Anti-thermalization:
Heating from cooling & vice versa

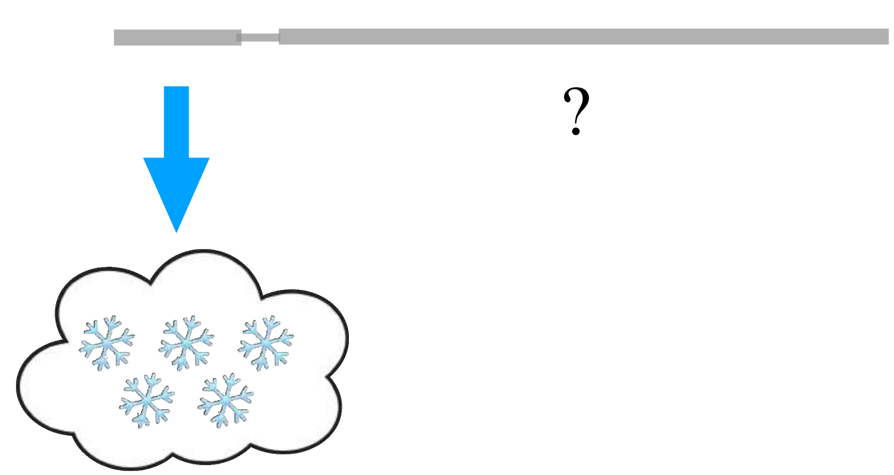
Shovan Dutta

Raman Research Institute

In collaboration with: Jaswanth Uppalapati (IISc)

Paul McClarty (CNRS)

Masud Haque (TU Dresden)



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RRI

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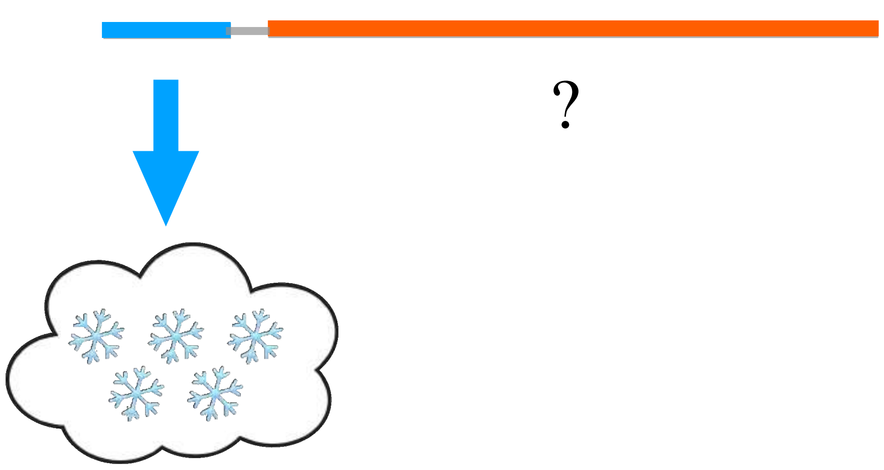

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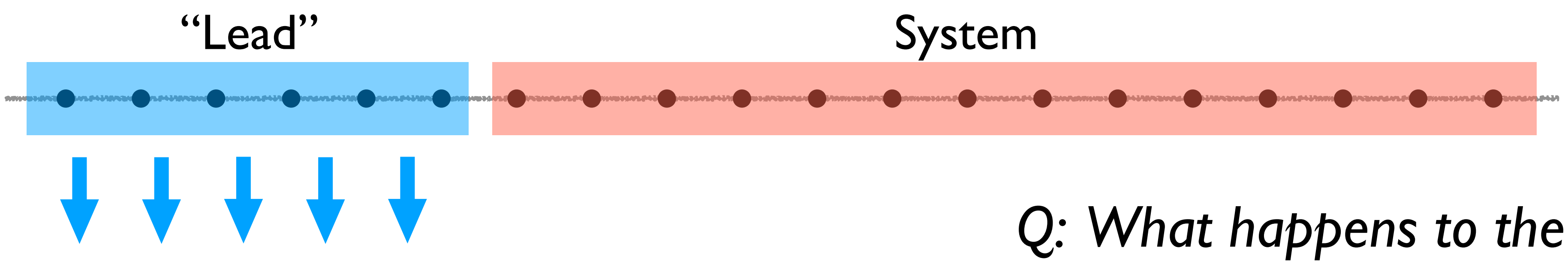
The setup



Q: What happens to the system?

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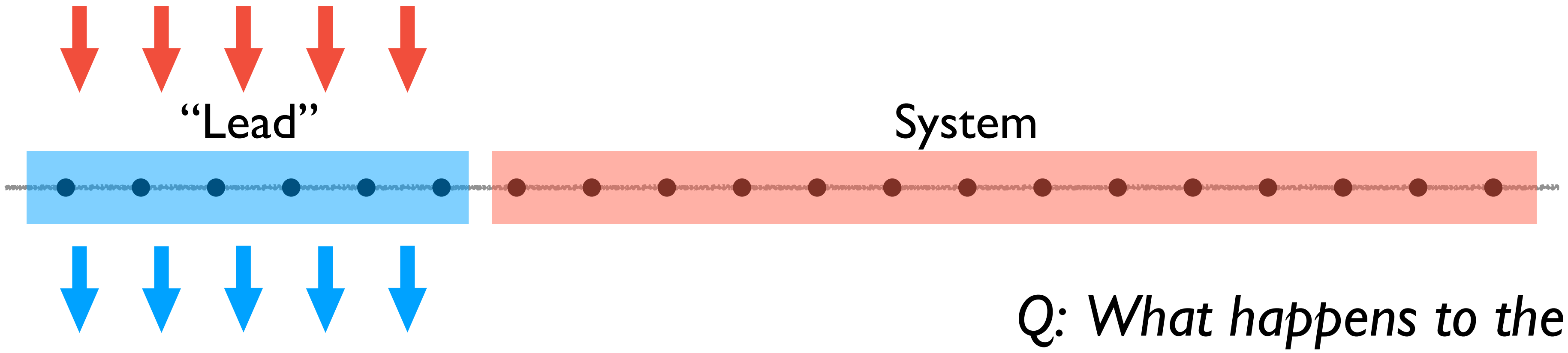

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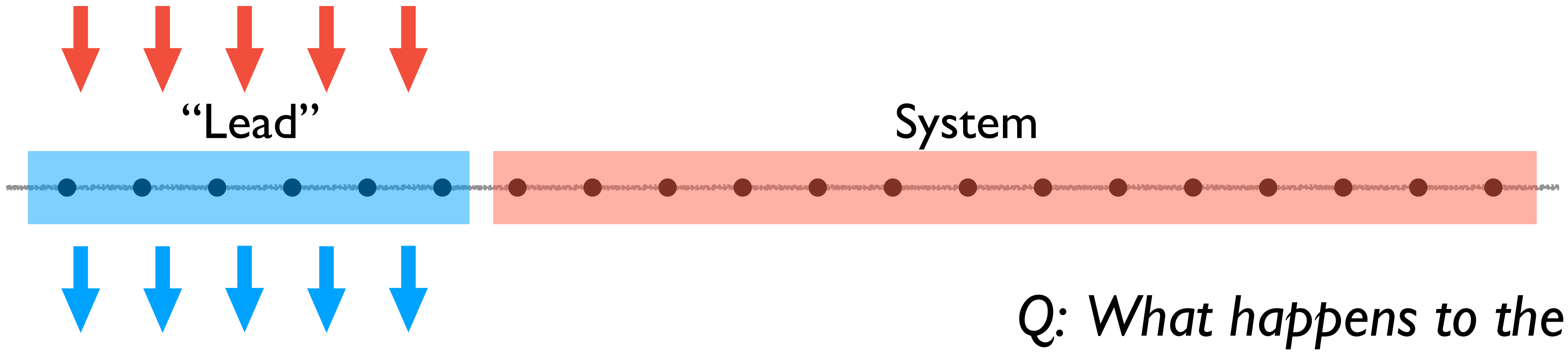

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Free-fermion lead + Markovian (Lindblad) dissipation — system reaches lead temperature for

- Infinite lead w/ bandwidth larger than system
- Weak system-lead coupling
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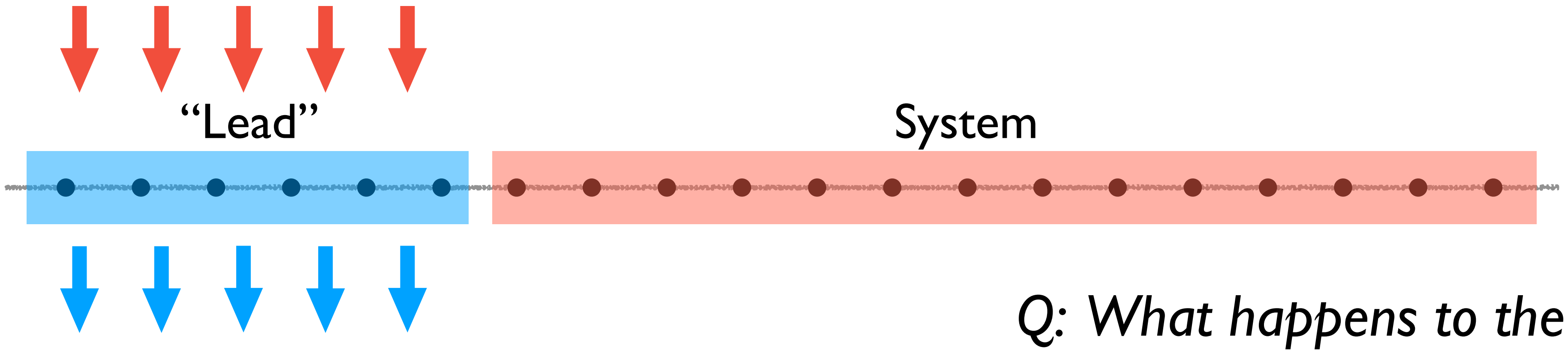

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Finite-size simulations: approximate sympathetic cooling + works best in above limits

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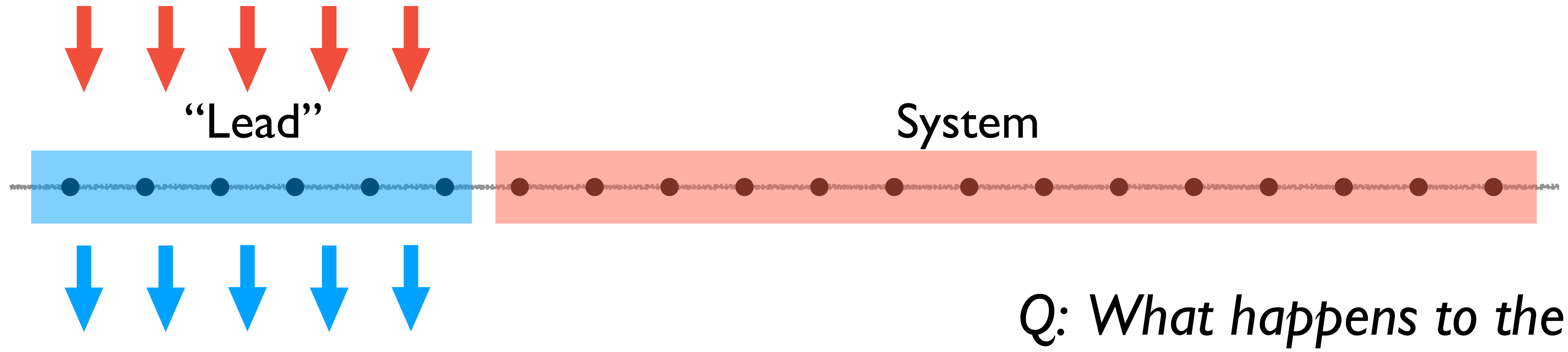

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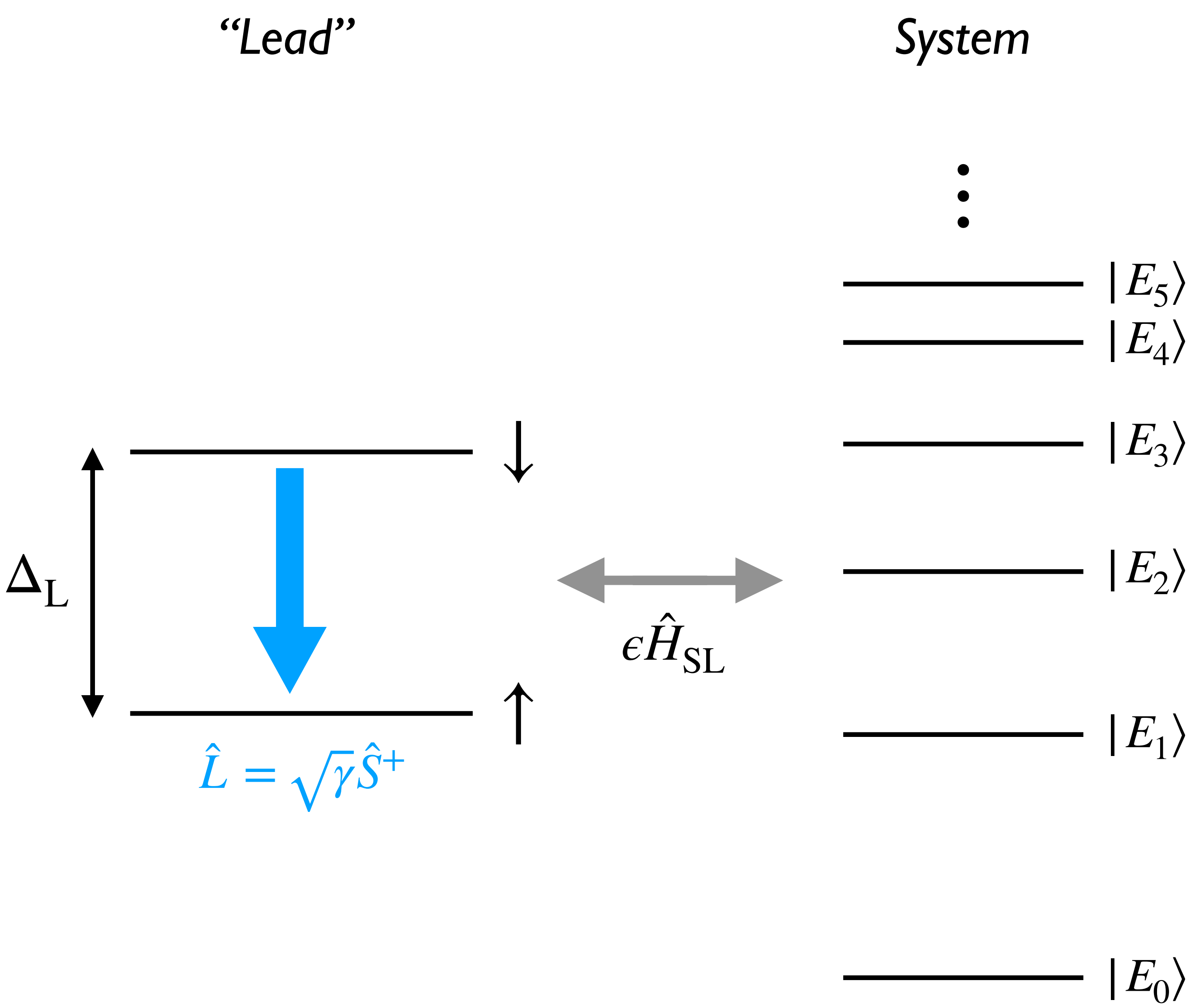
Here: Spectacular failure in presence of symmetry — heating by cooling
(Even in the above ideal limits)

Why we expect sympathetic cooling



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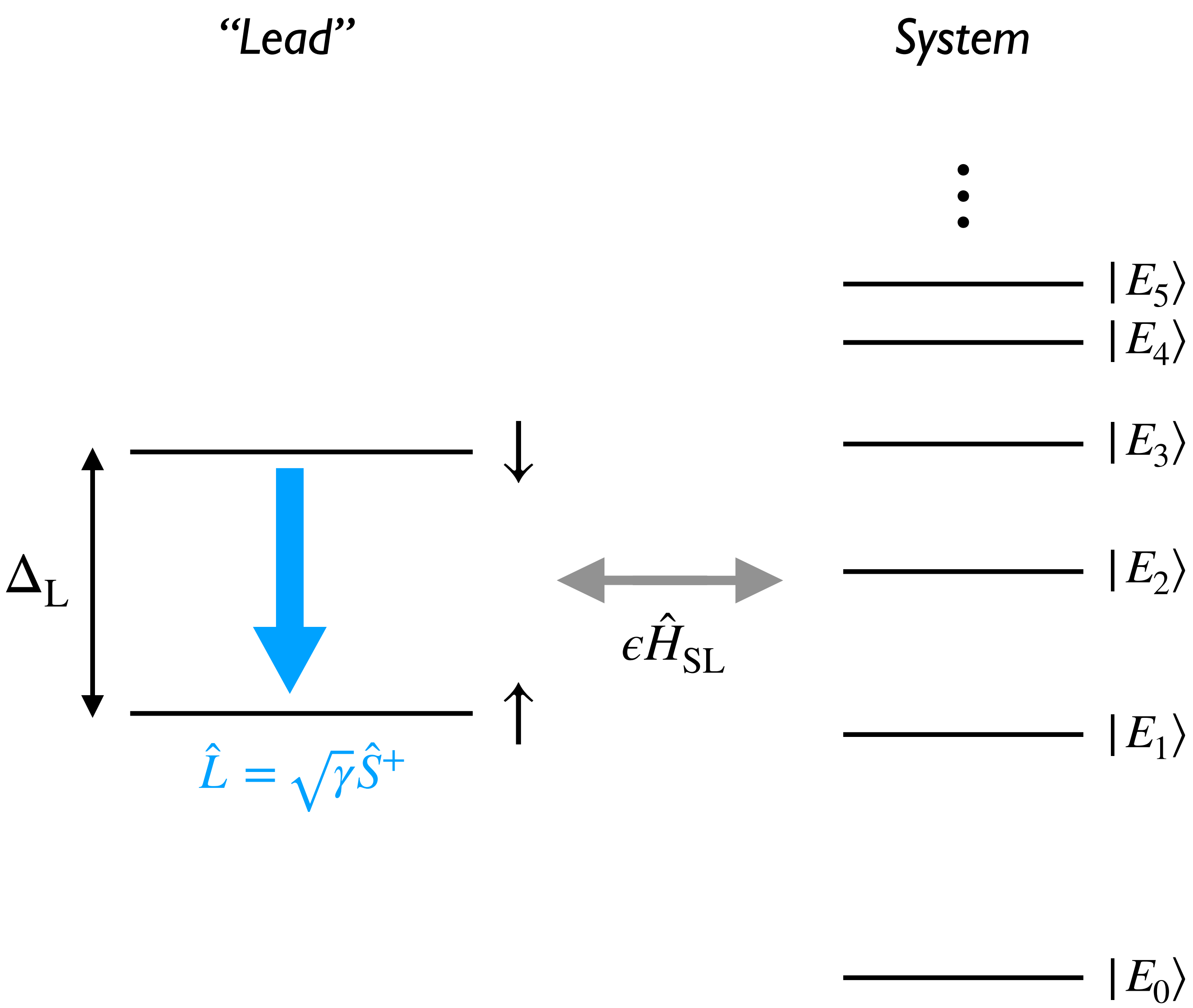

