



Caipyra 2025

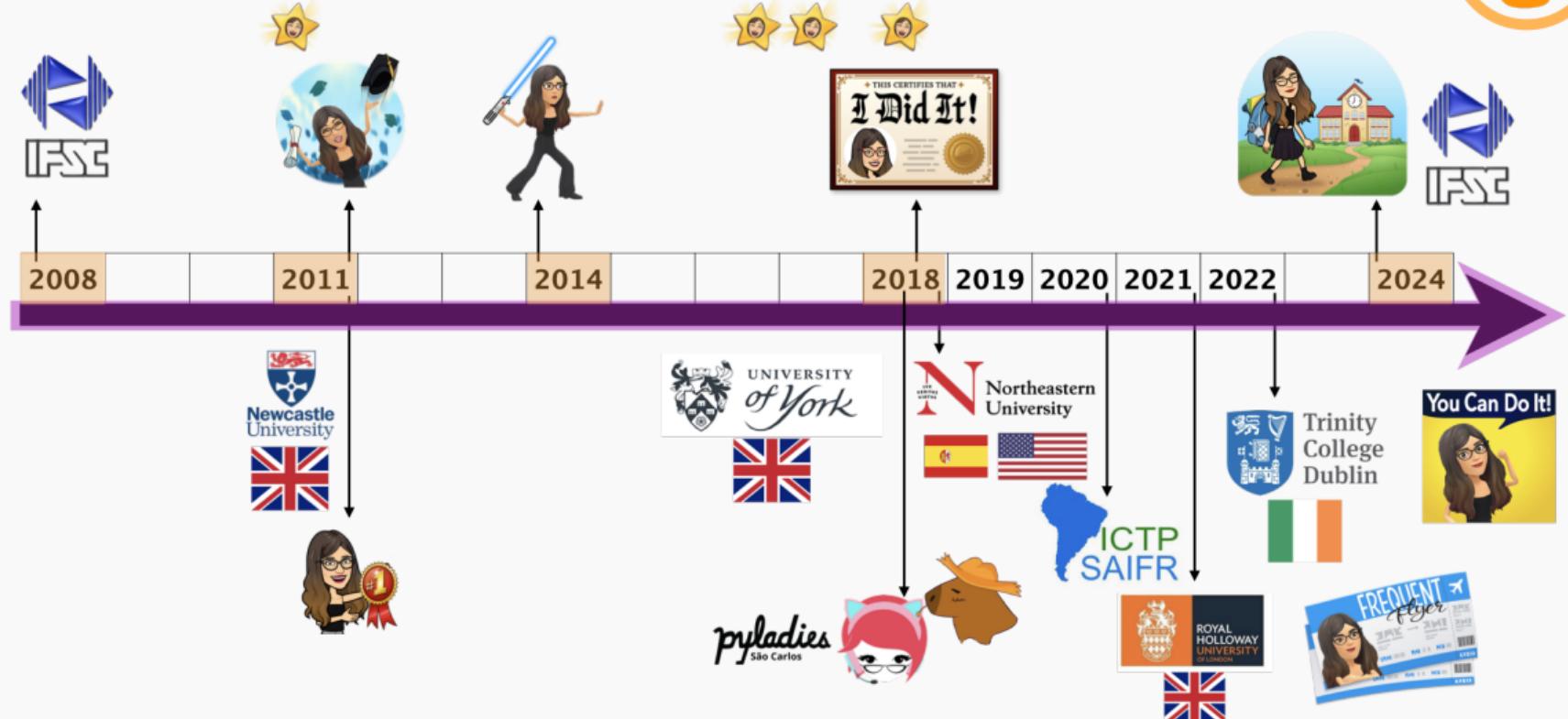
20 de Junho de 2025

Como fazer sorvete com qubits?
O efeito Mpemba quântico!

Krissia Zawadzki



Sobre mim





PHYSICAL REVIEW LETTERS 133, 140404 (2024)

Thermodynamics of the Quantum Mpemba Effect

Mattia Moroder^{1,*}, Oisín Culhane^{2,†}, Krissia Zawadzki^{2,3,‡}, and John Goold^{2,4,§}

¹*Department of Physics, Arnold Sommerfeld Center for Theoretical Physics (ASC), Munich Center for Quantum Science and Technology (MCQST), Ludwig-Maximilians-Universität München, 80333 München, Germany*

²*School of Physics, Trinity College Dublin, Dublin 2, Ireland*

³*Instituto de Física de São Carlos, Universidade de São Paulo, CP 369, 13560-970 São Carlos, São Paulo, Brazil*

⁴*Trinity Quantum Alliance, Unit 16, Trinity Technology and Enterprise Centre, Pearse Street, Dublin 2, D02YN67*



(Received 1 April 2024; accepted 3 September 2024; published 4 October 2024)

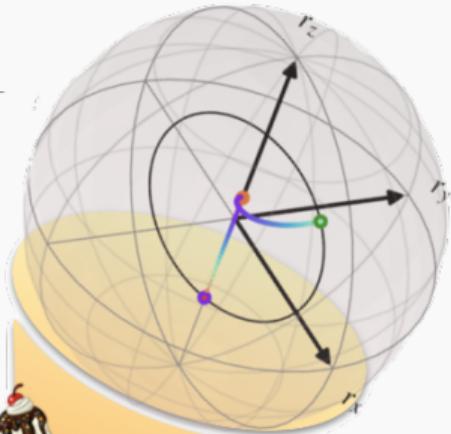


Krissia Zawadzki

[University of São Paulo](#)

Verified email at ifsc.usp.br

Quantum Thermodynamics Condensed Matter Theory Quantum Information



Quantum gelato makers



Mattia Moroder

LMU → Trinity College Dublin



Trinity
College
Dublin



Oisin Culhane

Trinity College Dublin



Trinity
College
Dublin



John Goold

Trinity College Dublin / Algorithimic



Trinity
College
Dublin

Quantum gelato makers





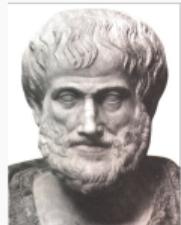
A história do efeito Mpemba
Mpemba na hype quântica
Sorvete de qubits
Conclusão e perspectivas



De Aristóteles ao sorvete do Erasto

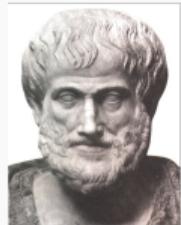


350 BC



"The inhabitants of Pontus when they encamp on the ice to fish pour warm water round their reeds that it may freeze the quicker"

De Aristóteles ao sorvete do Erasto

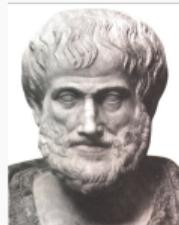


"The inhabitants of Pontus when they encamp on the ice to fish pour warm water round their reeds that it may freeze the quicker"



"Water that has been kept on a fire for a long time freezes faster than other"

De Aristóteles ao sorvete do Erasto



"The inhabitants of Pontus when they encamp on the ice to fish pour warm water round their reeds that it may freeze the quicker"

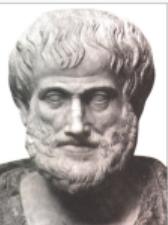


"Water that has been kept on a fire for a long time freezes faster than other"



"A little warm water will freeze more easily than completely cold"

De Aristóteles ao sorvete do Erasto



"The inhabitants of Pontus when they encamp on the ice to fish pour warm water round their reeds that it may freeze the quicker"



"Water that has been kept on a fire for a long time freezes faster than other"

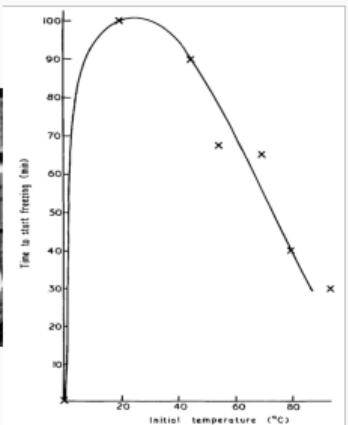


"A little warm water will freeze more easily than completely cold"

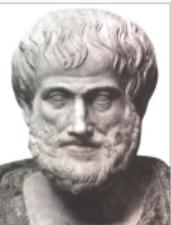


"Cool?"

E. B. Mpemba and D. G. Osborne,
Physics Education 4, 172 (1969).



De Aristóteles ao sorvete do Erasto



"The inhabitants of Pontus when they encamp on the ice to fish pour warm water round their reeds that it may freeze the quicker"



"Water that has been kept on a fire for a long time freezes faster than other"

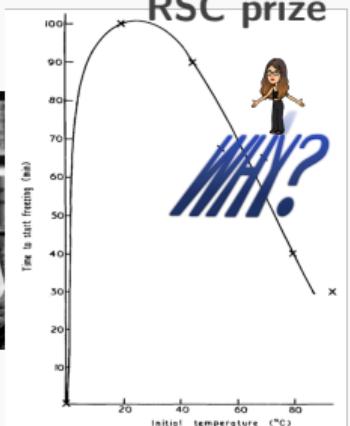


"A little warm water will freeze more easily than completely cold"

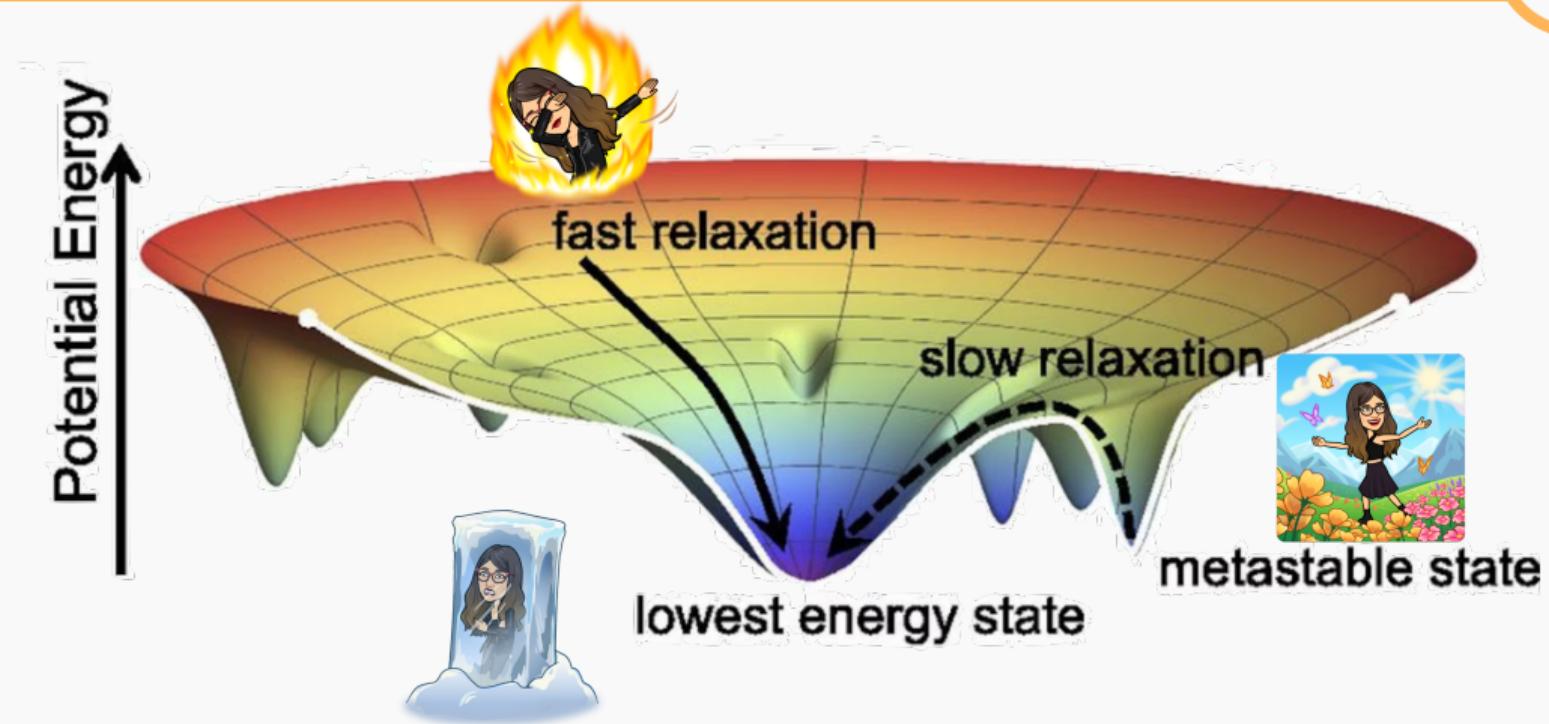


"Cool?"

