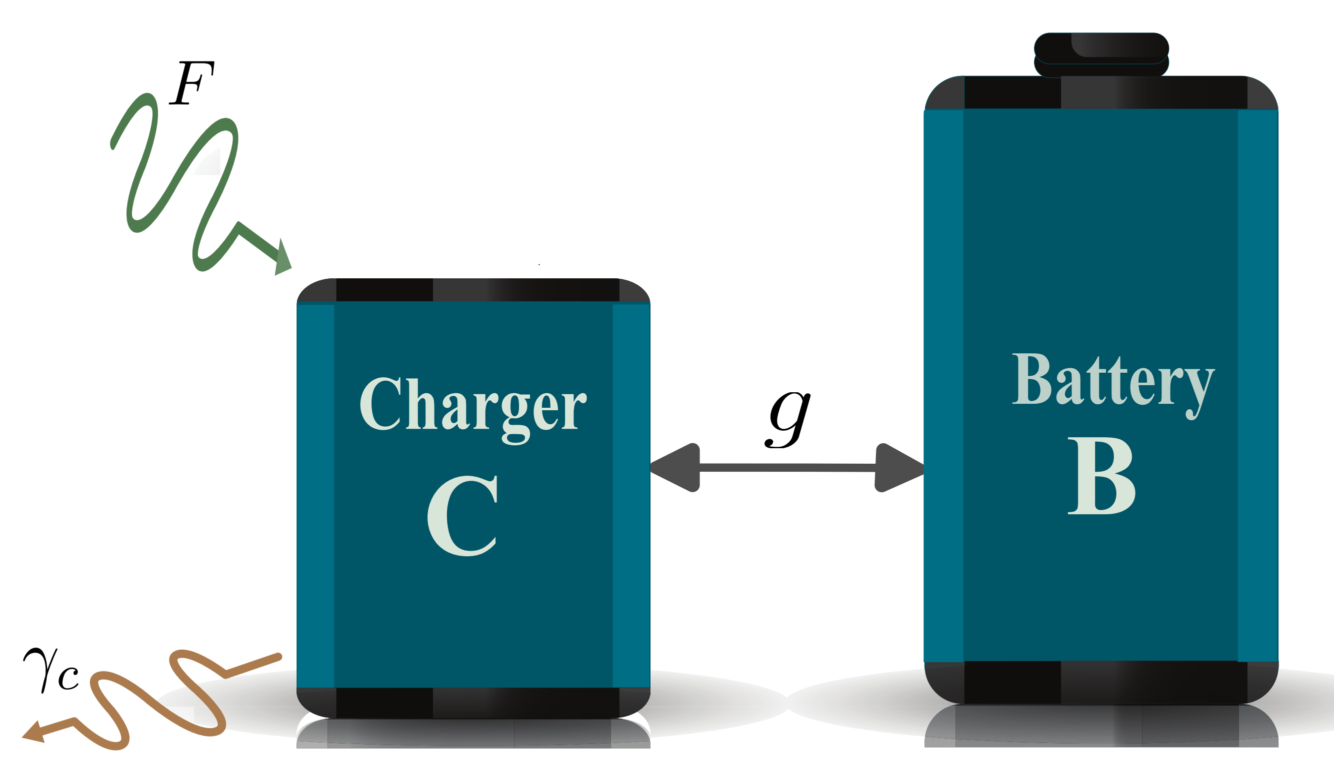

Dephasing Enabled Fast Charging of Quantum Batteries

B. Prasanna Venkatesh, IIT Gandhinagar

QuTraj 2025, ICTS-TIFR, Bangalore

Where do I come from?

Acknowledgements

Rahul Shastri
(–> Palacký University, Czechia)

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(–> CAEP Beijing)

Guo-Hua Xu

Zhejiang University, Hangzhou (PRC)

Talk Outline

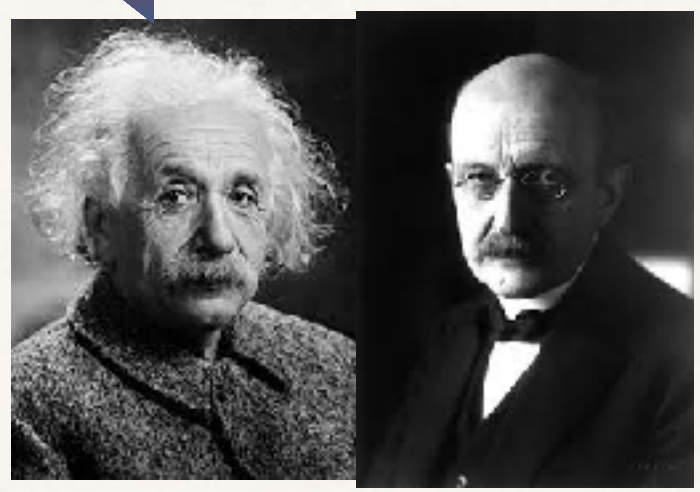
- Introduction
- Battery-Charger Set-up & Figures of Merit
- Results

Talk Outline

- Introduction
- Battery-Charger Set-up & Figures of Merit
- Results

Quantum

Thermodynamics

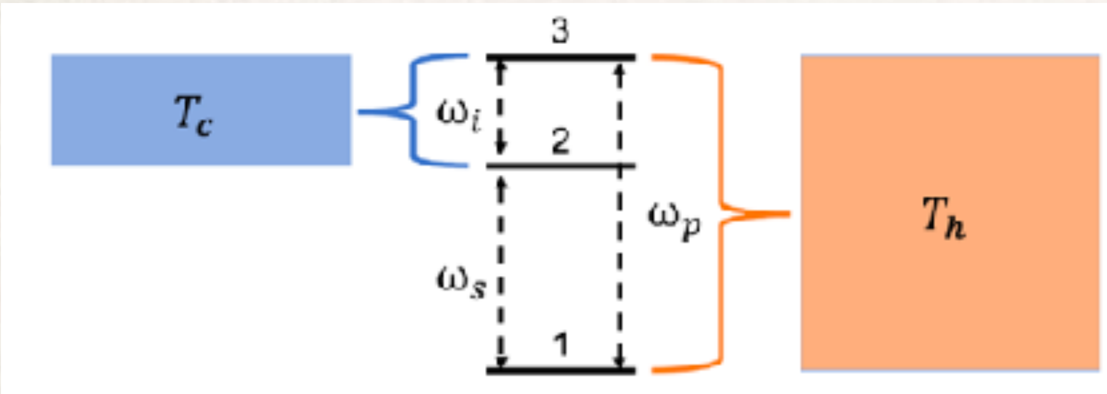


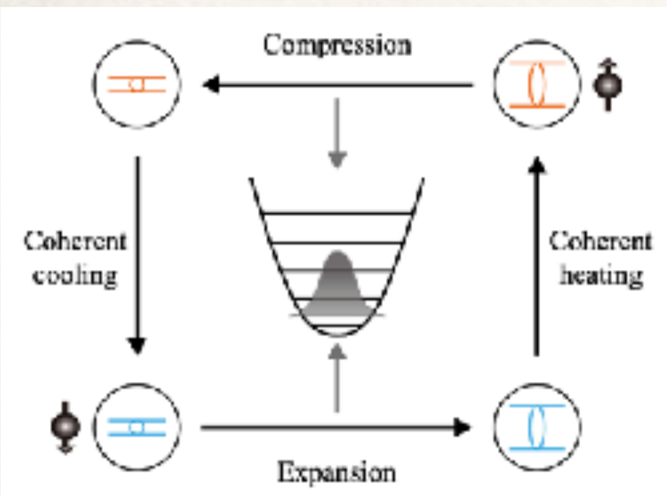
??

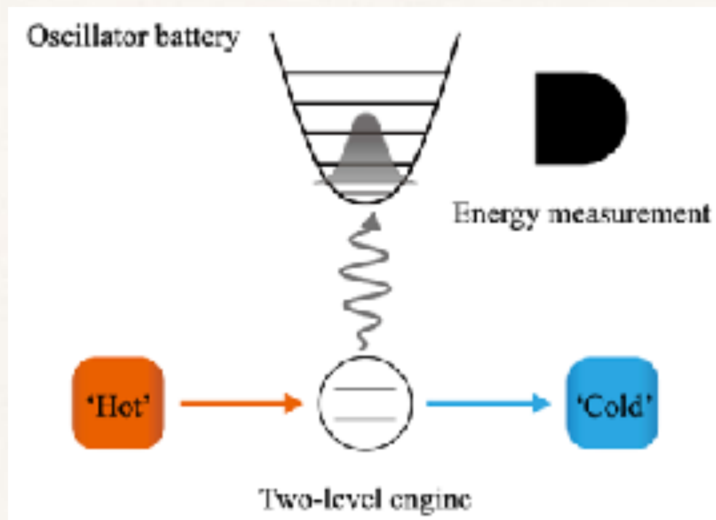
Non-equilibrium Quantum Thermodynamics

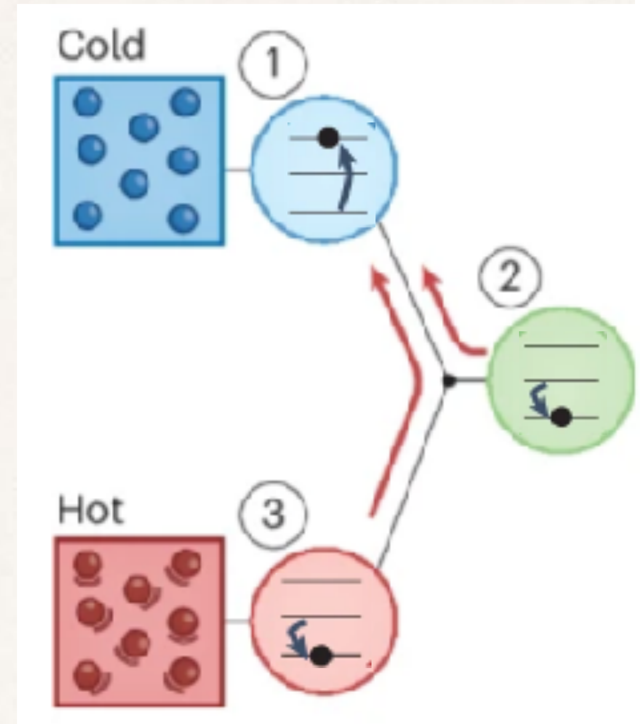
S. Vinjanampathy and J. Anders, Contemporary Physics, 57, 545 (2016)
R. Kosloff, arXiv:1801.08314
Slide Credit: Quantum Steampunk, Nicole Yunger-Halpern

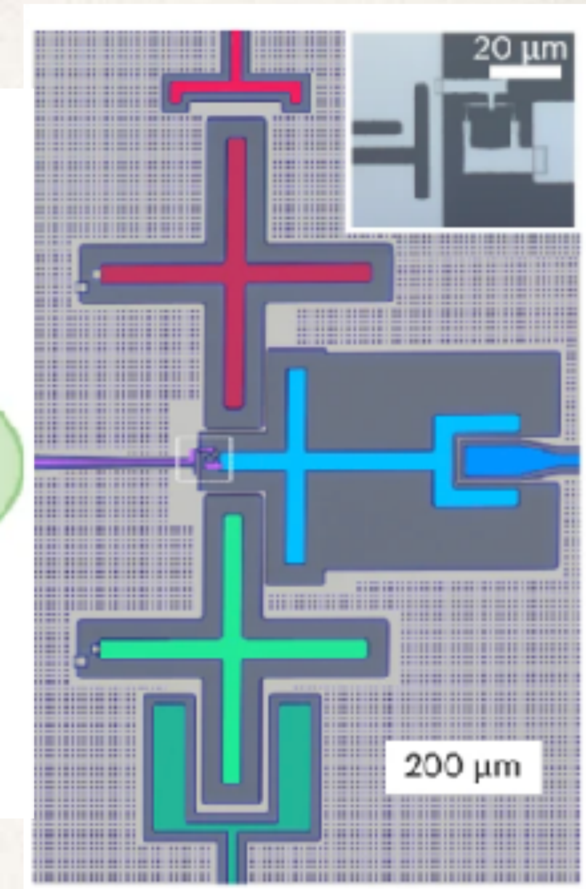
Quantum Thermal Machines











Aamir MA *et.al.*, Nat. Phys. (2025)
Blok & Landi, Nat. Phys. (2025)