Steady state given by transitions between system eigenstates due to $\hat{H}_{\rm SL}$

Perturbed eigenstates of $\hat{H}_{\rm total}$:

$$|\uparrow \otimes E_i\rangle_p = |\uparrow \otimes E_i\rangle + \epsilon \sum_j c_{i,j} |\downarrow \otimes E_j\rangle + \epsilon \sum_{j \neq i} d_{i,j} |\uparrow \otimes E_j\rangle + O(\epsilon^2)$$

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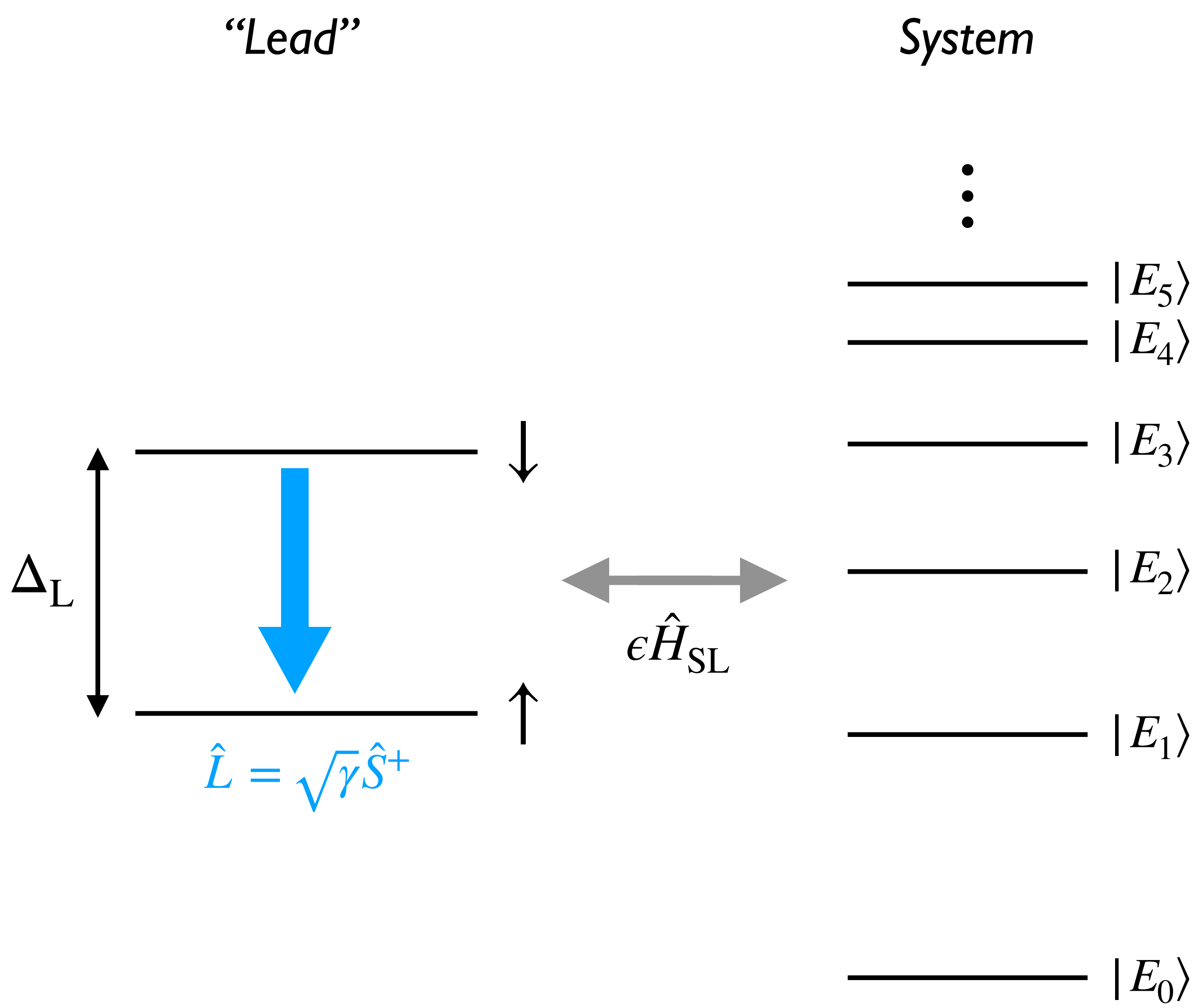

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$\Longrightarrow$ Transition rates

$$R_{i \to j} \approx \left| {}_p\langle \uparrow \otimes E_j | \hat{L} | \uparrow \otimes E_i \rangle_p \right|^2 \approx \gamma \epsilon^2 \frac{\left| \langle \downarrow \otimes E_j | \hat{H}_{SL} | \uparrow \otimes E_i \rangle \right|^2}{\left(E_i - E_j - \Delta_{\mathrm{L}}\right)^2}$$

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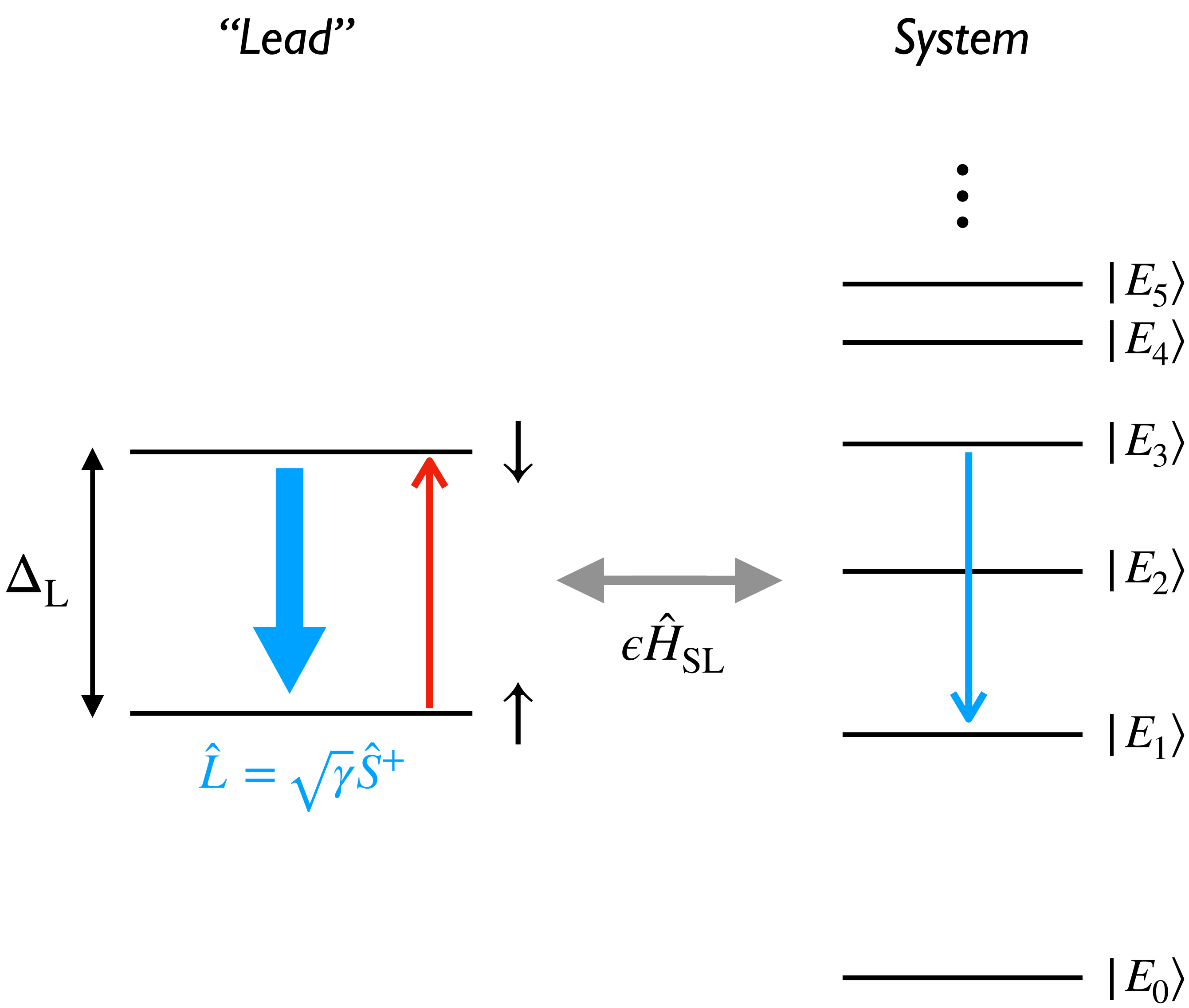

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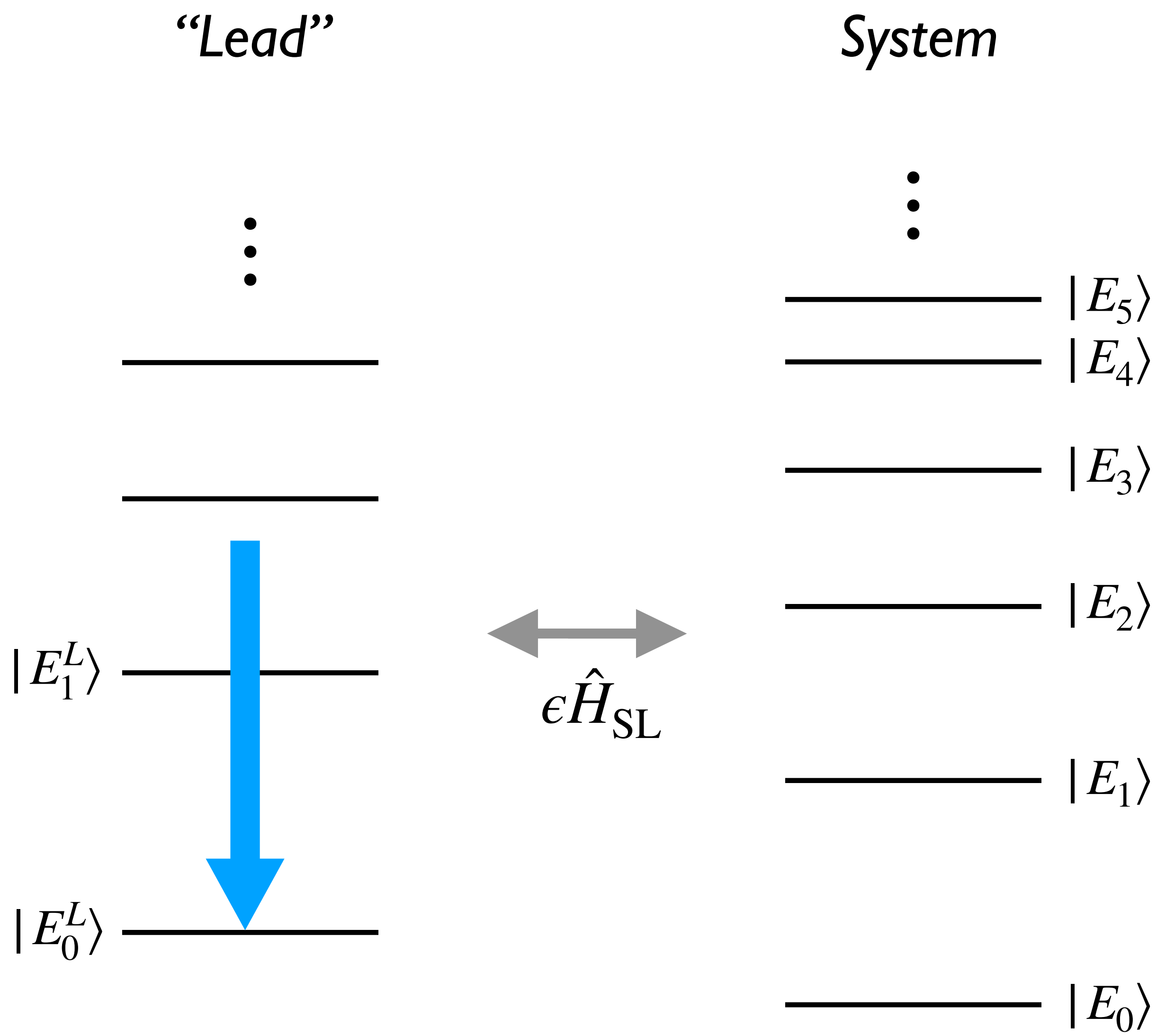
Resonant cooling for $E_i - E_j = \Delta_\mathrm{L}$

Heating by cooling — mechanism



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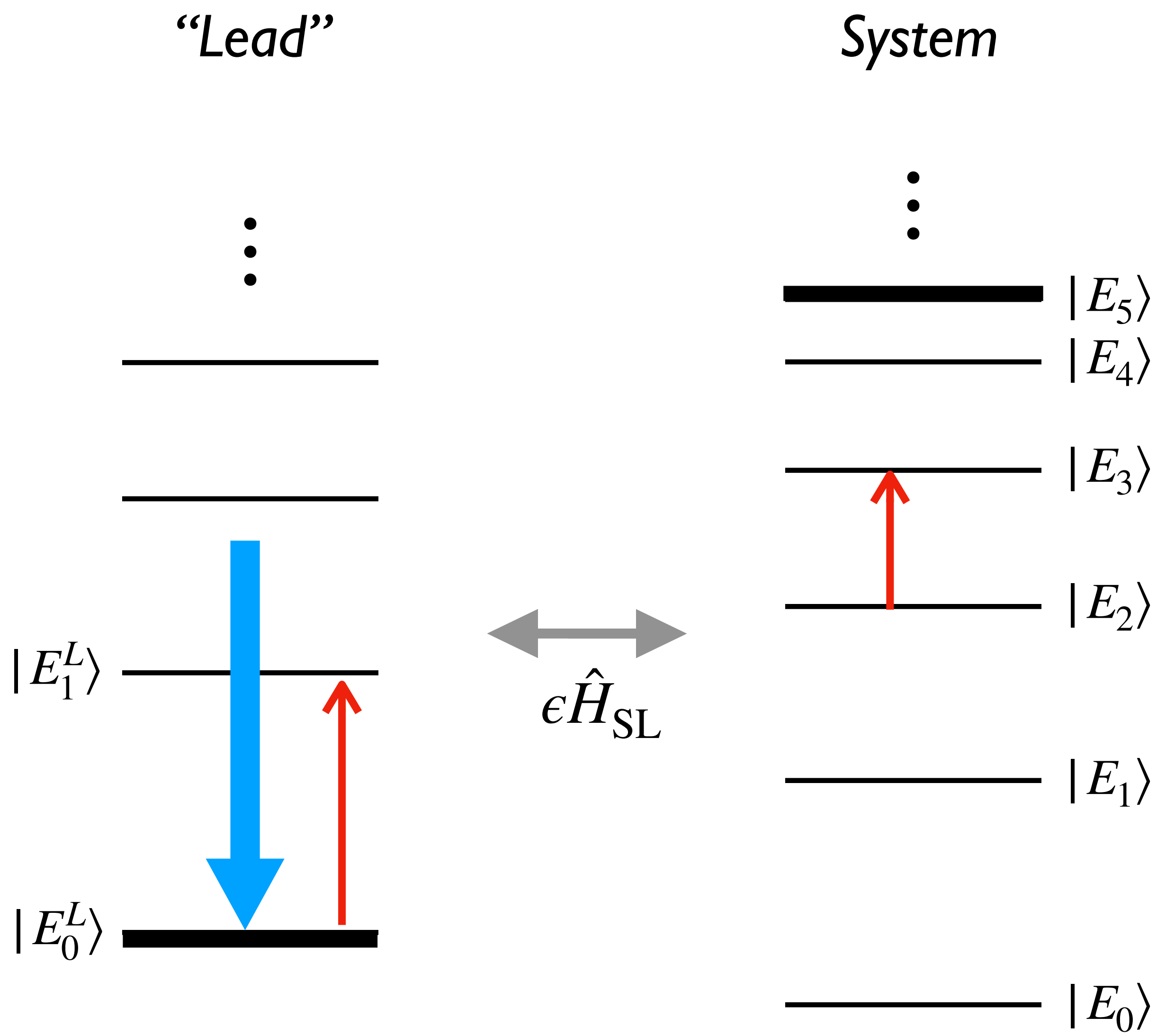

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Lead already in ground state

$\Longrightarrow$ Both move up in energy (before lead is cooled again)

$\Longrightarrow$ System heats to max energy

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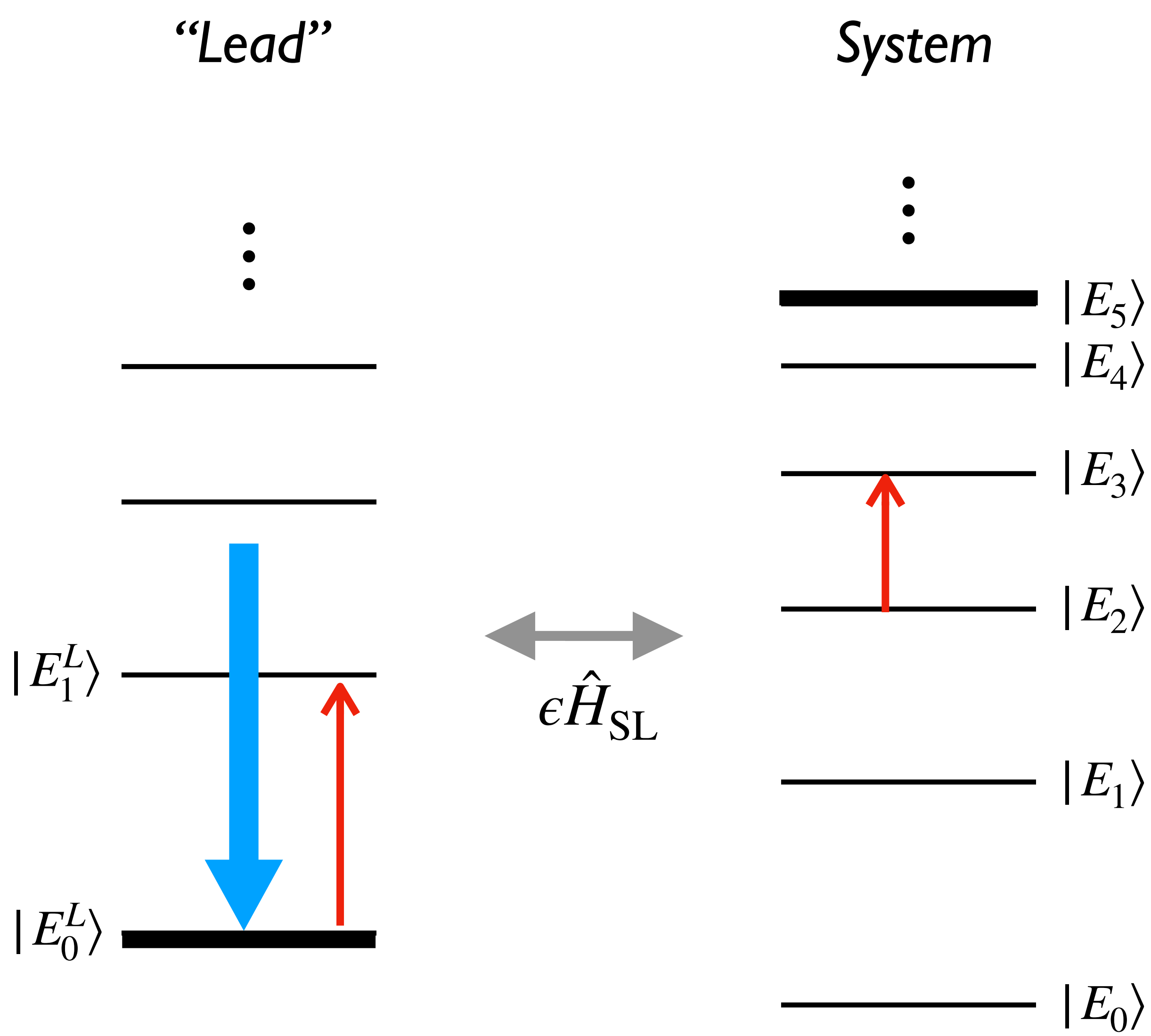