E. B. Mpemba and D. G. Osborne,
Physics Education 4, 172 (1969).

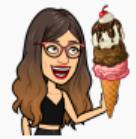


Intepretação do Mpemba: energia livre



S. G. Agrawal *El País* (2023)

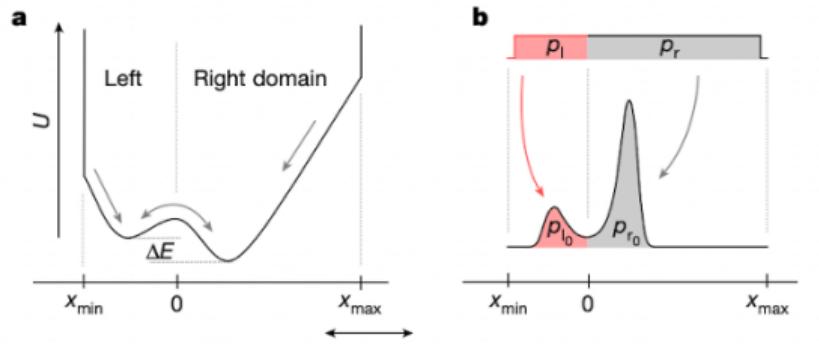
Mpemba clássico além de sorvete



Mpemba clássico além de sorvete

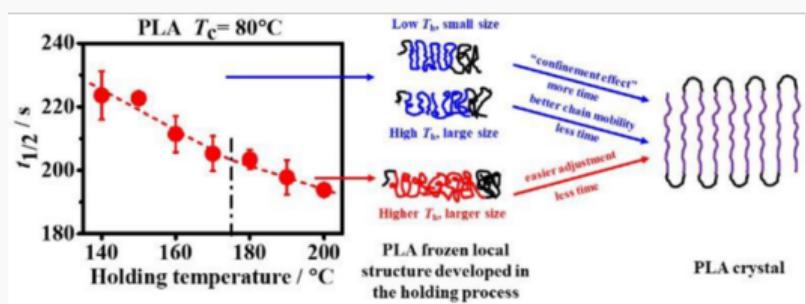


super resfriamento de sistemas coloidais



A. Kumar, J. Bechhoefer
Nature 584, 64–68 (2020)

cristalização de polímeros

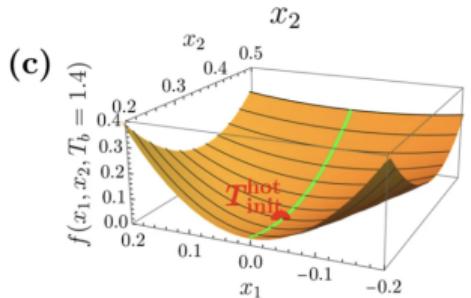
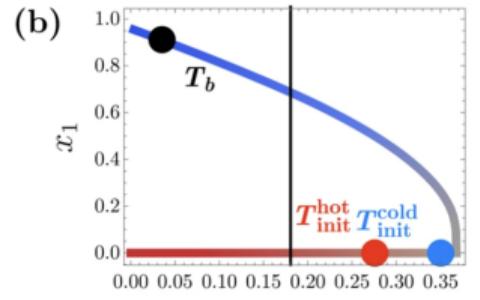
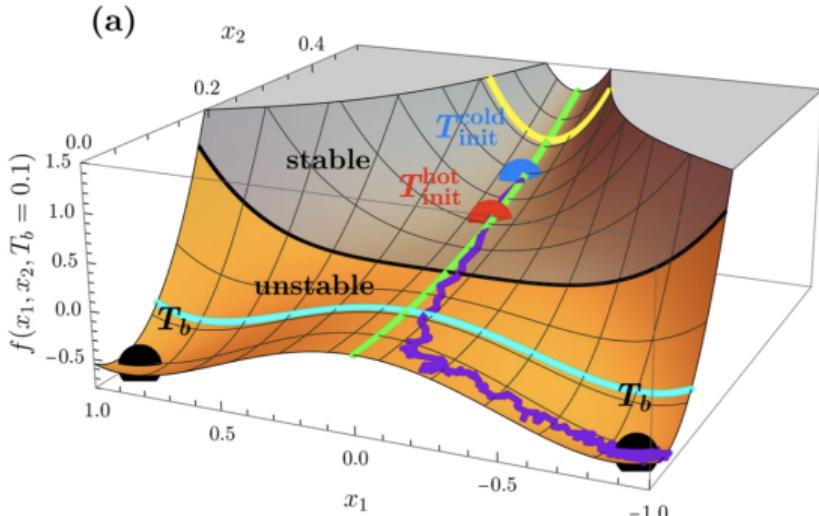


Cunliang Hu et al
Crystal Growth & Design 18, 10, 5757–5762 (2018)

Mpemba clássico além de sorvete

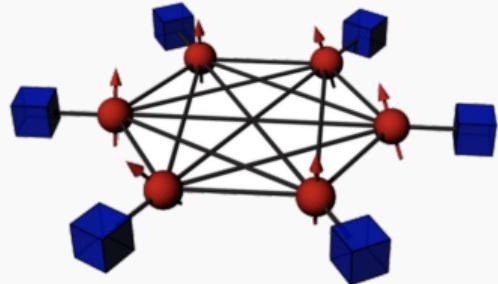


teoria de Landau para transições de fase de 2a ordem



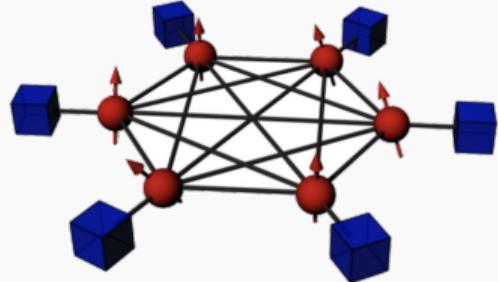
R. Holtzman and O. Raz
Comm Phys 280 (2022)

Mpemba quântico: de transições de fase até a hype de 2023



A. Nava and M. Fabrizio
Phys. Rev. B 100, 125102 (2019)

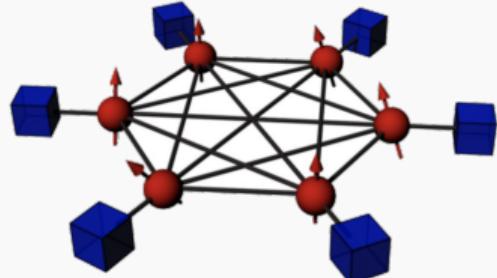
Mpemba quântico: de transições de fase até a hype de 2023



$$H = -h_x \sum_j \sigma_j^x - N \sum_{n=2}^m J_n \left(\frac{1}{N} \sum_j \sigma_j^z \right)^n$$

A. Nava and M. Fabrizio
Phys. Rev. B 100, 125102 (2019)

Mpemba quântico: de transições de fase até a hype de 2023



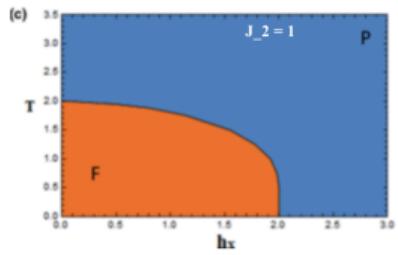
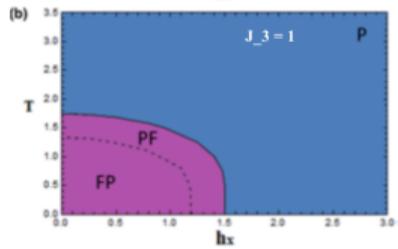
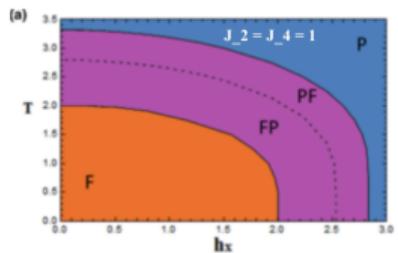
$$H = -h_x \sum_j \sigma_j^x - N \sum_{n=2}^m J_n \left(\frac{1}{N} \sum_j \sigma_j^z \right)^n$$

$$H_j = -h_x \sigma_j^x - h_z(\mathbf{m}) \sigma_j^x$$

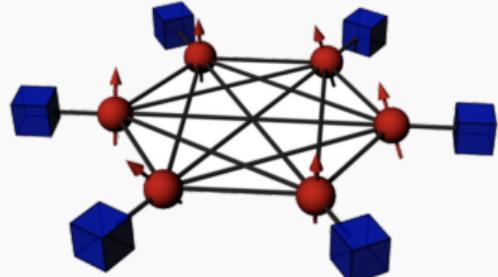
mean-field

$$h_z(\mathbf{m}) = \sum_{n=2}^m n J_n m_z^{n-1}$$

A. Nava and M. Fabrizio
Phys. Rev. B 100, 125102 (2019)



Mpemba quântico: de transições de fase até a hype de 2023



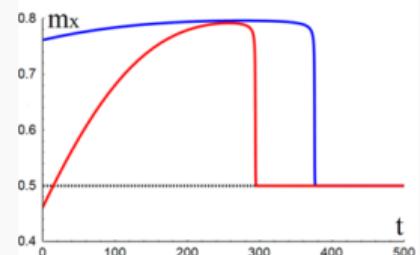
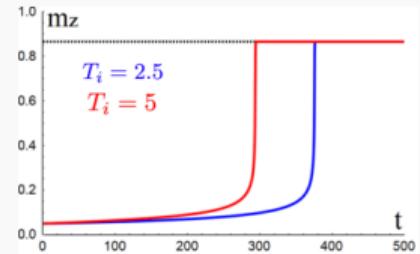
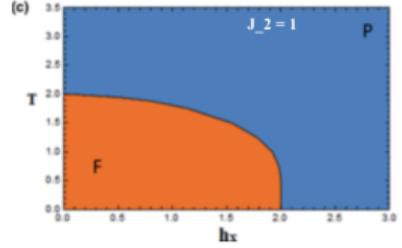
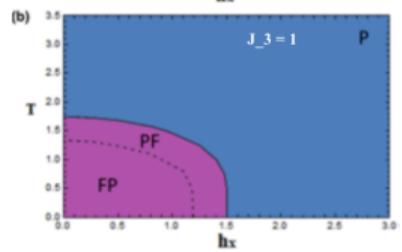
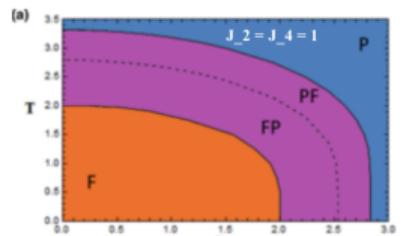
$$H = -h_x \sum_j \sigma_j^x - N \sum_{n=2}^m J_n \left(\frac{1}{N} \sum_j \sigma_j^z \right)^n$$

mean-field

$$H_j = -h_x \sigma_j^x - h_z(\mathbf{m}) \sigma_j^x$$

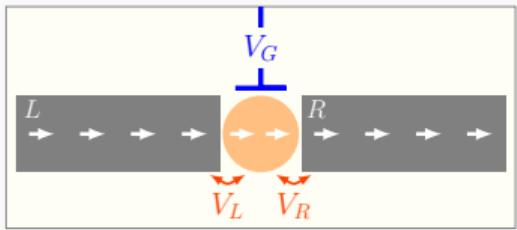
$$h_z(\mathbf{m}) = \sum_{n=2}^m n J_n m_z^{n-1}$$

A. Nava and M. Fabrizio
Phys. Rev. B 100, 125102 (2019)



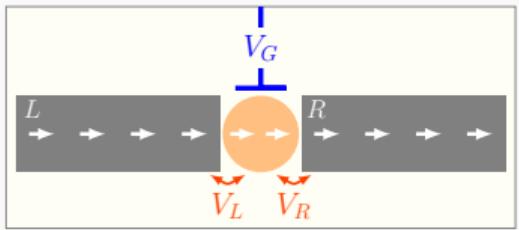
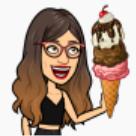
$$\begin{aligned} J_2 &= J_4 = 1, h_x = 2.5 \\ T_f &= 0.002 \ll T_i \end{aligned}$$

Boom de 2023: Mpemba quântico em um ponto quântico



A. K. Chatterjee, S. Takada, and H. Hayakawa
Phys. Rev. Lett. 131, 080402 (2023)

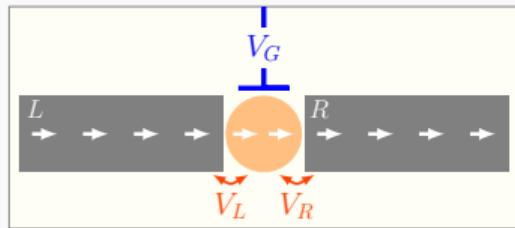
Boom de 2023: Mpemba quântico em um ponto quântico



$$H = V_G n_d + U n_{d\uparrow} n_{d\uparrow} + H_b + V$$

A. K. Chatterjee, S. Takada, and H. Hayakawa
Phys. Rev. Lett. 131, 080402 (2023)

Boom de 2023: Mpemba quântico em um ponto quântico



$$H = V_G n_d + U n_{d\uparrow} n_{d\uparrow} + H_b + V$$

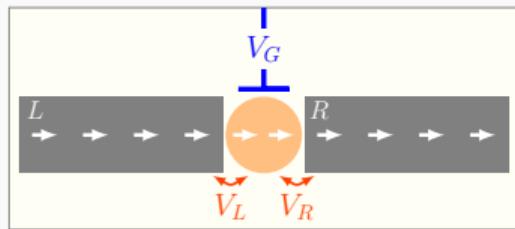
wide band
 $D \rightarrow \infty$
 sem Kondo
 $T \gg T_K$

equação mestra

$$\frac{d\hat{\rho}}{dt} = \hat{K}\hat{\rho}$$

A. K. Chatterjee, S. Takada, and H. Hayakawa
Phys. Rev. Lett. 131, 080402 (2023)

Boom de 2023: Mpemba quântico em um ponto quântico



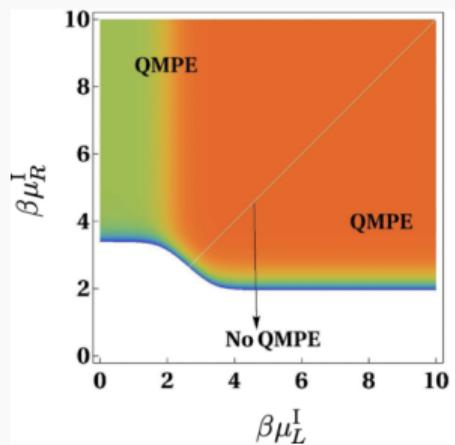
$$H = V_G n_d + U n_{d\uparrow} n_{d\downarrow} + H_b + V$$

wide band
 $D \rightarrow \infty$
 sem Kondo
 $T \gg T_K$

equação mestra

$$\frac{d\hat{\rho}}{dt} = \hat{K}\hat{\rho}$$

A. K. Chatterjee, S. Takada, and H. Hayakawa
Phys. Rev. Lett. 131, 080402 (2023)

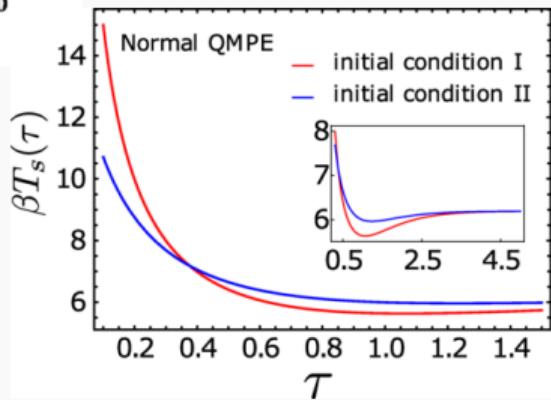


T efetiva

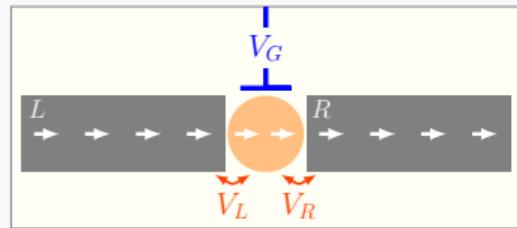
$$T_s(\tau) = \frac{\frac{\partial E_s(\tau)}{\partial \tau}}{\frac{\partial S_{vN}(\tau)}{\partial \tau}}$$

quench μ, T
 $\rho_\alpha^I(\tau) - \rho_\alpha^{II}(\tau) = 0$

tempo: parâmetro de ordem
 $\tilde{\tau}(\rho) = \max[\tau_1, \tau_2, \tau_3, \tau_4]$
 $\tilde{\tau}(\rho) \rightarrow \infty$ não é finito