W. Hou et.al, arXiv:2404.15075

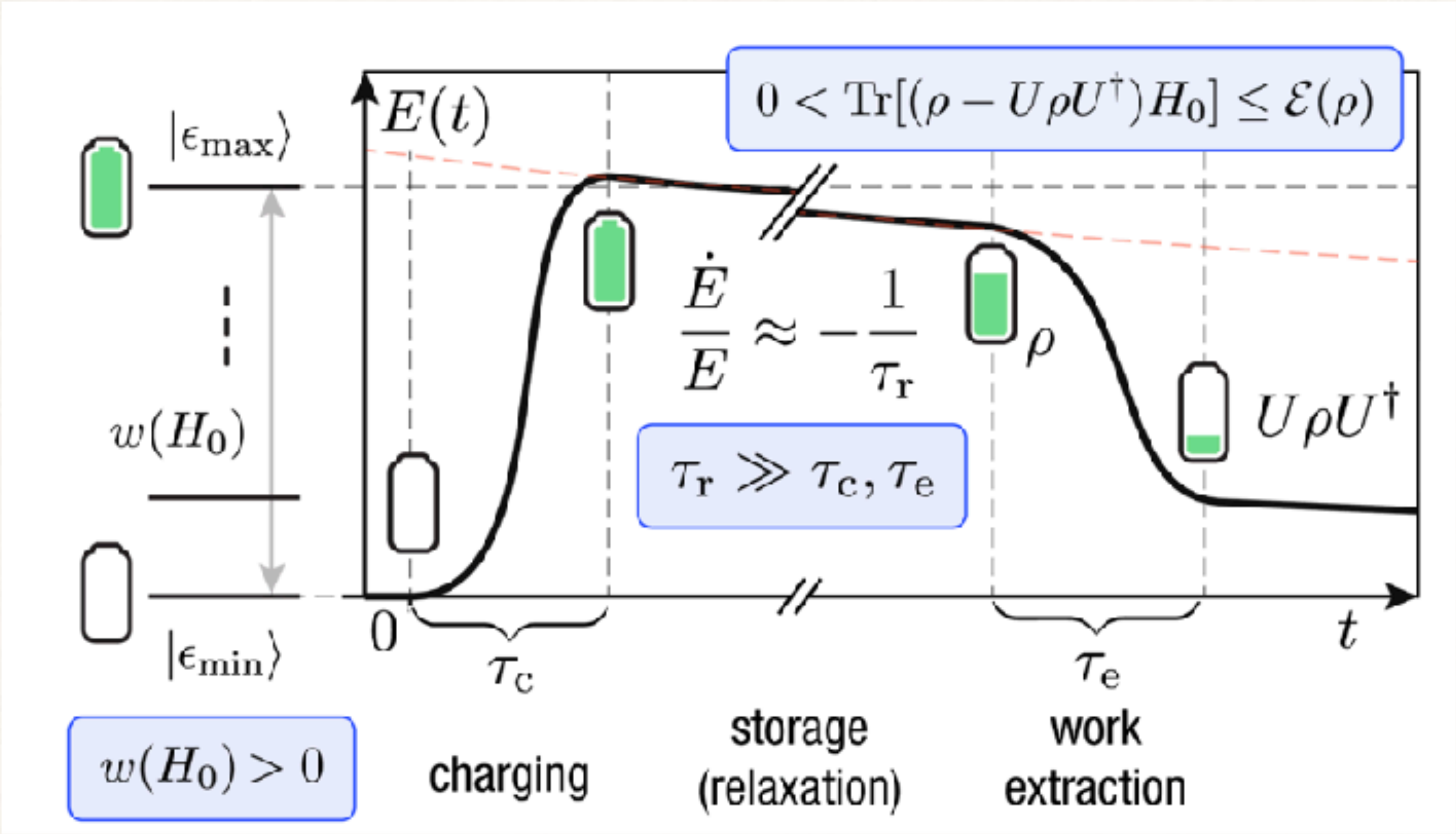
Heat Engines

Refrigerators

Quantum Effects for Enhanced Performance - Coherence, Entanglement, Non-Standard Baths, Correlated Many-Body States, Quantum Statistics…

S. Bhattacharjee and A. Dutta, EPJ B 94, 231 (2021)
Myers *et.al.*, AVS Quantum Sci. 4, 027101(2022)

Quantum Batteries



Quantum Systems as Energy Storage Devices

Reviews:
S. Bhattacharjee and A. Dutta, EPJ B 94, 231 (2021)
J. Quach et.al., Joule 7, 2195 (2023)
F. Campaioli et.al., Rev. Mod. Phys. 96, 031001 (2024)

Quantum Batteries

High Capacity, Fast Charging/Discharging, Stable Charging

Entanglement

Alicki & Fannes, PRE **87**, 042123 (2013)
Hovhannisyan *et al*., PRL 111, 240401 (2013)

Collective Effects Enhancement

F.Binder *et.al*., NJP 17, 075015 (2015).
Campaioli *et al*., PRL **118**, 150601 (2017)
S. Julià-Farré *et al*., PRR **2**, 023113 (2020)

Coherence

L.P. García-Pintos *et al*. , PRL 125, 040601 (2020)

Collective Effects Implementations

D. Ferraro et.al., PRL 120, 117702 (2018)
D. Rossini *et.al*., PRL 125, 236402 (2020)
D. Rosa et.al., JHEP 2020, 67 (2020)

Open Quantum Batteries

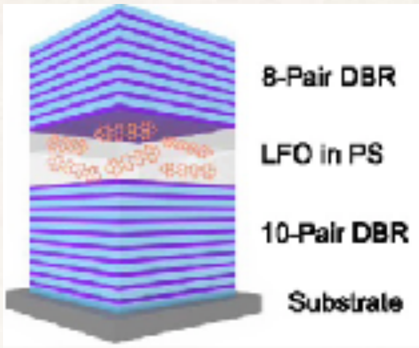
F. Barra, PRL 122, 210601 (2019).
D. Farina et.al., PRB 99, 035421 (2019).
J. Q. Quach, PR Applied 14, 024092(2020)
V. Shaghaghi et.al., *Entropy*, 25, 430 (2023)

….. many other works [pls see Rev. Mod. Phys. 96, 031001 (2024)]

Experimental Platforms

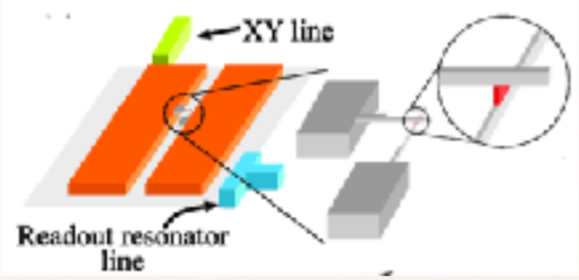
- Organic semiconductor microcavities

  Quach *et al.*, Sci. Adv. **8** 3160 (2022)



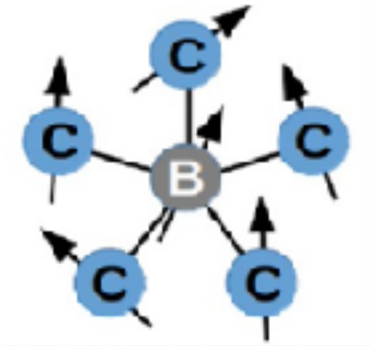
- Superconducting Circuits

  Hu *et al*., Q. Sci. Tech. **7**, 045018 (2022)



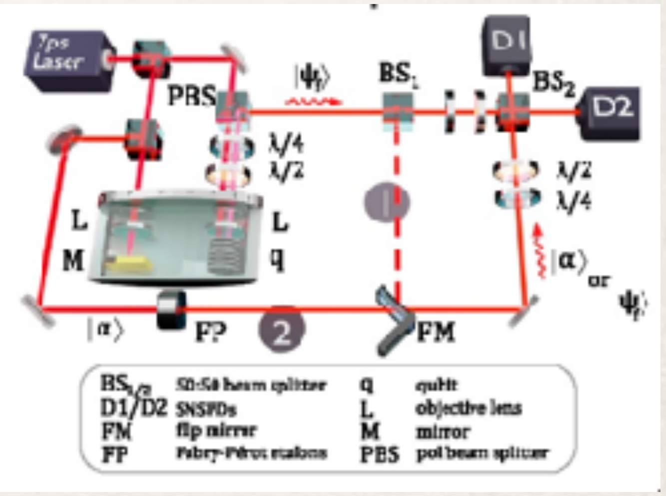
- NMR Spins

  Joshi & Mahesh, PRA **106**, 042601 (2022)



- Quantum Dots

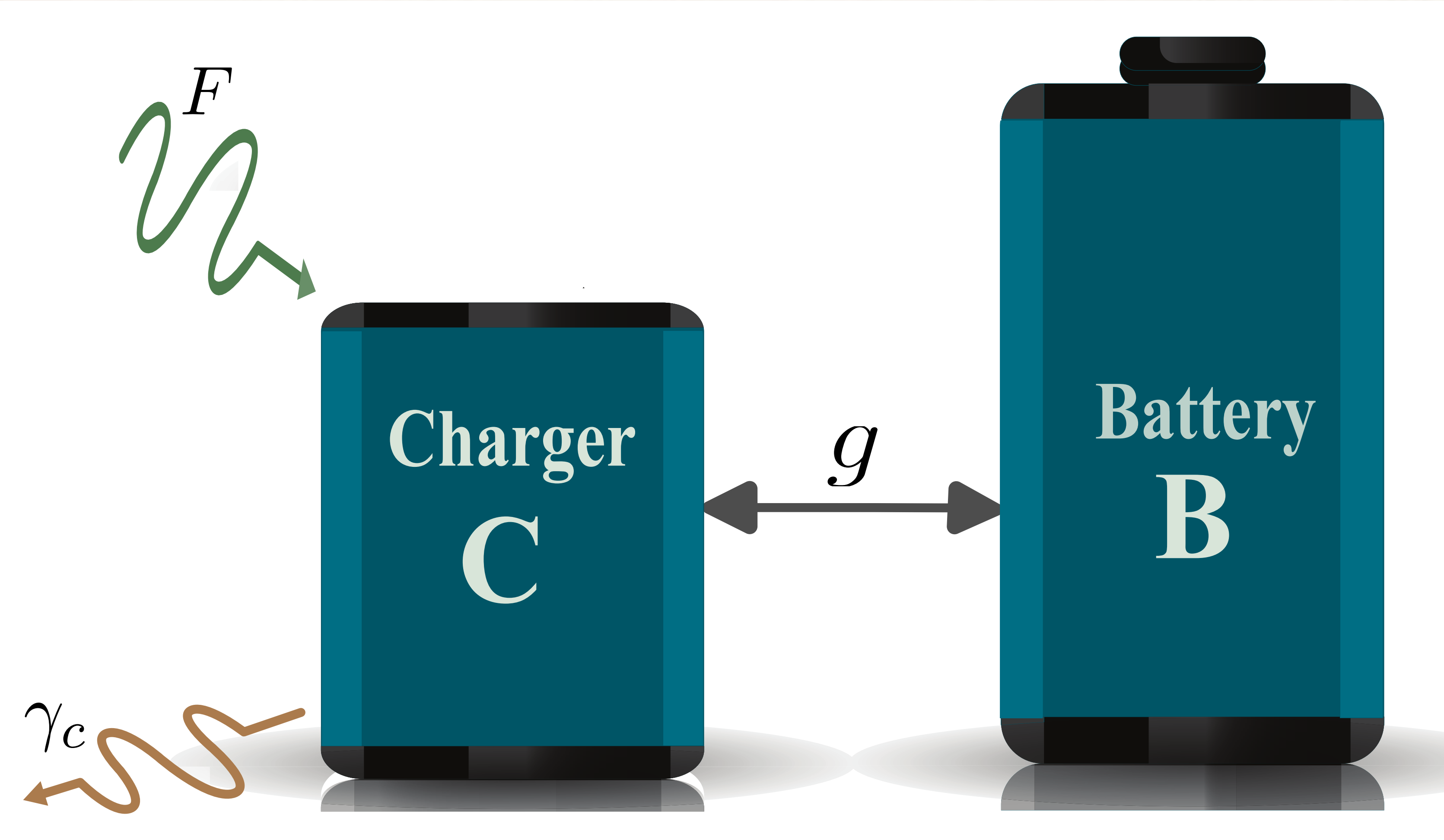
  Wenniger *et al*., PRL **131**, 260401 (2023)



- Quantum Computers

  Gemme *et al*., Batteries **8**, 43 (2022)

This Talk



Open Model of Quantum Battery - Dissipation (Dephasing) as a resource

R. Shastri et.al., npj Quantum Inf **11**, 9 (2025)

Talk Outline

- Introduction
- Battery-Charger Set-up & Figures of Merit
- Results

Dephasing

$$\begin{pmatrix} \rho_{ee} & \rho_{eg} \\ \rho_{ge} & \rho_{gg} \end{pmatrix} \to \begin{pmatrix} \rho_{ee} & \rho_{eg} e^{-\gamma t} \\ \rho_{ge} e^{-\gamma t} & \rho_{gg} \end{pmatrix}$$

Decay of coherences in energy basis

$$\frac{d\hat{\rho}(t)}{dt} = \gamma \left(\hat{L}\hat{\rho}(t)\hat{L} - \frac{\{\hat{L}^2, \hat{\rho}(t)\}}{2} \right)$$