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Lead already in ground state

$\implies$ Both move up in energy (before lead is cooled again)

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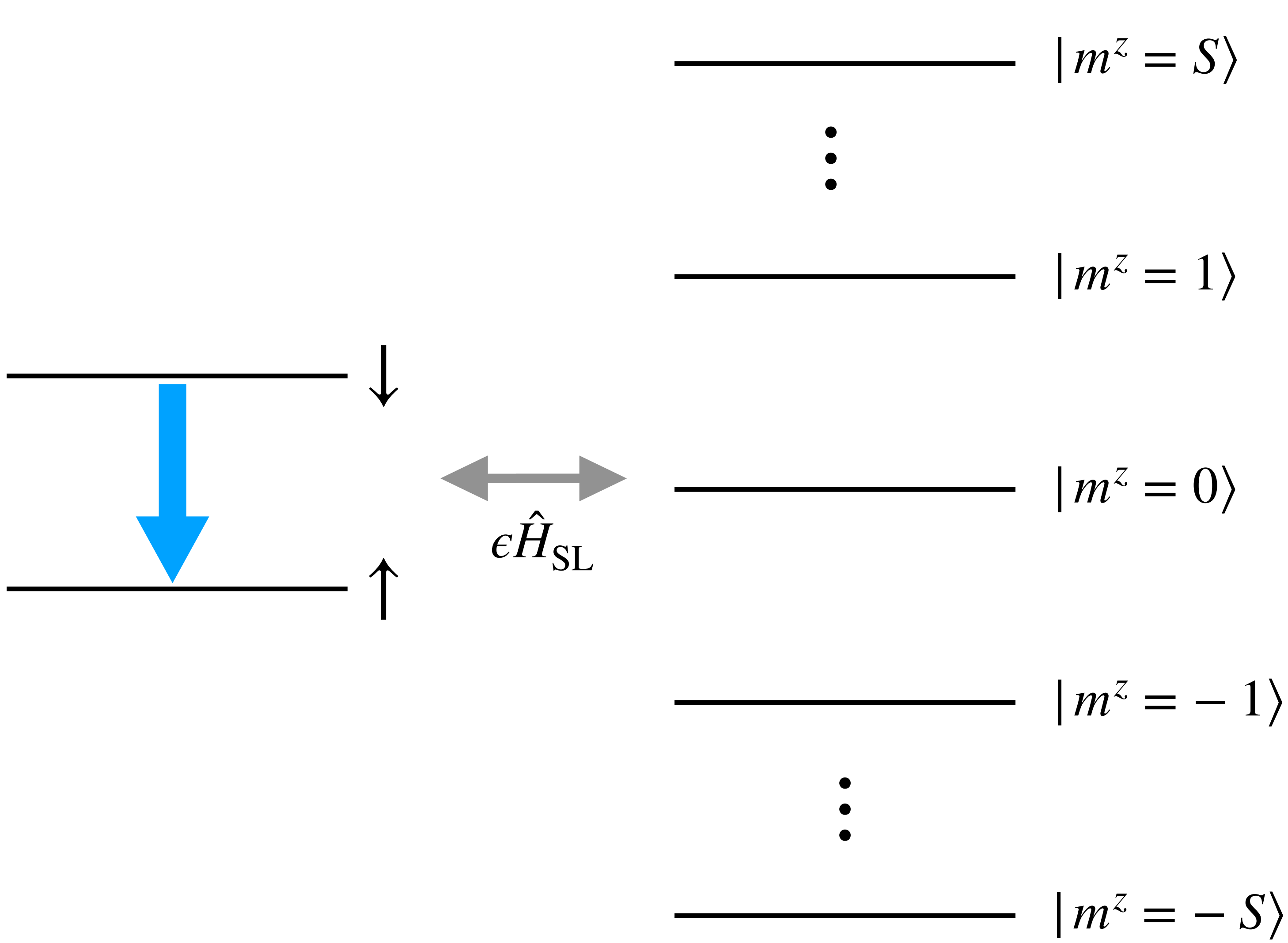
- No heating without cooling (i.e. no violation of 2nd law)
- Stop cooling $\implies$ temperature gradient remains due to total energy conservation
- Such coupling arises in simple, realizable systems!

Simplest case

"Lead" $\hat{H}_{\rm L} = -\Delta_{\rm L}\hat{\sigma}^z$

System $\hat{H}_{\rm S} = +\Delta_{\rm S}\hat{S}^z$

$\hat{H}_{\rm SL} = \hat{\sigma}^+\hat{S}^- + \hat{\sigma}^-\hat{S}^+$



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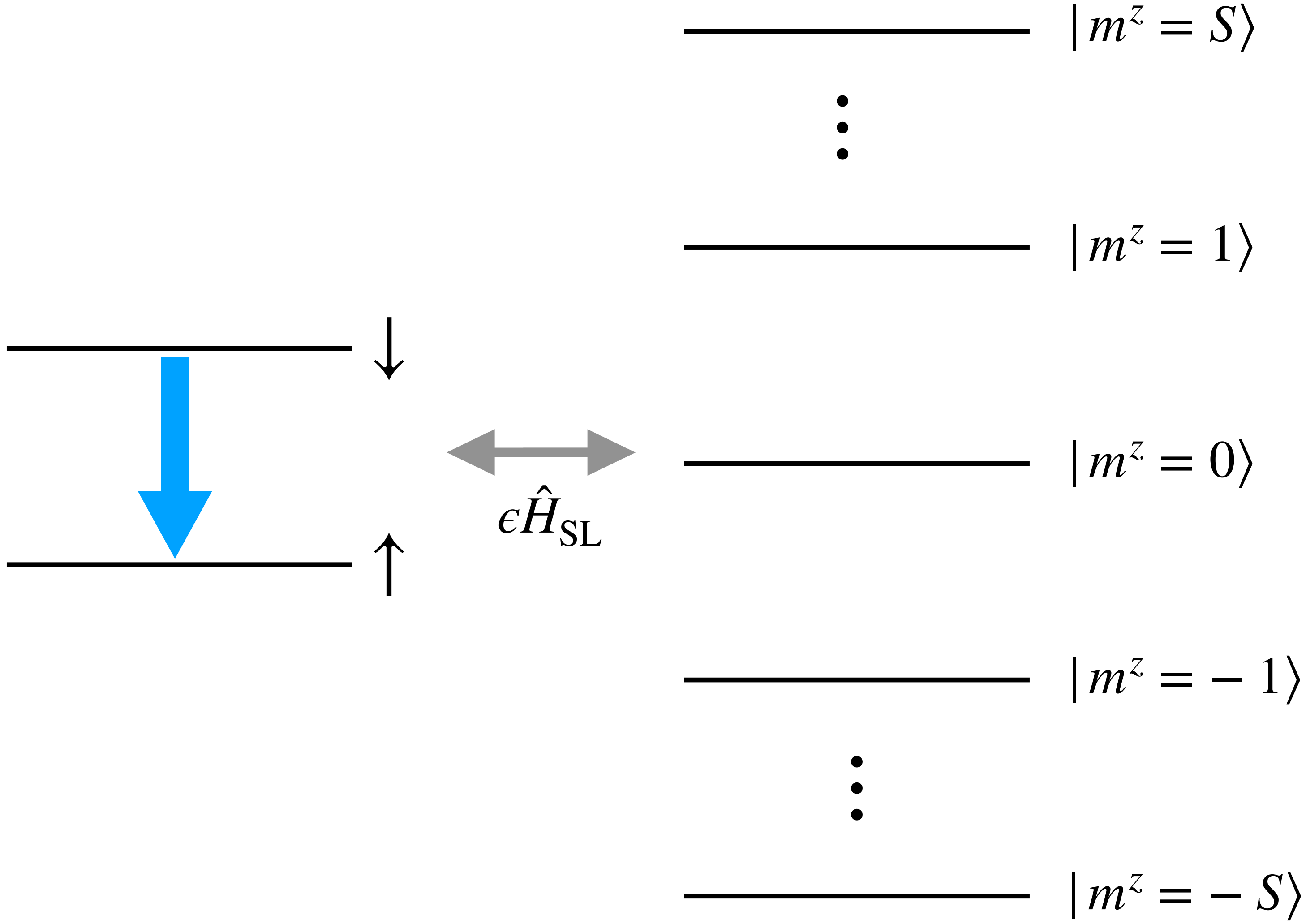

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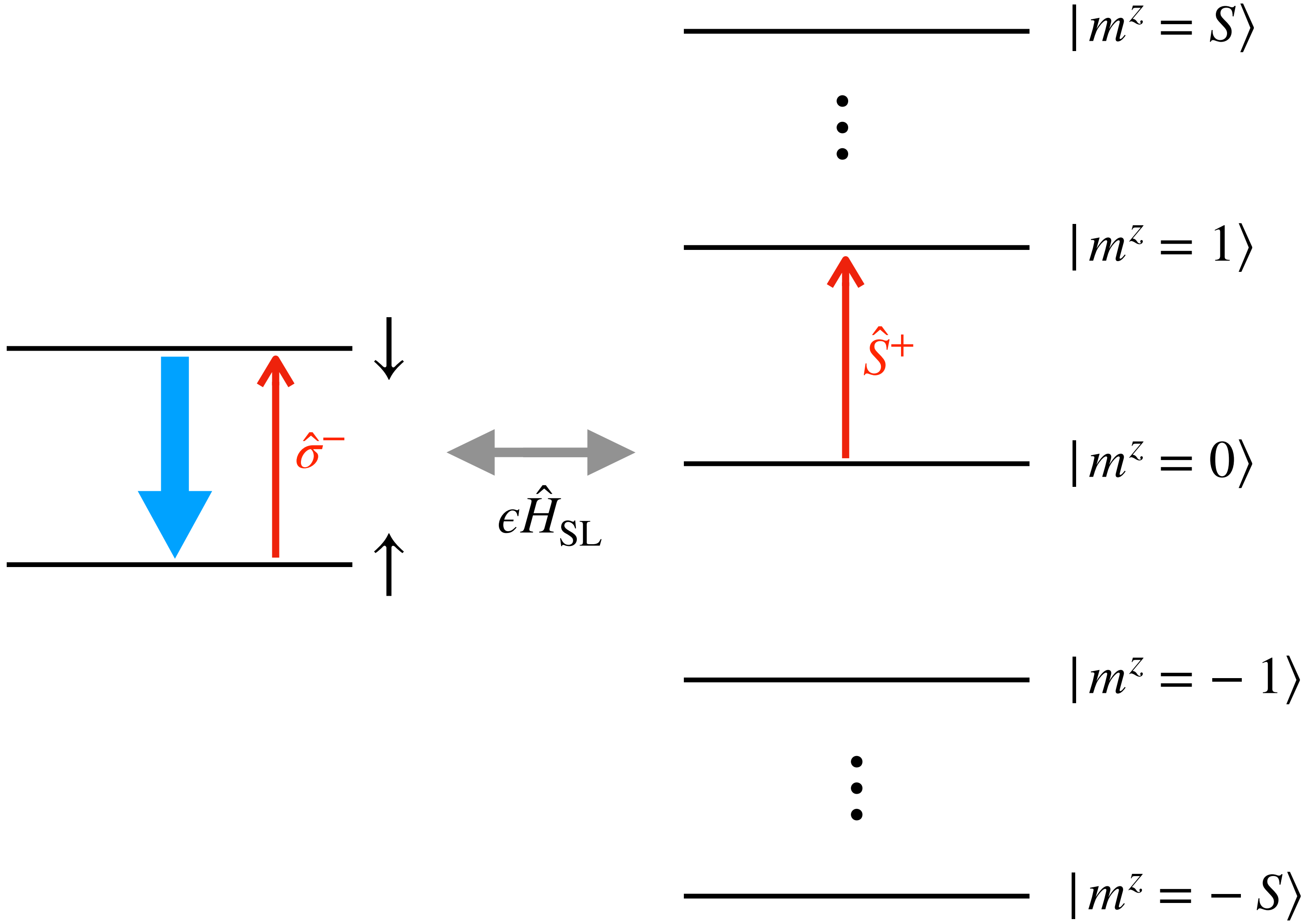

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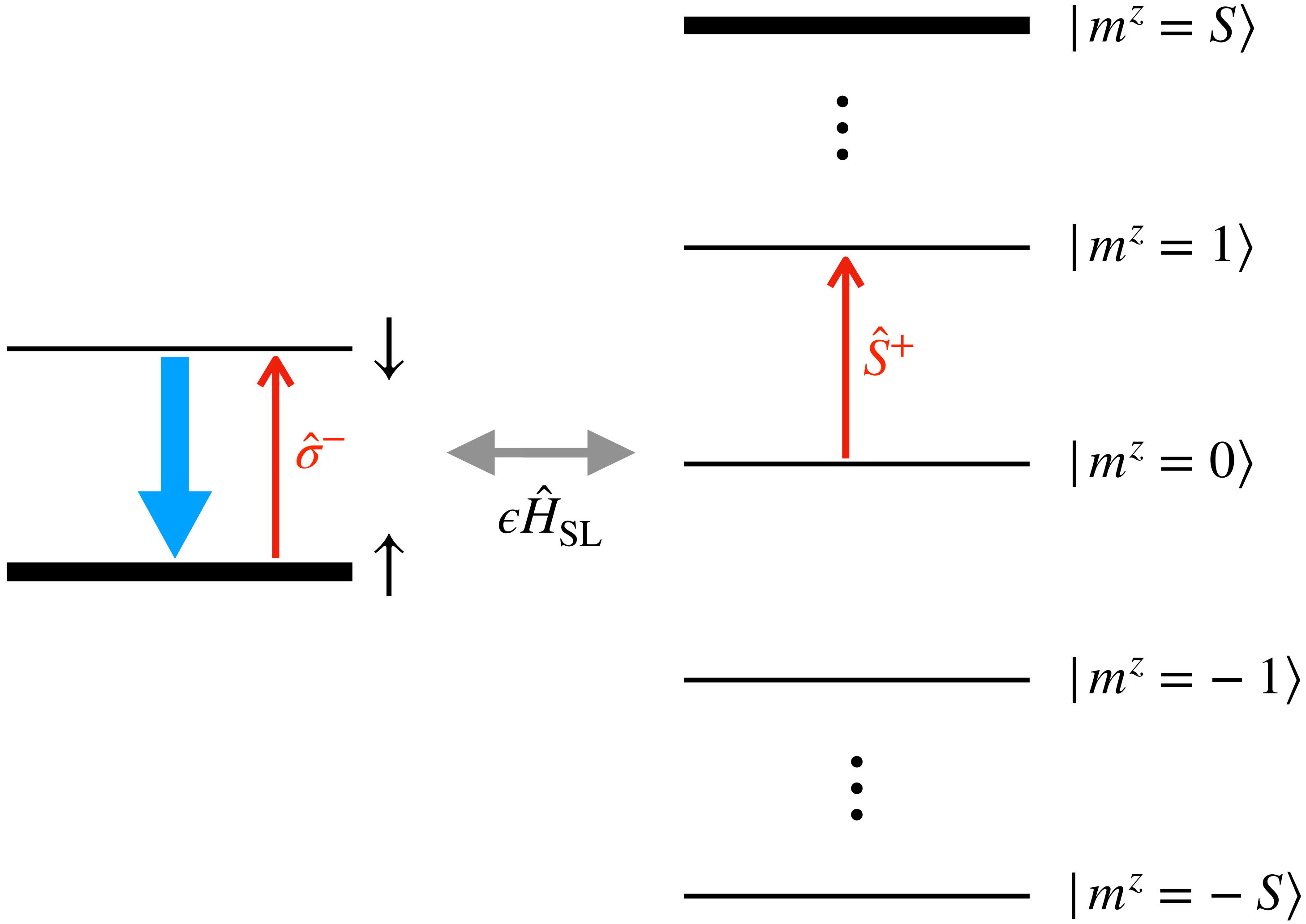

$\Longrightarrow$ System heats to max energy!

