single Particle Pump/2 Particle Losses

$$D_{pump}[\rho] = a^\dagger \rho a - \frac{1}{2}\left\{aa^\dagger, \rho\right\}$$

$$D_{losses}[\rho] = aa\rho a^\dagger a^\dagger - \frac{1}{2}\left\{a^\dagger a^\dagger aa, \rho\right\}$$

$$H = H_{loc} + \sum_k \omega_k b_k^\dagger b_k + \sum_k g_k \left(b_k^\dagger a + a^\dagger b\right)$$

$$H_{loc} = \omega_0 n + U n^2$$

Pump/Loss ratio: r

- <u>Lattice Analogue (via DMFT): Driven-Dissipative Bose Hubbard</u>

$$H = -\frac{J}{z}\sum_{\langle ij\rangle} a_i^\dagger a_j + \sum_i \omega_0 n_i + \frac{U}{2} n_i^2 \qquad L_{i1} = \sqrt{r\eta}\, a_i^\dagger \qquad L_{i2} = \sqrt{\eta}\, a_i a_i$$

$$\mathcal{D}[\rho] = \sum_{i\mu}\left(L_{i\mu}\rho L_{i\mu}^\dagger - \frac{1}{2}\left\{L_{i\mu}^\dagger L_{i\mu}, \rho\right\}\right)$$

Equilibrium Bosonic Anderson Impurity Model

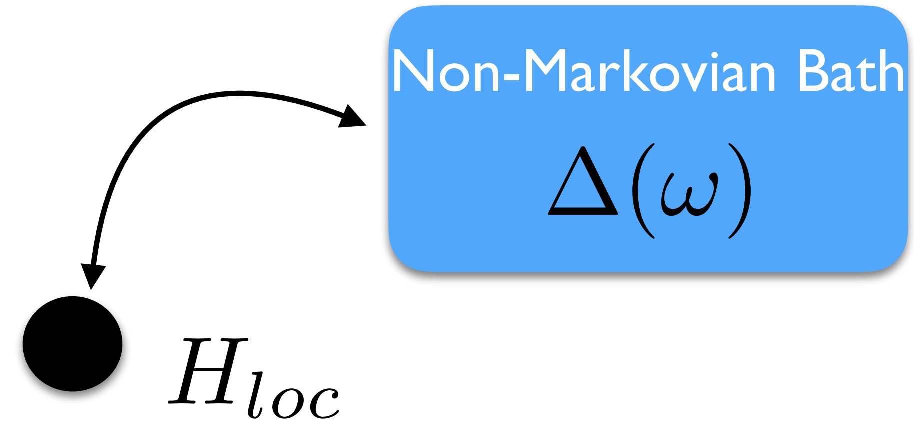
NRG: Lee, Bulla (2006, 2010)

$$H = H_{loc} + \sum_k \omega_k b_k^\dagger b_k + \sum_k g_k \left(b_k^\dagger a + a^\dagger b \right)$$