Boom de 2023: Mpemba quântico em um ponto quântico

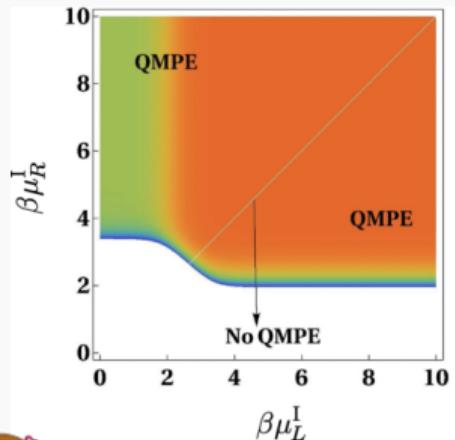


$$H = V_G n_d + U n_{d\uparrow} n_{d\uparrow} + \dots$$

wide band
 $D \rightarrow \infty$
 sem Kondo
 $T \gg T_K$

equação mestra

$$\frac{d\hat{\rho}}{dt} = \hat{K}\hat{\rho}$$



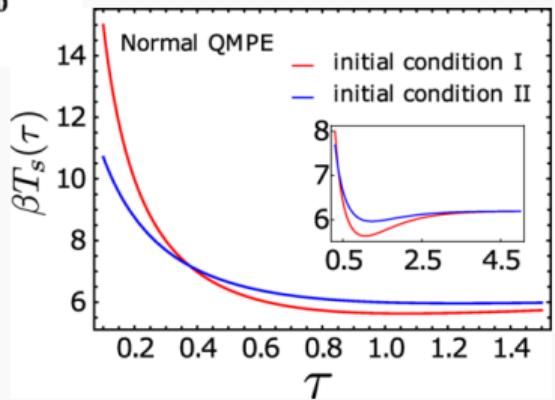
quench μ, T

$$\rho_\alpha^I(\tau) - \rho_\alpha^{II}(\tau) = 0$$

tempo: parâmetro de ordem

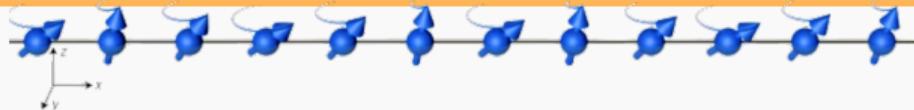
$$\tilde{\tau}(\rho) = \max[\tau_1, \tau_2, \tau_3, \tau_4]$$

$\tilde{\tau}(\rho) \rightarrow \infty$ não é finito



A. K. Chatterjee, S. Takada, and H. Hayakawa
Phys. Rev. Lett. 131, 080402 (2023)

Hype de 2023: Mpemba e quebra de simetria



C. Rylands et al

arXiv: 2310.04410 (2023)

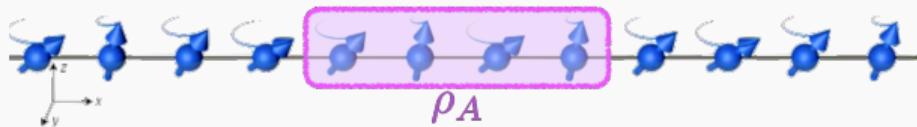
kriissia@ifsc.usp.br

Como fazer sorvete com qubits?

Caipyra

20 de Junho de 2025

Hype de 2023: Mpemba e quebra de simetria



$$\rho_A = \begin{pmatrix} \rho_{q_1} & * & * & * \\ * & \rho_{q_2} & & * \\ * & & \rho_{q_2} & * \\ * & * & * & \rho_{q_3} \end{pmatrix}$$

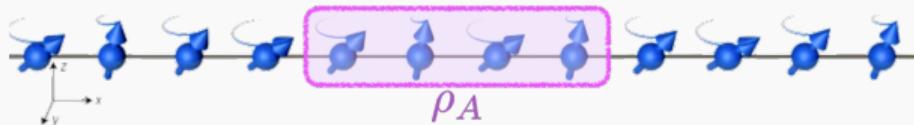
$$\rho_{A,Q} = \sum_{q_j} \Pi_{q_j} \rho_A \Pi_{q_j} = \begin{pmatrix} \rho_{q_1} \\ & \rho_{q_2} \\ & & \rho_{q_3} \end{pmatrix}$$

entanglement assymetry

$$\Delta S_A(t) = S(\rho_A(t)) - S(\rho_{A,Q}(t))$$

C. Rylands et al
arxiv: 2310.04419 (2023)

Hype de 2023: Mpemba e quebra de simetria



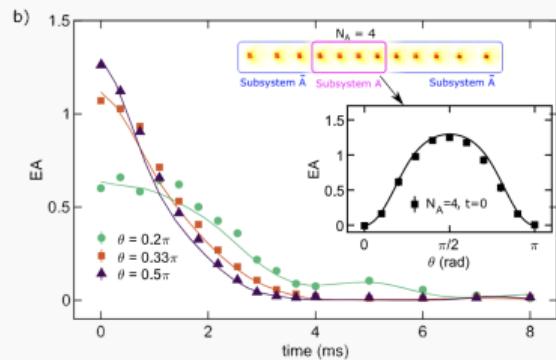
long-range XY

$$H = \sum_{i>j} \frac{J_0}{2|i-j|^\alpha} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y)$$

$$|\psi_0\rangle = e^{-i\theta \sum_j \sigma_j^y} |\uparrow\uparrow \dots\rangle$$

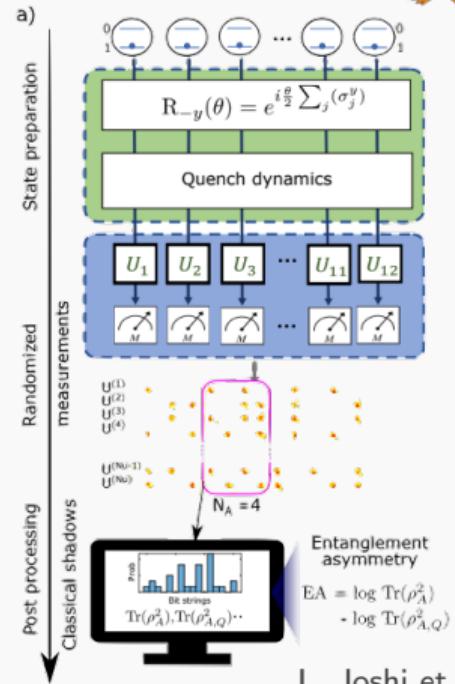
$$Q = 1/2 \sum_j \sigma_j^z$$

C. Rylands et al
arxiv: 2310.04419 (2023)



entanglement assymetry

$$\Delta S_A(t) = S(\rho_A(t)) - S(\rho_{A,Q}(t))$$



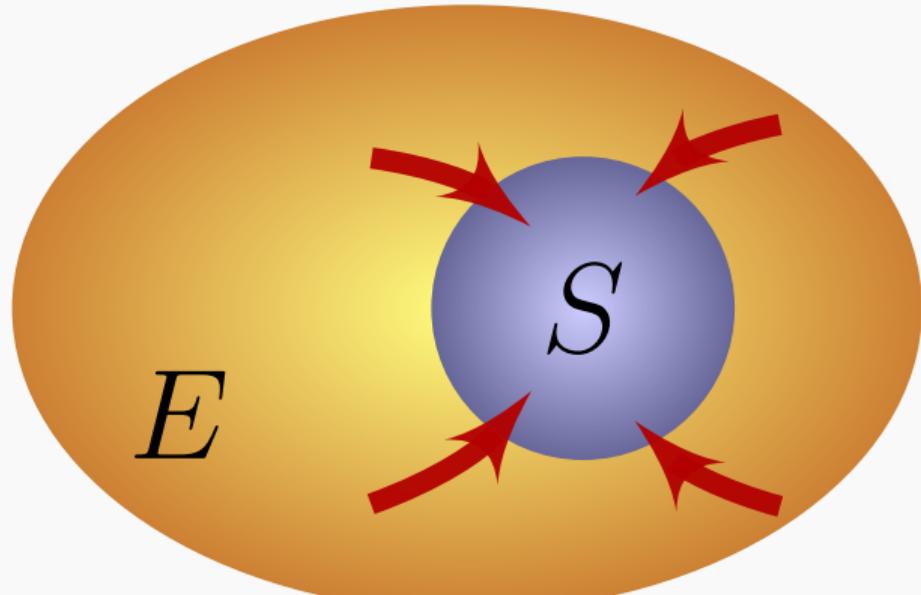
L. Joshi et al
arxiv: 2401.04270 (2024)



Uma explicação termodinâmica para o Mpemba quântico



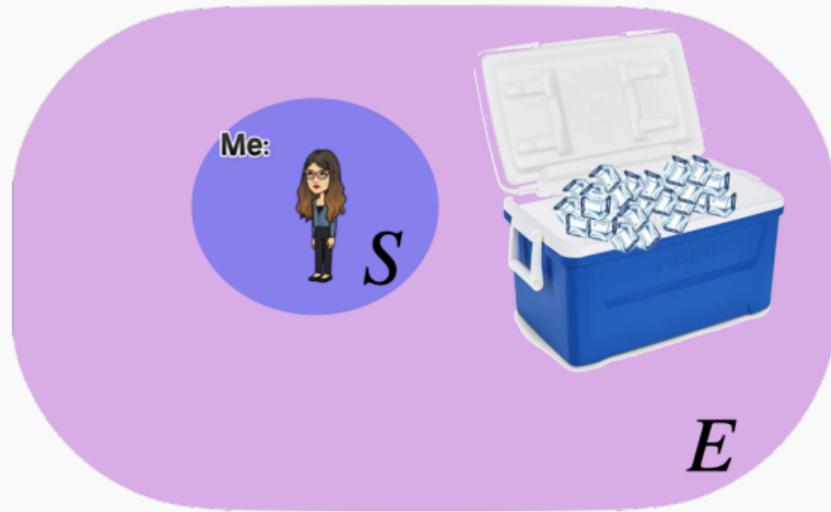
$$\hat{H}_T = \hat{H}_S + \hat{H}_E + \hat{V}_{SE}$$



Uma explicação termodinâmica para o Mpemba quântico



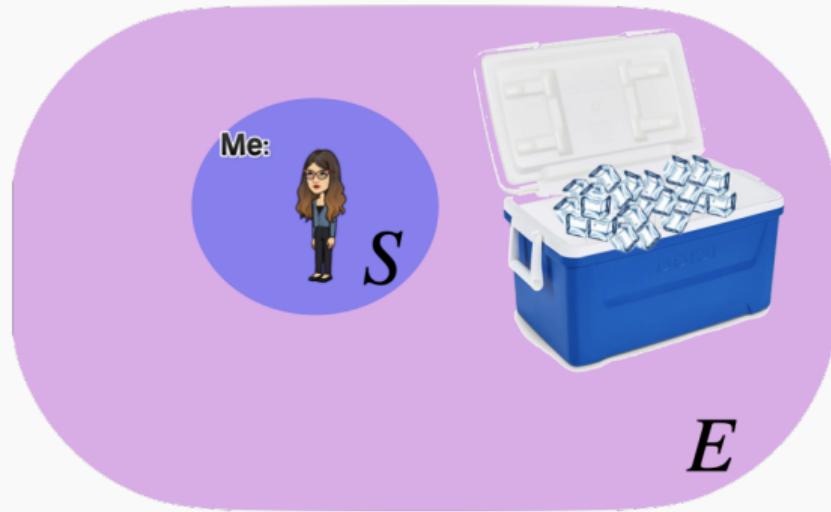
$$\hat{H}_T = \hat{H}_S + \hat{H}_E + \hat{V}_{SE}$$



Uma explicação termodinâmica para o Mpemba quântico



$$\hat{H}_T = \hat{H}_S + \hat{H}_E + \hat{V}_{SE}$$



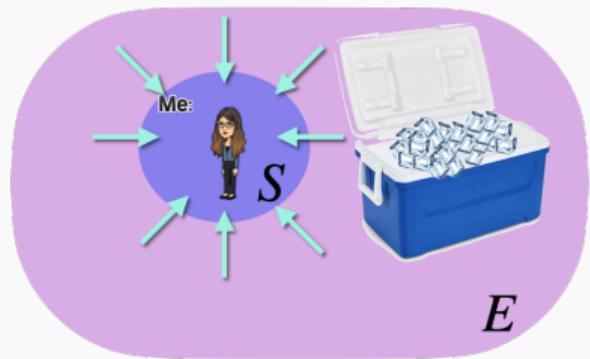
Uma explicação termodinâmica para o Mpemba quântico



$$\hat{H}_T = \hat{H}_S + \hat{H}_E + \hat{V}_{SE}$$

$$\hat{\rho}_S(t) = \text{Tr}_E[\hat{\mathcal{U}}(t)\hat{\rho}_S(0) \otimes \hat{\rho}_E(0)\hat{\mathcal{U}}^\dagger(t)]$$

$$\hat{\mathcal{U}}(t) = \mathcal{T}e^{-i\int dt \hat{H}_T(t)}$$



Uma explicação termodinâmica para o Mpemba quântico



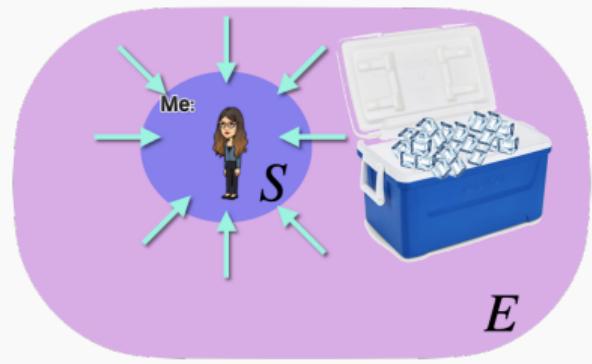
$$\hat{H}_T = \hat{H}_S + \hat{H}_E + \hat{V}_{SE}$$

$$\hat{\rho}_S(t) = \text{Tr}_E[\hat{\mathcal{U}}(t)\hat{\rho}_S(0) \otimes \hat{\rho}_E(0)\hat{\mathcal{U}}^\dagger(t)]$$