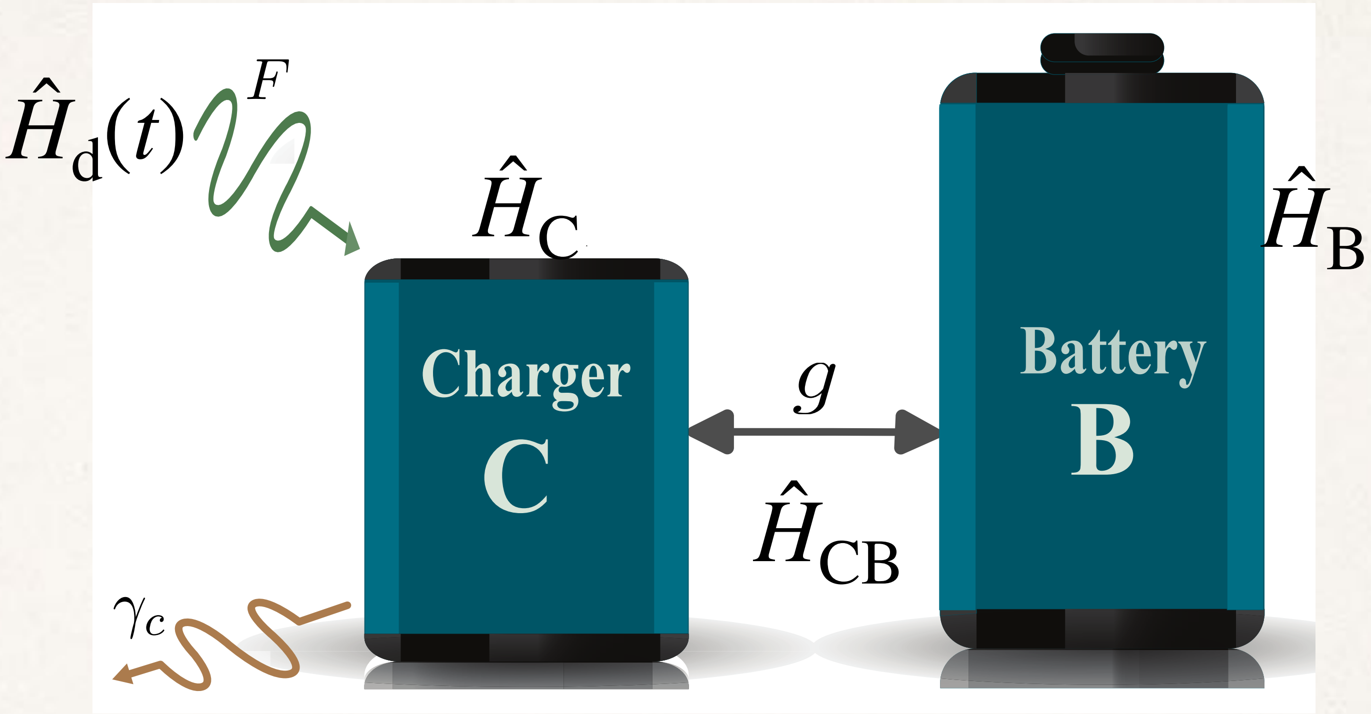
$$\hat{L} \propto \hat{H}$$

Physical Realization:

- Continuous energy Measurement
- Noisy external classical field for TLS

$$\hat{H}_{\text{stoch}}(t) = B(t)\hat{\sigma}_z, \quad B(t) = \sqrt{\frac{\gamma}{2}}\xi(t)$$

Battery + Dephased Charger

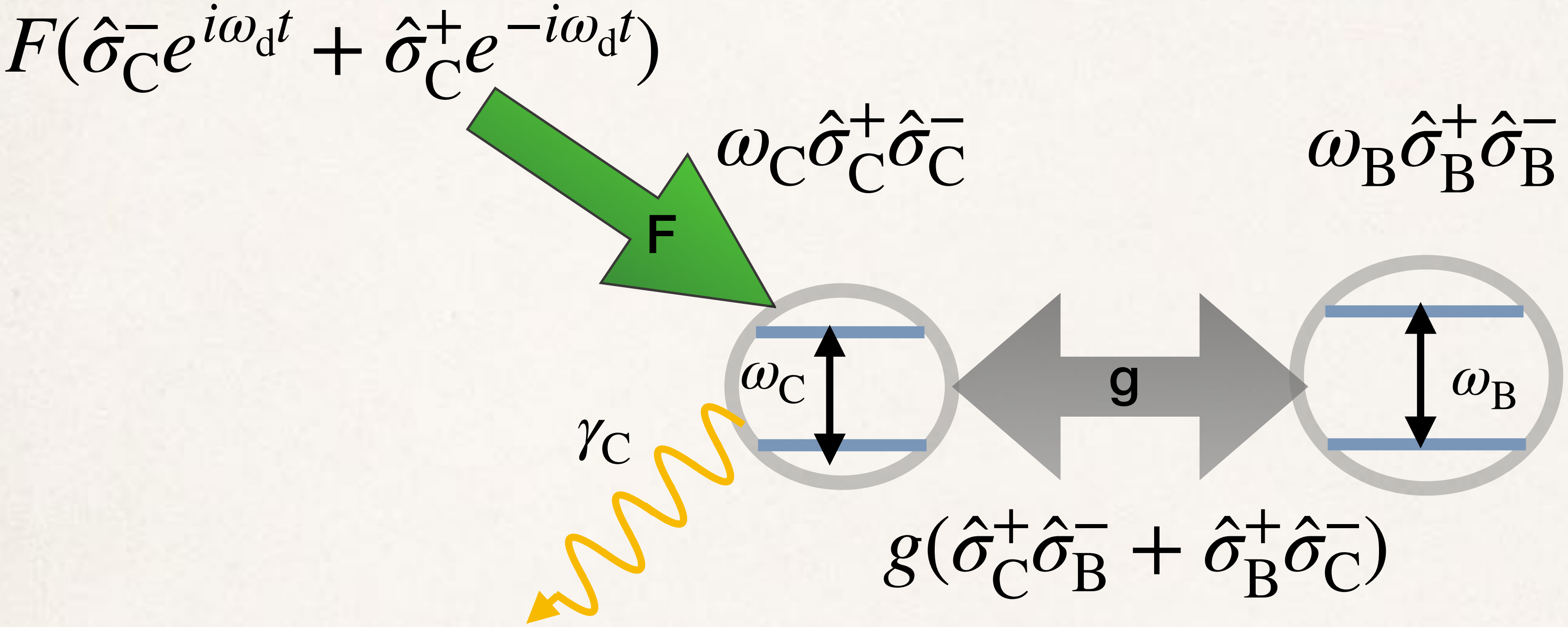


$$\gamma_C \left(\hat{L}_C \hat{\rho}(t) \hat{L}_C - \frac{\{\hat{L}_C^2, \hat{\rho}(t)\}}{2} \right), \left[\hat{L}_C, \hat{H}_C \right] = 0$$

$$\hat{H}(t) = \hat{H}_C + \hat{H}_d(t) + \hat{H}_B + \hat{H}_{CB}$$

$$\frac{d\hat{\rho}(t)}{dt} = -i \left[\hat{H}, \hat{\rho}(t) \right] + \gamma_C \left(\hat{L}_C \hat{\rho}(t) \hat{L}_C - \frac{\{\hat{L}_C^2, \hat{\rho}(t)\}}{2} \right)$$

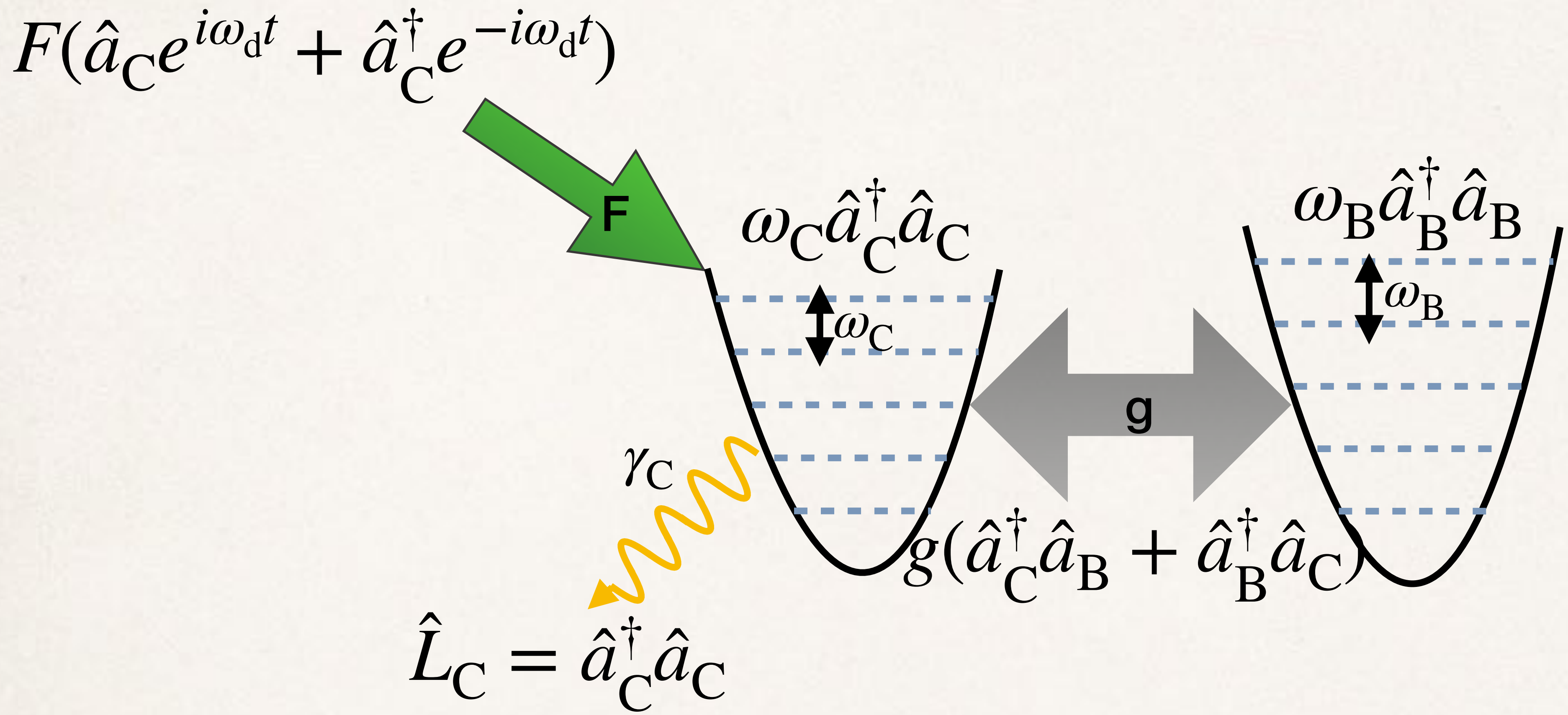
Two Level Systems (TLSs)



$$\hat{L}_{\mathrm{C}} = \hat{\sigma}_{\mathrm{C}}^{+} \hat{\sigma}_{\mathrm{C}}^{-} = (\mathbb{I} + \hat{\sigma}_{\mathrm{C}}^{z})/2$$

$$\frac{d\hat{\rho}(t)}{dt} = -i\left[\hat{H}, \hat{\rho}(t)\right] + \gamma_{\mathrm{C}}\left(\hat{L}_{\mathrm{C}} \hat{\rho}(t) \hat{L}_{\mathrm{C}} - \frac{\{\hat{L}_{\mathrm{C}}^{2}, \hat{\rho}(t)\}}{2}\right)$$

Harmonic Oscillators (HOs)



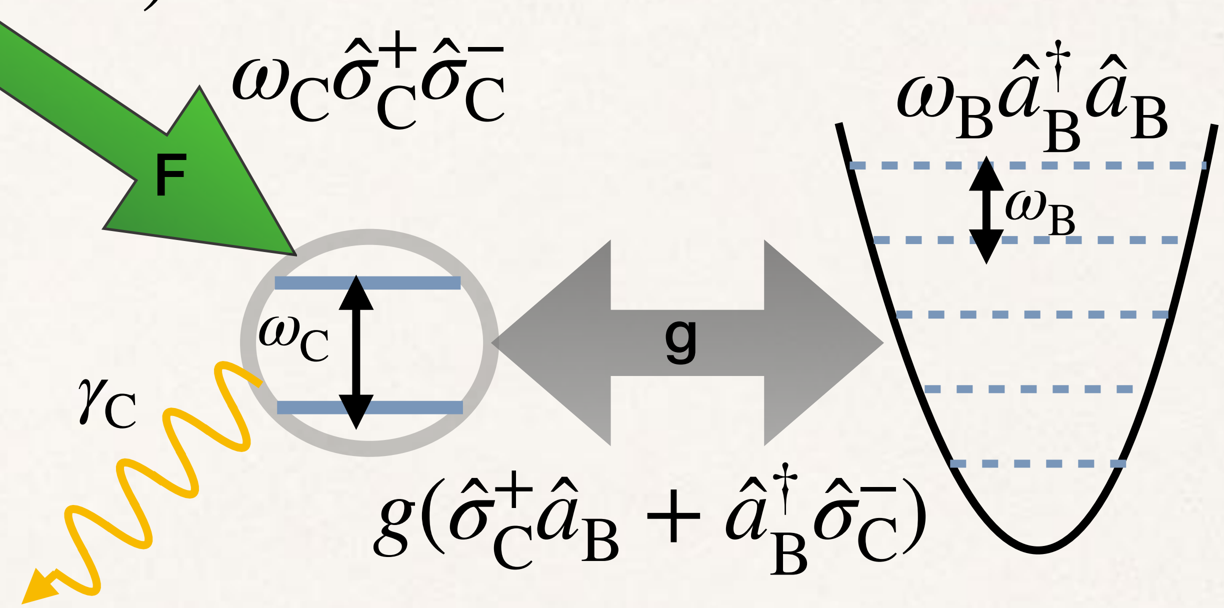
$$\frac{d\hat{\rho}(t)}{dt} = -i\left[\hat{H}, \hat{\rho}(t)\right] + \gamma_C \left(\hat{L}_C \hat{\rho}(t) \hat{L}_C - \frac{\{\hat{L}_C^2, \hat{\rho}(t)\}}{2} \right)$$

Hybrid TLS-HO

$$F(\hat{\sigma}_C^- e^{i\omega_d t} + \hat{\sigma}_C^+ e^{-i\omega_d t})$$

$$\omega_C \hat{\sigma}_C^+ \hat{\sigma}_C^-$$

$$\omega_B \hat{a}_B^\dagger \hat{a}_B$$



$$g(\hat{\sigma}_C^+ \hat{a}_B + \hat{a}_B^\dagger \hat{\sigma}_C^-)$$

$$\hat{L}_C = \hat{\sigma}_C^+ \hat{\sigma}_C^- = (\mathbb{I} + \hat{\sigma}_C^z)/2$$

$$\frac{d\hat{\rho}(t)}{dt} = -i\left[\hat{H}, \hat{\rho}(t)\right] + \gamma_C \left(\hat{L}_C \hat{\rho}(t) \hat{L}_C - \frac{\{\hat{L}_C^2, \hat{\rho}(t)\}}{2} \right)$$