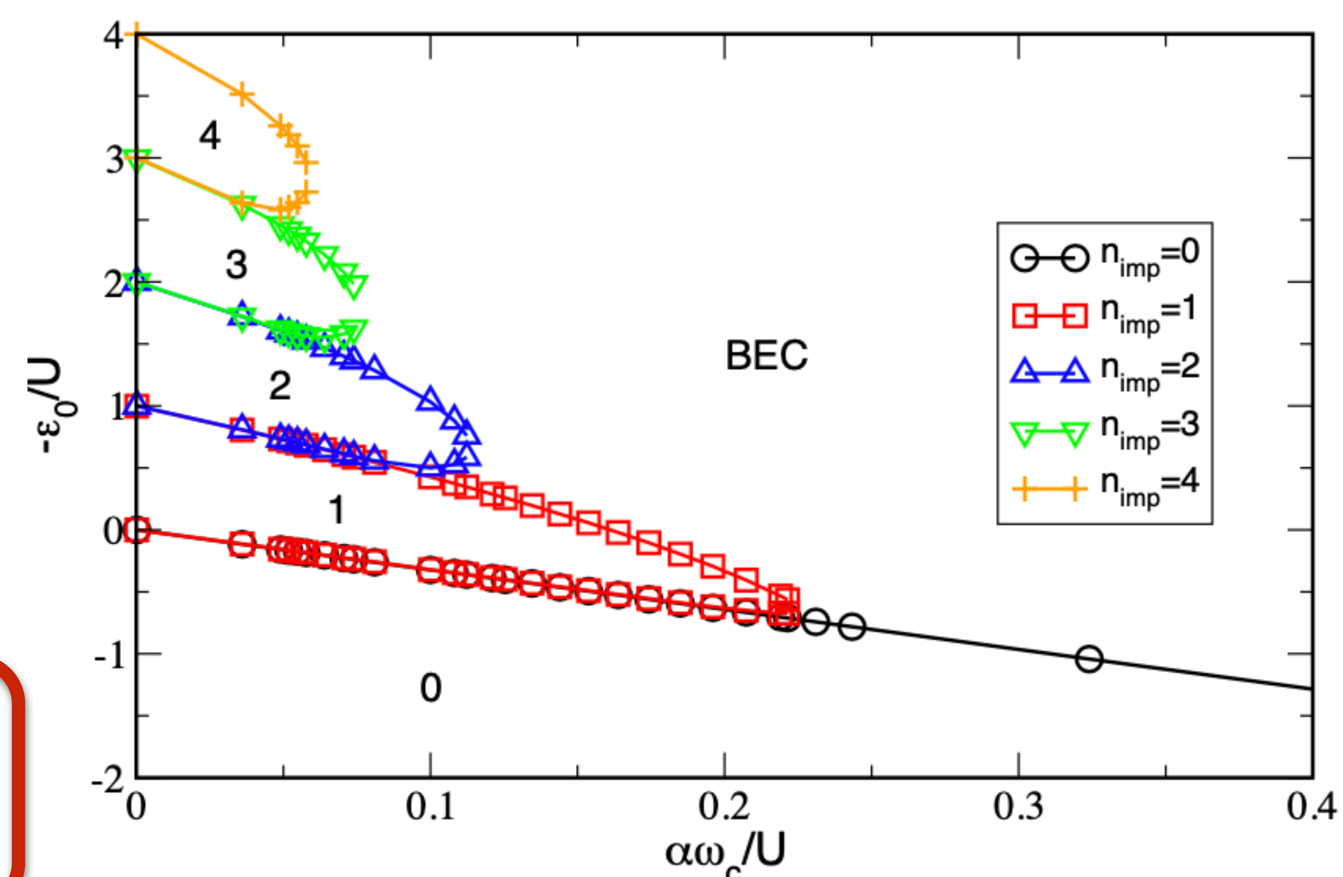
$$H_{loc} = \omega_0 n + U n^2$$

$$\Delta(\omega) = \pi \sum_k V_k^2 \delta(\omega - \varepsilon_k)$$

$$= 2\pi \, \alpha \, \omega_c^{1-s} \, \omega^s \, , \; 0 < \omega < \omega_c$$

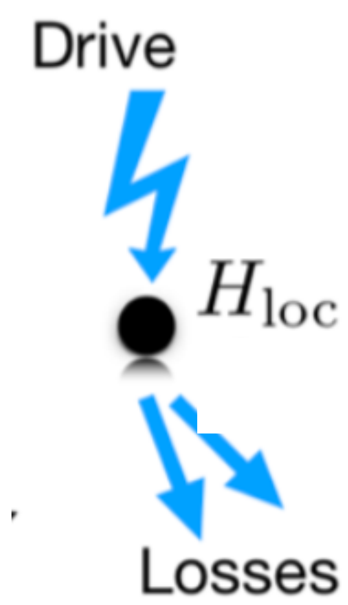


- Model for a static impurity in a BEC
- Quantum Phase Transition between local incoherent (Mott) and local BEC phase



- What happens in presence of drive/ dissipation?

Driven-Dissipative Bosonic Anderson Impurity (No-bath)



$$i\partial_t \rho = -i[H_{loc}, \rho] + r\eta D_{pump}[\rho] + \eta D_{losses}[\rho]$$

- Bose-Hubbard single site

$$H_{loc} = \omega_0 n + U n^2$$

- Single Particle Pump/2 Particle Losses

$$D_{pump}[\rho] = a^\dagger \rho a - \frac{1}{2}\{aa^\dagger, \rho\}$$

$$D_{losses}[\rho] = aa\rho a^\dagger a^\dagger - \frac{1}{2}\{a^\dagger a^\dagger aa, \rho\}$$

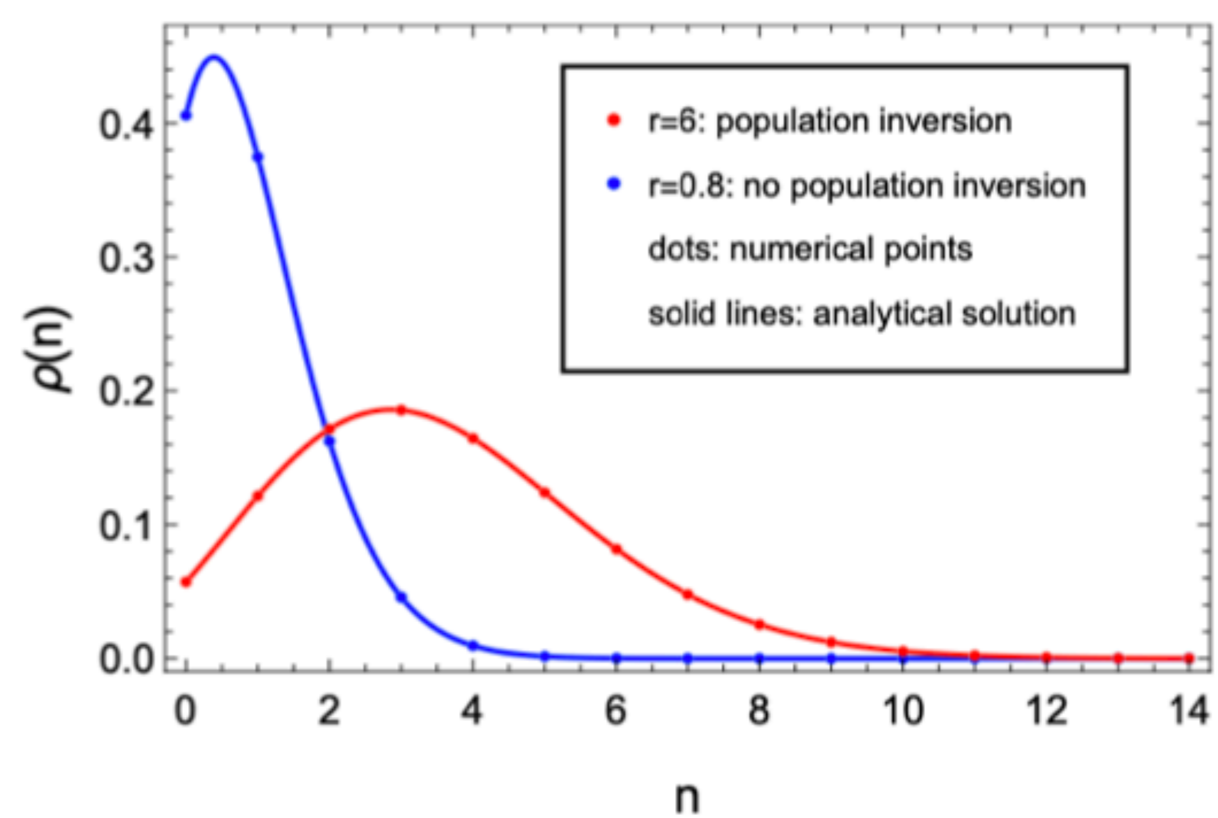
- Steady-State Density Matrix is known analytically
  - M. Dykman (1978)