GKSL eq mestra, aka Lindblad

$$\frac{d\hat{\rho}(t)}{dt} = \mathcal{G}\hat{\rho}(t)$$

$$\hat{\mathcal{U}}(t) = \mathcal{T}e^{-i\int dt \hat{H}_T(t)}$$



- $\hat{\rho}_S(0) \otimes \hat{\rho}_E(0)$ validade
- Born: $\hat{\rho}_T(t) = \hat{\rho}_S(t) \otimes \hat{\rho}_E(0)$
- Markov: $\tau_S \gg \tau_E$
- secular: $|\omega_{ij} - \omega_{pq}| \ll \tau_S^{-1}$

Uma explicação termodinâmica para o Mpemba quântico



$$\hat{H}_T = \hat{H}_S + \hat{H}_E + \hat{V}_{SE}$$

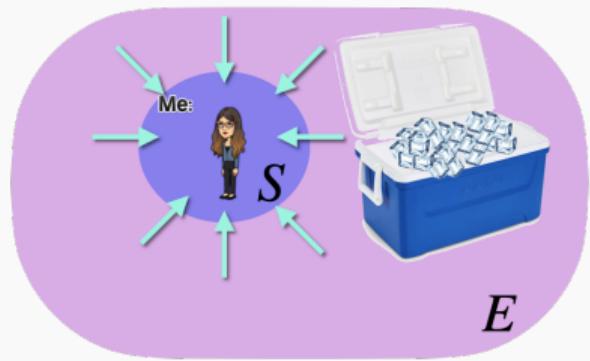
$$\hat{\rho}_S(t) = \text{Tr}_E[\hat{\mathcal{U}}(t)\hat{\rho}_S(0) \otimes \hat{\rho}_E(0)\hat{\mathcal{U}}^\dagger(t)]$$

GKSL eq mestra, aka Lindblad

$$\frac{d\hat{\rho}(t)}{dt} = \mathcal{G}\hat{\rho}(t)$$



$$\hat{\mathcal{U}}(t) = \mathcal{T}e^{-i\int dt \hat{H}_T(t)}$$



- $\hat{\rho}_S(0) \otimes \hat{\rho}_E(0)$ validade
- Born: $\hat{\rho}_T(t) = \hat{\rho}_S(t) \otimes \hat{\rho}_E(t)$
- Markov: $\tau_S \gg \tau_E$
- secular: $|\omega_{ij} - \omega_{pq}| \ll \tau_S^{-1}$



equação mestra



$$\frac{d\hat{\rho}(t)}{dt} = \mathcal{G}\hat{\rho}(t)$$

Liouvillian
super
operador

$$\mathcal{G}[.] = \underbrace{-i[\hat{H}, .]}_{\text{unitaria}} + \underbrace{\mathcal{D}(.)}_{\text{dissipativa}}$$



equação mestra

$$\frac{d\hat{\rho}(t)}{dt} = \mathcal{G}\hat{\rho}(t)$$



Liouvillian
super
operador

$$\mathcal{G}[.] = \underbrace{-i[\hat{H}, .]}_{\text{unitaria}} + \underbrace{\mathcal{D}(.)}_{\text{dissipativa}}$$

operadores de jump

$$\mathcal{D}(\cdot) = \sum_{\omega} \gamma(\omega) \left[\hat{L}(\omega)(\cdot)\hat{L}^{\dagger}(\omega) - \frac{1}{2}\{\hat{L}^{\dagger}(\omega)\hat{L}(\omega), \cdot\} \right]$$



equação mestra

$$\frac{d\hat{\rho}(t)}{dt} = \mathcal{G}\hat{\rho}(t)$$



Liouvillian
super
operador

$$\mathcal{G}[.] = \underbrace{-i[\hat{H}, .]}_{\text{unitaria}} + \underbrace{\mathcal{D}(.)}_{\text{dissipativa}}$$

operadores de jump

$$\mathcal{D}(\cdot) = \sum_{\omega} \gamma(\omega) \left[\hat{L}(\omega)(.)\hat{L}^{\dagger}(\omega) - \frac{1}{2} \{ \hat{L}^{\dagger}(\omega)\hat{L}(\omega), . \} \right]$$

interação

$$\hat{V}_{SE} \propto \hat{S} \otimes \hat{E}$$

transições internas

$$\hat{L}(\omega) = \sum_{\omega=\epsilon'-\epsilon} \langle \epsilon | \hat{S} | \epsilon' \rangle | \epsilon \rangle \langle \epsilon' |$$

taxas de transição

$$\gamma(\omega) = \int_{-\infty}^{\infty} dt e^{i\omega t} \langle \hat{E}(t) \hat{E}^{\dagger}(0) \rangle$$

Liouvilliano: super ingrediente para o Mpemba quântico



equação mestra

$$\frac{d\hat{\rho}(t)}{dt} = \mathcal{G}\hat{\rho}(t)$$

**Liouvillian
super
operador**

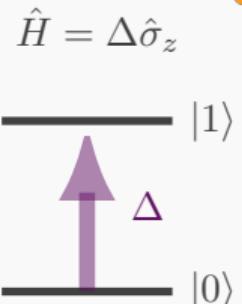
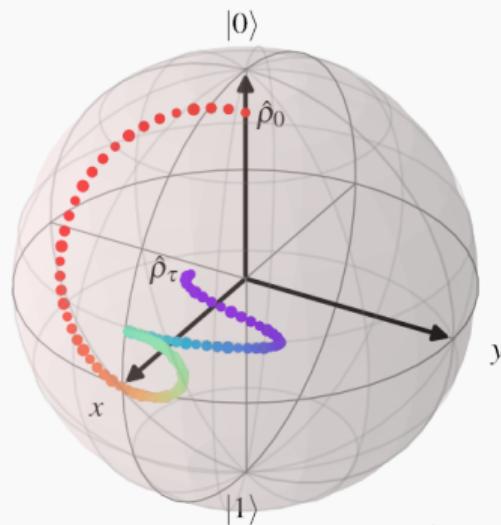
$$\mathcal{G}[\cdot] = \underbrace{-i[\hat{H}, \cdot]}_{\text{unitaria}} + \underbrace{\mathcal{D}(\cdot)}_{\text{dissipativa}}$$

operadores de jump

$$\mathcal{D}(\cdot) = \sum_{\omega} \gamma(\omega) \left[\hat{L}(\omega)(\cdot)\hat{L}^{\dagger}(\omega) - \frac{1}{2} \{ \hat{L}^{\dagger}(\omega)\hat{L}(\omega), (\cdot) \} \right]$$

interação

$$\hat{V}_{SE} \propto \hat{S} \otimes \hat{E}$$



transições internas

$$\hat{L}(\omega) = \sum_{\omega=\epsilon'-\epsilon} \langle \epsilon | \hat{S} | \epsilon' \rangle | \epsilon \rangle \langle \epsilon' |$$

taxas de transição

$$\gamma(\omega) = \int_{-\infty}^{\infty} dt e^{i\omega t} \langle \hat{E}(t) \hat{E}^{\dagger}(0) \rangle$$

Decomposição espectral do gerador



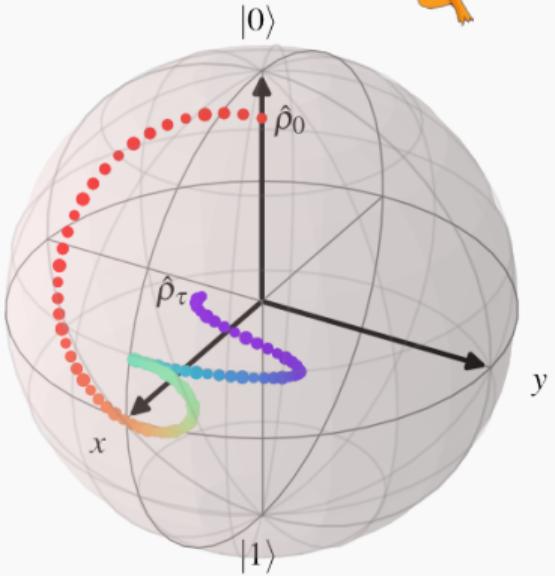
GKSL master-eq $\frac{d\hat{\rho}(t)}{dt} = \mathcal{G}\hat{\rho}(t)$

gerador $\mathcal{G}[\cdot] = \underbrace{-i[\hat{H}, \cdot]}_{\text{unitary}} + \underbrace{\mathcal{D}(\cdot)}_{\text{dissipativa}}$

operadores jump

$$\mathcal{D}(\cdot) = \sum_l \hat{L}_l(\cdot)\hat{L}_l^\dagger - \frac{1}{2}\{\hat{L}_l^\dagger\hat{L}_l, (\cdot)\}$$

evolução $\hat{\rho}(t) = e^{\mathcal{G}t}\hat{\rho}(0)$

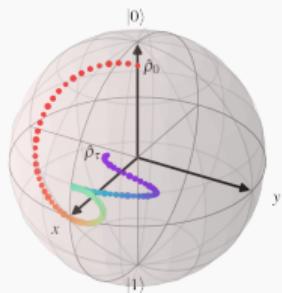




Decomposição espectral do gerador

evolução

$$\hat{\rho}(t) = e^{\mathcal{G}t} \hat{\rho}_i$$

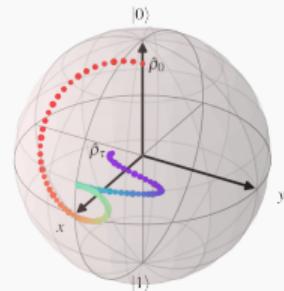


Decomposição espectral do gerador



evolução

$$\hat{\rho}(t) = e^{\mathcal{G}t} \hat{\rho}_i$$



decomposição espectral

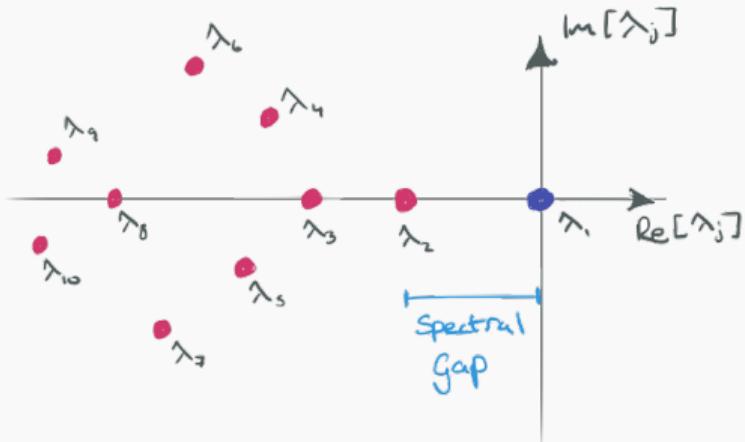
$$0 = \lambda_1 < |\Re(\lambda_2)| \leq |\Re(\lambda_3)| \leq \dots \leq |\Re(\lambda_K)|$$

left eig-vec

$$\mathcal{G}^\dagger[\hat{l}_k] = \lambda_k \hat{l}_k$$

right eig-vec

$$\mathcal{G}[\hat{r}_k] = \lambda_k \hat{r}_k$$





Decomposição espectral do gerador

evolução

$$\hat{\rho}(t) = e^{\mathcal{G}t} \hat{\rho}_i$$

$$\rightarrow \hat{\tau} + \sum_{k=2}^K \text{Tr}(\hat{l}_k \hat{\rho}_i) \hat{r}_k e^{\lambda_k t}$$

↓ ↓
estado estacionário overlaps com modos k

decomposição espectral

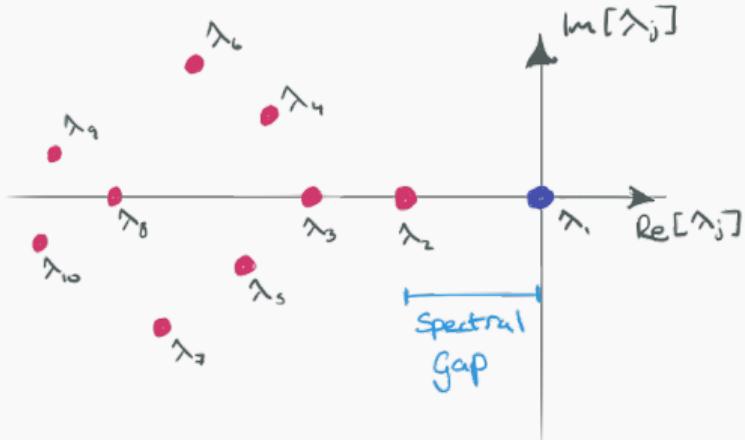
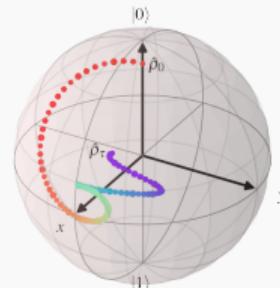
$$0 = \lambda_1 < |\Re(\lambda_2)| \leq |\Re(\lambda_3)| \leq \dots \leq |\Re(\lambda_K)|$$

left eig-vec

$$\mathcal{G}^\dagger[\hat{l}_k] = \lambda_k \hat{l}_k$$

right eig-vec

$$\mathcal{G}[\hat{r}_k] = \lambda_k \hat{r}_k$$



Decomposição espectral do gerador



evolução
 $\hat{\rho}(t) = e^{\mathcal{G}t} \hat{\rho}_i$

$$\rightarrow \hat{\tau} + \sum_{k=2}^K \text{Tr}(\hat{l}_k \hat{\rho}_i) \hat{r}_k e^{\lambda_k t}$$

estado estacionário overlaps com modos k

decomposição espectral

$$0 = \lambda_1 < |\Re(\lambda_2)| \leq |\Re(\lambda_3)| \leq \dots \leq |\Re(\lambda_K)|$$