Also for nonuniform spacing

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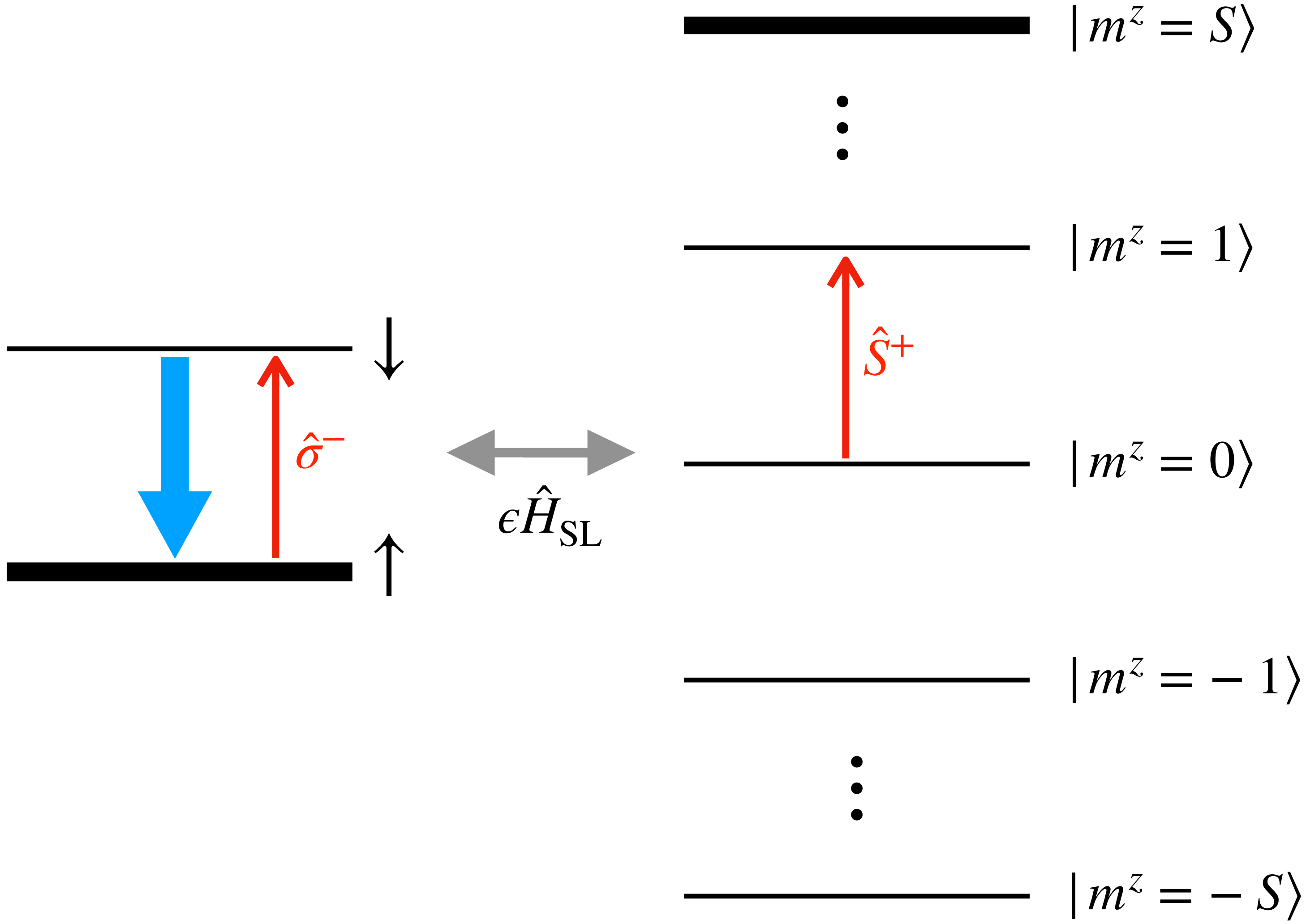

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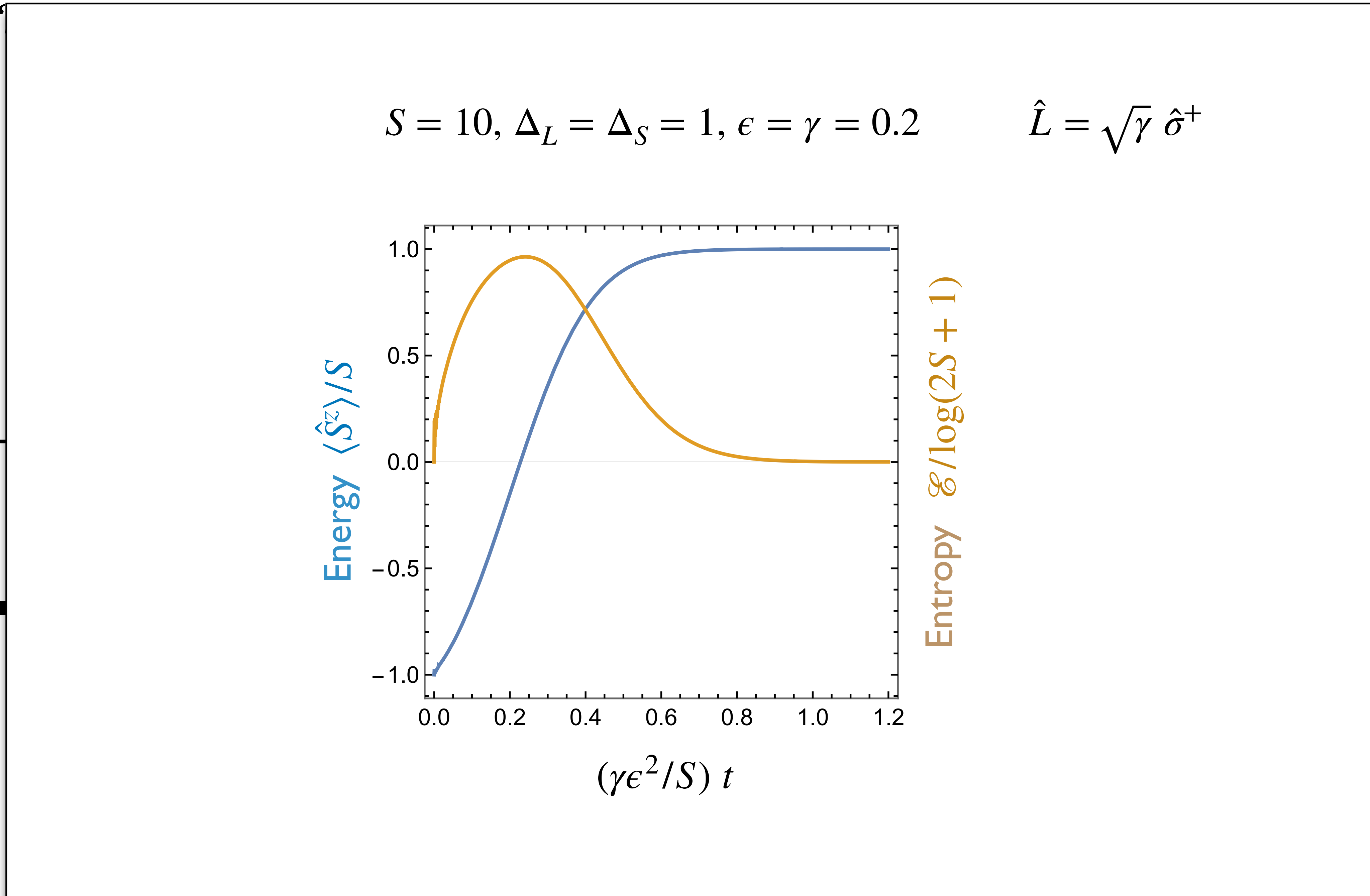
Also for nonuniform spacing

$\boxed{\text{(1) } E_L \text{ decreases w/ } \sigma^z, \text{ (2) } E_S \text{ increases w/ } S^z, \text{ (3) Coupling conserves } \sigma^z + S^z}$

Simplest case

“

$\hat{H}_{\mathrm{L}}$



ax energy!

spacing

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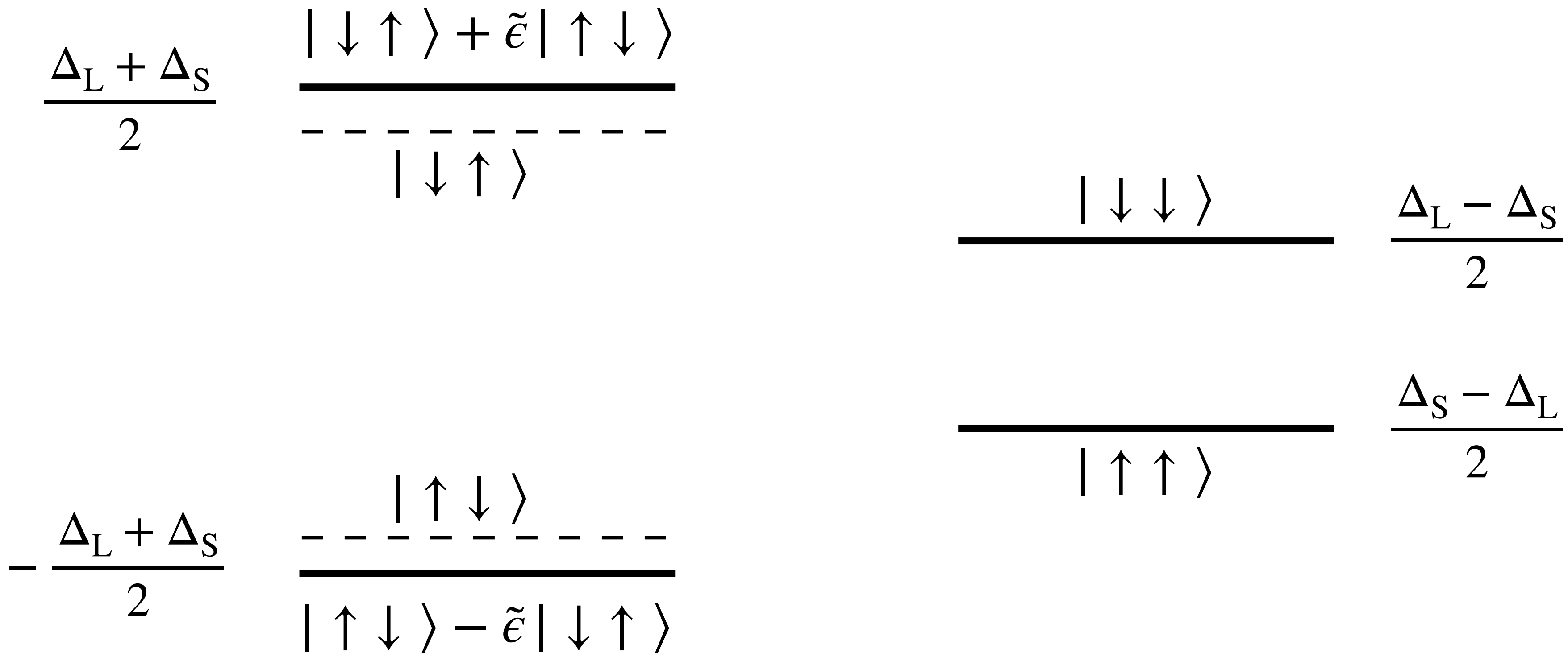

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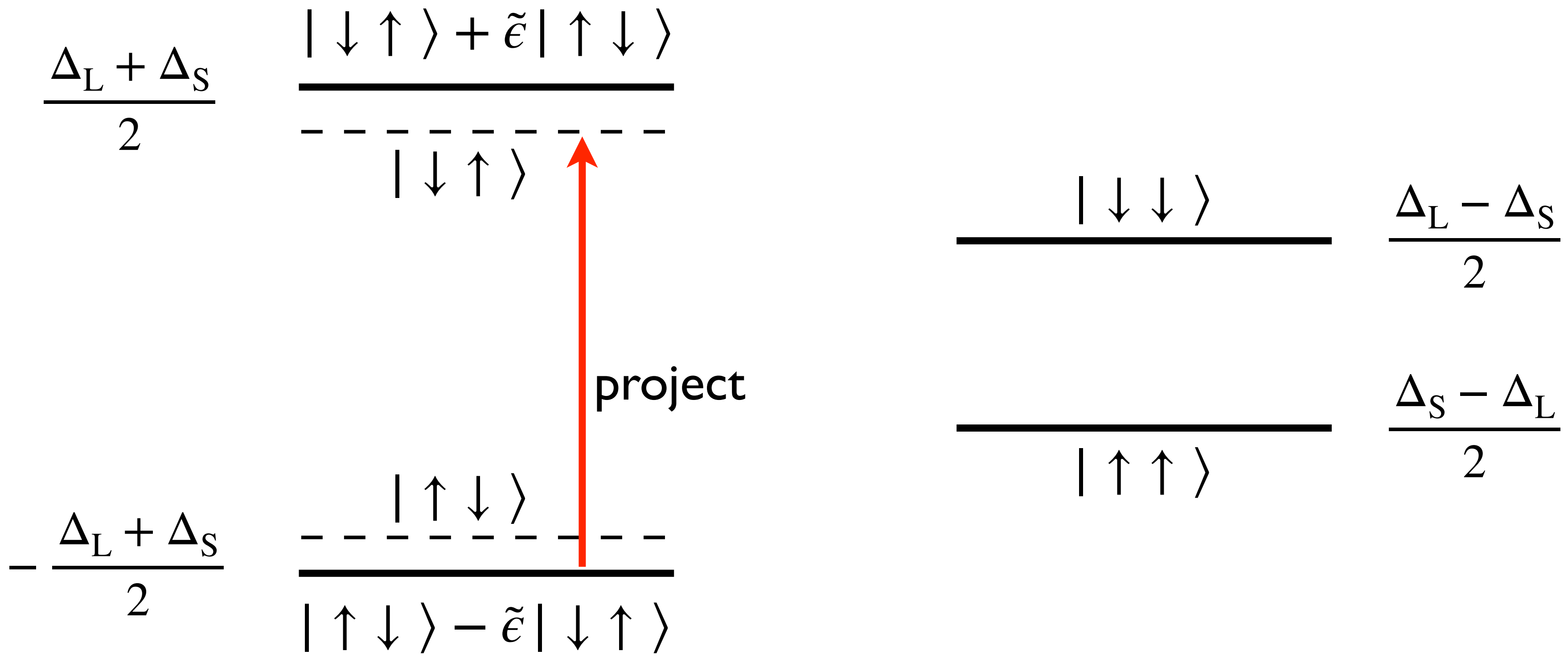

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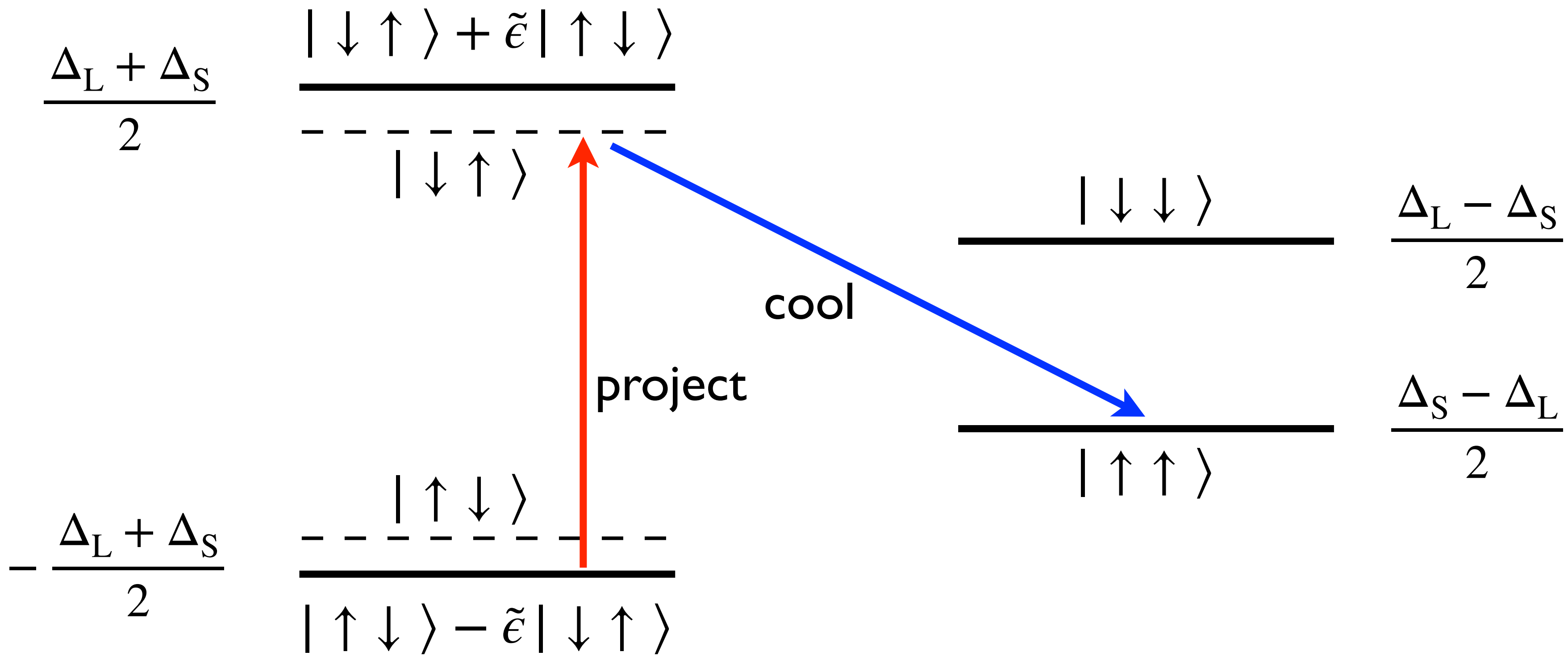

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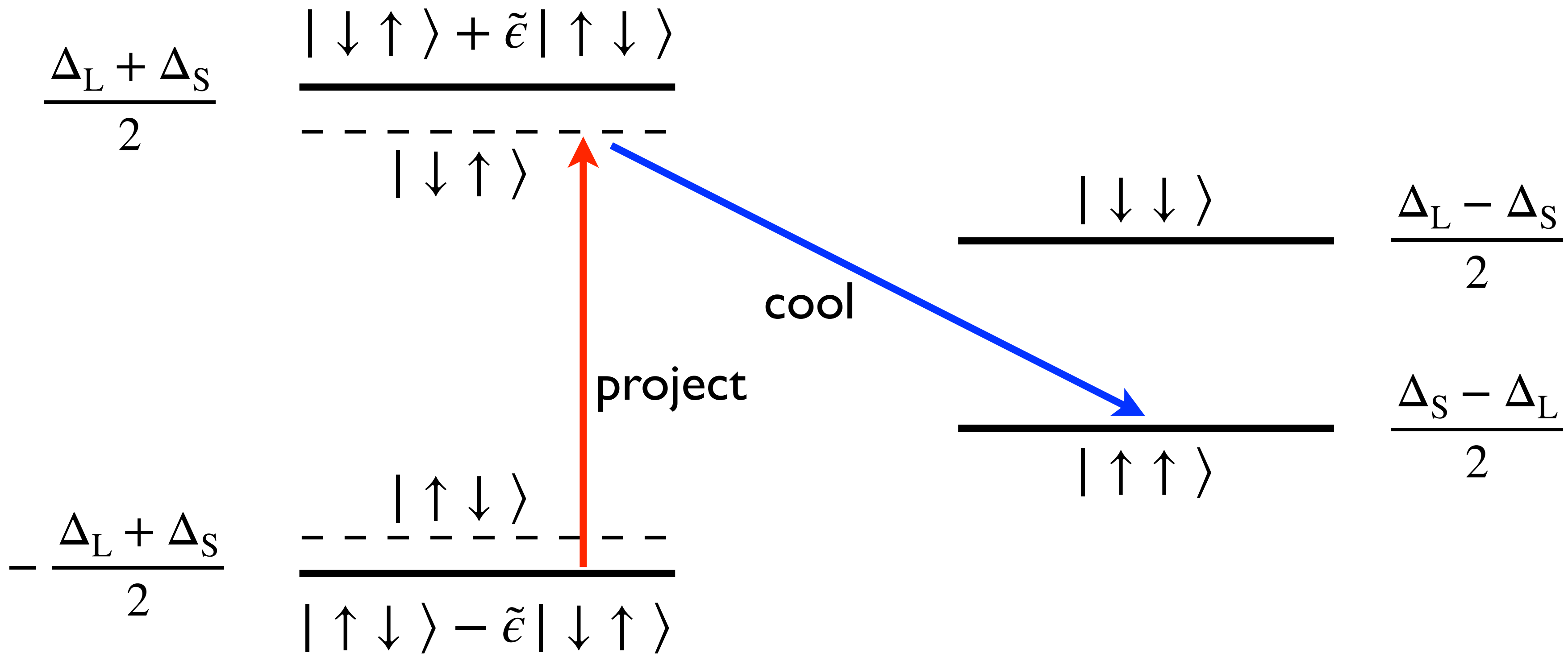