Figures of Merit

Battery Energy

$$E_{\rm B} = {\rm Tr}_{\rm B}\left[\hat{\rho}_{\rm B}\hat{H}_{\rm B}\right]$$

Ergotropy

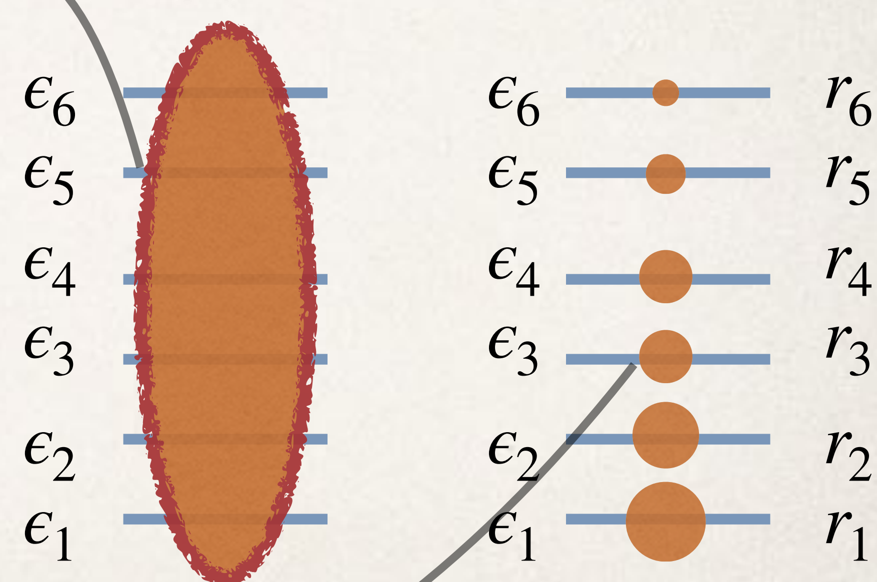
Maximum extractable energy
"quality of energy"
Allahverdyan *et al*. EPL **67**, 565 (2004)

$$\mathscr{E}_{\rm B} = E_{\rm B} - \min_{\hat{U}_{\rm B}}{\rm Tr}_{\rm B}\left[\hat{U}_{\rm B}\hat{\rho}_{\rm B}\hat{U}^\dagger_{\rm B}\hat{H}_{\rm B}\right] = {\rm Tr}[\hat{\rho}_{\rm B}\hat{H}_{\rm B}] - {\rm Tr}[\hat{\rho}_{\rm P}\hat{H}_{\rm B}]$$

$$\hat{H}_{\rm B} = \sum_{j=1}^{N} \epsilon_j |\epsilon_j\rangle\langle\epsilon_j| \qquad \hat{\rho}_{\rm B} = \sum_{j=1}^{N} r_j |r_j\rangle\langle r_j|$$

$$\epsilon_1 \le \epsilon_2 \le \cdots \le \epsilon_N \qquad r_1 \ge r_2 \ge \cdots \ge r_N$$

$$\hat{\rho}_{\rm P} = \sum_{j=1}^{N} r_j |\epsilon_j\rangle\langle\epsilon_j|$$



Figures of Merit

Battery Energy

$$E_{\mathrm{B}} = \mathrm{Tr}_{\mathrm{B}}\left[\hat{\rho}_{\mathrm{B}}\hat{H}_{\mathrm{B}}\right]$$

Ergotropy

$$\mathscr{E}_{\mathrm{B}} = E_{\mathrm{B}} - \min_{\hat{U}_{\mathrm{B}}}\mathrm{Tr}_{\mathrm{B}}\left[\hat{U}_{\mathrm{B}}\hat{\rho}_{\mathrm{B}}\hat{U}^{\dagger}_{\mathrm{B}}\hat{H}_{\mathrm{B}}\right]$$

Charging Time

$$\left|\frac{E_{\mathrm{B}}(\tau) - E_{\mathrm{B}}(\infty)}{E_{\mathrm{B}}(0) - E_{\mathrm{B}}(\infty)}\right| = e^{-n}$$

Figures of Merit - TLS

Battery Energy

$$E_{\mathrm{B}} = \frac{\omega_{\mathrm{B}}}{2}\left(\langle \hat{\sigma}^z_{\mathrm{B}} \rangle + 1\right)$$

Ergotropy

$$\mathscr{E}_{\mathrm{B}} = \frac{\omega_{\mathrm{B}}}{2}\left(\sqrt{\langle \hat{\sigma}^z_{\mathrm{B}} \rangle^2 + 4\langle \hat{\sigma}^+_{\mathrm{B}} \rangle \langle \hat{\sigma}^-_{\mathrm{B}} \rangle} + \langle \hat{\sigma}^z_{\mathrm{B}} \rangle\right)$$

Charging Time

$$\left| \frac{E_{\mathrm{B}}(\tau) - E_{\mathrm{B}}(\infty)}{E_{\mathrm{B}}(0) - E_{\mathrm{B}}(\infty)} \right| = e^{-n}$$

Figures of Merit - HO

Battery Energy

$$E_{\mathrm{B}} = \omega_{\mathrm{B}} \langle \hat{a}^\dagger_{\mathrm{B}} \hat{a}_{\mathrm{B}} \rangle$$

Ergotropy

$$\mathcal{E}_{\mathrm{B}} = E_{\mathrm{B}} - \min_{\hat{U}_{\mathrm{B}}} \mathrm{Tr}_{\mathrm{B}} \left[\hat{U}_{\mathrm{B}} \hat{\rho}_{\mathrm{B}} \hat{U}^\dagger_{\mathrm{B}} \hat{H}_{\mathrm{B}} \right]$$

Charging Time

$$\left| \frac{E_{\mathrm{B}}(\tau) - E_{\mathrm{B}}(\infty)}{E_{\mathrm{B}}(0) - E_{\mathrm{B}}(\infty)} \right| = e^{-n}$$

Talk Outline

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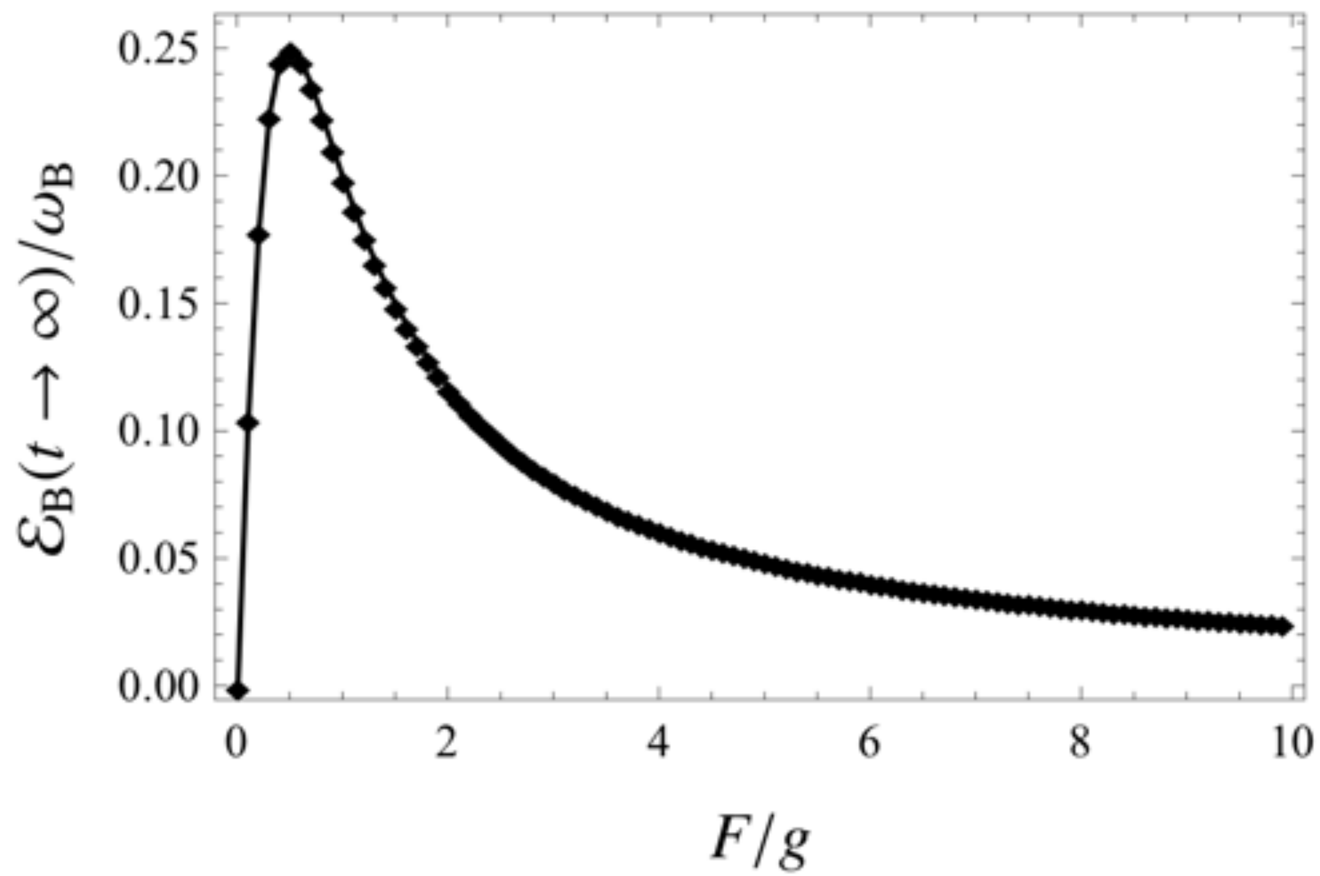
TLS at Resonance - Steady State