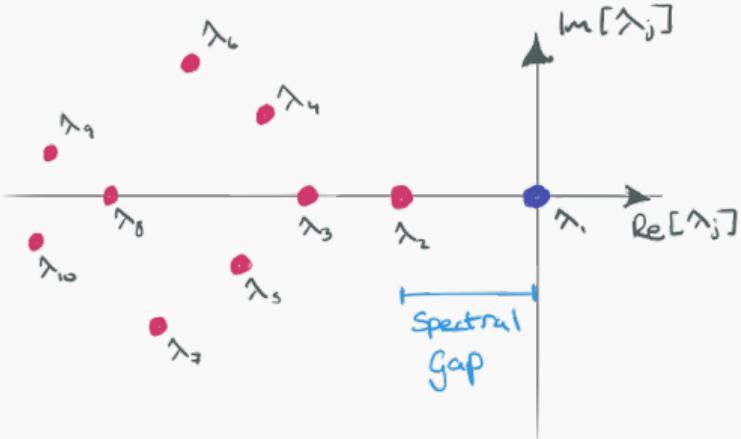
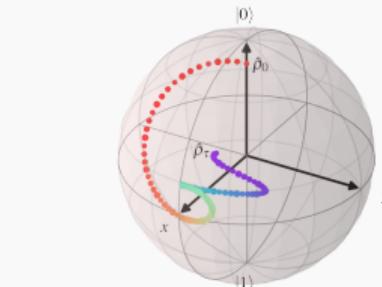
left eig-vec
 $\mathcal{G}^\dagger[\hat{l}_k] = \lambda_k \hat{l}_k$

right eig-vec
 $\mathcal{G}[\hat{r}_k] = \lambda_k \hat{r}_k$



**decaimento
relaxação**

$$|\hat{\rho}(t) - \hat{\tau}| \propto \exp(\Re \lambda_2 t)$$



Ativando o Mpemba em sistemas quânticos dissipativos



$$\hat{\rho}(t) = \hat{\tau} + \sum_{k=2}^K \text{Tr}(\hat{l}_k \hat{\rho}_i) \hat{r}_k e^{\lambda_k t}$$



$$\mathcal{O}_2 = \left| \text{Tr}(\hat{l}_2 \hat{\rho}_i) \right| \rightarrow 0$$

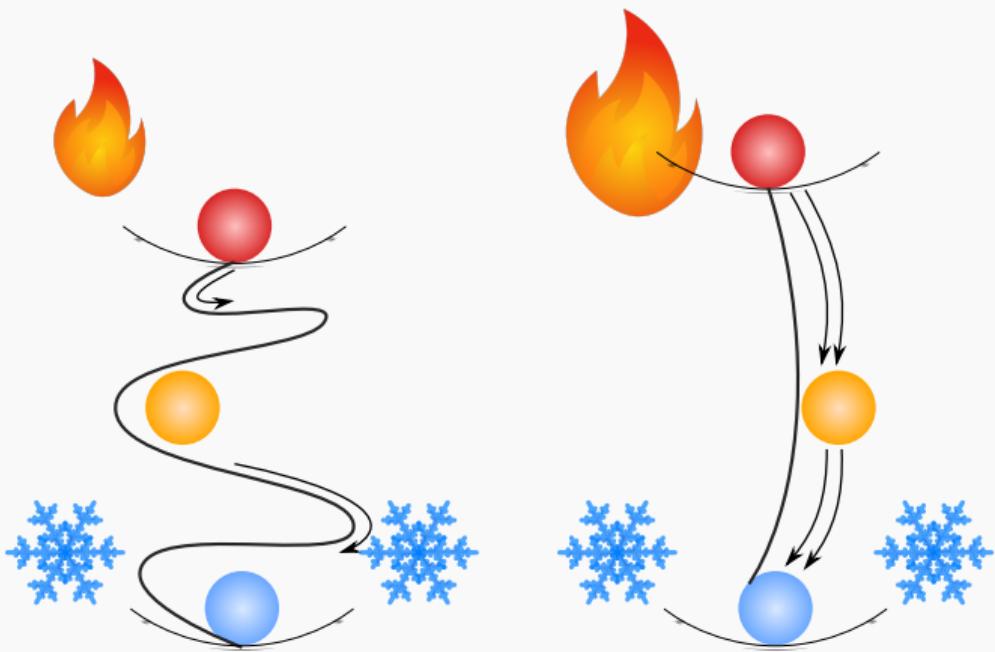
Ativando o Mpemba em sistemas quânticos dissipativos

13

$$\hat{\rho}(t) = \hat{\tau} + \sum_{k=2}^K \text{Tr}(\hat{l}_k \hat{\rho}_i) \hat{r}_k e^{\lambda_k t}$$



$$\mathcal{O}_2 = \left| \text{Tr}(\hat{l}_2 \hat{\rho}_i) \right| \rightarrow 0$$



Ativando o Mpemba em sistemas quânticos dissipativos

13

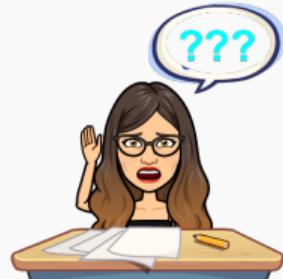
$$\hat{\rho}(t) = \hat{\tau} + \sum_{k=2}^K \text{Tr}(\hat{l}_k \hat{\rho}_i) \hat{r}_k e^{\lambda_k t}$$



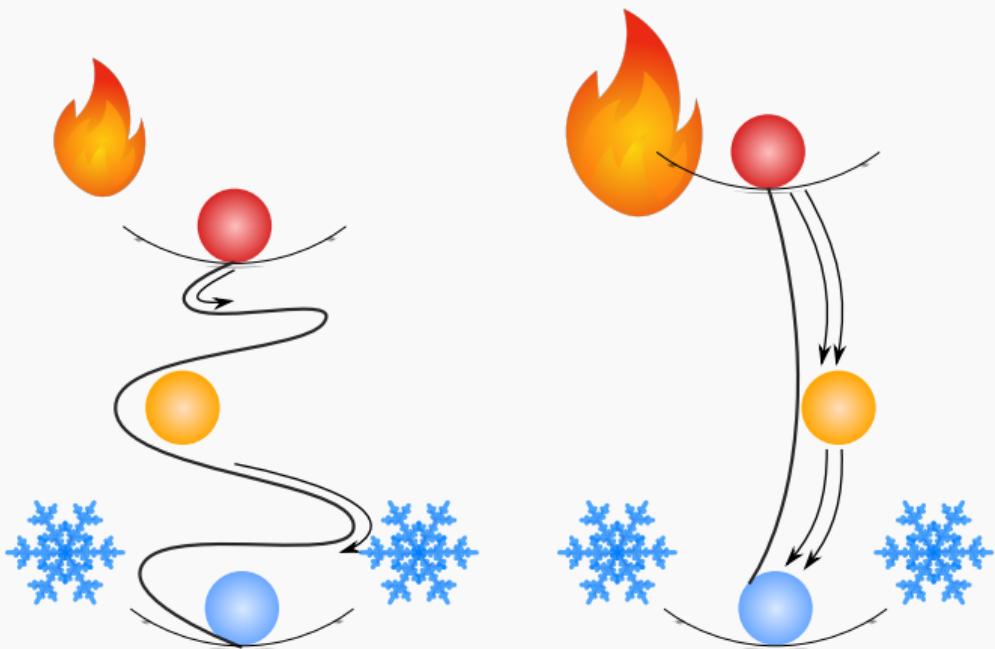
como?

$$\mathcal{O}_2 = \left| \text{Tr}(\hat{l}_2 \hat{\rho}_i) \right| \rightarrow 0$$

receita?



Como fazer sorvete com qubits?



Primeira receita para o Mpemba quântico



$$\hat{\rho}(t) = \hat{\tau} + \sum_{k=2}^K \text{Tr}(\hat{l}_k \hat{\rho}_i) \hat{r}_k e^{\lambda_k t}$$



$$\mathcal{O}_2 = \left| \text{Tr}(\hat{l}_2 \hat{\rho}_i) \right| \rightarrow 0$$





Primeira receita para o Mpemba quântico

$$\hat{\rho}(t) = \hat{\tau} + \sum_{k=2}^K \text{Tr}(\hat{l}_k \hat{\rho}_i) \hat{r}_k e^{\lambda_k t}$$



$$\mathcal{O}_2 = \left| \text{Tr}(\hat{l}_2 \hat{\rho}_i) \right| \rightarrow 0$$

rodar o estado inicial

$$\left| \text{Tr}(\hat{l}_2 \hat{U} \hat{\rho}_i \hat{U}^\dagger) \right| = 0$$



F. Carollo, A. Lasanta, and I. Lesanovsky
Phys. Rev. Lett. 127, 060401 (2021)





Primeira receita para o Mpemba quântico

$$\hat{\rho}(t) = \hat{\tau} + \sum_{k=2}^K \text{Tr}(\hat{l}_k \hat{\rho}_i) \hat{r}_k e^{\lambda_k t}$$



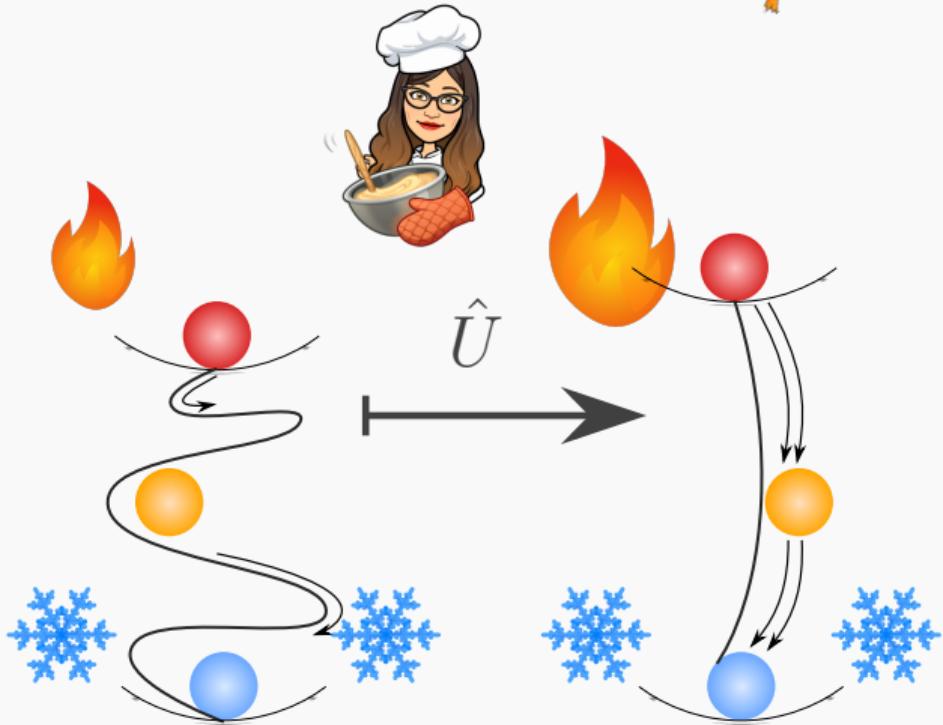
$$\mathcal{O}_2 = \left| \text{Tr}(\hat{l}_2 \hat{\rho}_i) \right| \rightarrow 0$$

rodar o estado inicial

$$\left| \text{Tr}(\hat{l}_2 \hat{U} \hat{\rho}_i \hat{U}^\dagger) \right| = 0$$

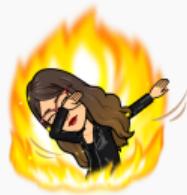


F. Carollo, A. Lasanta, and I. Lesanovsky
Phys. Rev. Lett. 127, 060401 (2021)





Receita de Moroder+Culhane+Zawadzki+Goold



Davies map

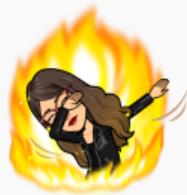
$$\hat{\mathcal{G}} = \hat{\mathcal{G}}_p \oplus \hat{\mathcal{G}}_c$$



$$\hat{U} = \hat{U}_2 \hat{U}_1$$

M. Moroder, KZ, O. Culhane, J. Goold
Phys Rev Lett 133 (14), 140404 (2024)

Receita de Moroder+Culhane+Zawadzki+Goold



Davies map

$$\hat{\mathcal{G}} = \hat{\mathcal{G}}_p \oplus \hat{\mathcal{G}}_c$$

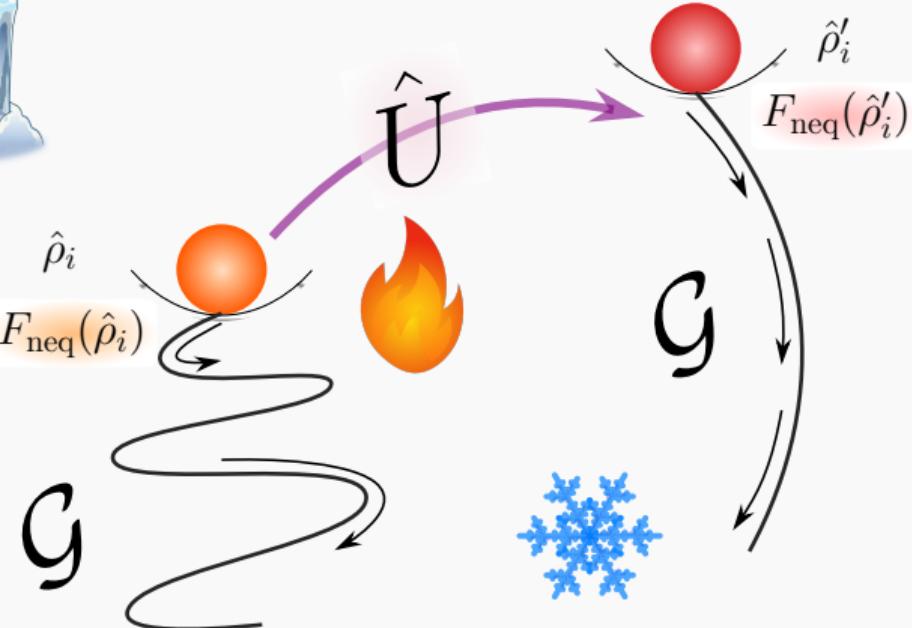


$$\hat{U} = \hat{U}_2 \hat{U}_1$$

entropia
relativa
quântica

$$F_{\text{eq}} = -\beta^{-1} \ln Z$$

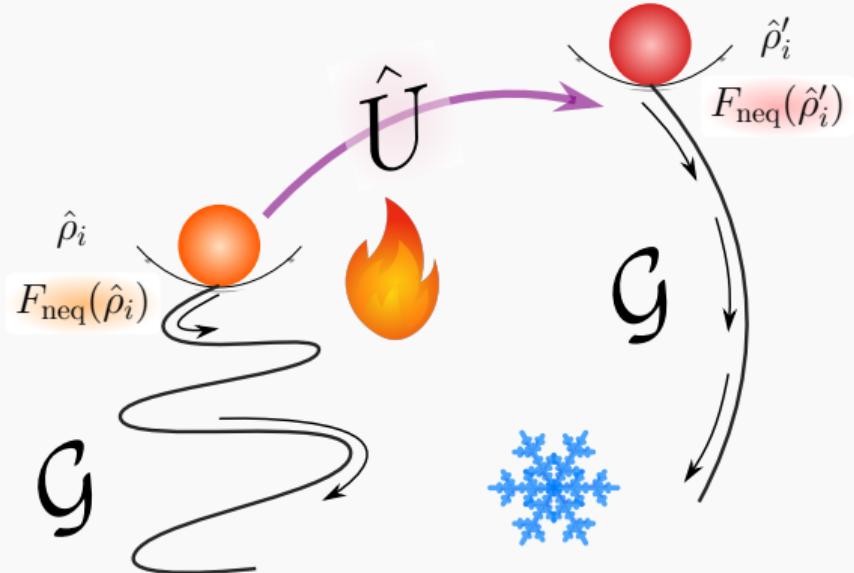
$$F_{\text{neq}}(\hat{\rho}(t)) = \frac{1}{\beta} D(\hat{\rho}(t) || \hat{\tau}_\beta) + F_{\text{eq}}(\hat{\tau}_\beta)$$