Energy comes from the measurement device

Finite temperature

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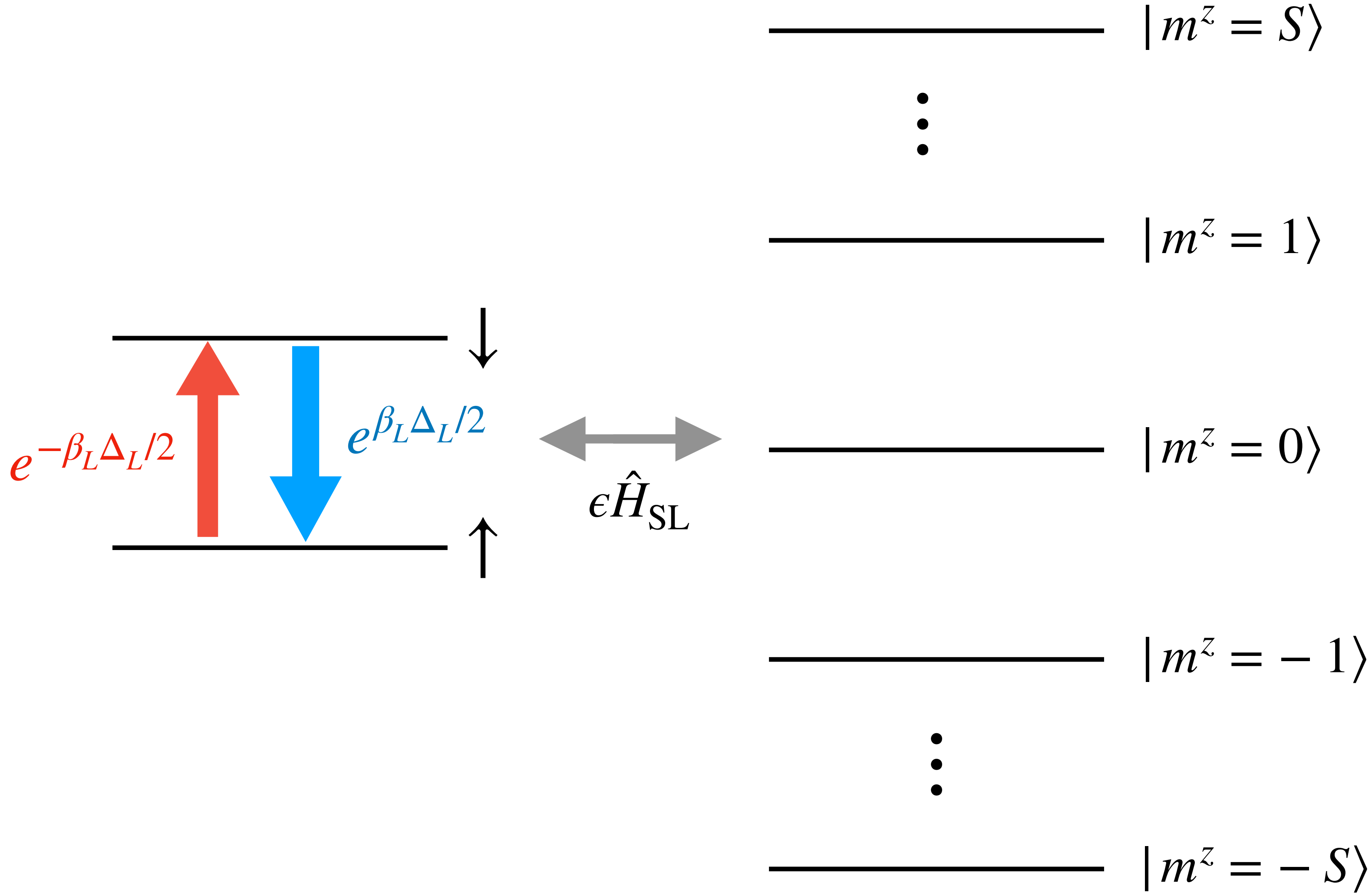

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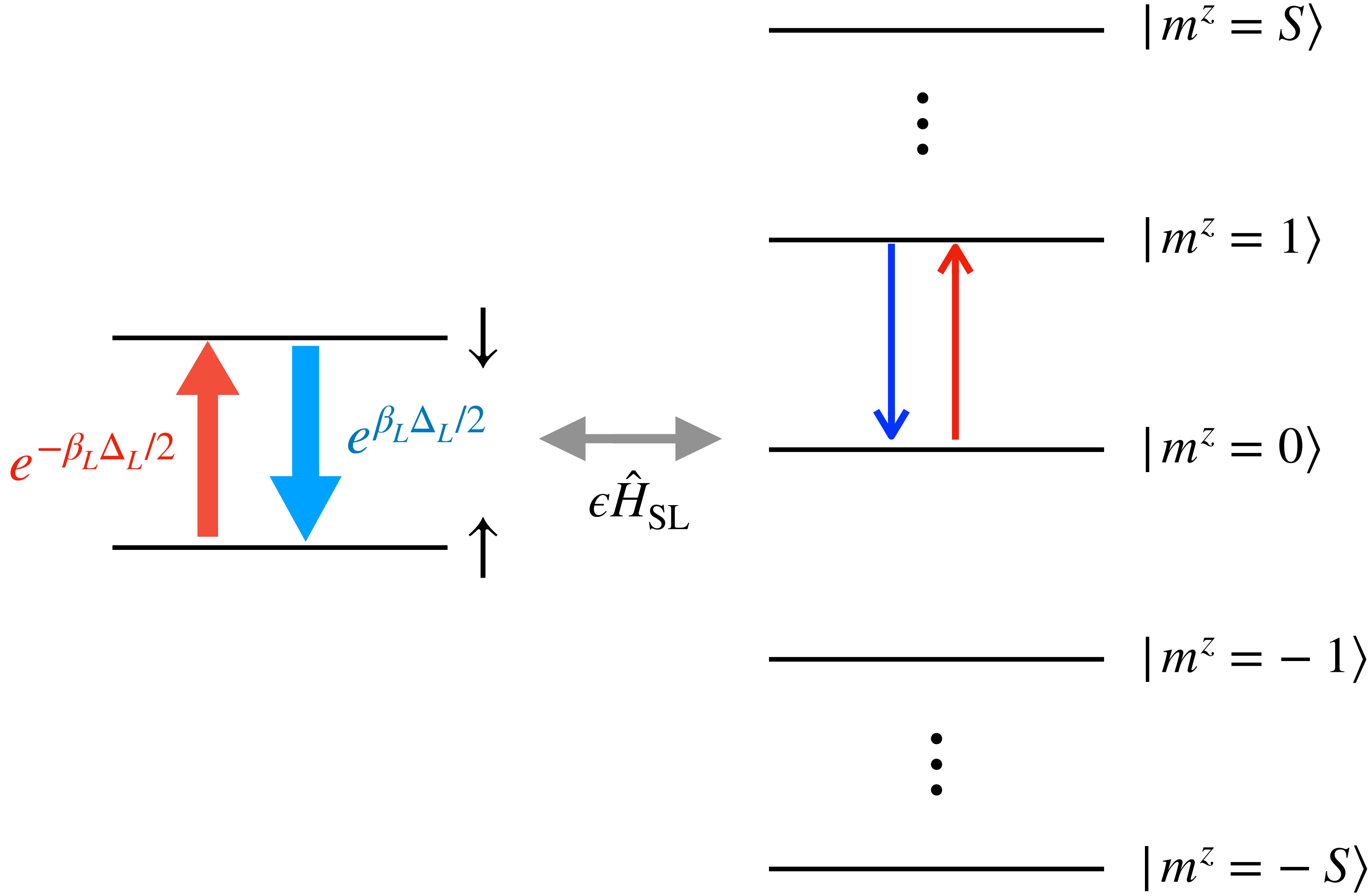

$R_{m^z+1\to m^z}$	$R_{m^z\to m^z+1}$
$\dfrac{e^{-\beta_L\Delta_L/2}}{(\Delta_L+\Delta_S)^2}$	$\dfrac{e^{\beta_L\Delta_L/2}}{(\Delta_L+\Delta_S)^2}$

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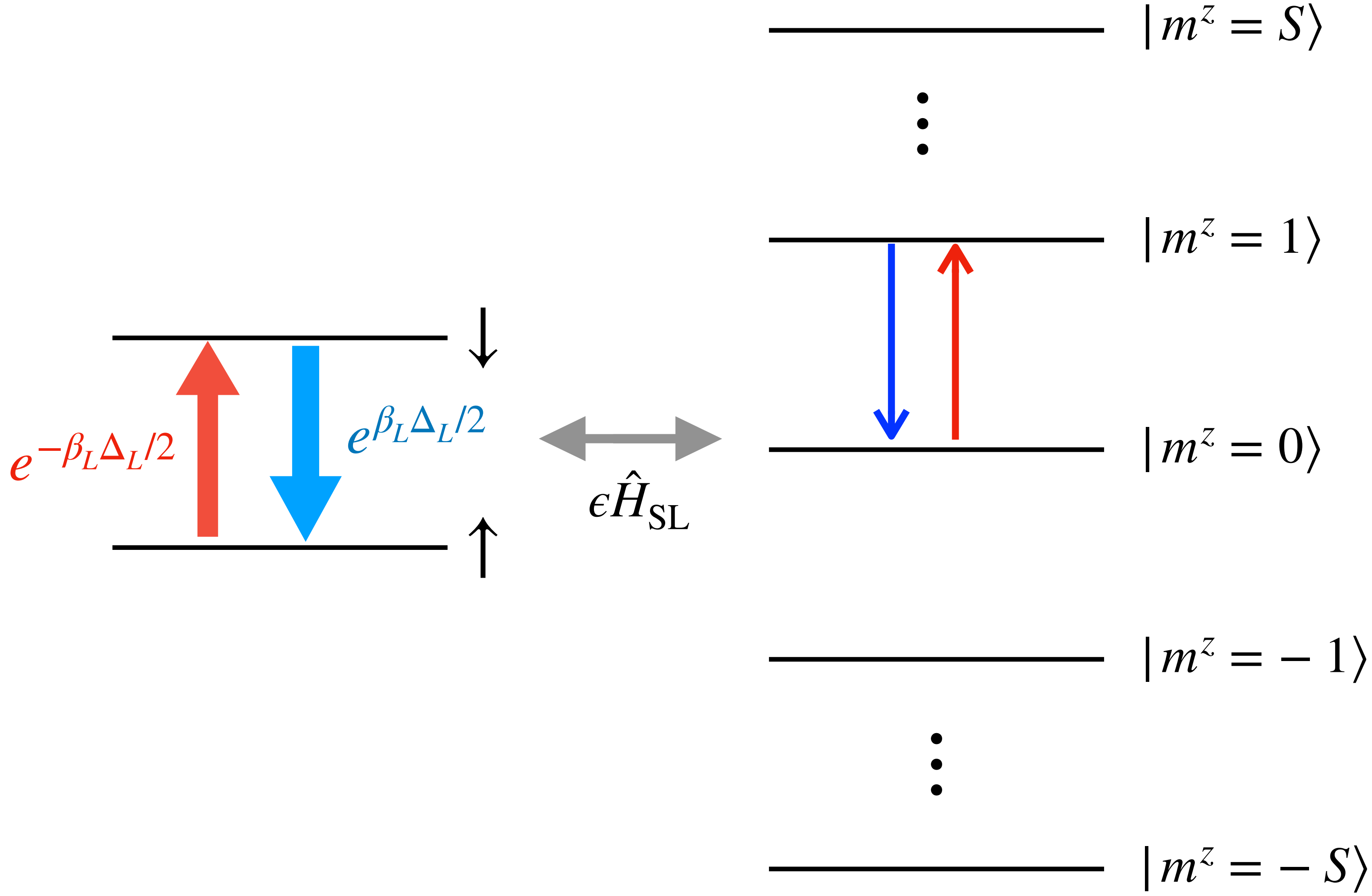

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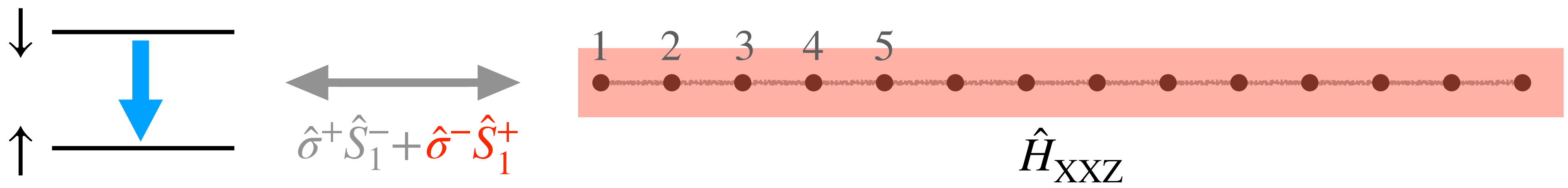
$\dfrac{e^{-\beta_L \Delta_L/2}}{(\Delta_L + \Delta_S)^2}$	$\dfrac{e^{\beta_L \Delta_L/2}}{(\Delta_L + \Delta_S)^2}$

$$\implies \beta_S = -\frac{\Delta_L}{\Delta_S} \beta_L$$

Extended system

Same argument for generic system that preserves total S^z (e.g. XXZ chain)



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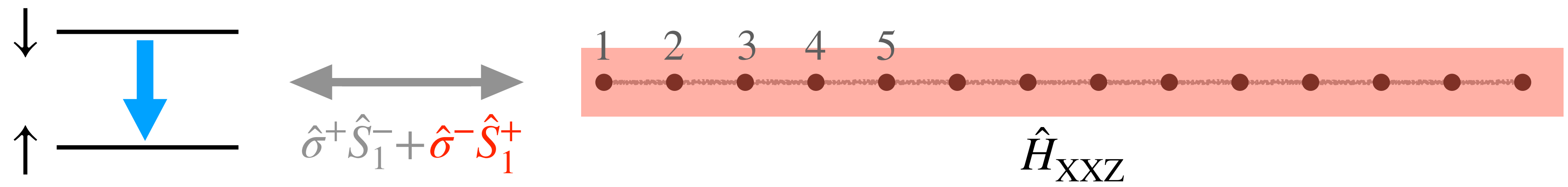

Not localized — excitation at site 1 is carried away into the bulk

$\Longrightarrow$ System heats to $|\uparrow\uparrow\ldots\uparrow\rangle$ — which can be anywhere in the spectrum

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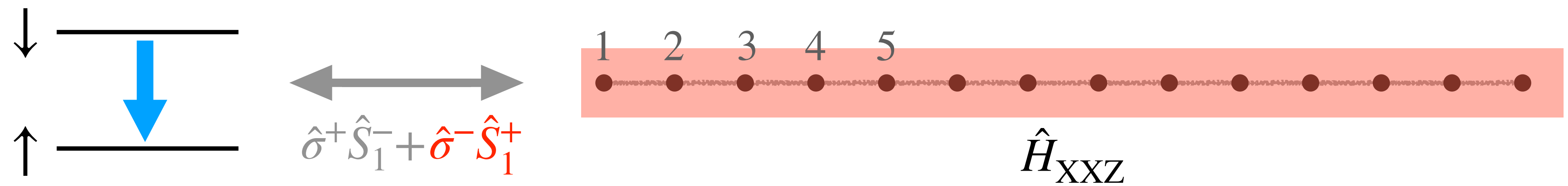

