Cascaded dynamics of a periodically driven dissipative dipolar system

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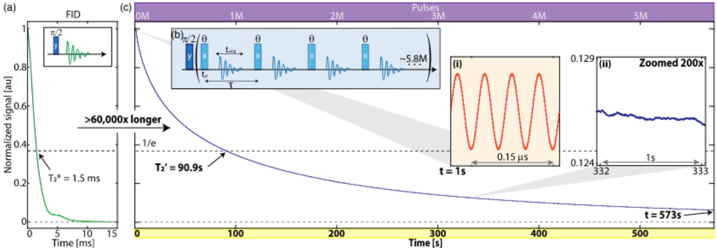
Evolution of a many-body quantum system

- Quantum dynamics of a system of particles may have multiple stages[1]
  - Prethermalization
    - Partial loss of initial memory
    - Quasi-equilibrium
    - Conserved quantities
  - Thermalization
    - Complete loss of initial memory
    - No conserved quantity
  - Equilibration / Relaxation to steady-state
- Prethermalization in driven dipolar (dissipative) systems

[1] Ueda, *Nature Reviews Physics* **2**, 669–681 (2020)

Recent experiments on prethermalization

- Floquet prethermalization on dilute systems[2,3]
- Time to prethermalize $\ll$ Time for equilibration



[2] Peng *et al.* *Nature Physics* **17**, 444-447 (2021)

[3] Beatrez *et al.* *Phys. Rev. Lett.* **127**, 170603 (2021)

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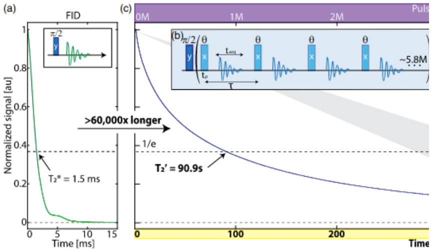

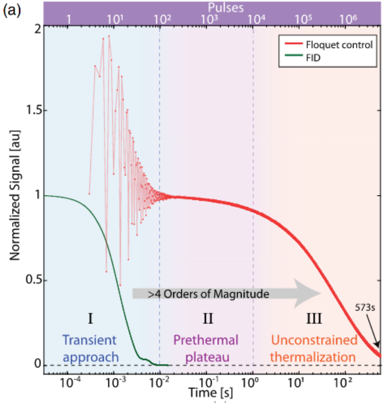

[2] Peng *et al. Nature Physics* **17**, 444-447 (2021)

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A DIFFERENT QUANTUM MASTER EQUATION

- Fluctuations of the energy levels of the bath
- $\mathcal{H}_{\mathrm{E}} = \sum_j f_j(t)|\phi_j\rangle\langle\phi_j|$. $f_j(t)$ are Gaussian white noise.
- Causes exponential decay of bath coherences (τ_c)
- System dynamics (timescale T_R) is slow; fluctuations are fast.
- $\tau_c \ll \Delta t \ll T_R$
- Couplings + Drive + System-bath coupling $\longrightarrow \mathcal{H}_{\mathrm{eff}}$
- Coarse-grained form: $\rho_s(t+\Delta t) = \rho_s(t) - i \int_t^{t+\Delta t} dt_1 \, \mathrm{Tr}_{\mathrm{E}}[H_{\mathrm{eff}}(t_1), \rho(t_1)]$
- Construct $U(t_1, t) \approx U_{\mathrm{E}}(t_1, t) - \int_t^{t_1} dt_2 \; H_{\mathrm{eff}}(t_2) U_{\mathrm{E}}(t_2, t)$
- Coarse-graining + Born approximation $\longrightarrow$ Fluctuation-Regulated Quantum Master Equation[4].

[4] Arnab Chakrabarti & RB, PRA, (2018)

FRQME

- Standard GKLS form[5]

  $\dot{\rho}_s =$

  $-i[H_{couplings+drive}(t), \rho_s(t)] - \mathcal{D}_{\mathrm{system-bath}}[\rho_s] - \mathcal{D}_{\mathrm{couplings+drive}}[\rho_s]$
- $\mathcal{D}[\rho_s] = \sum_{i,j} \gamma_{i,j} \left(a_i \rho_s a_j^\dagger - \frac{1}{2} \left\{ a_j^\dagger a_i, \rho_s \right\} \right)$
- Exponential kernels in all dissipators $\Rightarrow$ Lorentzian spectral density.
- Other applications of FRQME:
  - Light shifts and Bloch-Siegert shifts[6],
  - Optimal clockspeed of QC[7],
  - Emergence of Born rule[8].

[5] Arnab Chakrabarti & RB, PRA, (2018)
[6] Arpan Chatterjee & RB, PRA (2020)
[7] Nilanjana Chanda & RB, PRA (2020)
[8] Nilanjana Chanda & RB, PRA (2021)