☆ Incoherent mixture of bosons (rho diagonal in Fock space)

$$\langle a \rangle = \mathrm{Tr}\left(\rho_{ss} a\right) = 0$$

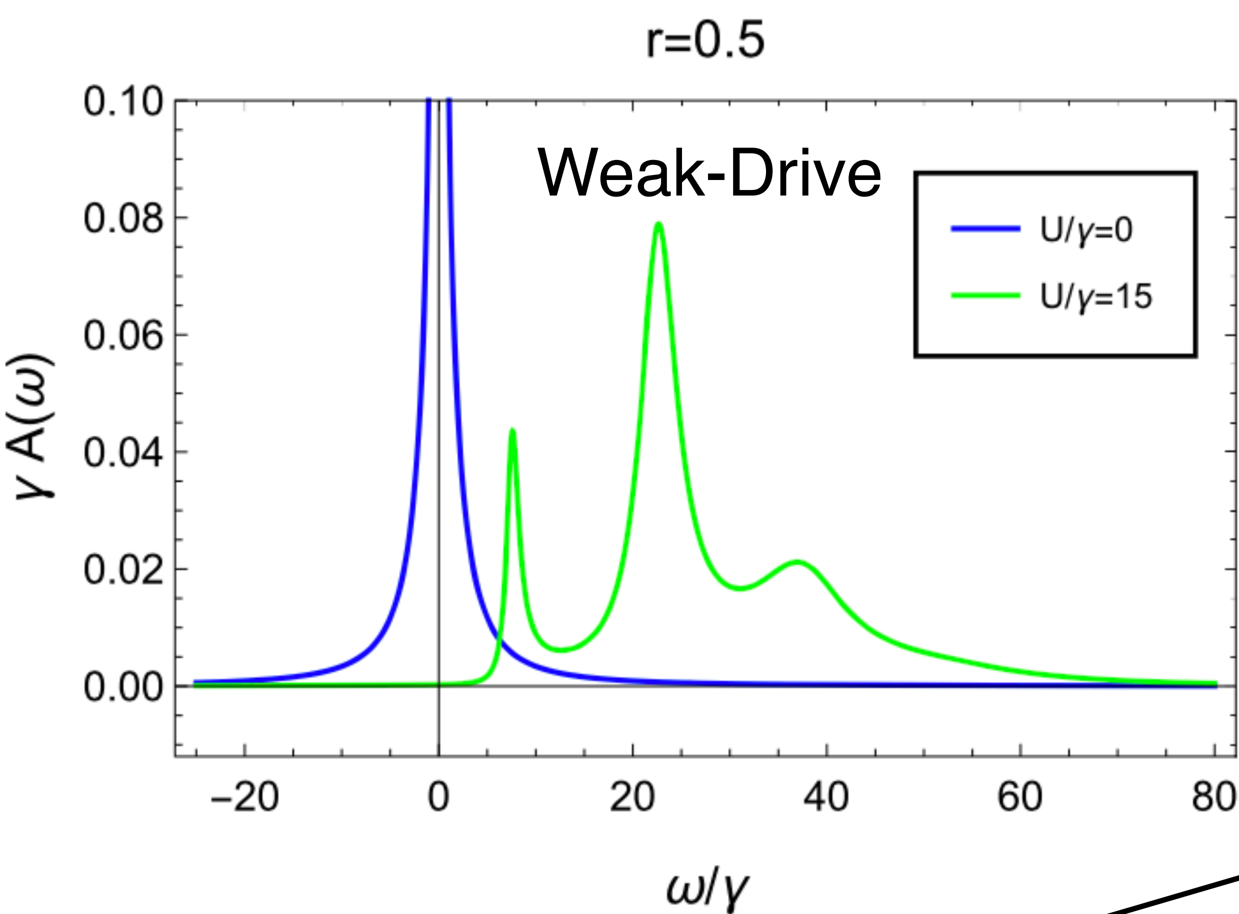
☆ ρ_{ss} **independent** on H_{loc} , only on pump/losses ratio r