$$\omega_C = \omega_d = \omega_B$$



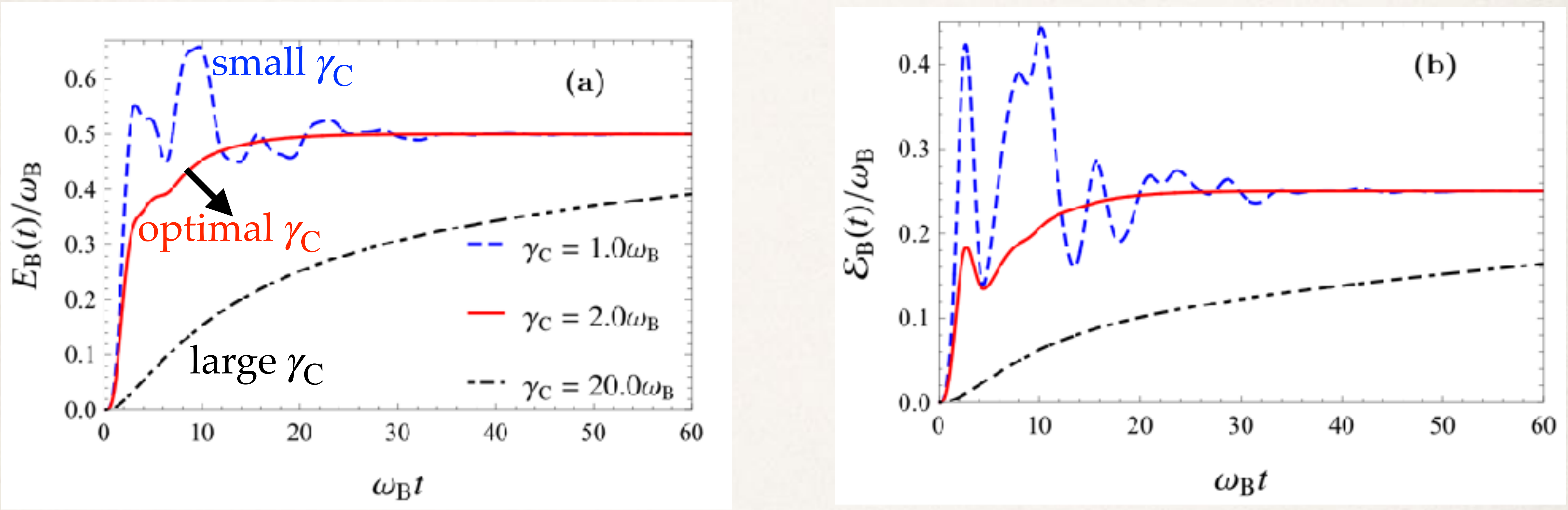
$$E_B(t \to \infty) = \frac{1}{2},$$

$$\mathcal{E}_B(t \to \infty) = \frac{\frac{F}{g}}{1 + 4\frac{F^2}{g^2}}.$$

TLS at Resonance - Charging Dynamics

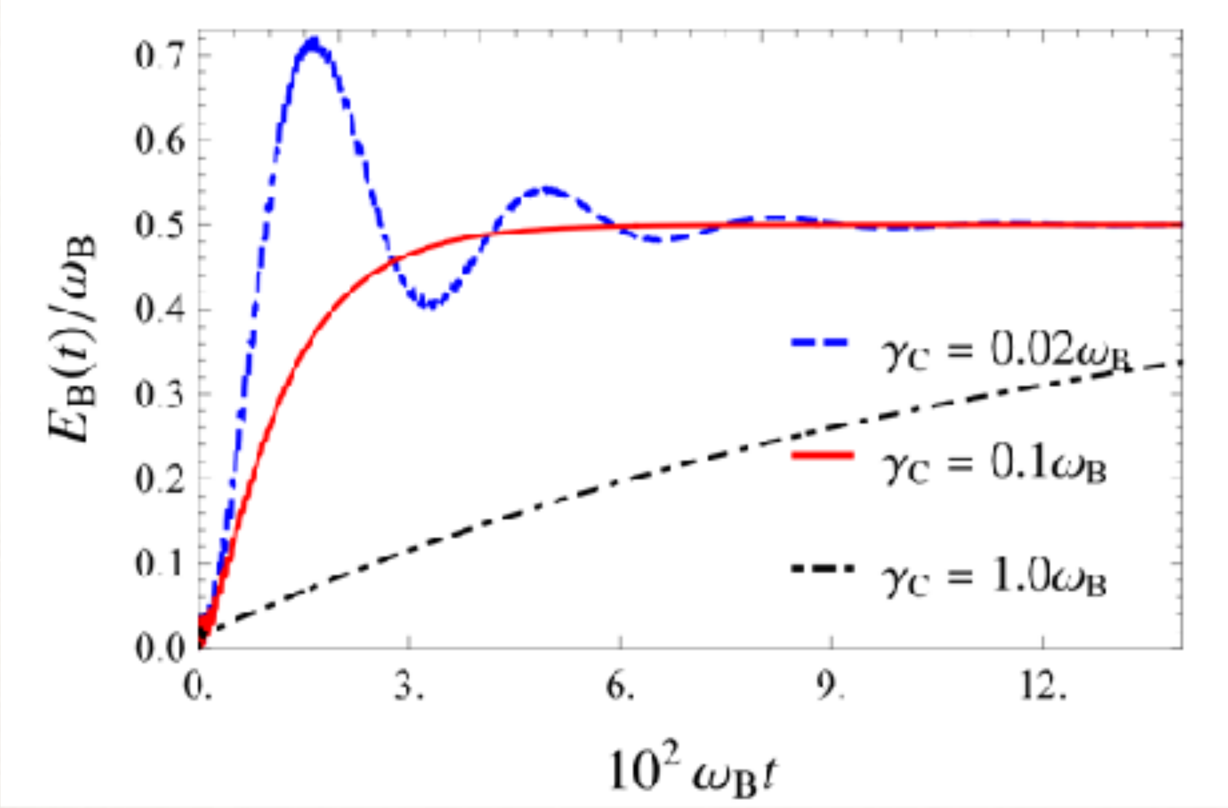
$F/g = 0.5$ (intermediate optimal driving)

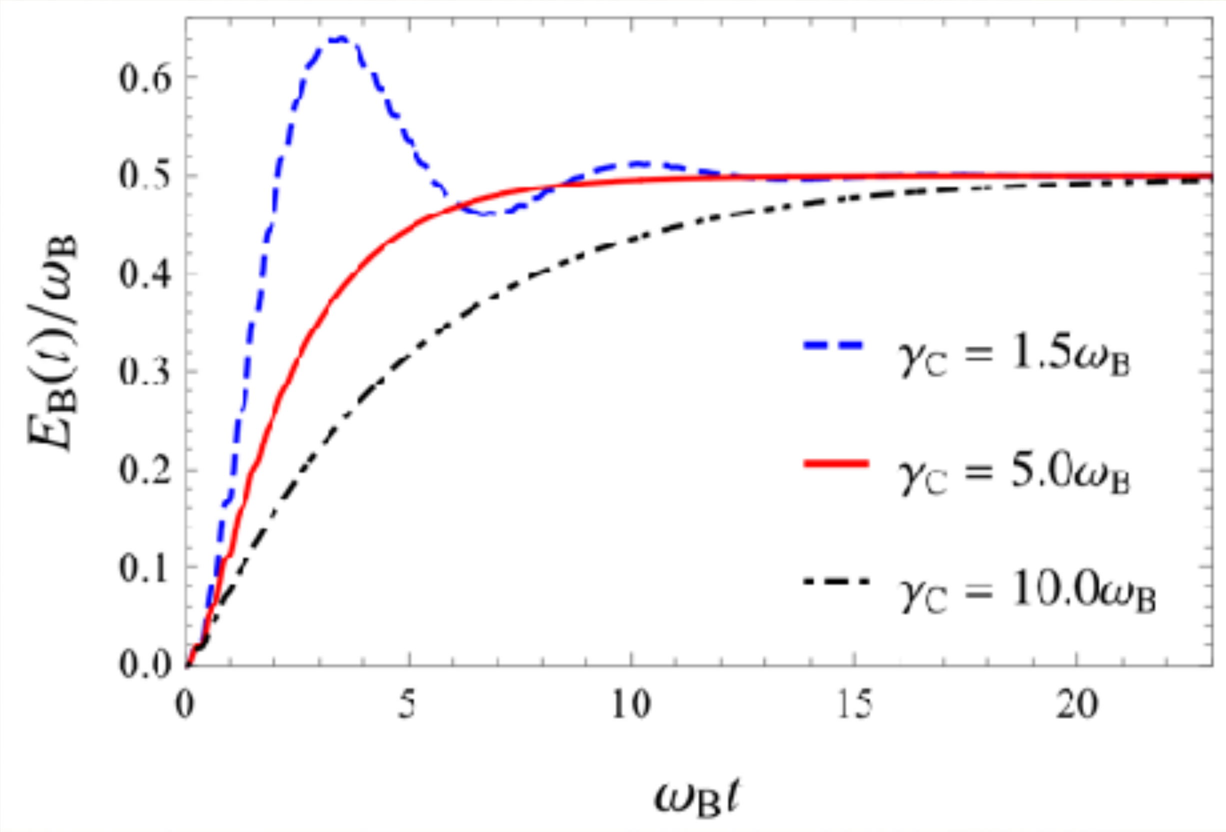
$g = \omega_B$ (throughout)



Moderate Dephasing Leads to Fast Charging!

TLS at Resonance - Charging Dynamics





$F/g = 0.1$

Weak Driving

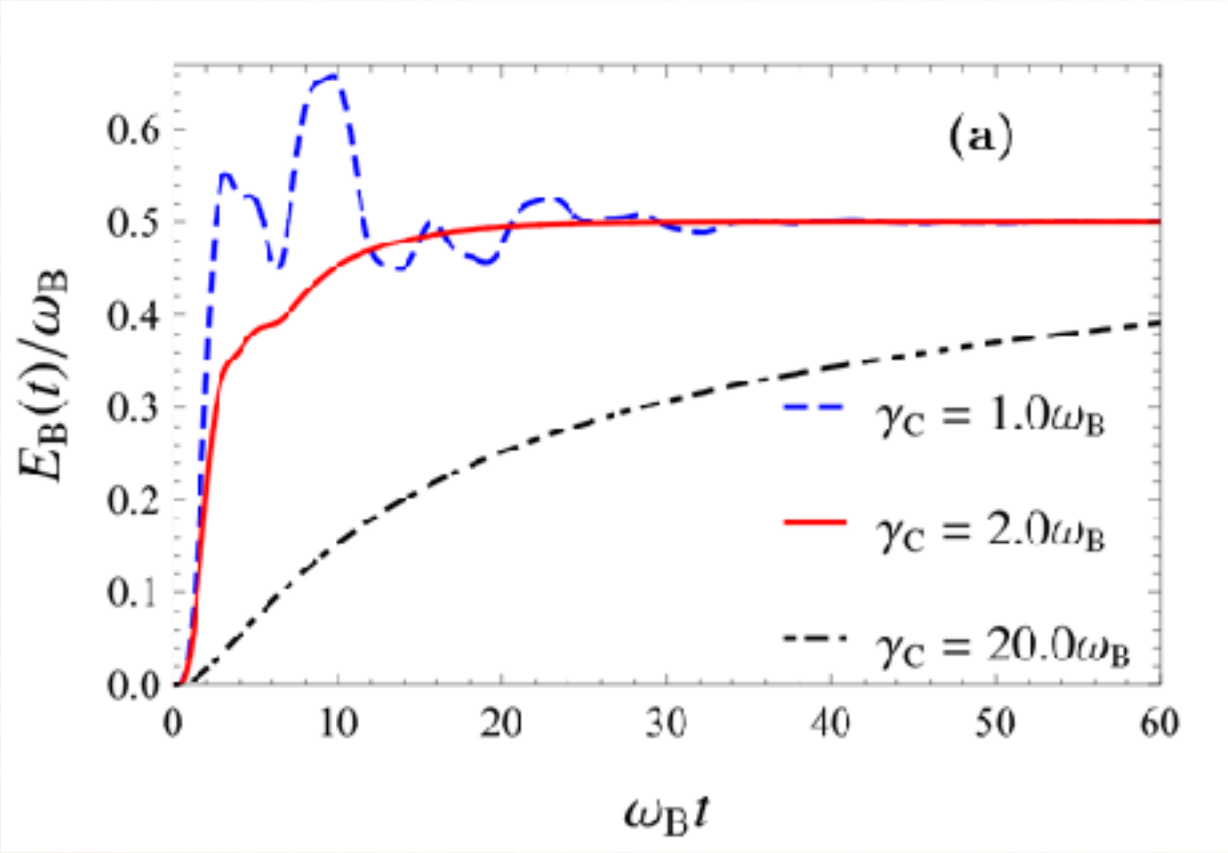
$F/g = 10$

Strong Driving

Moderate Dephasing Leads to Fast Charging!

TLS at Resonance - Charging Dynamics

Moderate Dephasing Leads to Fast Charging



Shock Absorber

- Small Dephasing - Oscillation
- Large Dephasing - quantum Zeno

Transient Maxima - impractical, require fine control

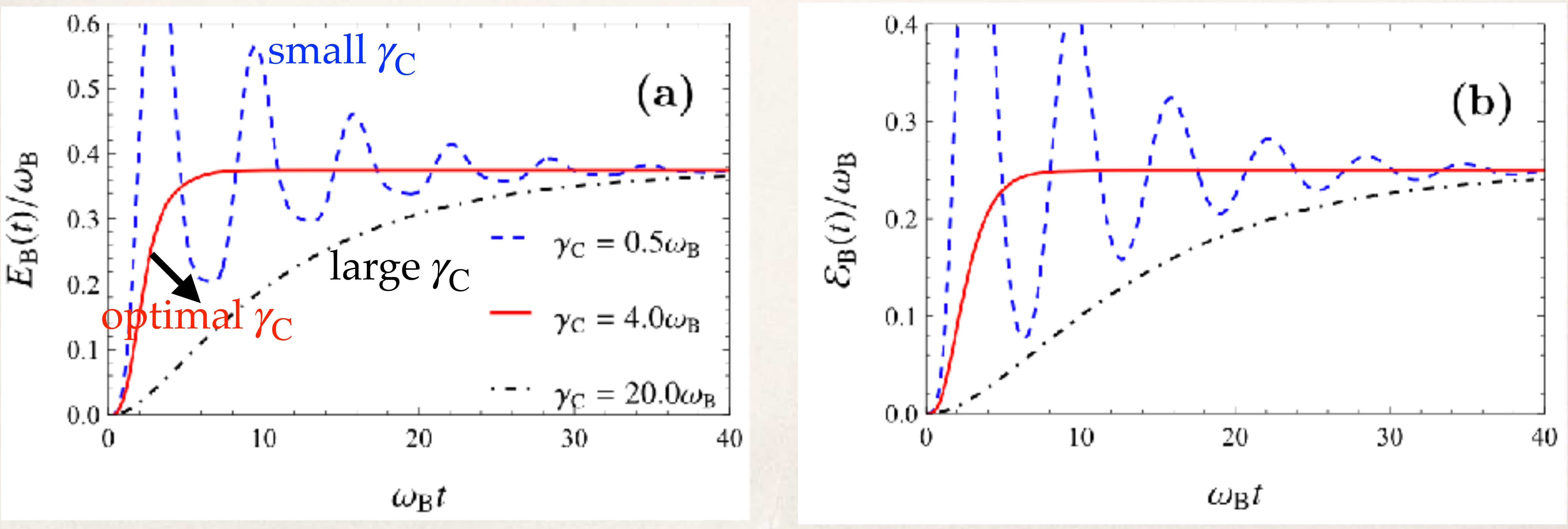
Universal Competition under Dephasing

Competition:

Coherent Oscillation vs Quantum Zeno Freezing

Universal for systems under dephasing

HOs at resonance



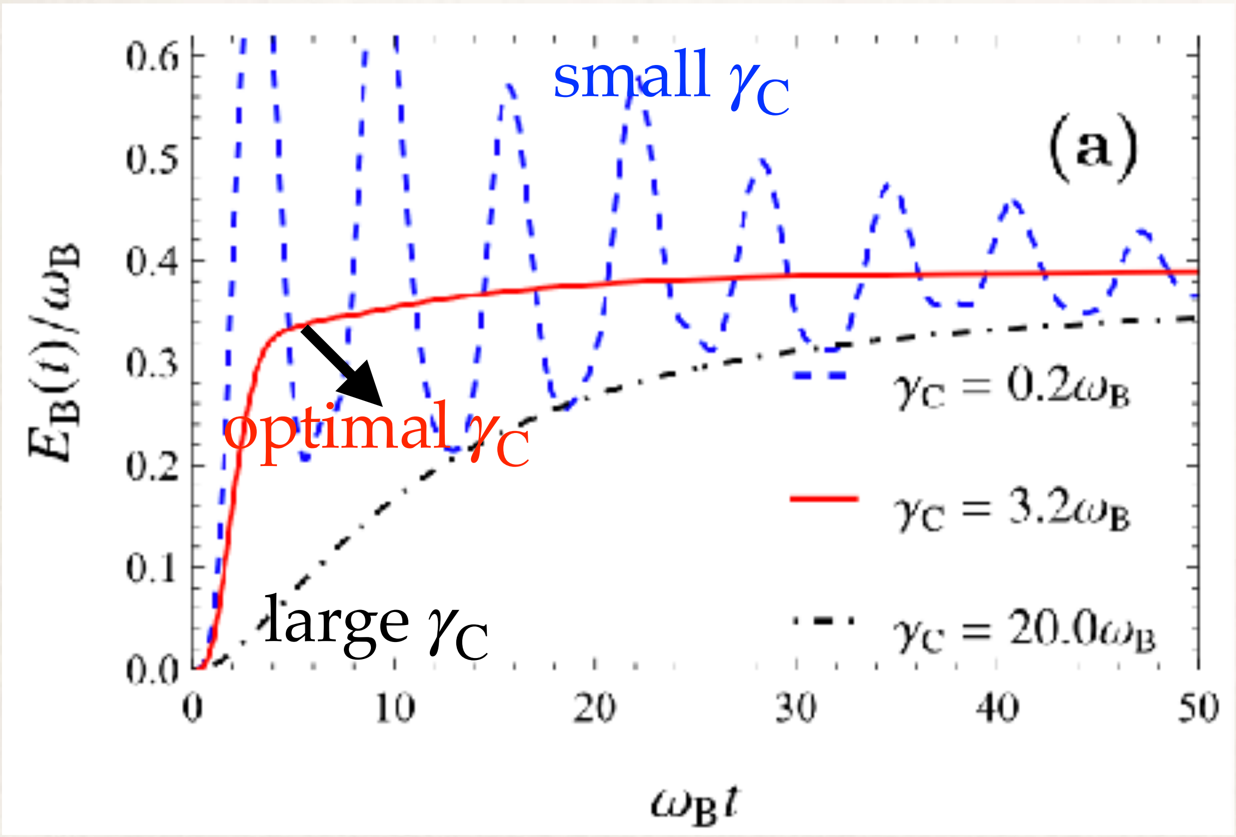
Universal Competition under Dephasing

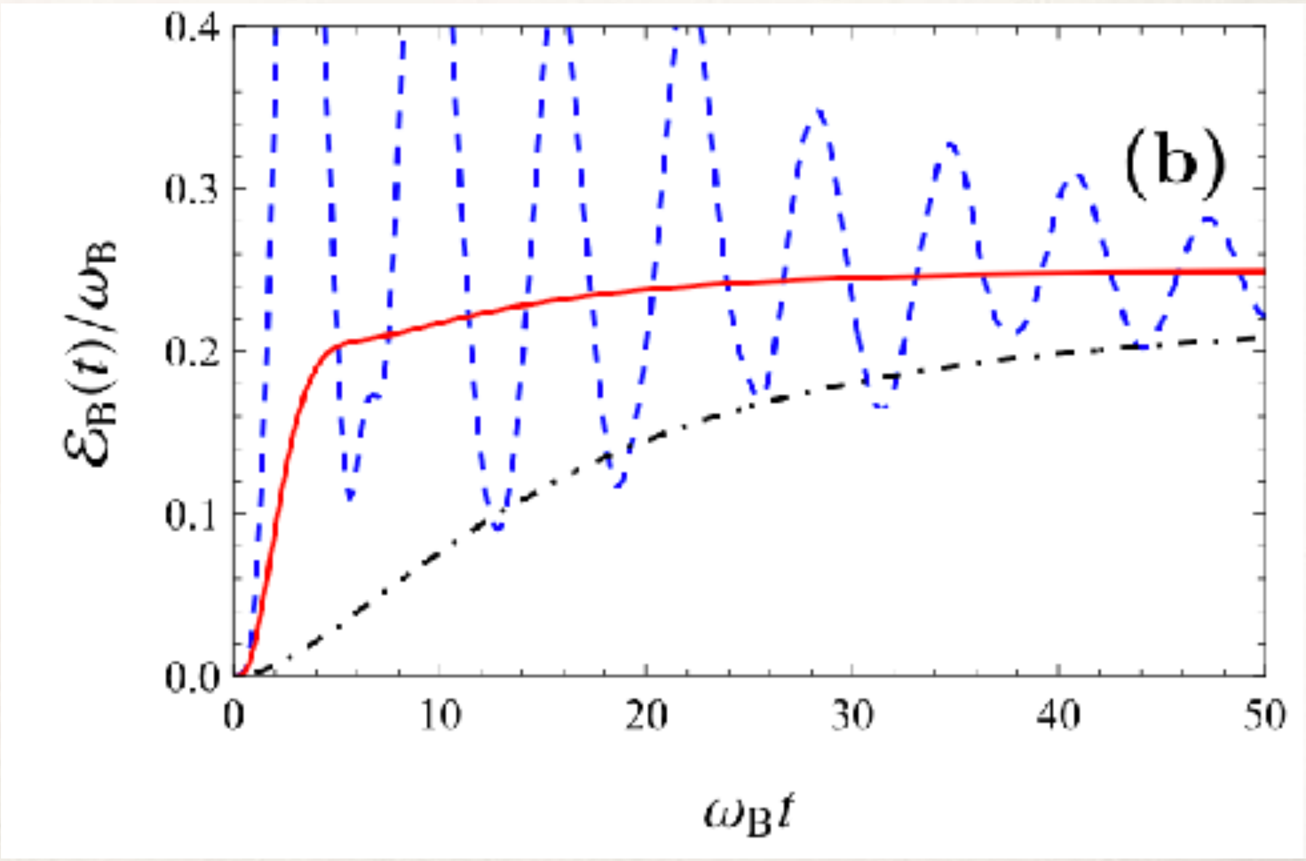
Competition:

Coherent Oscillation vs Quantum Zeno Freezing

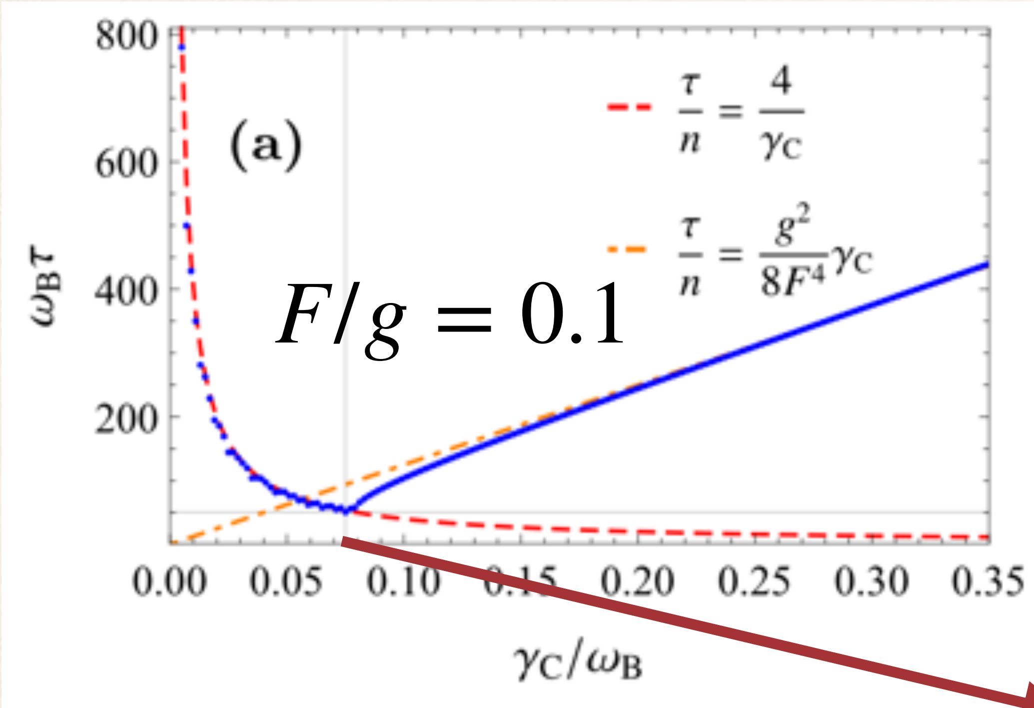
Universal for systems under dephasing

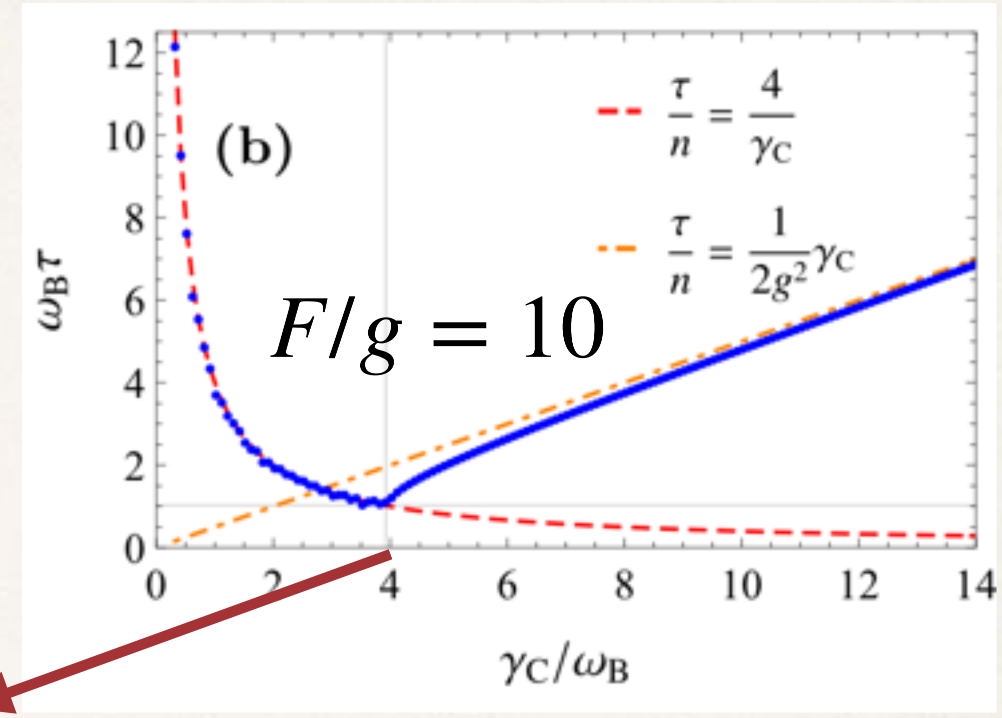
TLS-HO at resonance





TLS - Charging Time vs Dephasing





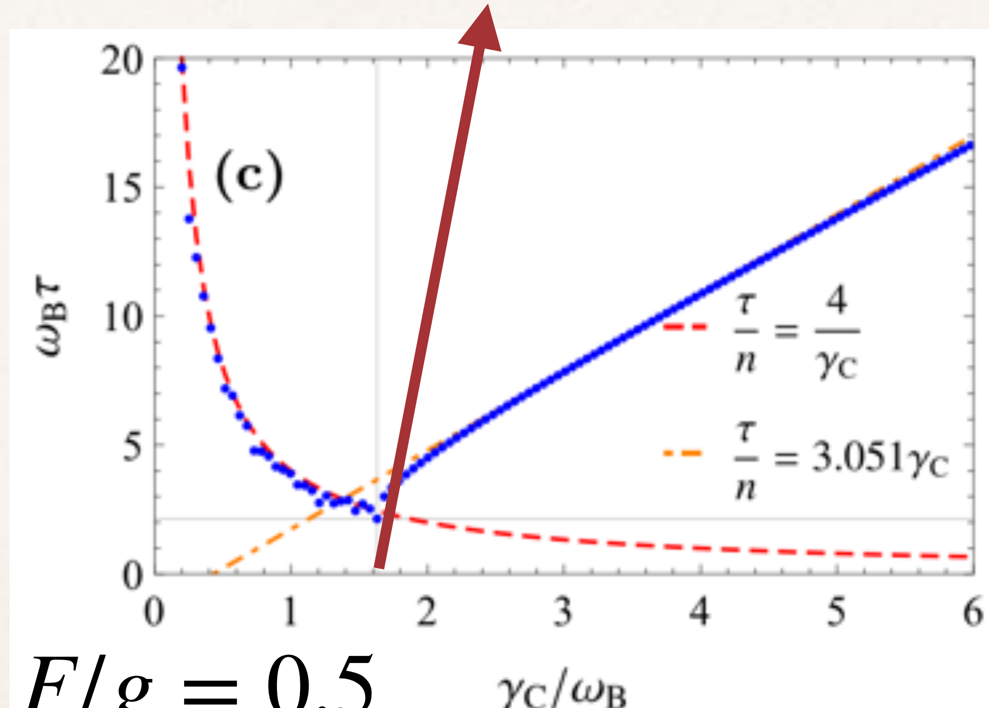
Optimal

γ_C

Weak Dephasing

$\gamma_C \ll \{F, g\}$

$$\tau \sim \frac{1}{\gamma_C}$$



Strong Dephasing

$\gamma_C \gg \{F, g\}$

$$\tau \sim \frac{\gamma_C}{[\omega^2]}$$

Min τ when $\frac{1}{\gamma_C} \sim \frac{\gamma_C}{[\omega^2]}$

TLS - Optimal Dephasing Analytical Results

	F/g >> 1	F/g << 1
$\gamma_C \ll g$	$\tau \sim \frac{4n}{\gamma_C}$	$\tau \sim \frac{4n}{\gamma_C}$
$\gamma_C \gg \{g, F\}$	$\tau \sim \frac{n}{2g^2}\gamma_C$	$\tau \sim \frac{ng^2}{F^4}\gamma_C$