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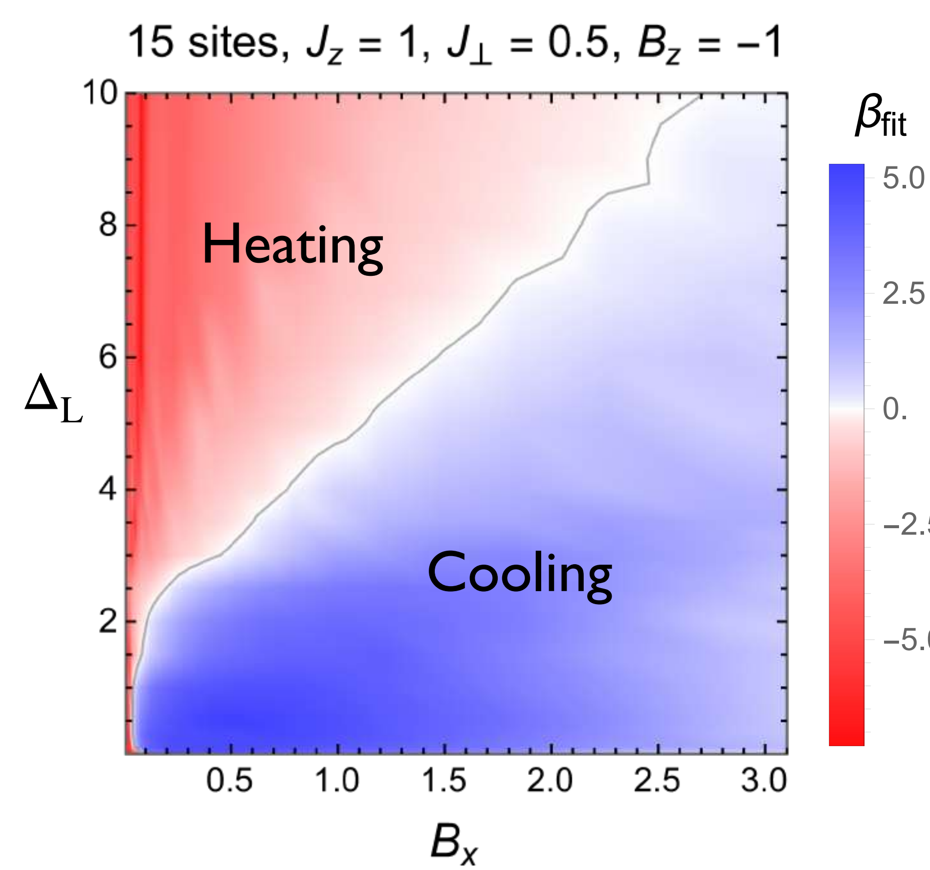
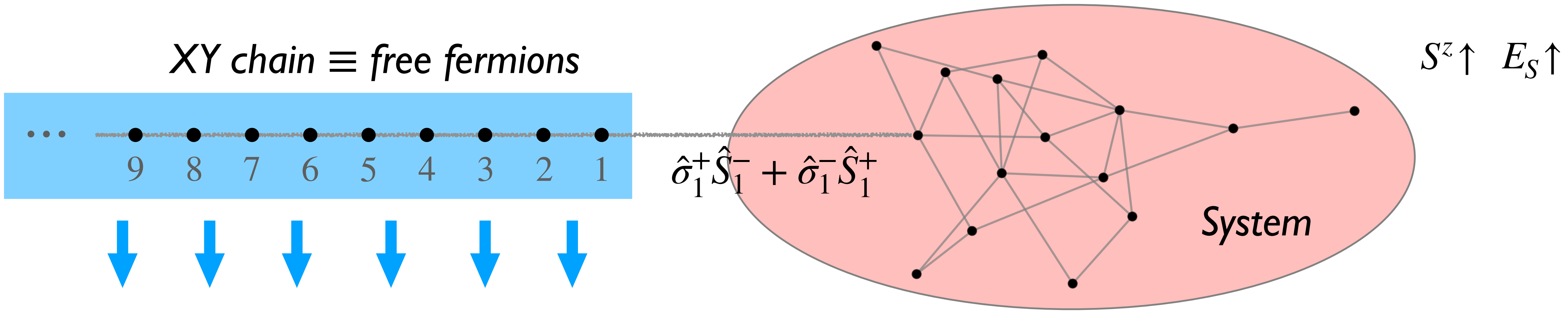
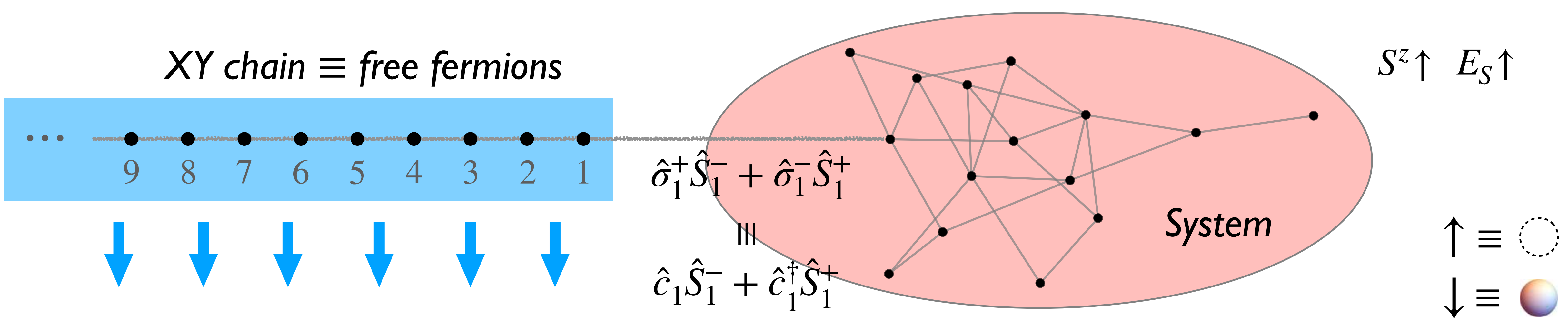
$$\hat{H}_{\mathrm{XXZ}} = \sum_i \left[J_z \hat{S}_i^z \hat{S}_{i+1}^z + J_\perp\left(\hat{S}_i^x \hat{S}_{i+1}^x + \hat{S}_i^y \hat{S}_{i+1}^y\right) - B^z \hat{S}_i^z \underbrace{- \hat{B}^x \hat{S}_i^x}_{\text{symmetry breaking}}\right]$$



Infinite lead + generic system




XY chain ≡ free fermions
9 8 7 6 5 4 3 2 1
$\hat{\sigma}_1^+\hat{S}_1^- + \hat{\sigma}_1^-\hat{S}_1^+$
$\equiv$
$\hat{c}_1\hat{S}_1^- + \hat{c}_1^\dagger\hat{S}_1^+$
System
$S^z\uparrow \quad E_S\uparrow$
$\uparrow \equiv$
$\downarrow \equiv$

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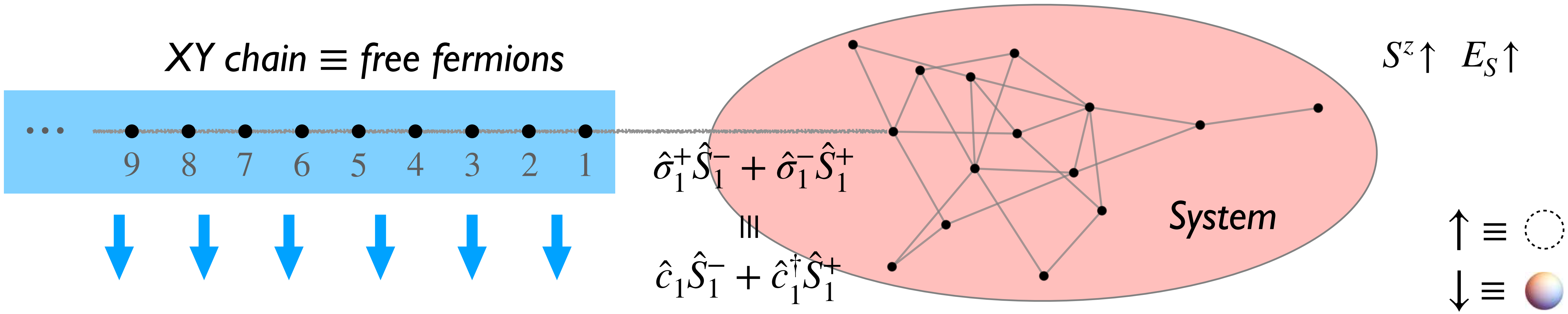
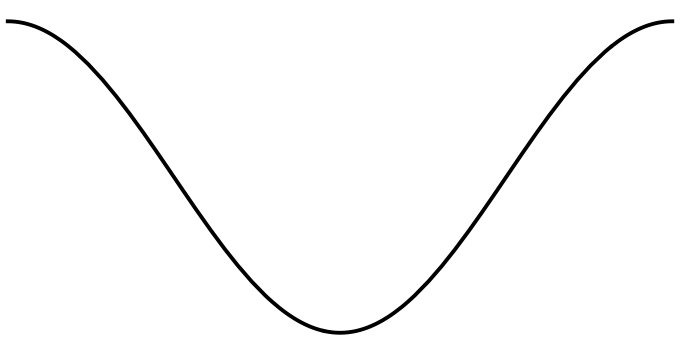


Lead spectrum for single-particle excitations: $\varepsilon_{\mathrm{L}}(k) = -2J\cos k$



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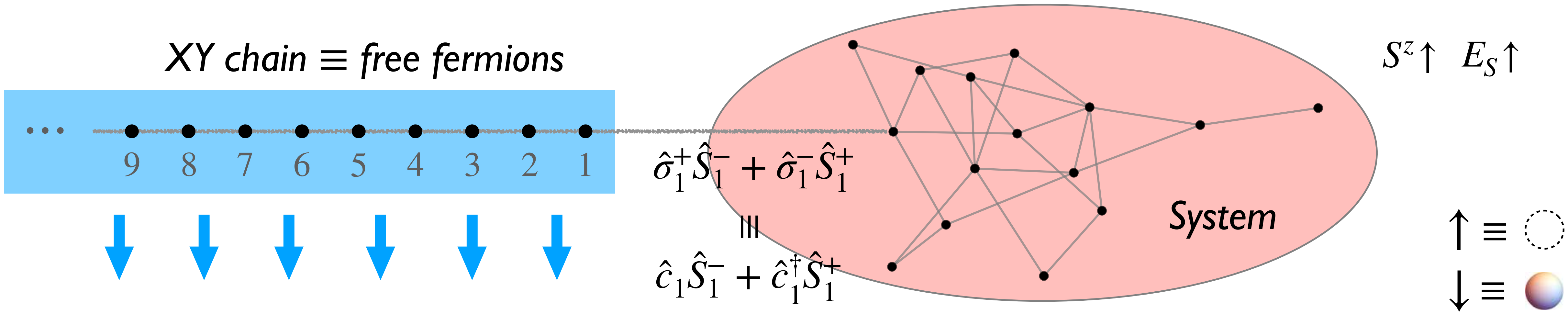

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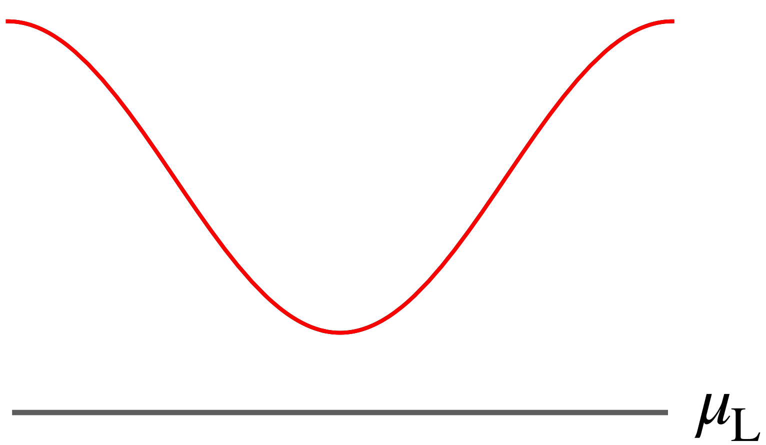
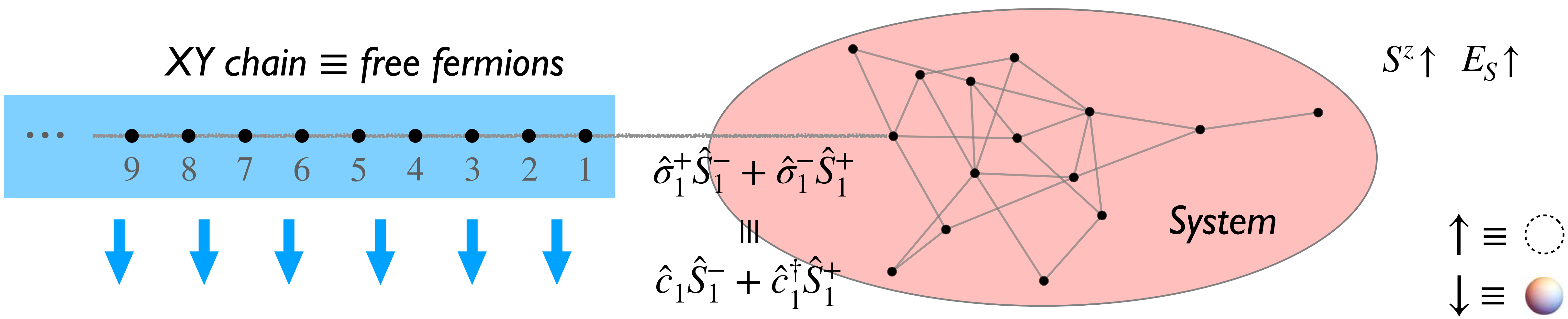


Only particle excitations: $\hat{c}_1\hat{S}_1^- + \hat{c}_1^\dagger\hat{S}_1^+$

$\Longrightarrow$ Heats to maximum S^z



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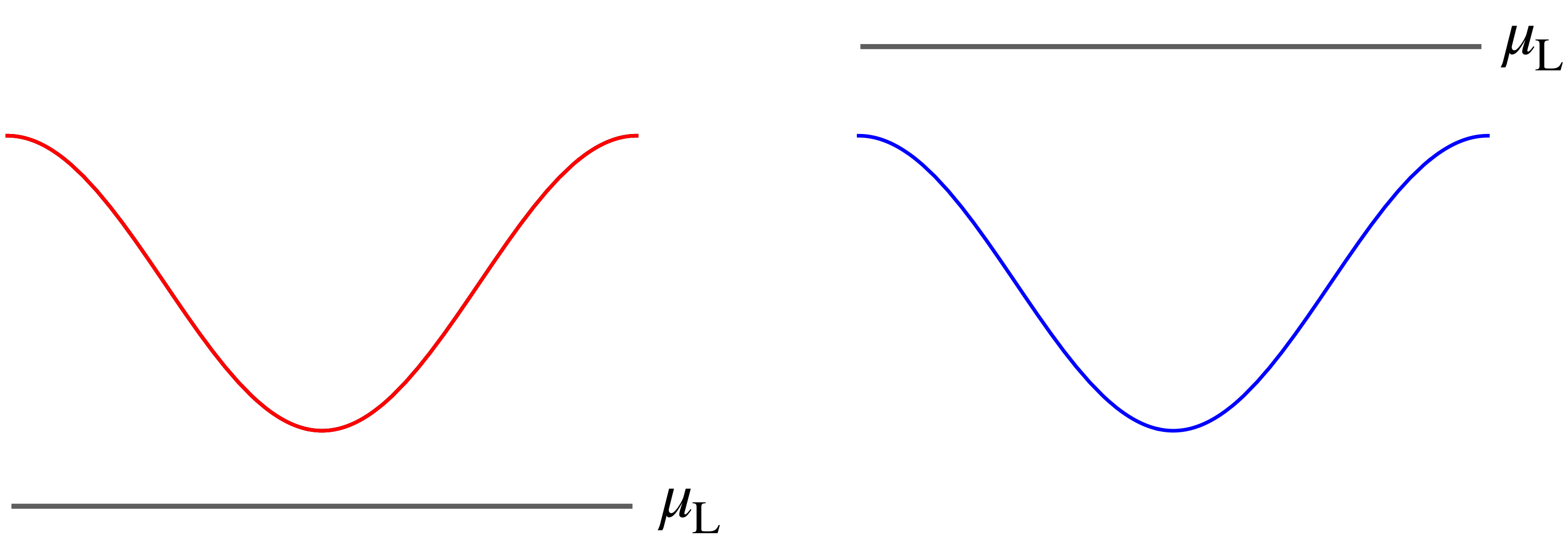

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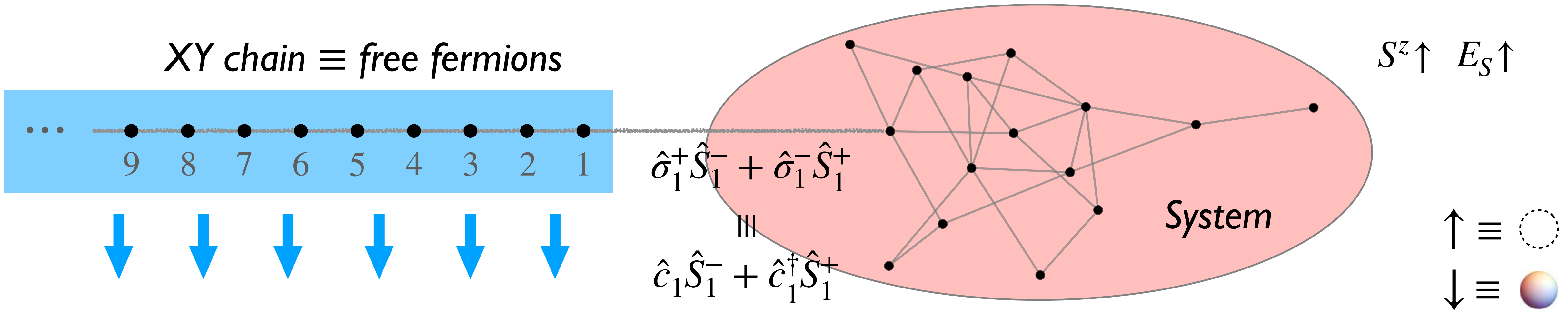
Only hole excitations: $\hat{c}_1 \hat{S}_1^- + \hat{c}_1^\dagger \hat{S}_1^+$
$\Longrightarrow$ Cools to minimum S^z

Infinite lead + generic system



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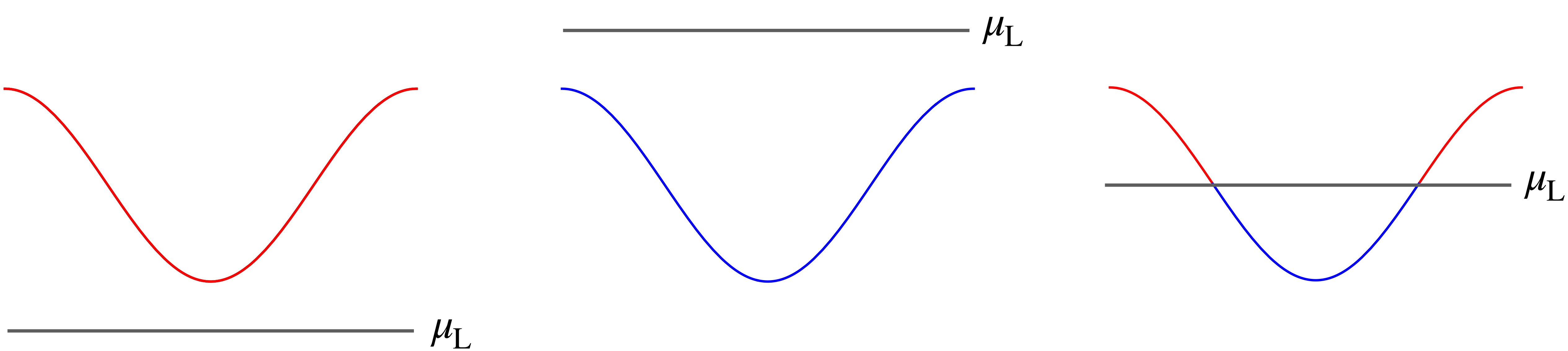

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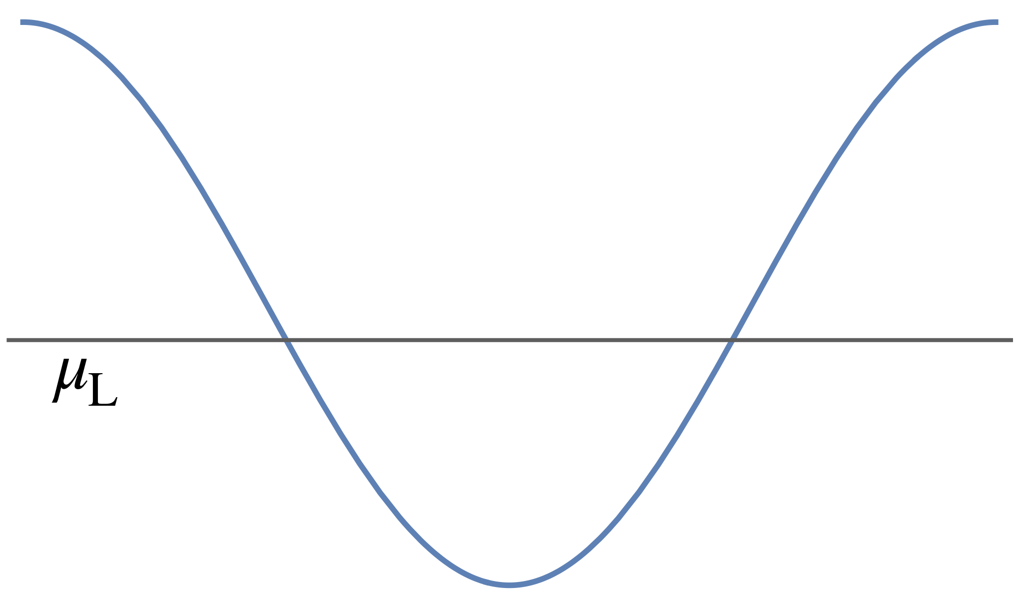
Both: $\hat{c}_1\hat{S}_1^- + \hat{c}_1^\dagger\hat{S}_1^+$
$\Longrightarrow$ Intermediate state