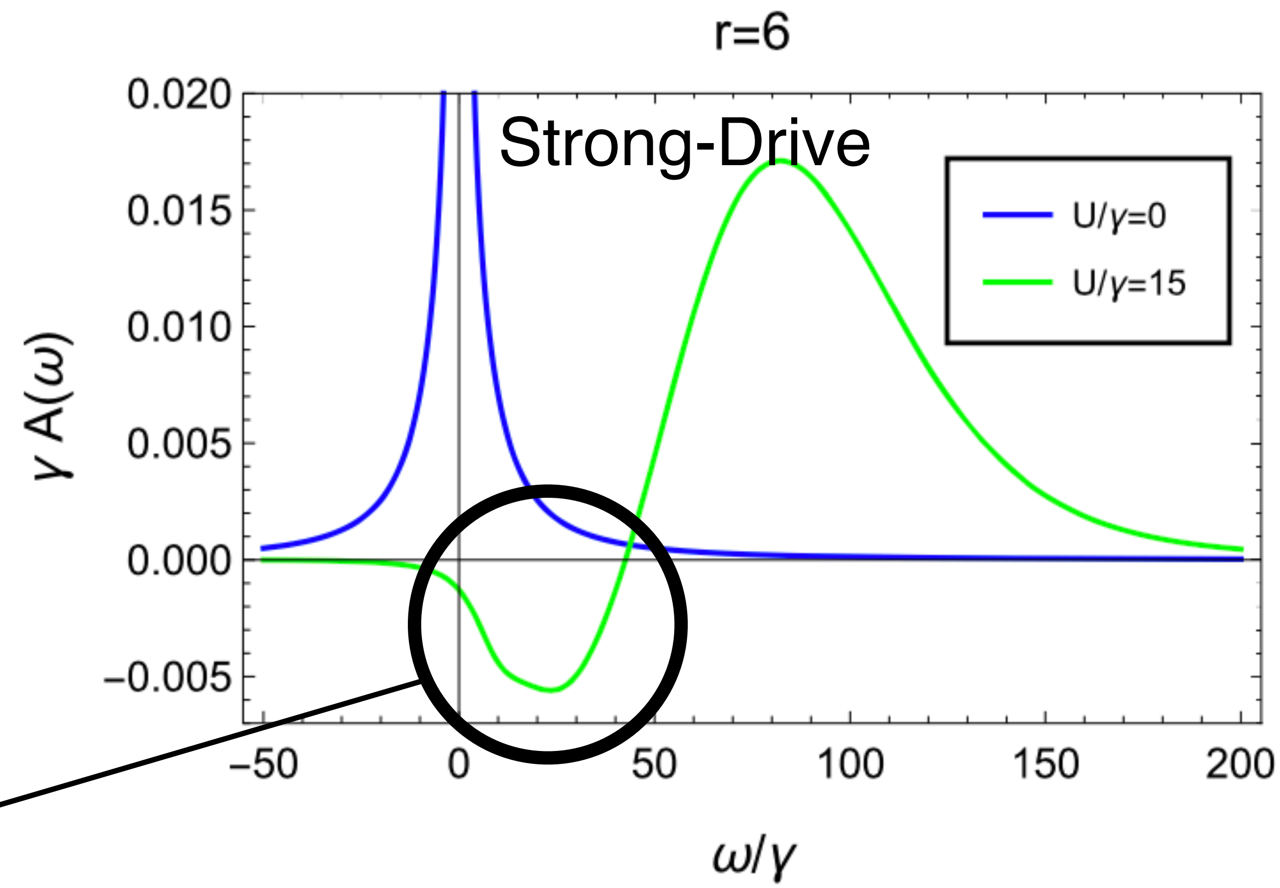
☆ Population Inversion depending on the drive strength



Spectral Functions and Onset of Energy Emission

$$A(\omega) = -\frac{1}{\pi}\mathrm{Im}G^R(\omega) \qquad G^R(t) = -i\theta(t)\langle[a(t), a^\dagger(0)]\rangle$$





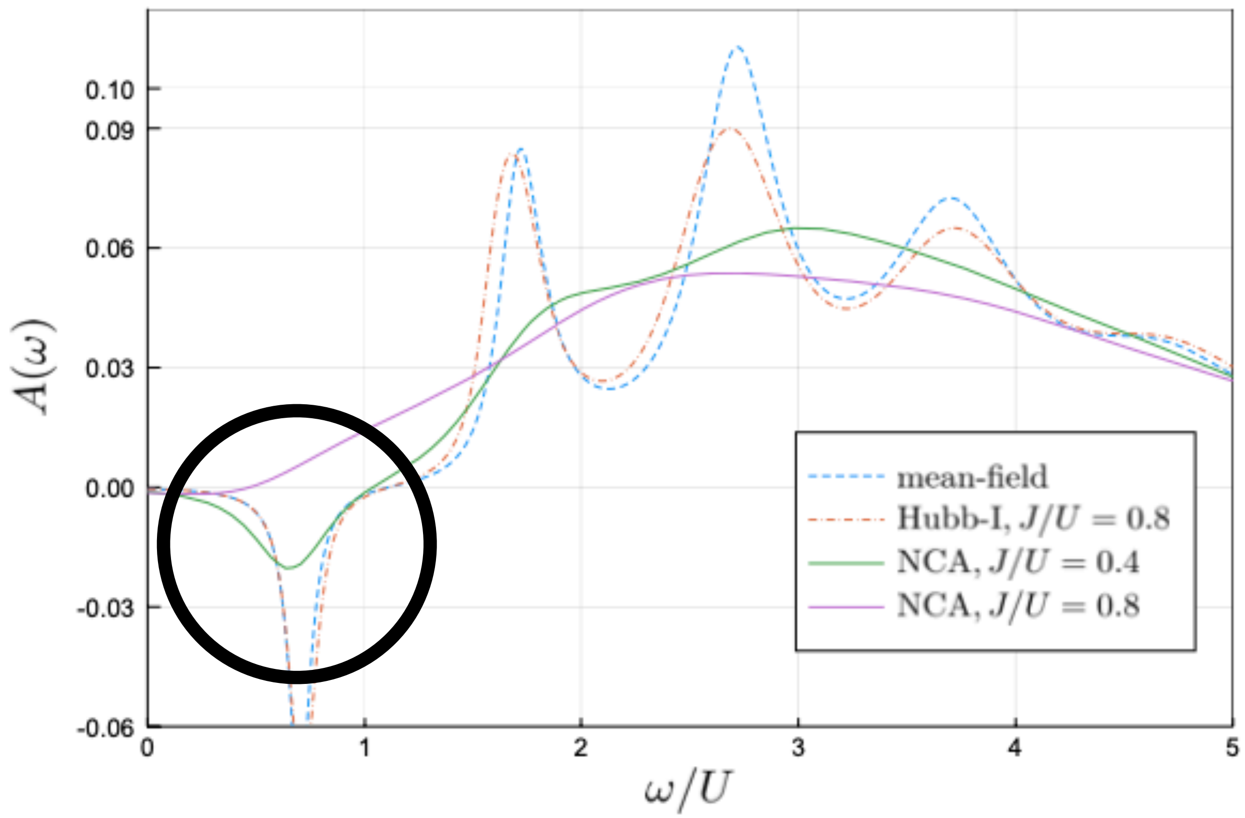
- Negative Density of States (NDoS) at $\omega > 0$ $\qquad A(\omega) \sim (\omega - \Omega_0)$