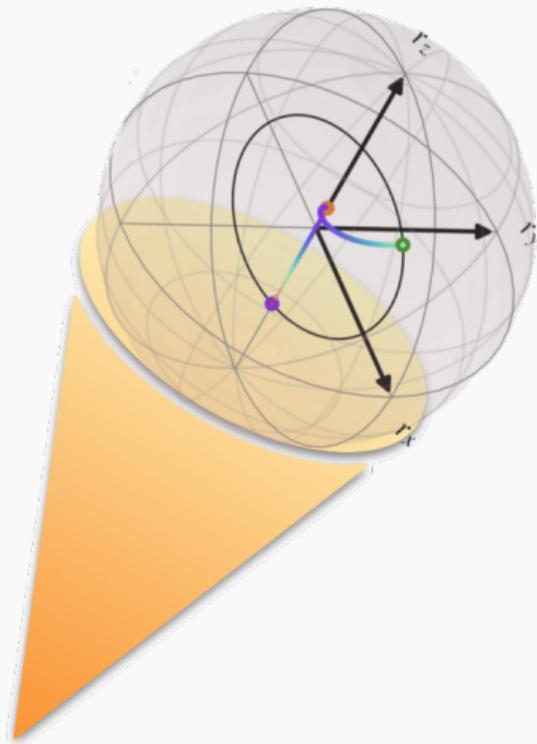
M. Moroder, KZ, O. Culhane, J. Goold
Phys Rev Lett 133 (14), 140404 (2024)



Testando e degustando nossa receita

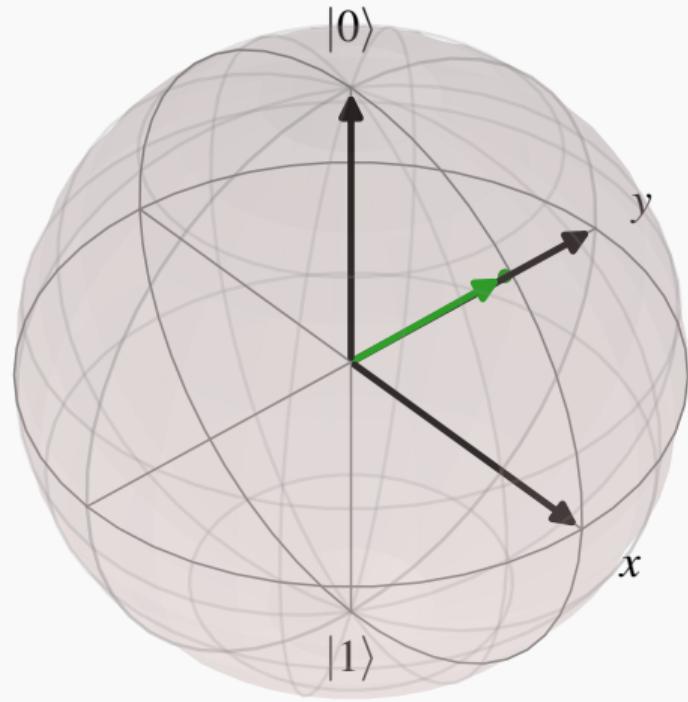


O gelato de um qubit





O gelato de um qubit



estado inicial $\hat{\rho}_i = \frac{1}{2}(\mathbb{1} + \mathbf{r} \cdot \hat{\sigma})$

evolução unitária $\hat{H}_i = \omega \hat{\sigma}_z$

operadores jump

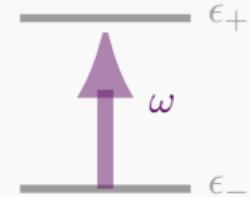
$$\hat{L}_{10}^+(\beta) = \sqrt{1 + f_\beta^+(\epsilon_+ - \epsilon_-)} |\epsilon_+\rangle \langle \epsilon_-|$$

$$\hat{L}_{01}^-(\beta) = \sqrt{f_\beta^+(\epsilon_+ - \epsilon_-)} |\epsilon_-\rangle \langle \epsilon_1|$$

transições

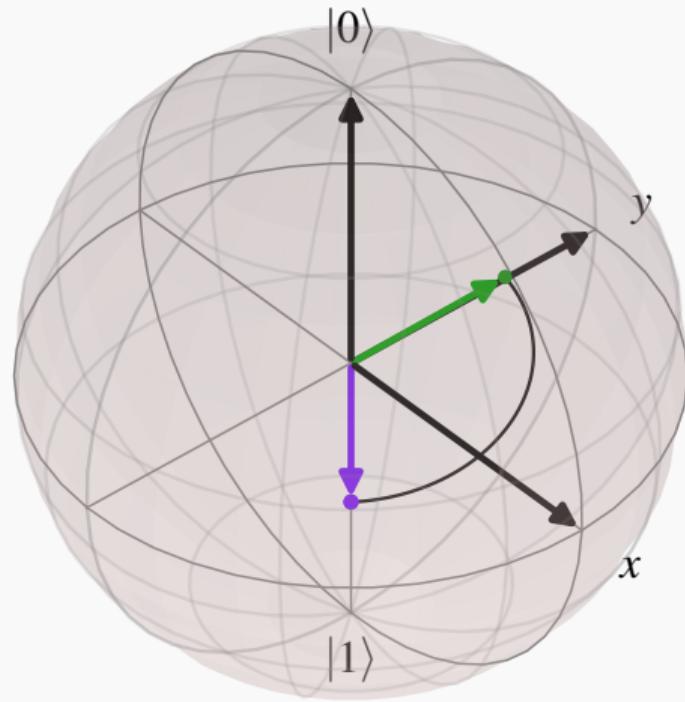
$$\epsilon_{\pm} = \pm\omega$$

$$|\epsilon_{\pm}\rangle = \alpha_{\pm} |0\rangle + \beta_{\pm} |1\rangle$$





O gelato de um qubit



estado inicial $\hat{\rho}_i = \frac{1}{2}(\mathbb{1} + \mathbf{r} \cdot \hat{\sigma})$

evolução unitária $\hat{H}_i = \omega \hat{\sigma}_z$

operadores $\hat{L}_{10}^+(\beta) = \sqrt{1 + f_\beta^+(\epsilon_+ - \epsilon_-)} |\epsilon_+\rangle \langle \epsilon_-|$
jump

$$\hat{L}_{01}^-(\beta) = \sqrt{f_\beta^+(\epsilon_+ - \epsilon_-)} |\epsilon_-\rangle \langle \epsilon_1|$$

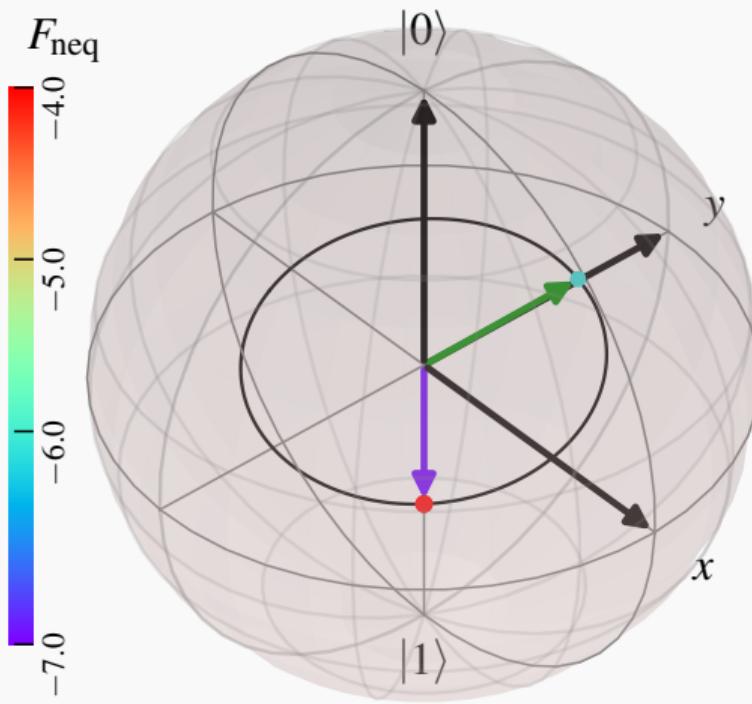
transições

$$\epsilon_{\pm} = \pm\omega$$

$$|\epsilon_{\pm}\rangle = \alpha_{\pm} |0\rangle + \beta_{\pm} |1\rangle$$



O gelato de um qubit



estado inicial $\hat{\rho}_i = \frac{1}{2}(\mathbb{1} + \mathbf{r} \cdot \hat{\sigma})$

evolução unitária $\hat{H}_i = \omega \hat{\sigma}_z$

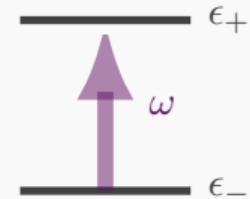
operadores jump $\hat{L}_{10}^+(\beta) = \sqrt{1 + f_\beta^+(\epsilon_+ - \epsilon_-)} |\epsilon_+\rangle \langle \epsilon_-|$

$$\hat{L}_{01}^-(\beta) = \sqrt{f_\beta^+(\epsilon_+ - \epsilon_-)} |\epsilon_-\rangle \langle \epsilon_1|$$

transições

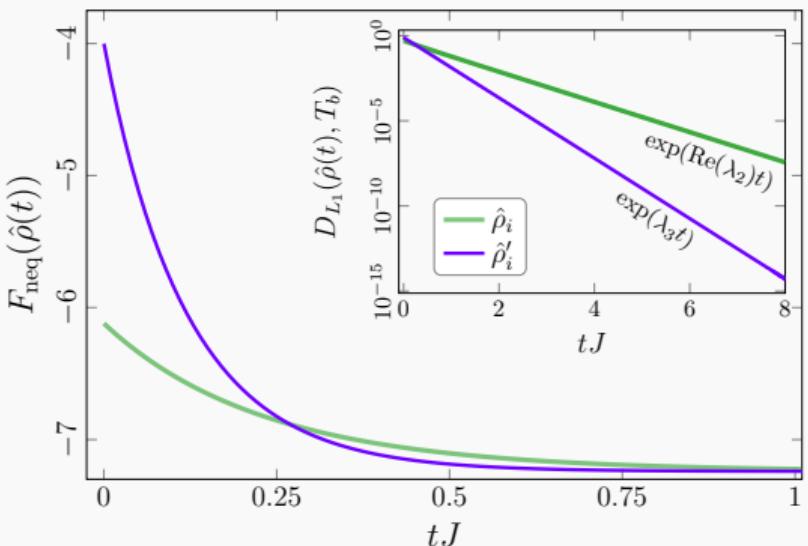
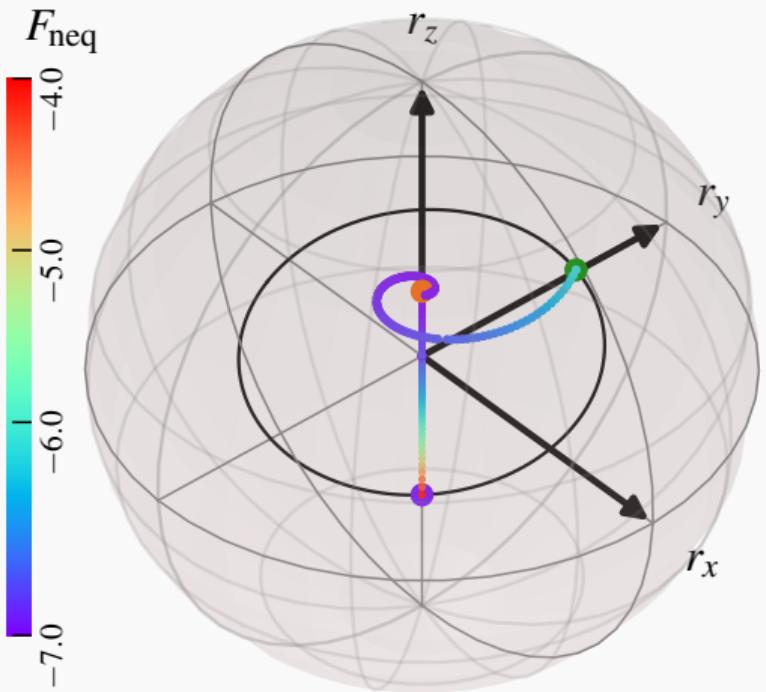
$$\epsilon_{\pm} = \pm\omega$$