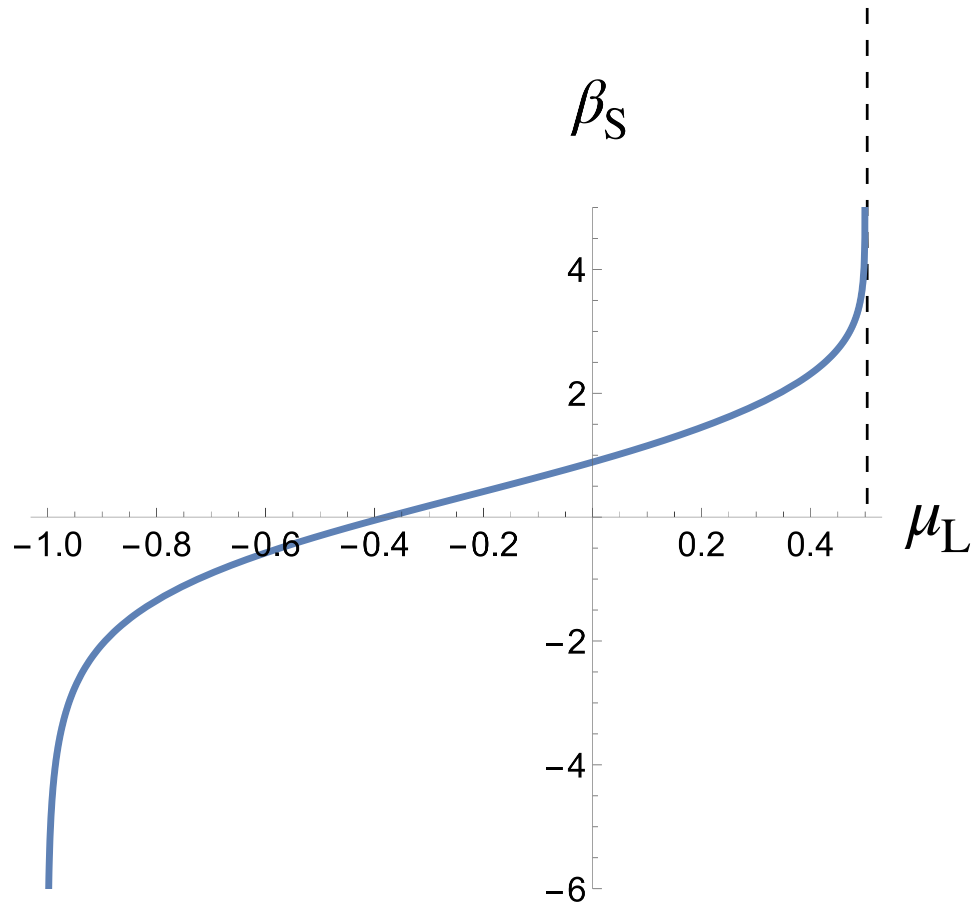
Free-fermion lead + N-level system

$$\hat{H}_S = \Delta_S \hat{S}^z$$

$$R_{m^z \to m^z+1} \propto \gamma \epsilon^2 \int_{\varepsilon_L(k) > \mu_L} \frac{dk \sin^2 k}{(\Delta_S + |\varepsilon_L(k) - \mu_L|)^2} \qquad R_{m^z+1 \to m^z} \propto \gamma \epsilon^2 \int_{\varepsilon_L(k) < \mu_L} \frac{dk \sin^2 k}{(\Delta_S - |\varepsilon_L(k) - \mu_L|)^2}$$

$$\varepsilon_L(k) = -\cos k$$





$\Delta_S = 1.5$

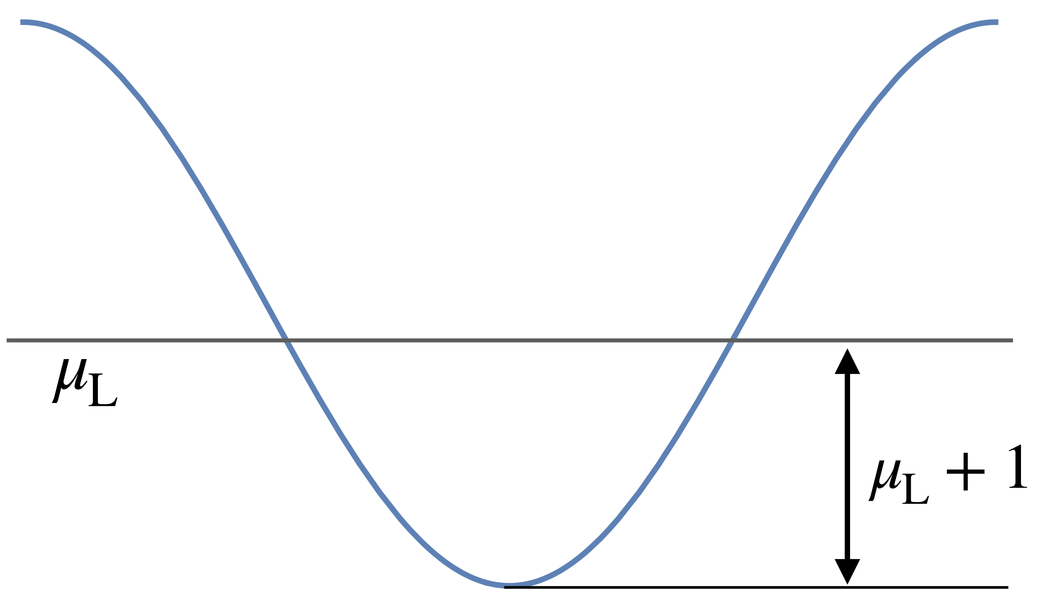
Analytic solution using detailed balance

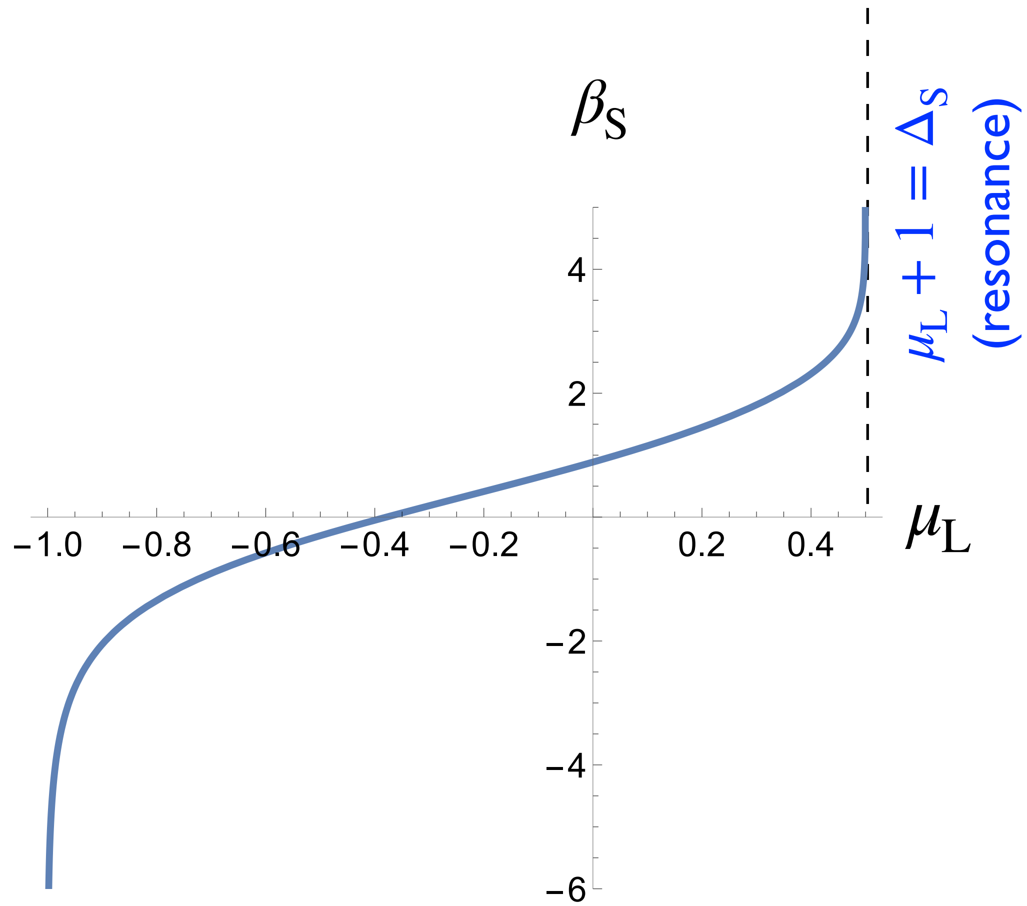
Free-fermion lead + N-level system

$\hat{H}_\mathrm{S} = \Delta_\mathrm{S}\hat{S}^z$

$$R_{m^z\to m^z+1} \propto \gamma\epsilon^2 \int_{\varepsilon_L(k)>\mu_L} \frac{dk\,\sin^2 k}{(\Delta_S + |\varepsilon_L(k)-\mu_L|)^2} \qquad R_{m^z+1\to m^z} \propto \gamma\epsilon^2 \int_{\varepsilon_L(k)<\mu_L} \frac{dk\,\sin^2 k}{(\Delta_S - |\varepsilon_L(k)-\mu_L|)^2}$$

$\varepsilon_\mathrm{L}(k) = -\cos k$





$\Delta_\mathrm{S} = 1.5$

Analytic solution using detailed balance

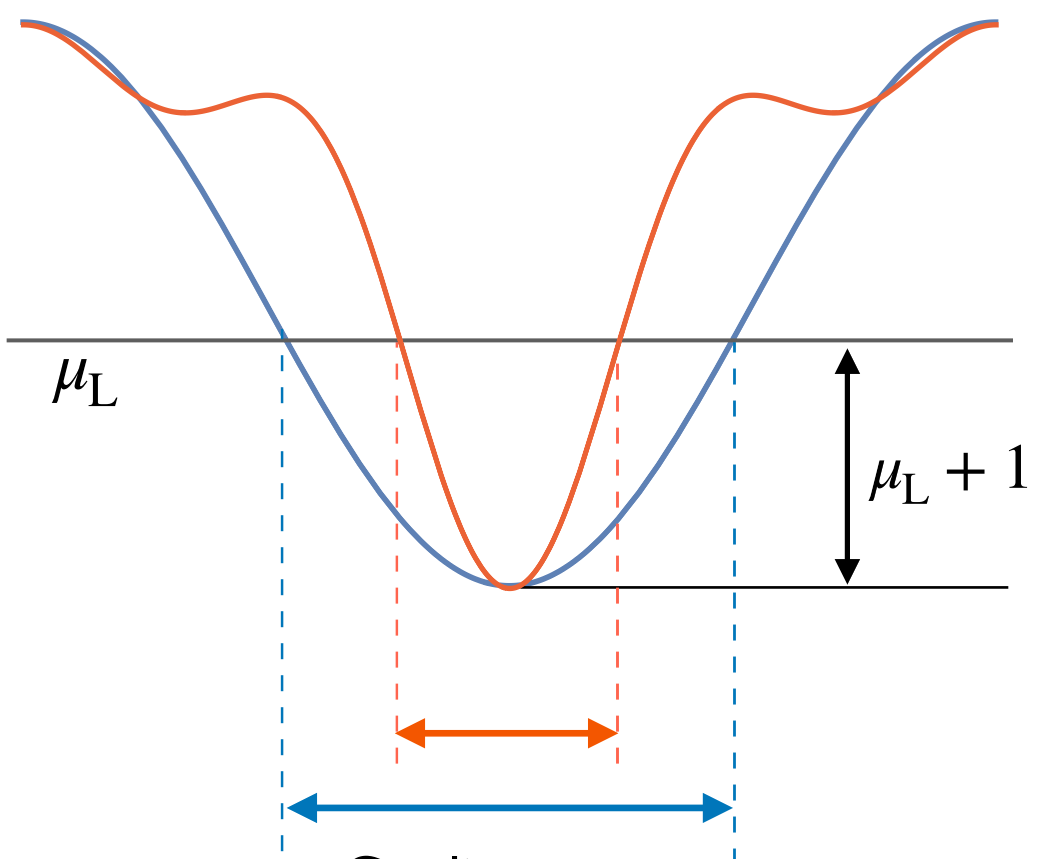
Free-fermion lead + N-level system

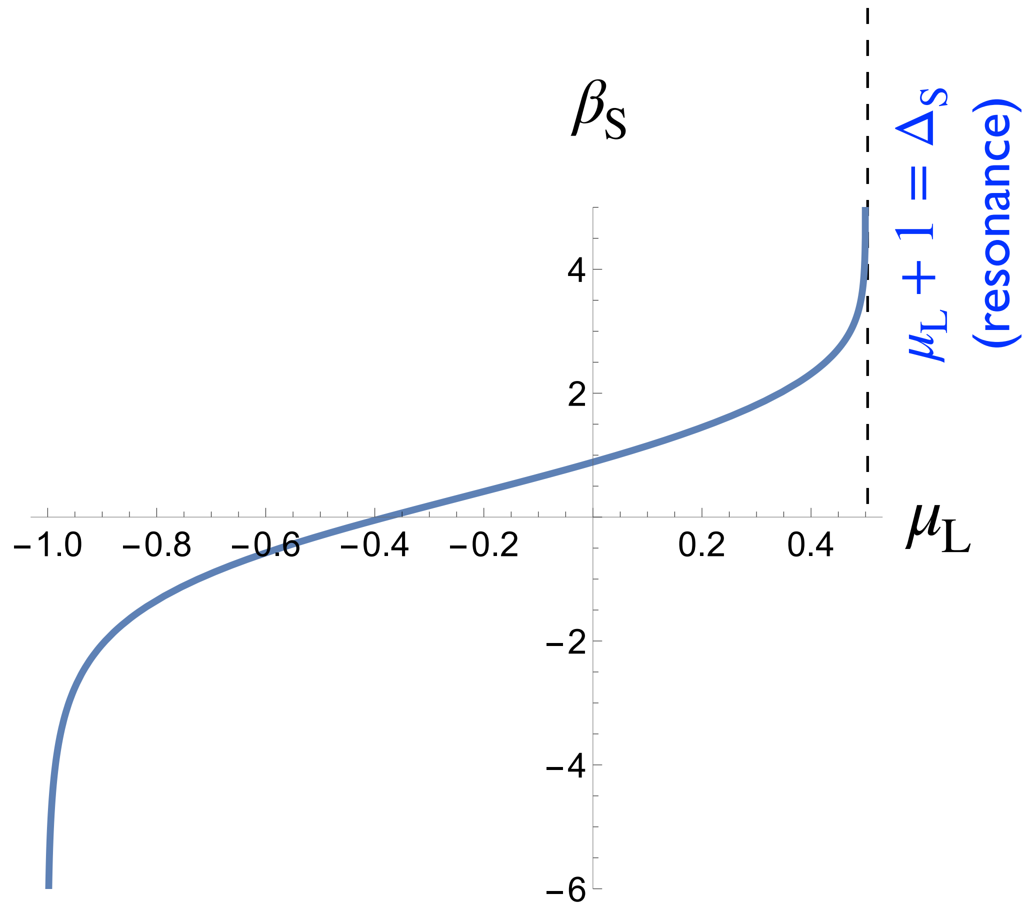
$\hat{H}_{\rm S} = \Delta_{\rm S} \hat{S}^z$

$R_{m^z \to m^z+1} \propto \gamma \epsilon^2 \int_{\varepsilon_L(k) > \mu_L} \frac{dk \sin^2 k}{(\Delta_S + |\varepsilon_L(k) - \mu_L|)^2}$ $\quad R_{m^z+1 \to m^z} \propto \gamma \epsilon^2 \int_{\varepsilon_L(k) < \mu_L} \frac{dk \sin^2 k}{(\Delta_S - |\varepsilon_L(k) - \mu_L|)^2}$

$\varepsilon_{\rm L}(k) = -\cos k$

$\varepsilon_{\rm L}(k) \sim -\sum_{n=1}^{3} \frac{1}{n} \cos(nk)$ Fewer modes cool





$\Delta_{\rm S} = 1.5$

Analytic solution using detailed balance

Free-fermion lead + N-level system

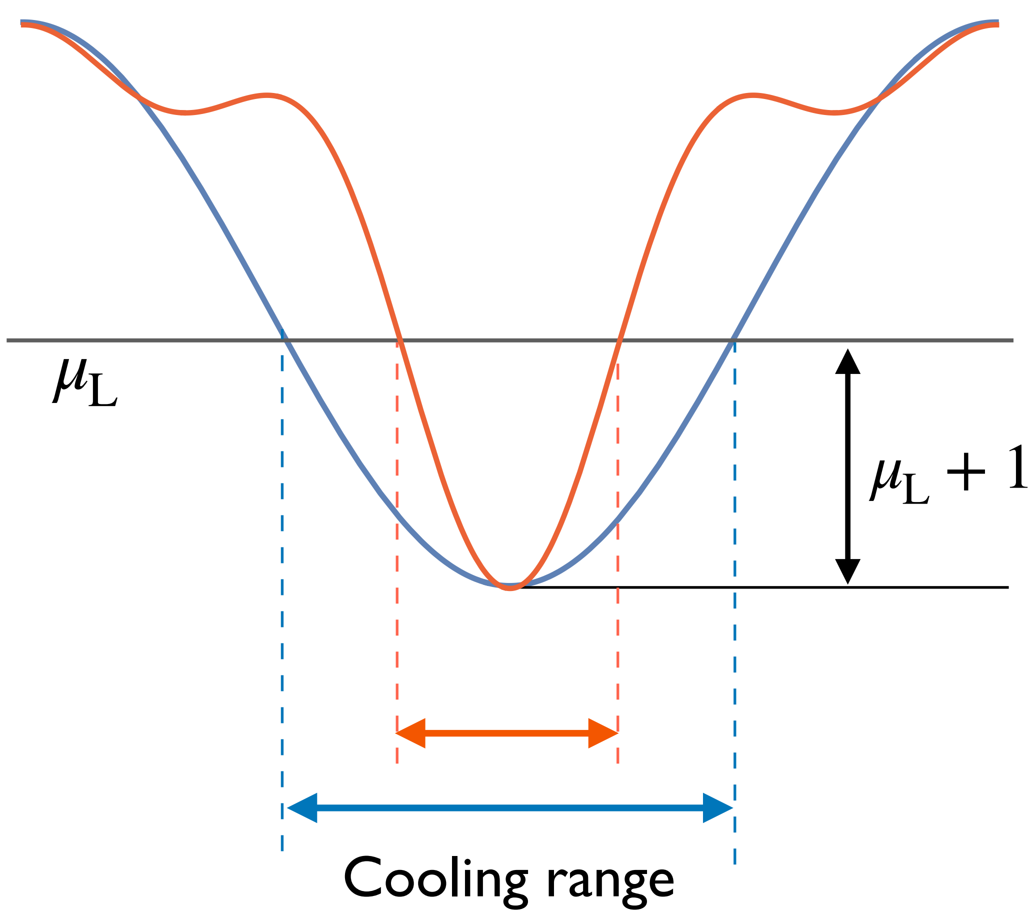
$$\hat{H}_{\rm S} = \Delta_{\rm S}\hat{S}^z$$