- Physical Meaning: Absorbed Power due to perturbation at frequency ω $\qquad \dot{W} = v_0^2 \omega A(\omega)$

- Negative Absorbed Power = **Gain** —> Weak Drive (seed) leads to Energy Emission

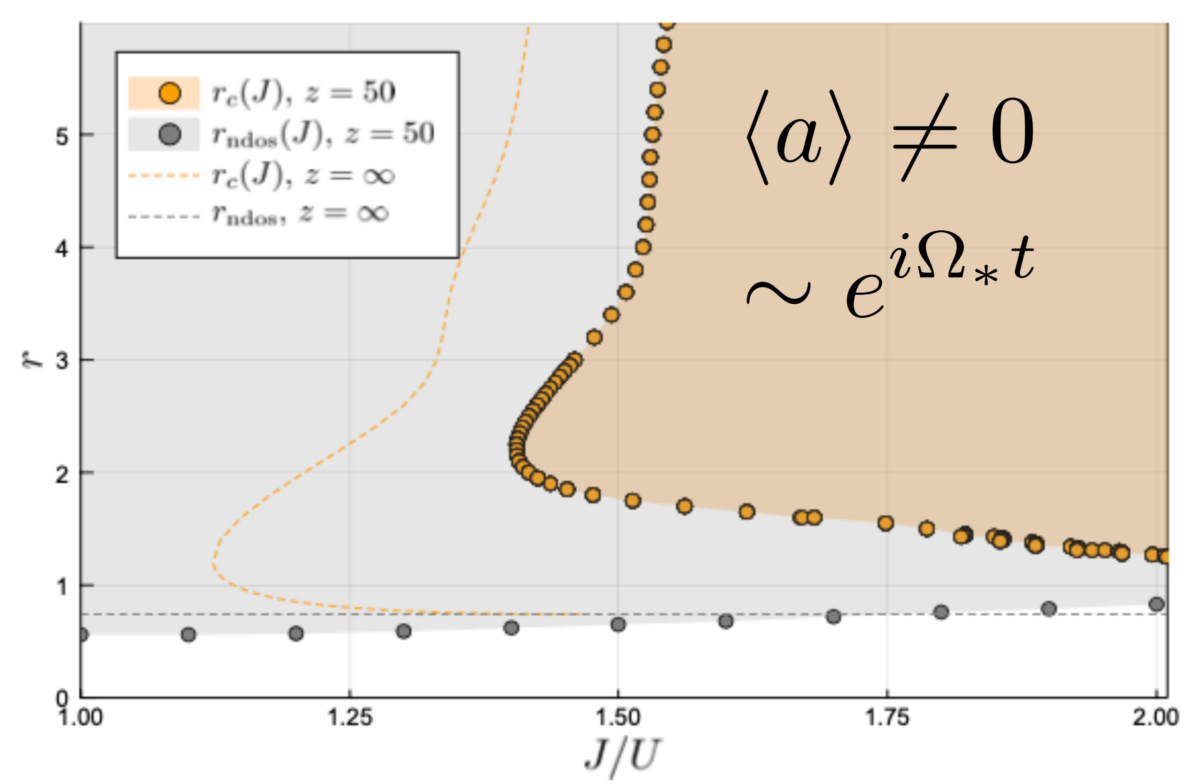
• O. Scarlatella, A. Clerk, M. Schiro', NJP 2019

Role of the Quantum Bath and Consequences for the Lattice Problem via DMFT



- Increasing hopping destroys the NDoS - non-trivial feedback from finite connectivity

- A nonequilibrium mechanism for destruction of ordered phases: Bath/ Hopping induced decoherence



- O. Scarlatella, A. Clerk, R. Fazio, M. Schiro', PRX(2021)

Strong 2BodyLosses Regime and Quantum Zeno Effect

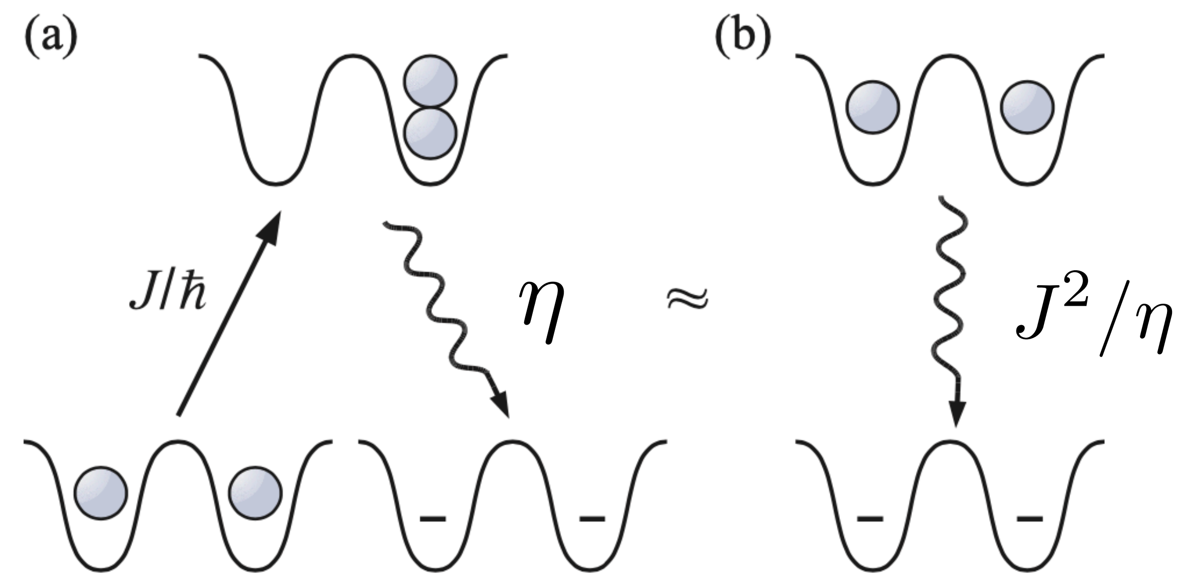
- Driven-Dissipative Bose Hubbard:

$$H = -\frac{J}{z}\sum_{\langle ij\rangle} a_i^\dagger a_j + \sum_i \omega_0 n_i + \frac{U}{2} n_i^2$$

$$\mathcal{D}[\rho] = \sum_{i\mu}\left(L_{i\mu}\rho L_{i\mu}^\dagger - \frac{1}{2}\left\{L_{i\mu}^\dagger L_{i\mu}, \rho\right\}\right)$$

$$L_{i1} = \sqrt{r\eta}\, a_i^\dagger \qquad L_{i2} = \sqrt{\eta}\, a_i a_i$$

$\eta \gg J$



Syassen et al, Science(2008);Garcia-Ripoll et al, New Journal of Physics (2009)

- With no pump and large 2body losses only single occupied and empty sites effectively remain

- Dissipative hard-core boson regime

- Slow Power-law density decay to the vacuum (beyond mean-field)

$$n(t) \sim 1/\sqrt{t}$$

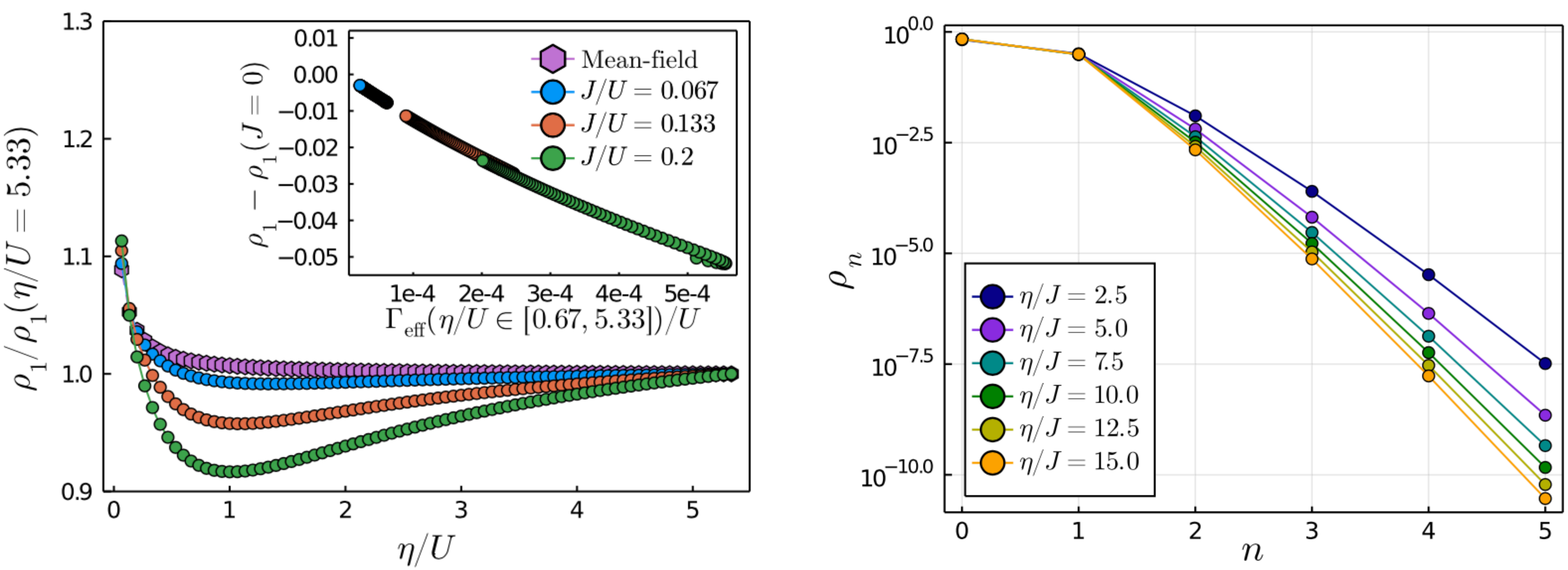
D. Rossini et al, Phys. Rev. A (2021)

Pump+Losses: Steady-State Quantum Zeno Effect

- O. Scarlatella, A. Clerk, R. Fazio, M. Schiro', PRX(2021)

- Finite density stationary state can be obtained with small drive (parametrically smaller than losses) $r \ll 1$

- Results with DMFT/NCA:

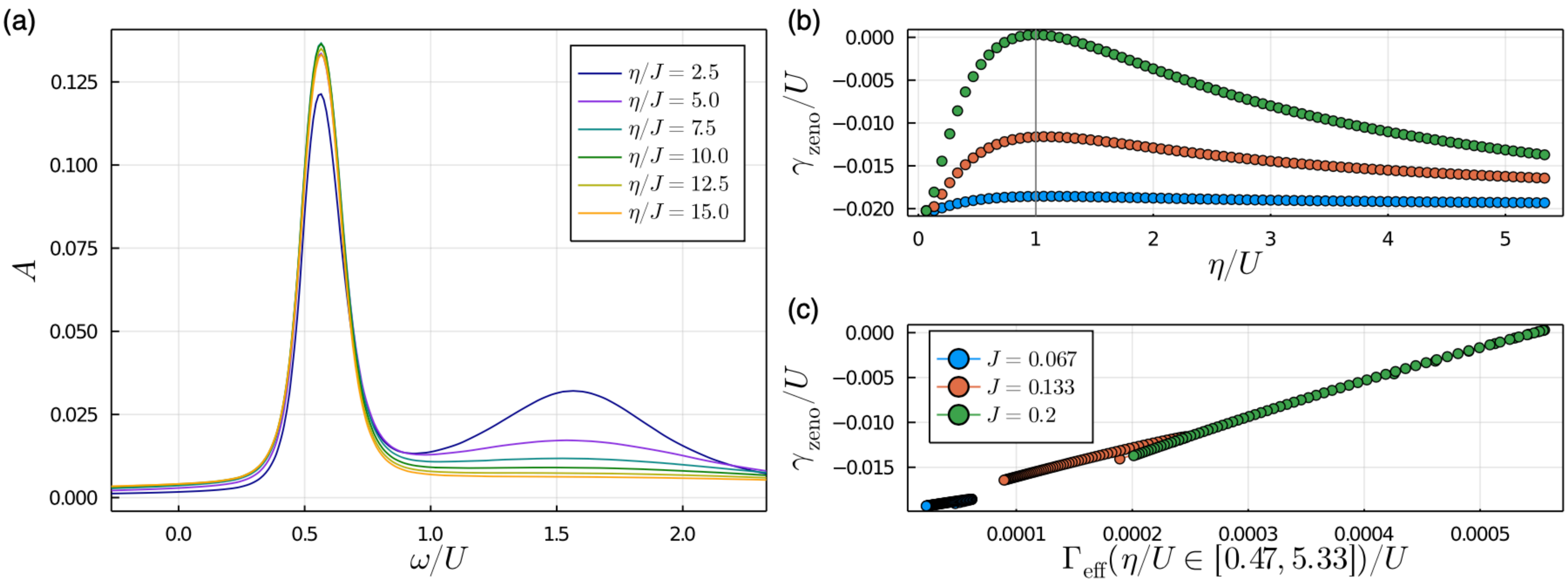


- Zeno subspace is still 0,1 bosons but now the relative weight is controlled by the pump/loss ratio

- DMFT captures the Zeno scale! J^2/η

QZE in the single-particle Lifetime

- Emergence of hard-core constraint results in a single peak in the spectral function