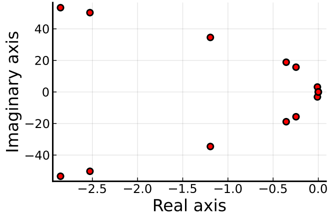
Spin-locking revisited

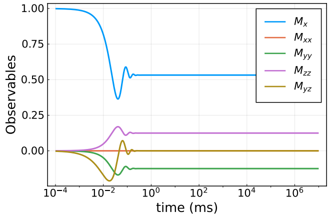
- Zeeman $\mathcal{H}_S^\circ = \sum_{i=1}^{2} \frac{1}{2}\omega_\circ \sigma_z^i$
- Full dipolar Hamiltonian $\rightarrow \sum_{m=-2}^{2} (-1)^m \omega_{d_m} \mathcal{T}_2^m e^{im\omega_\circ t} = H_{\mathrm{dip}}^{\mathrm{sec}} + H_{\mathrm{dip}}^{\mathrm{nonsec}}$
- Circularly polarized drive $\mathcal{H}_{\mathrm{drive}}(t) \Longrightarrow \frac{1}{2}\omega_1 \sum_i \sigma_x^i$
- $\dot{\rho}_s =$
  $-i[H_{drive}(t)+H_{\mathrm{dip}}^{\mathrm{sec}}, \rho_s(t)]-\mathcal{D}_{\mathrm{drive+sec}}[\rho_s]-\mathcal{D}_{\mathrm{nonsec}}[\rho_s]-\mathcal{D}_{\mathrm{sys-bath}}[\rho_s]$
- Spectral densities $\propto \frac{\tau_c}{1+(m\omega_\circ\tau_c)^2}$
- $\omega_1, \omega_{d_m} \gg \omega_{SL}$ (relaxed later)
- $\omega_\circ \tau_c \gg 1$ (relaxed later)
- $||\mathcal{D}_{\mathrm{drive+sec}}[\rho_s]|| \gg ||\mathcal{D}_{\mathrm{nonsec}}[\rho_s]|| \gg ||\mathcal{D}_{\mathrm{sys-bath}}[\rho_s]||$

Emergence of a prethermal phase

- $\dot{\rho}_s = -i[H_{drive}(t) + H^{\rm sec}_{\rm dip}, \rho_s(t)] - \mathcal{D}_{\rm drive+sec}[\rho_s]$

- Non-commuting part vanishes.
- Emergence of prethermal phase[9]
- Conserved quantities[10]
  1. $\langle J^2 \rangle \equiv \langle \vec{\sigma}^1 . \vec{\sigma}^2 \rangle$
     Dipolar order
  2. $3\omega_{d_0} \langle \sigma_z^1 \sigma_z^2 \rangle + 2\omega_1 \sum_i \langle \sigma_x^i \rangle$
     Prethermal order
  3. $\langle \sigma_x^1 \sigma_x^2 \rangle$
- Decay rate of transients $(4\omega_1^2 + 9\omega_d^2/4)\tau_c$

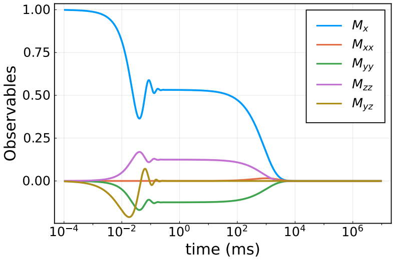


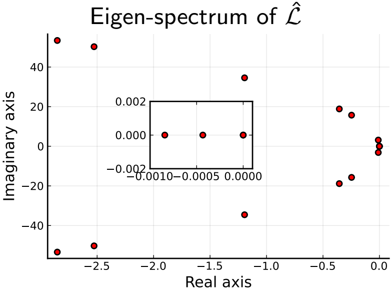


[9] Arnab Chakrabarti & RB arXiv.1911.07607
[10] Saptarshi Saha & RB, PRA (2023)

Decay of the prethermal phase

- $\dot{\rho}_s = -i[H_{drive}(t) + H_{\rm dip}^{\rm sec}, \rho_s(t)] - \mathcal{D}_{\rm drive+sec}[\rho_s] - \mathcal{D}_{\rm nonsec}[\rho_s]$
- Spectral densities $\propto \dfrac{\tau_c}{1 + (m\omega_\circ \tau_c)^2}$
- Conserved quantity:
  $\langle J^2 \rangle \equiv \langle \vec{\sigma}^1 . \vec{\sigma}^2 \rangle$
  Dipolar order[11]
- A longer timescale

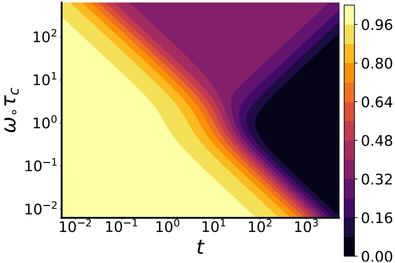




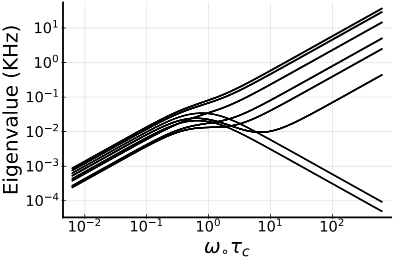
[11] Saptarshi Saha & RB, PRA (2023)

Prethermal plateau: critical limits

- Prethermal phase requires $\omega_0\tau_c > 1$

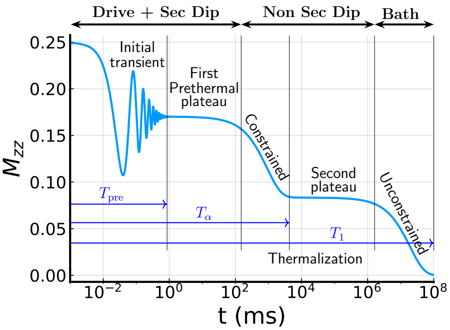


- Eigenvalues as a function of $\omega_0\tau_c$
- $\omega_\circ\tau_c = 1$ is a critical point



THE CASCADE

M_{zz} shows additional plateau. Dipolar order survives the non-secular dissipator.



Saptarshi Saha

Arnab Chakrabarti

Saptarshi Saha & RB, PRA (2023)
Arnab Chakrabarti & RB arXiv.1911.07607

- ☞ Emergence and subsequent decay of the prethermal plateau
- ☞ Critical conditions for the existence of prethermal plateau
- ☞ Constrained thermalization due to non-secular dipolar Hamiltonian
- ☞ $\omega_\circ \tau_c$ plays a critical role in separating the timescales
- ☞ Prethermalization could be multi-stage process

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