$$|\epsilon_{\pm}\rangle = \alpha_{\pm} |0\rangle + \beta_{\pm} |1\rangle$$





O gelato de um qubit



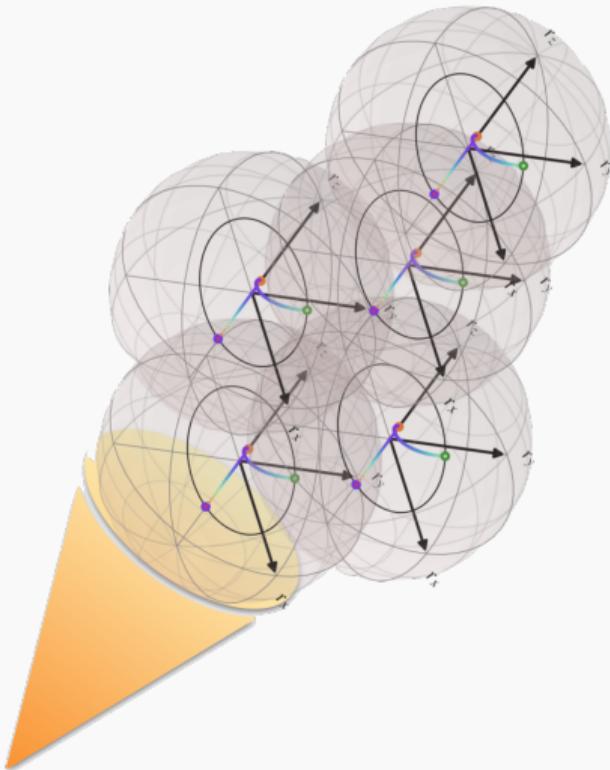
$$T_b = 10J$$

$$\omega = 5J$$

$$\mathbf{r}_i = (0.506, 0.659, 0.556)$$

$$\mathbf{r}'_i = (0, 0, -0.545)$$

Mais qubits: efeitos de correlações

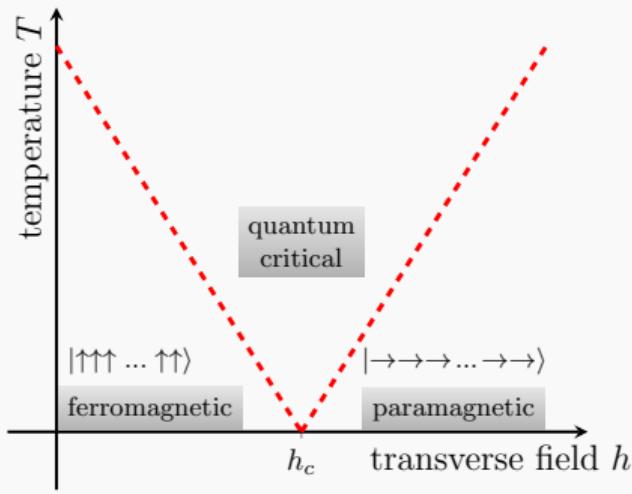




Mais qubits: efeitos de correlações

cadeia Ising no campo transverso

$$\hat{H} = -J \sum_{j=1}^L [h \hat{\sigma}_j^x + \hat{\sigma}_j^z \hat{\sigma}_{j+1}^z]$$

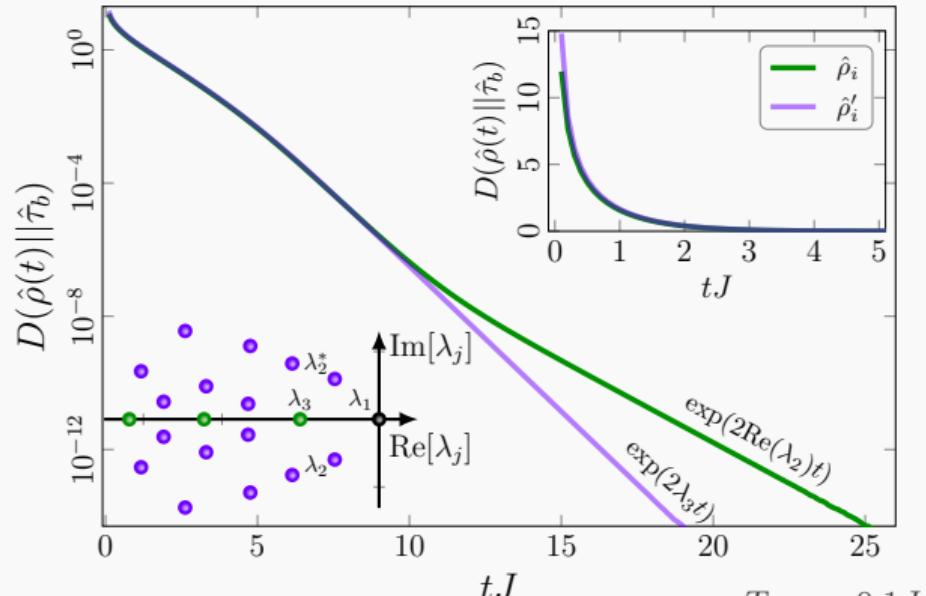
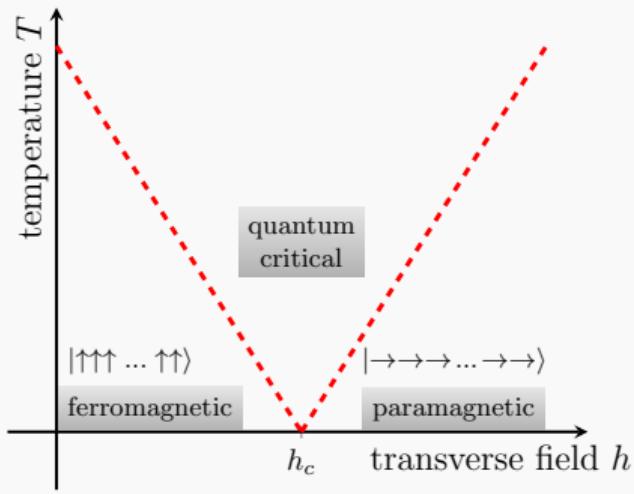


Mais qubits: efeitos de correlações



cadeia Ising no campo transverso

$$\hat{H} = -J \sum_{j=1}^L [h \hat{\sigma}_j^x + \hat{\sigma}_j^z \hat{\sigma}_{j+1}^z]$$



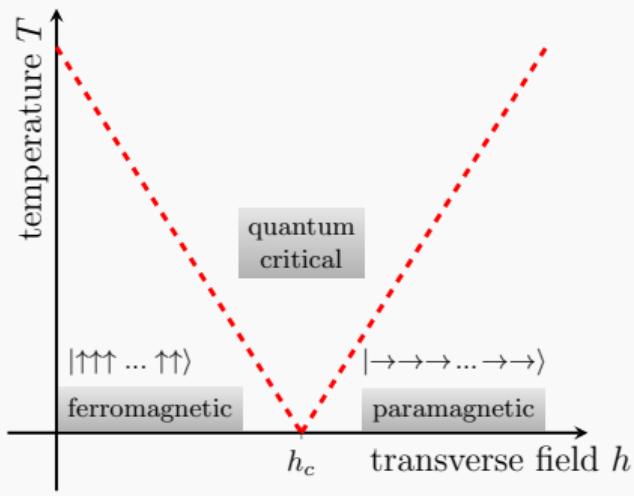
$$T_b = 0.1J$$

Mais qubits: efeitos de correlações

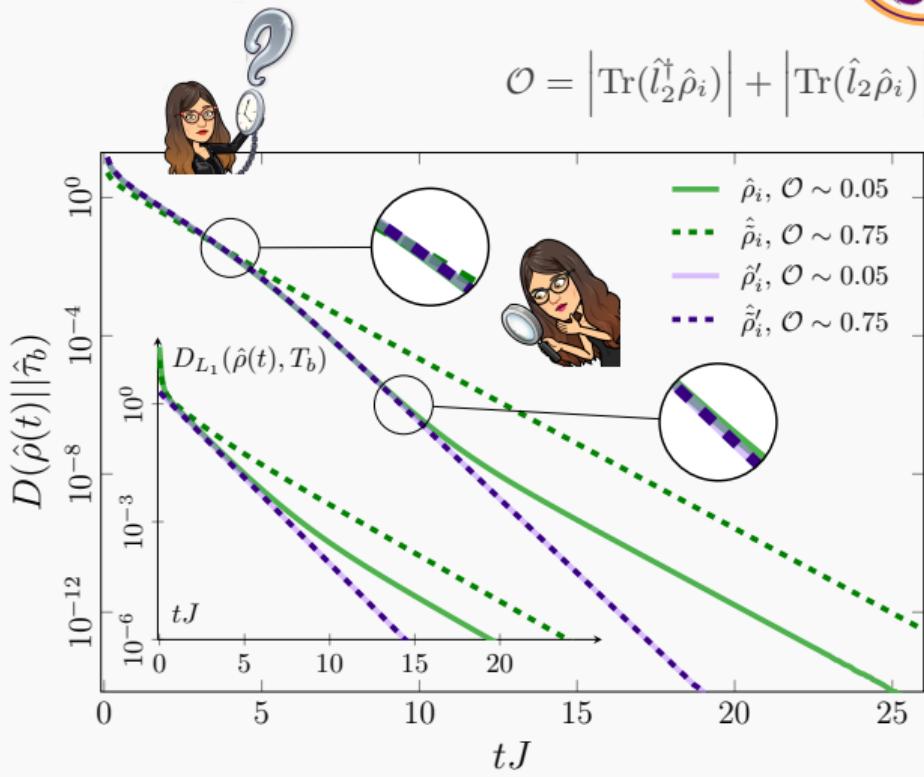


cadeia Ising no campo transverso

$$\hat{H} = -J \sum_{j=1}^L [h \hat{\sigma}_j^x + \hat{\sigma}_j^z \hat{\sigma}_{j+1}^z]$$



$$\mathcal{O} = \left| \text{Tr}(\hat{l}_2^\dagger \hat{\rho}_i) \right| + \left| \text{Tr}(\hat{l}_2 \hat{\rho}_i) \right|$$



Conclusão e perspectivas



Efeito Mpemba quântico

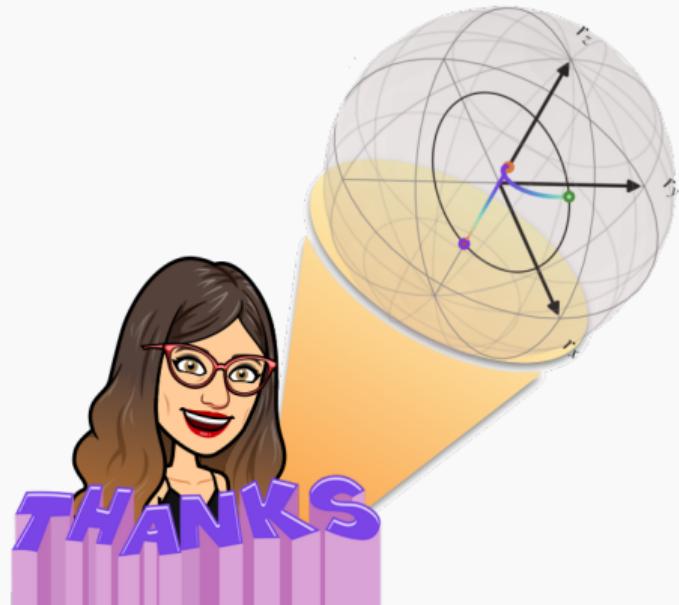
- ▶ ocorre sempre que $\mathcal{O}_{\text{slow}} \rightarrow 0$
- ▶ $F_{\text{neq}}(\hat{\rho})$ chave para metaestabilidade

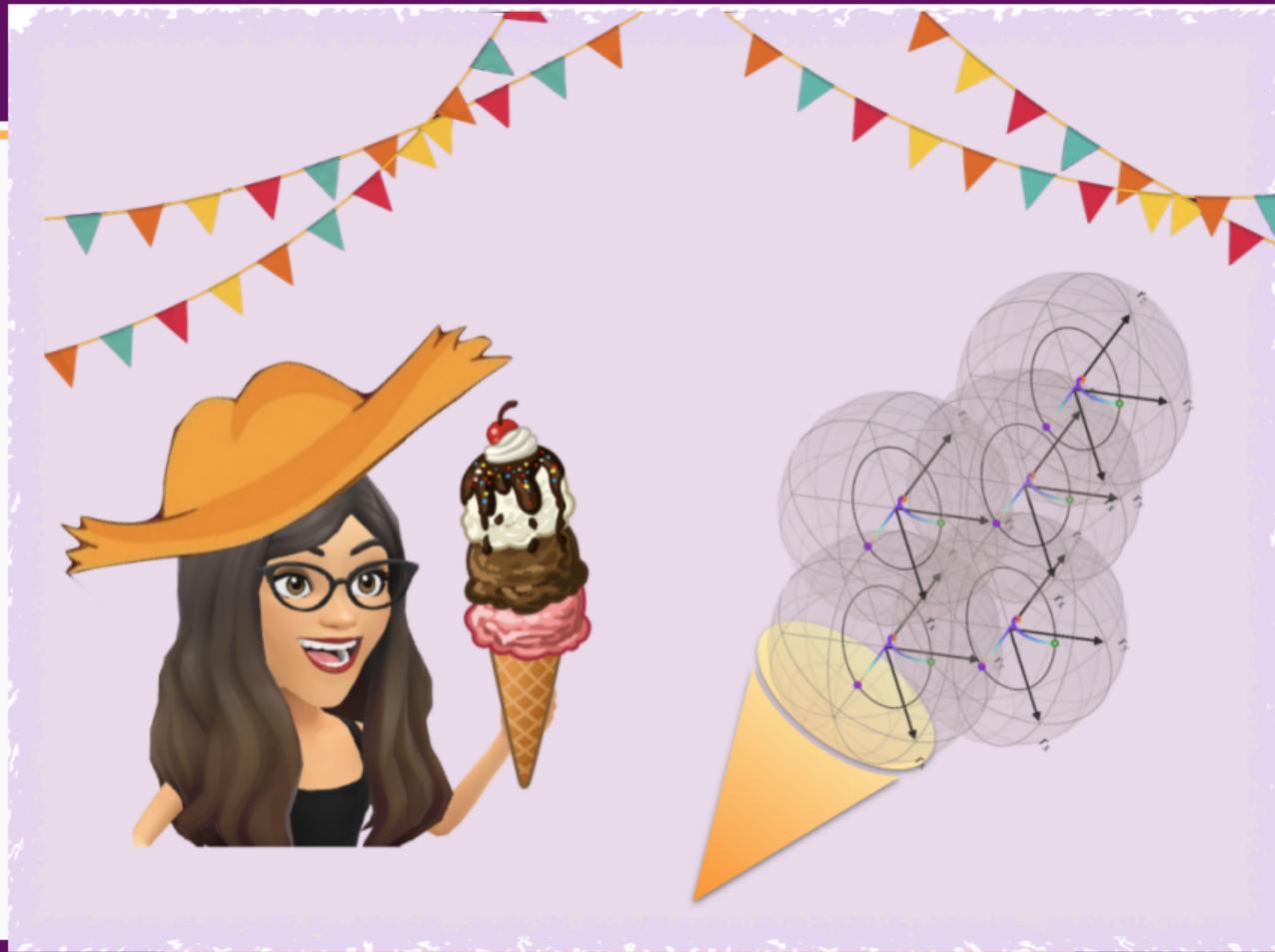
Rota rápida para termalização

- ▶ \hat{U} : elimina coerências + permuta populações
- ▶ qubit: classical entropia $\mathcal{P} \propto \exp 2\lambda_3 t$ acelerada exponencialmente
- ▶ ++ qubits: espectro denso do operador \mathcal{G} exige receita rebuscada