Optimal Dephasing

$$\gamma_C^\star \overset{F \ll g}{\approx} \frac{8F^2}{\sqrt{2}g},$$

$$\gamma_C^\star \overset{F \gg g}{\approx} 2\sqrt{2}g,$$

$$\tau^\star \sim \frac{4}{\gamma_C^\star}$$

Charging Strategy

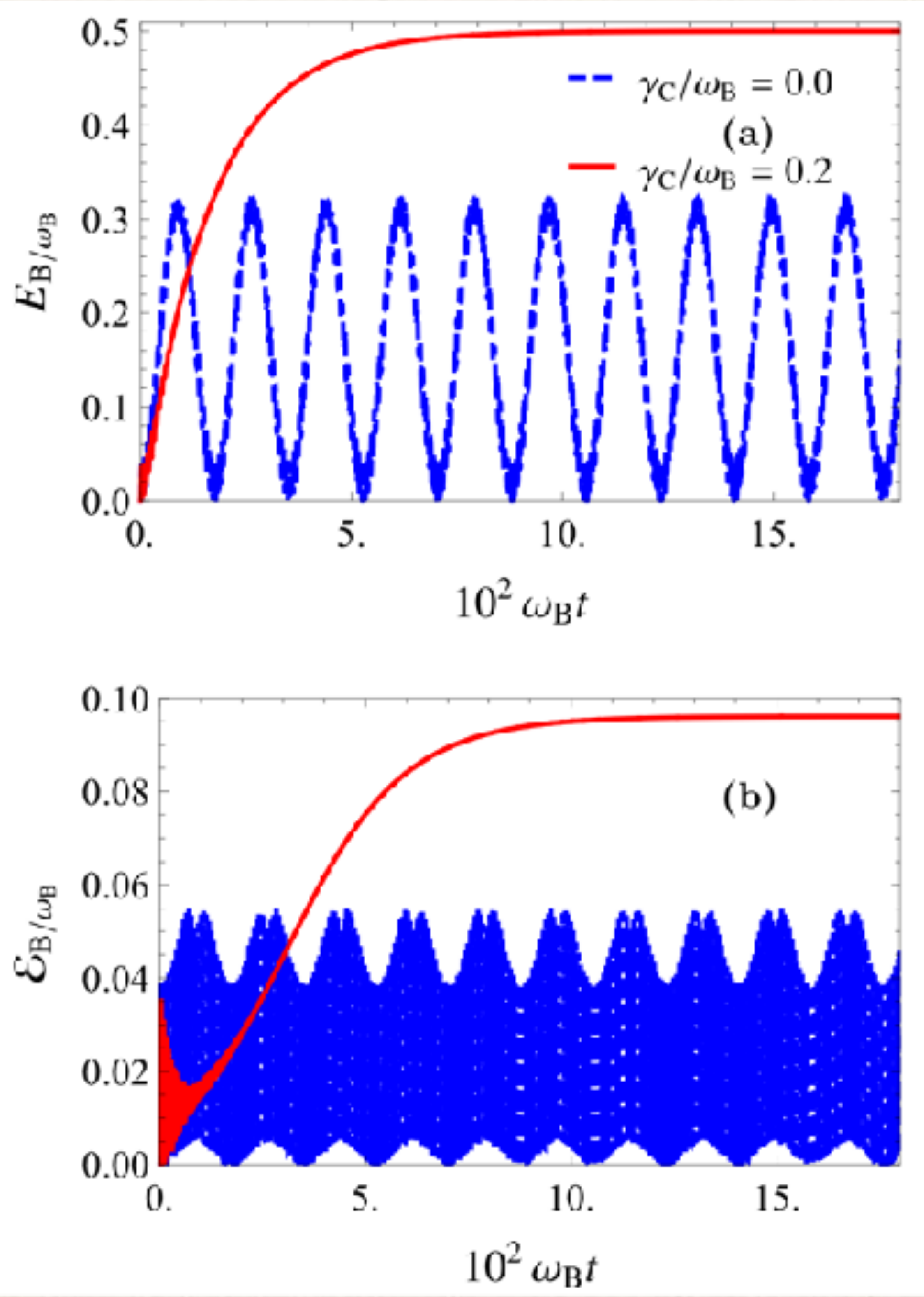
Choose F/g = 0.5, maximising steady state ergotropy

Since $\gamma_{\mathrm{C}}^{\star} \sim a\dfrac{F}{g}F + bg$, make {F, g} as large as possible

$$\gamma_{\mathrm{C}}^{\star} \overset{F \ll g}{\approx} \frac{8F^2}{\sqrt{2}g},$$

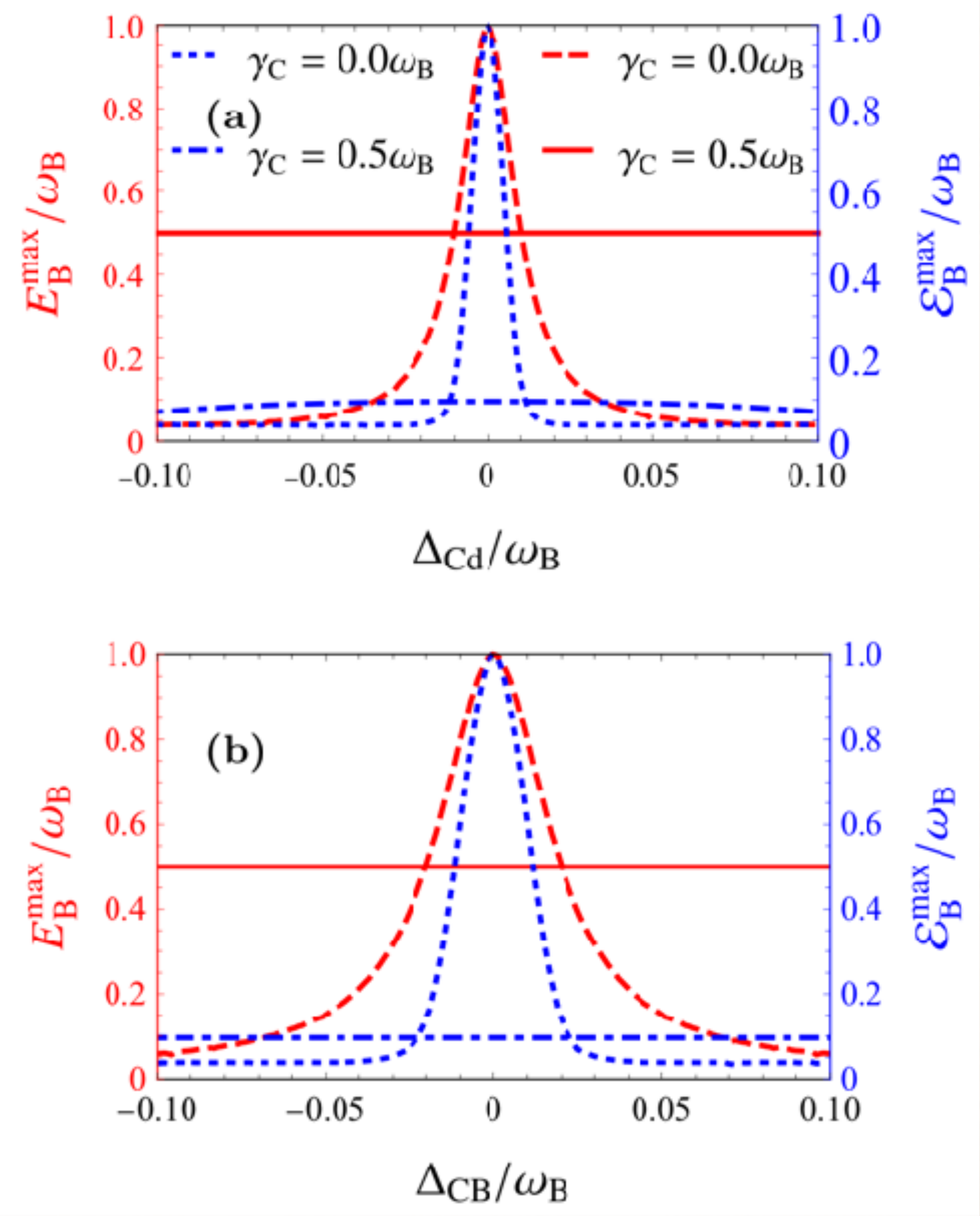
$$\gamma_{\mathrm{C}}^{\star} \overset{F \gg g}{\approx} 2\sqrt{2}g,$$

TLS - Robustness To Detuning



$$\Delta_{Cd} = \Delta_{Bd} = 0.015\omega_B$$

TLS - Robustness To Detuning

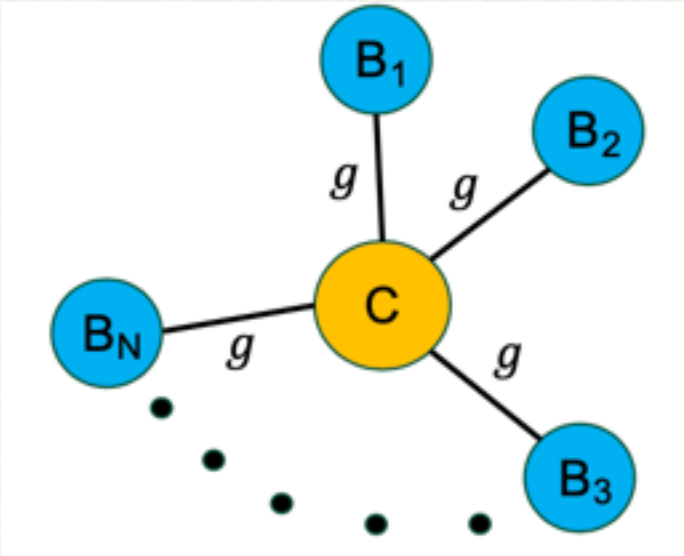


Summary

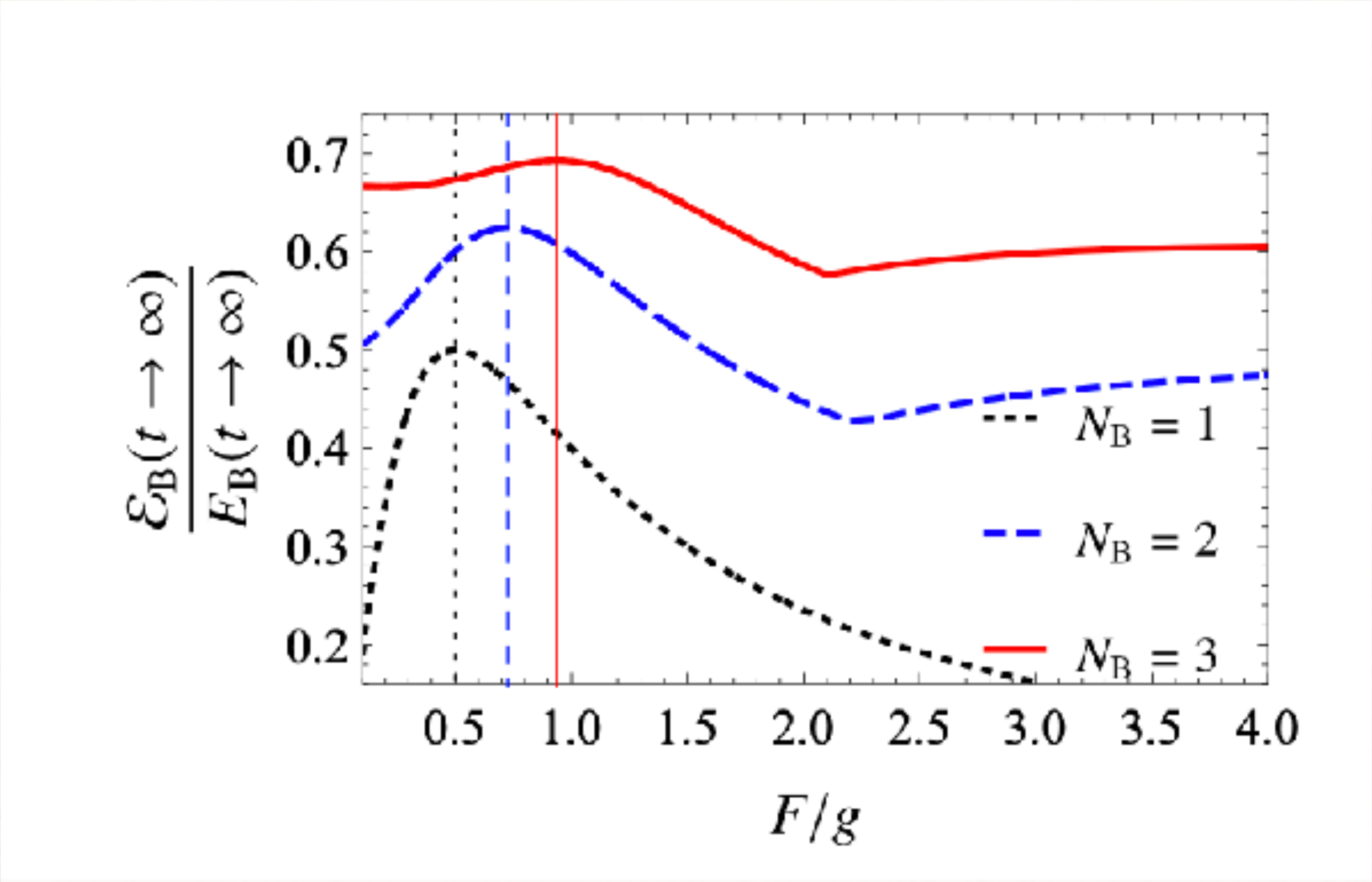
- Moderate Dephasing of Charger leads to fast and stable battery charging
- General Behaviour - Coherent Oscillations vs Quantum Zeno Trade off
- Dephasing - Robustness w.r.t. Finite Detuning