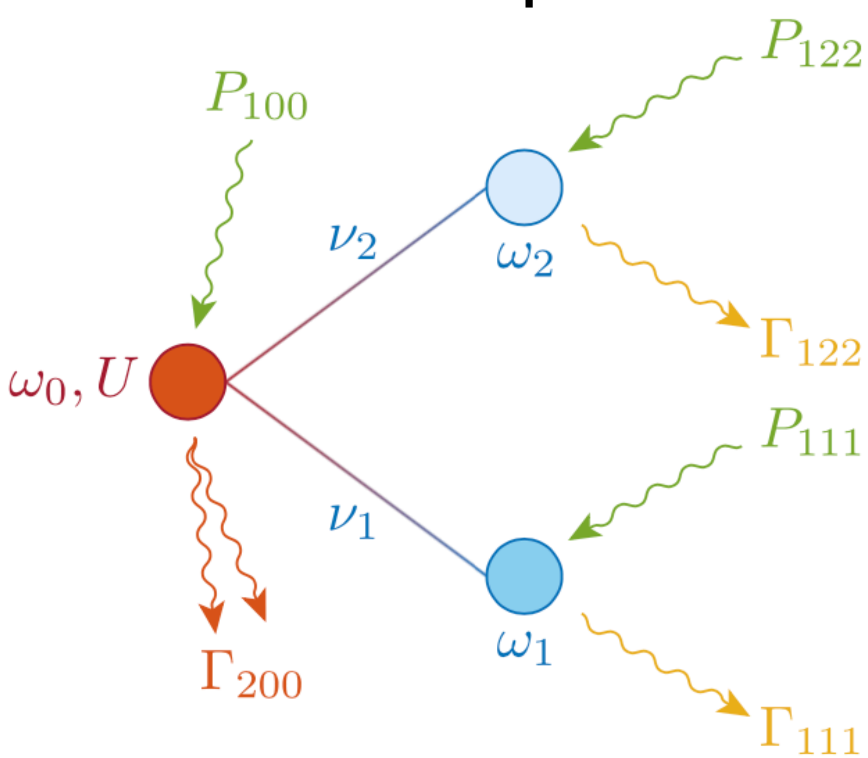


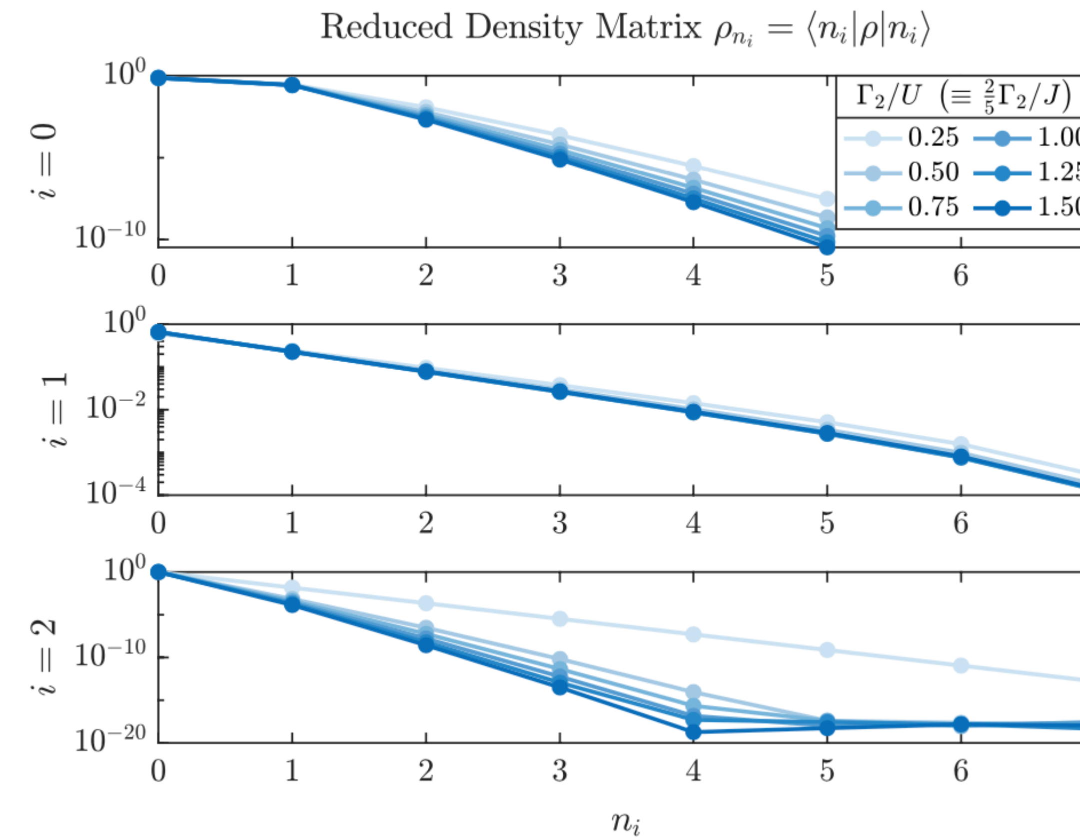
- Lifetime of 1 boson state sensitive to QZE

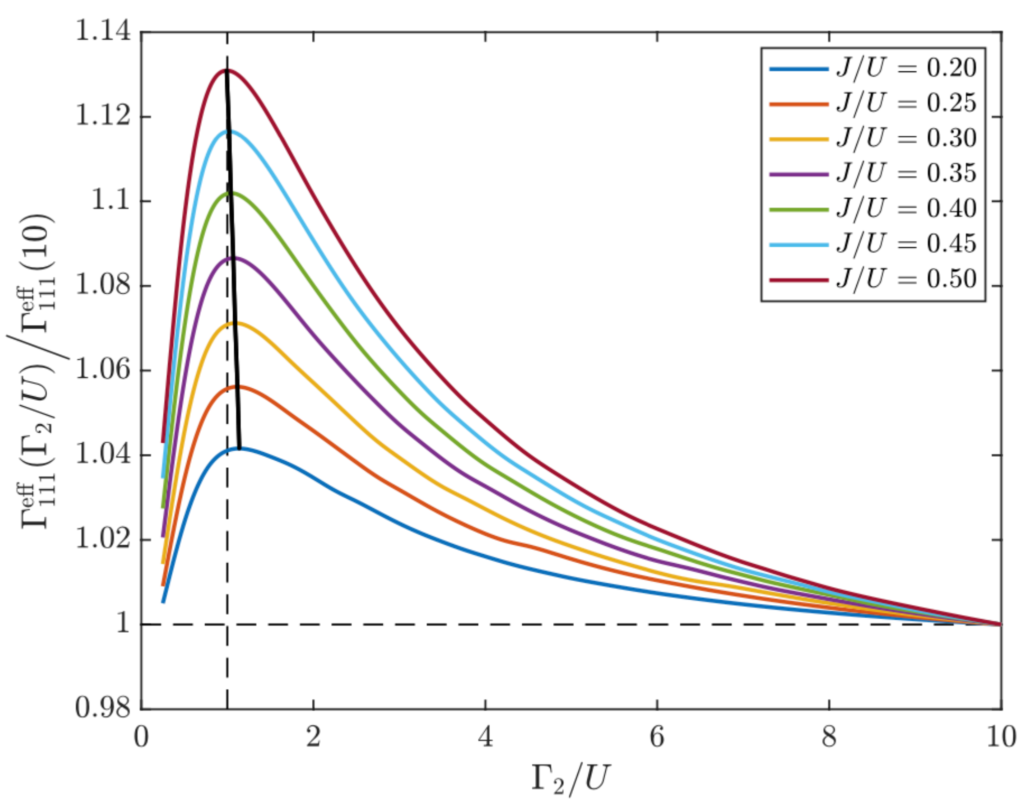
Impurity Perspective on Quantum Zeno

Secli, Capone, Schiro (in preparation)

- How does the quantum bath look like in the Zeno Regime?







- Only 1 bath site is essentially populated! Effective Bose-Hubbard Dimer

- Life-time of the bath site contains Quantum Zeno Scale

Conclusions

- [x] New frontier: Markovian Quantum Impurity Models
- [x] New methods needed! (Dissipative interactions+ frequency dependent bath)
- [x] Bosonic Anderson Impurity Model and the role of 2-body losses (Zeno and beyond)
- [ ] Open Problems: Fermionic Impurities + Dissipation? Luttinger Liquids? Kondo?

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