Futuro:

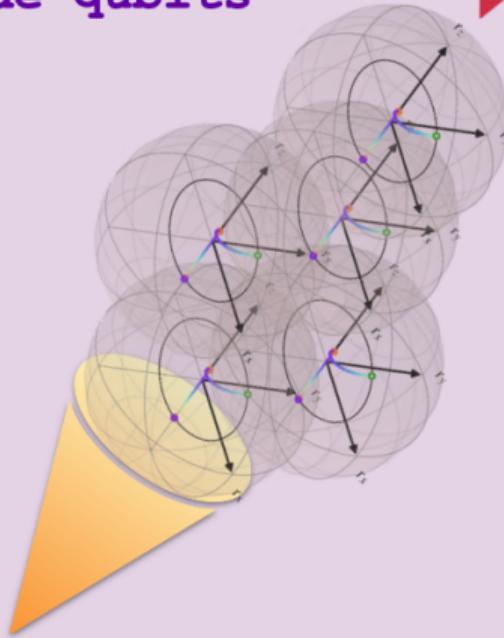
- ▶ interpretação geométrica: arXiv:2409.06083
- ▶ experimentos: RMN + computador quântico ...



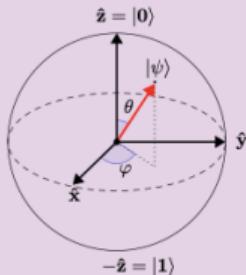




Sorvete de qubits



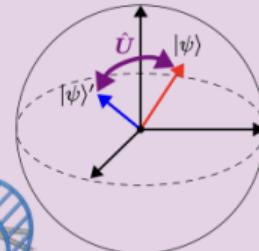
Ingredientes



- 1 sistema quântico
- 1 banho térmico



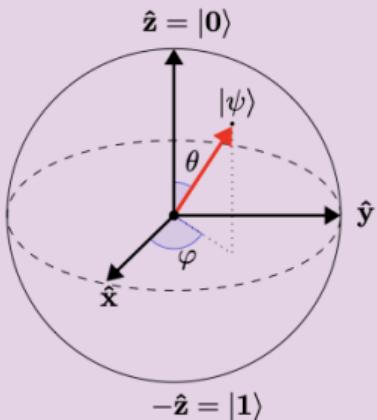
- 1 mapa de Davies
- 2 rotações





Modo de preparo

Pegue o seu sistema quântico favorito (ou, o que tem na geladeira). Minha primeira tentativa, eu só tinha um qubit no estado $\hat{\rho}_i$.



Vi que também tinha um campo magnético em z. Então, eu tinha um Hamiltoniano \hat{H} ok para testar.



Modo de preparo

Agora, introduzi o banho térmico. No caso, o cooler que vai resfriar o qubit, nosso futuro sorvete.



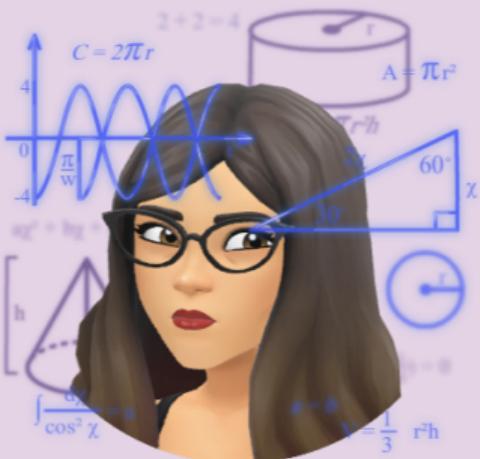
O banho está a uma temperatura T_b , que assim como nosso freezer permanece a mesma quando colocamos comida.



Modo de preparo

O próximo passo exige um pouco de conhecimento de culinária quântica ... algo que você vê no Larrousse's clássico

...



Vamos precisar de um mapa de Davies para encontrar como o nosso qubit poderia virar sorvete quando entra no cooler.

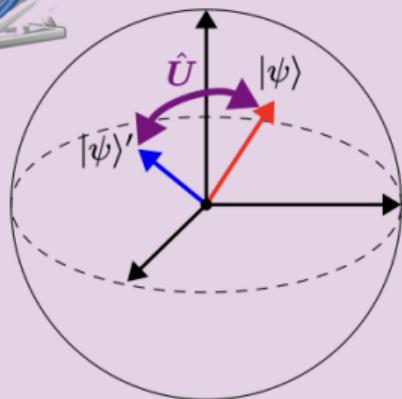


Modo de preparo

Agora, o ingrediente central: rotação!



Precisamos rodar o qubit para remover suas coerências e permutar as populações.



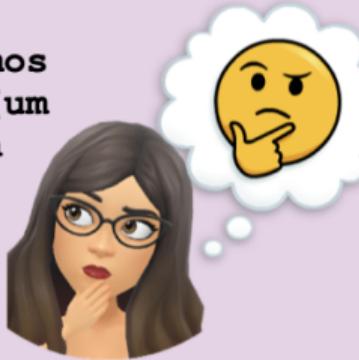
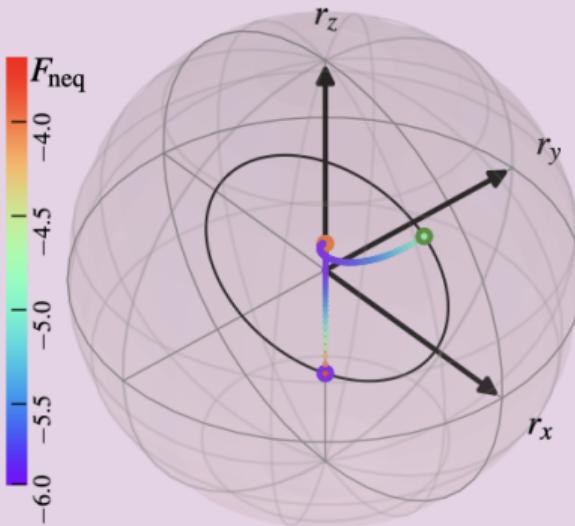
$$\hat{U} = \underbrace{\hat{U}_2}_{pop} \underbrace{\hat{U}_1}_{coe}$$

Isso vai
eliminar coisas que
fazem o congelamento
durar eras...



Expectativa

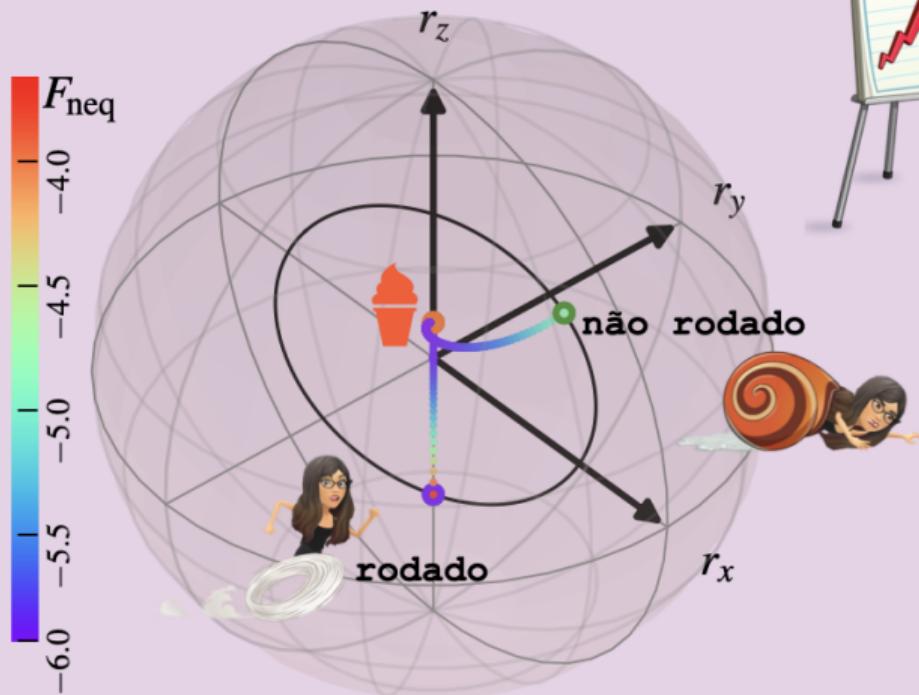
Para ver se funcionou, precisaremos medir o tempo que duas misturas (um qubit sem a rotação e outro com a rotação) demorou para termalizar



Podemos monitorar a energia livre:
vermelho é quente e
azul é frio.

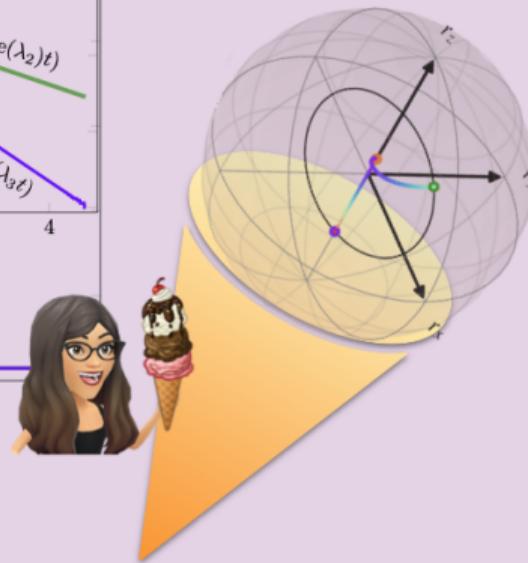
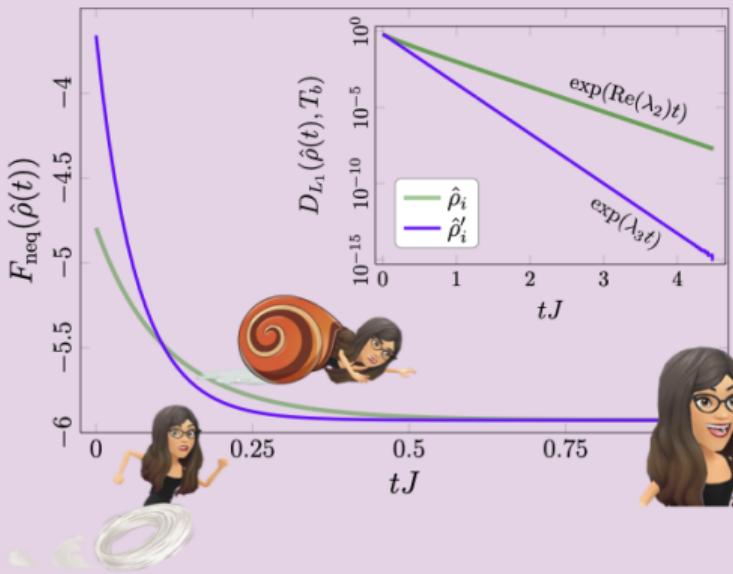


Realidade

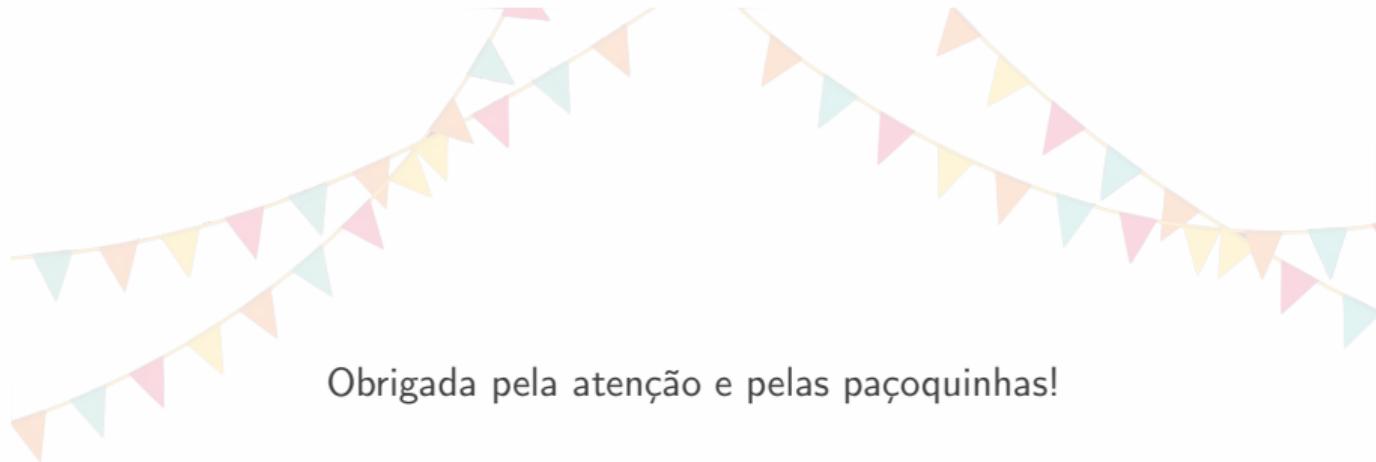


o qubit rodado vai direto para o ponto de sorvete!

Cool?



Refrescados e adocicados graças à física!



Obrigada pela atenção e pelas paçoquinhas!