R. Shastri et.al., npj Quantum Inf **11**, 9 (2025)

Outlook- Enhancing Ergotropy

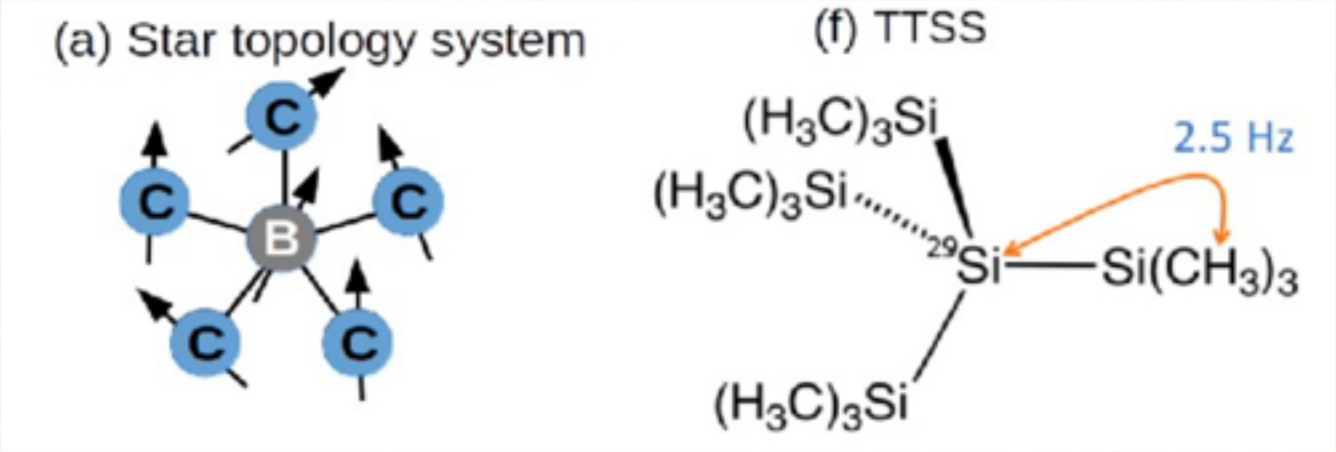


Star Config



Outlook- Experimental Implementation

NMR System



1 Battery - coupled to multiple charger

Battery - Central Nuclear Spin (I = 1/2)

Charger - ^{1}H Nuclear Spin

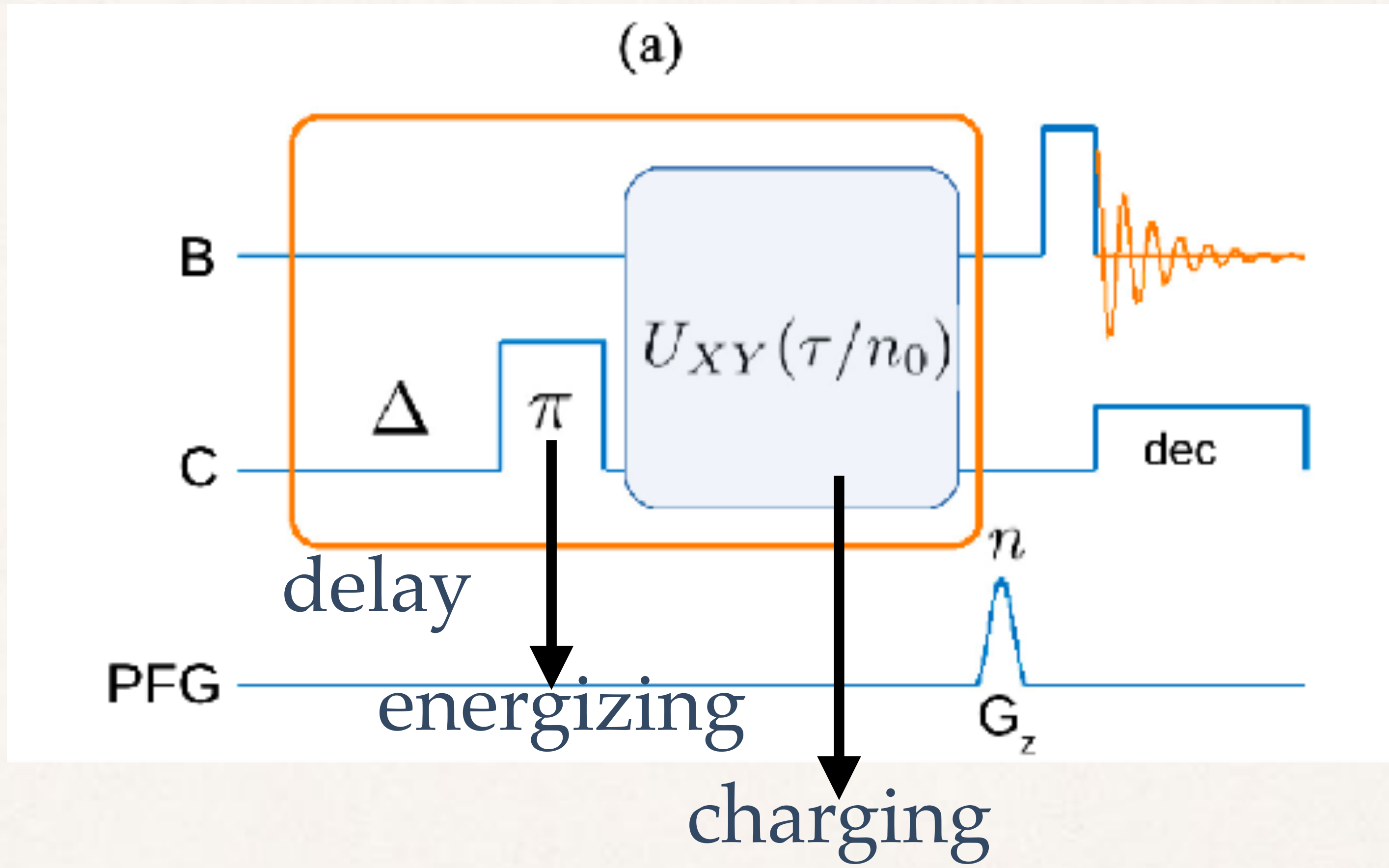
$\hat{S}_{x,y,z}$ - Battery spin

$$\hat{H} = J(\hat{S}_x \hat{I}_x + \hat{S}_y \hat{I}_y)$$

$\hat{I}_{x,y,z} = \sum_{i=1}^{N} I^i_{x,y,z}$ - Battery spin

Joshi & Mahesh, PRA **106**, 042601 (2022)

Outlook- Experimental Implementation



storage times: battery $T_1^{\mathrm{B}} \gg T_1^{\mathrm{C}}$ charger

Asymptotic Charging -iteratively re-energizing chargers after delay

Joshi & Mahesh, PRA **106**, 042601 (2022)

Other Topics of Current Interest

Collective Dissipation of Oscillator Dipoles
Strongly Coupled to 1-D Electromagnetic Reservoirs

Poster

Ipsita Bar

Indicators of Chaos in the Closed and Open Dicke Model

Poster

Prasad Pawar

Thank you

Additional Slides

tem as ρ, the maximum amount of work which can be extracted from it during this cyclic process is known as *ergotropy* [9, 199, 279–282], defined as

$$\mathcal{E}^1 = \overline{W}^1_{U,\max} = \mathrm{Tr}\left[\rho h_0\right] - \min_{U(\tau)\in SU(d)} \{\mathrm{Tr}\left[U(\tau)\rho U(\tau)^\dagger h_0\right]\}$$
$$= \mathrm{Tr}\left[\rho h_0\right] - \mathrm{Tr}\left[\sigma_\rho h_0\right], \quad (139)$$

where the superscript '1' denotes that we are working with a single *cell* or single copy of the system, $\overline{W}^1_{U,\max}$ denotes the maximum work that can be extracted (negative of the work done, $\overline{W} = -W$) using unitary operations, and $U(\tau)$ are unitary time-evolution operators acting for the duration of time τ. Note that the state corresponding to ρ, defined as the state having zero ergotropy. Hence, no energy can be extracted from σ_ρ through cyclic unitary processes, that is

$$\Delta E = -\overline{W}^1_U$$
$$= \mathrm{Tr}\left[U\sigma_\rho U^\dagger h_0\right] - \mathrm{Tr}\left[\sigma_\rho h_0\right] \geq 0, \quad \forall\, U \in SU(d), \quad (140)$$

where a positive value of ΔE corresponds to a negative work extraction, or equivalently, a work deposition on the system. In general, it can be shown that a state is passive if it is diagonal in the energy eigen-basis of the system with non-decreasing diagonal elements (populations), when arranged in the order of non-increasing energies, i.e., $\sigma = \sum_{j=1}^{d} s_j \left|j\right\rangle\left\langle j\right|$ with $s_j \geq s_{j+1}$ for $\varepsilon_j \leq \varepsilon_{j+1}$ [197, 198]. Consequently, the passive state σ_ρ which can be attained by means of local unitary operations on ρ is unique in nature. Unless otherwise mentioned, we shall use the notation σ_ρ to denote the unique passive state corresponding to ρ in the rest of the article.

Response: We would like to first point out a scaling property present in the dynamics of the charger-battery system described via Eqs. (11) and (12) in the previous version or Eqs. (A3) and (A4) in the modified version of the draft in the resonant case. The solutions only depend on the ratios of quantities F/g and γ_{C}/g. While we have chosen $g = \omega_{\mathrm{B}}$ in the results for the sake of presentation, the results hold good for even smaller coupling g, as long as we make a proportional change in γ_{C}. Thus we can always understand our results as being calculated for small values of g/ω_{B} such that the local master equation is valid. Moreover, since this leads even smaller values of $\gamma_{\mathrm{C}}/\omega_{\mathrm{B}}$ as per the scaling we described, the weak dissipation limit required for usual GKLS master equation is well satisfied. Note that in this case, γ_{C}/g can still be significantly large but since the system's energy scale is determined by $\{\omega_{\mathrm{B}} = \omega_{\mathrm{C}}\} \gg g$ in this regime, this does not violate the Born approximation required for the GKLS master equations. To illustrate this, in Fig. R2 we have plotted the charging dynamics for the same values of γ_{C}/g and F/g as in Fig. 2 of the paper, but with much smaller value of $g = 0.1\omega_{\mathrm{B}}$. It is clear that the results remain exactly the same. In the revised draft, we have added a remark in the

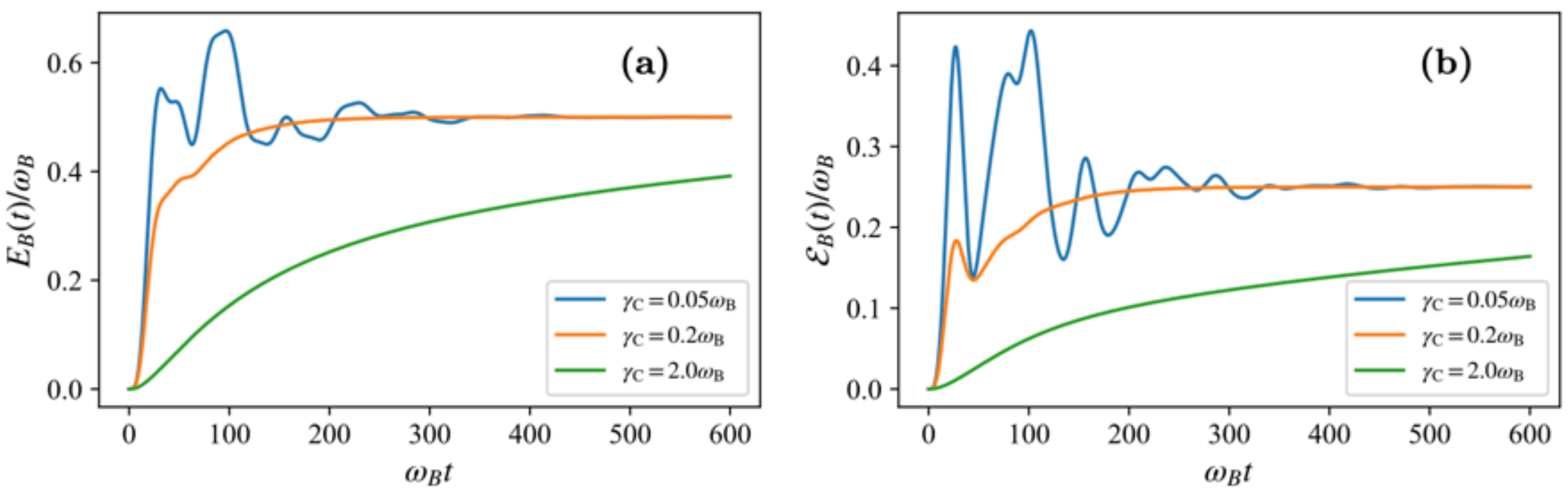


Figure R2: Figure 2 of main paper with $F = 0.05\omega_{\mathrm{B}}$, and $g = 0.1\omega_{\mathrm{B}}$ ($F/g = 0.5$).