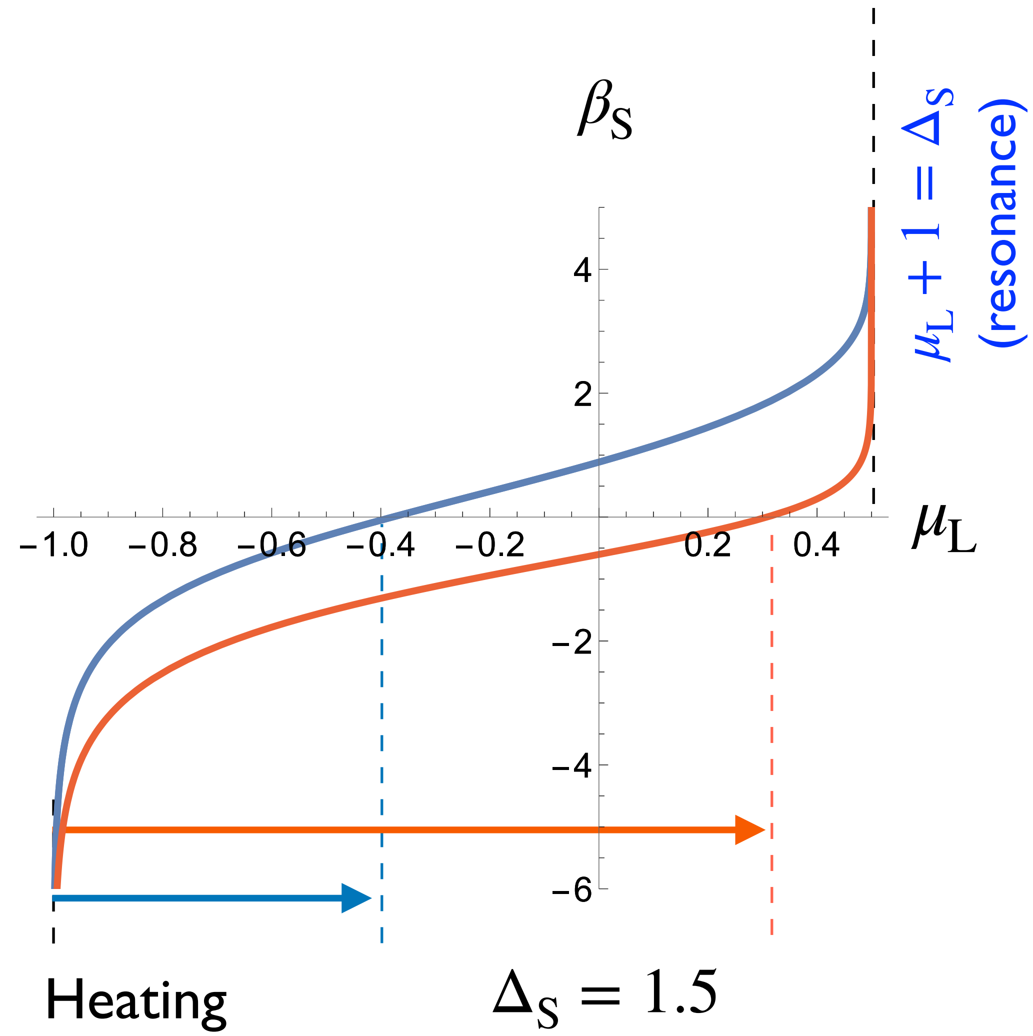
$$R_{m^z\to m^z+1} \propto \gamma\epsilon^2 \int_{\varepsilon_L(k)>\mu_L} \frac{dk\,\sin^2 k}{(\Delta_S + |\varepsilon_L(k)-\mu_L|)^2} \qquad R_{m^z+1\to m^z} \propto \gamma\epsilon^2 \int_{\varepsilon_L(k)<\mu_L} \frac{dk\,\sin^2 k}{(\Delta_S - |\varepsilon_L(k)-\mu_L|)^2}$$

$$\varepsilon_{\rm L}(k) = -\cos k$$

$$\varepsilon_{\rm L}(k) \sim -\sum_{n=1}^{3}\frac{1}{n}\cos(nk)$$

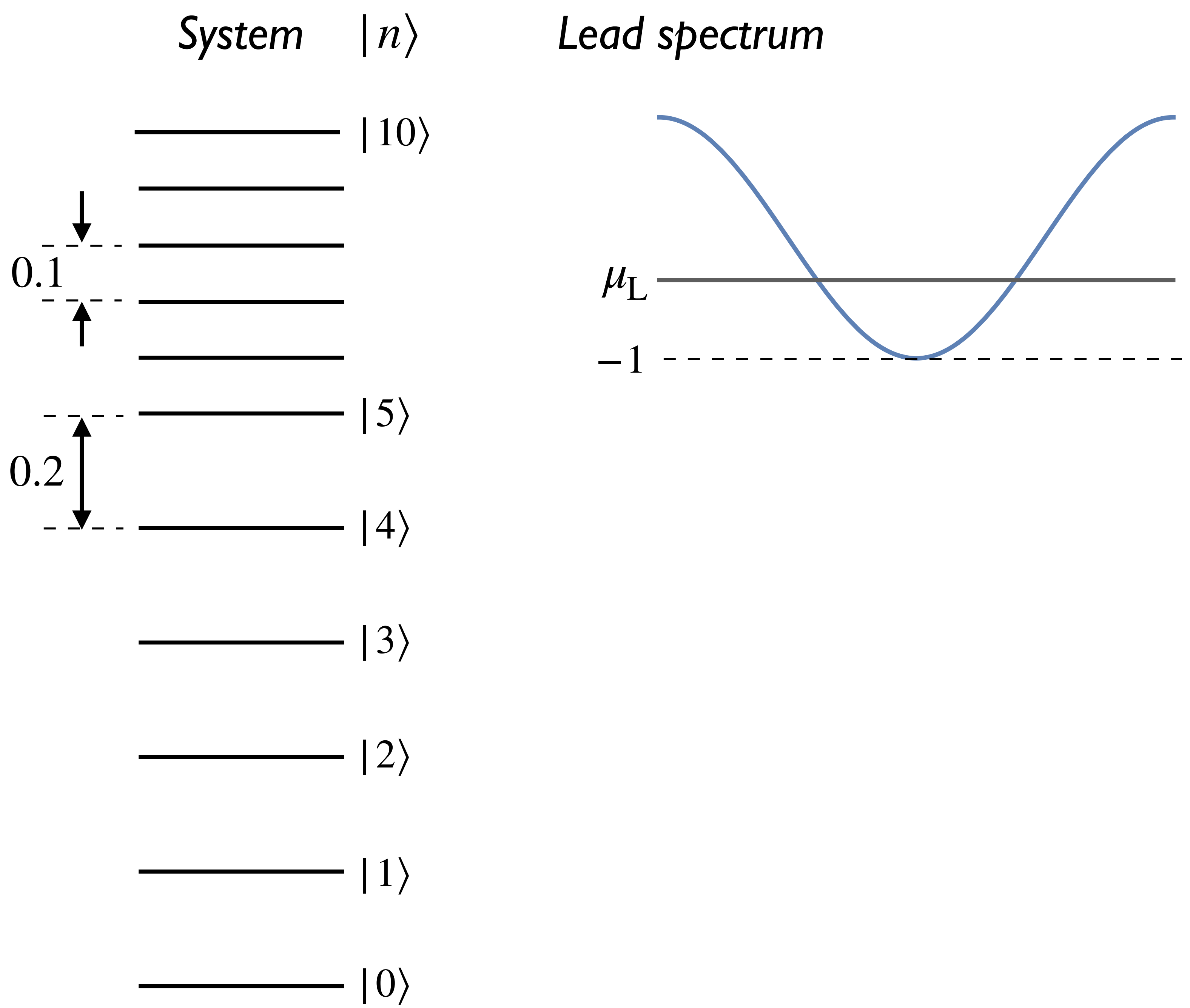
Fewer modes cool $\Longrightarrow$ more heating





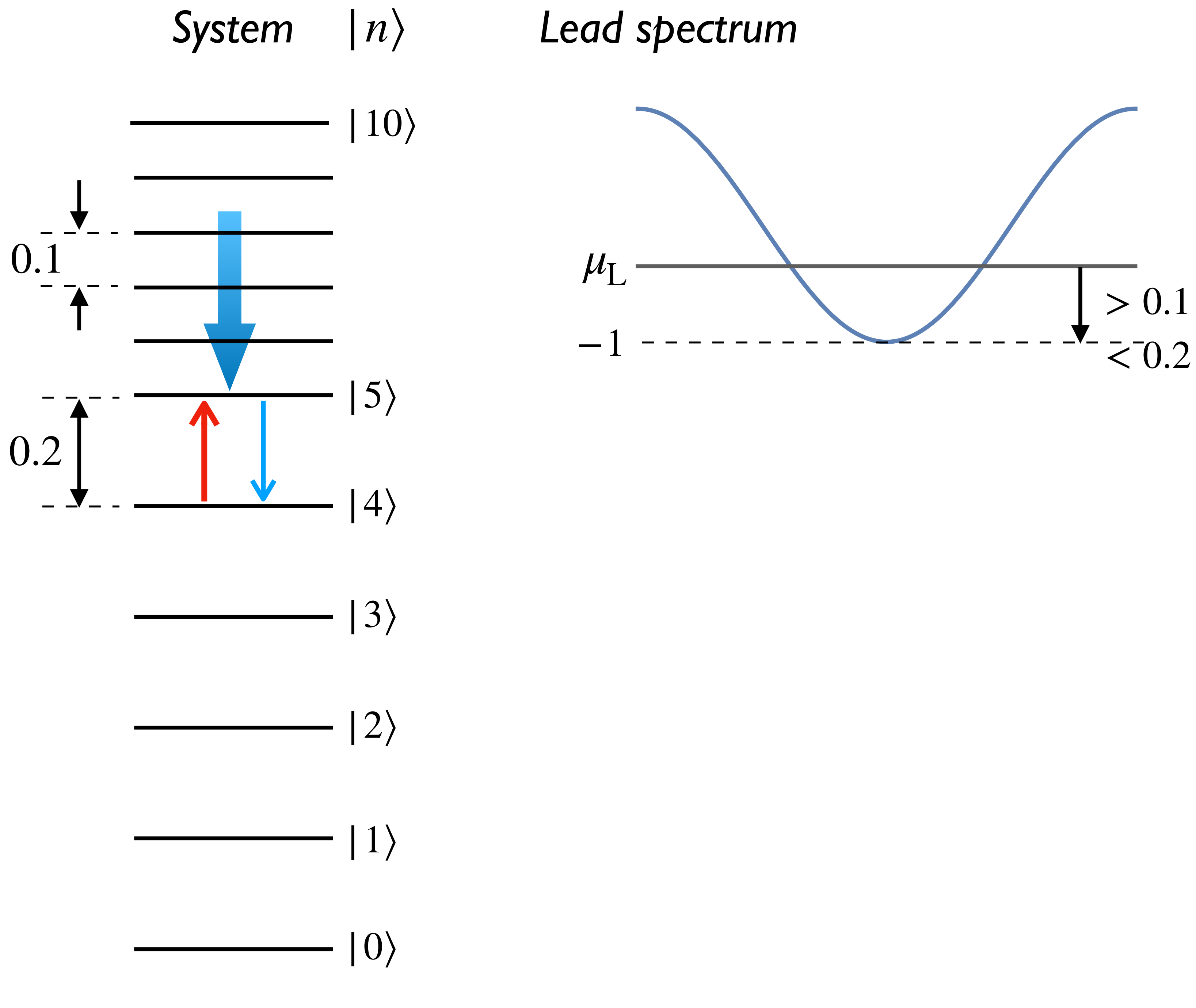
Analytic solution using detailed balance

Corollary 1: Mid-spectrum nonclassical steady state



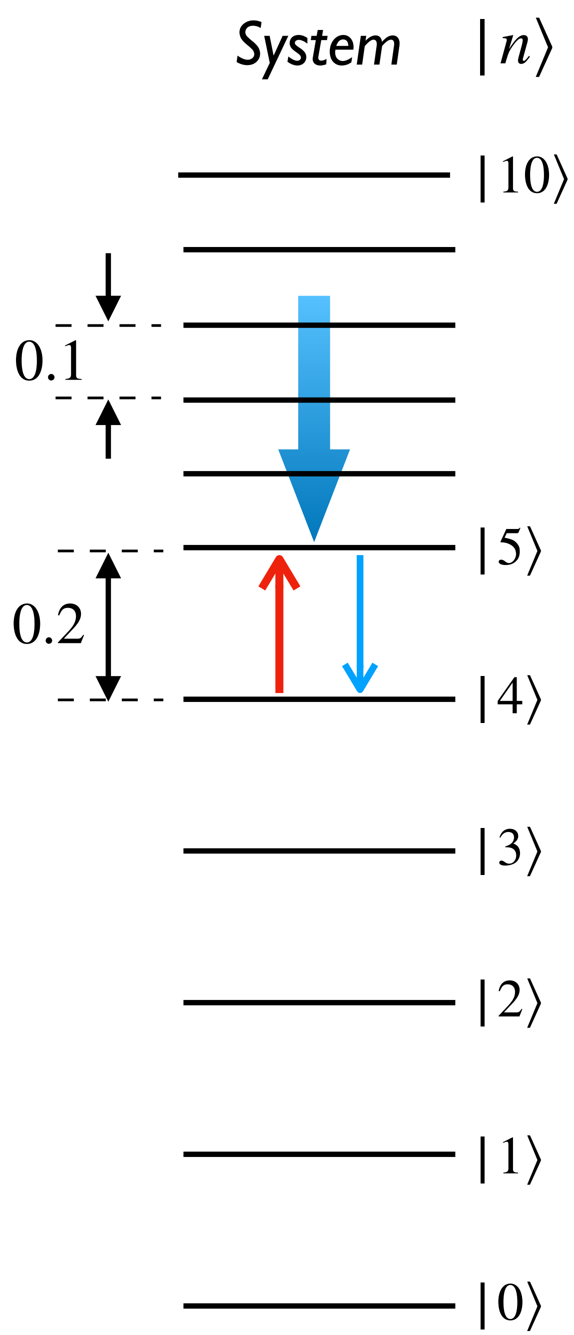
"Nonlinear cavity"

Corollary 1: Mid-spectrum nonclassical steady state



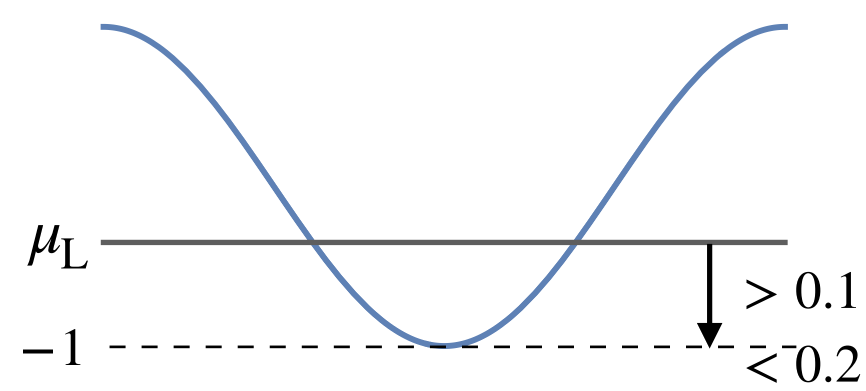
"Nonlinear cavity"

Corollary 1: Mid-spectrum nonclassical steady state

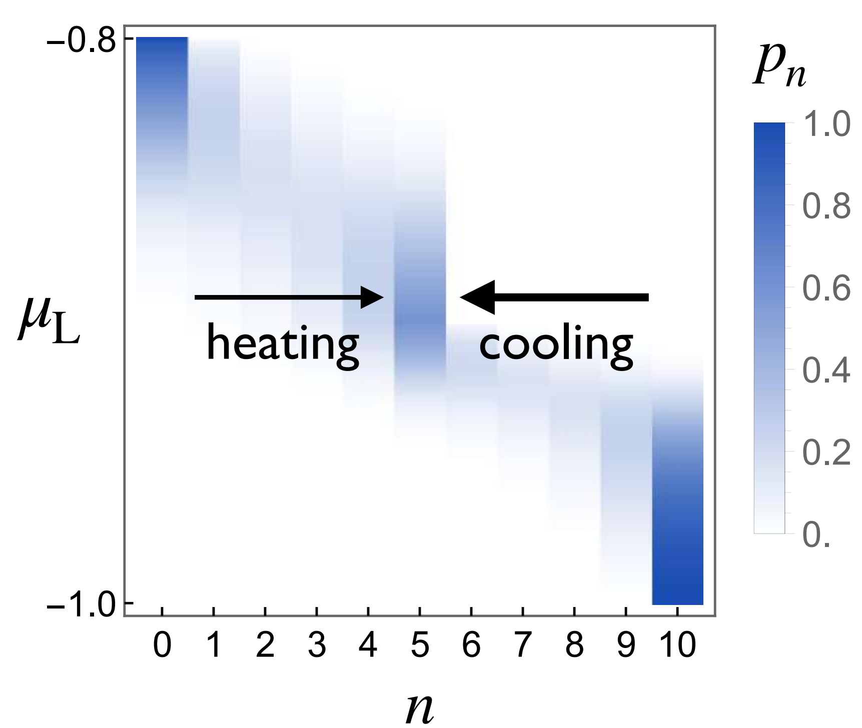


"Nonlinear cavity"

Lead spectrum

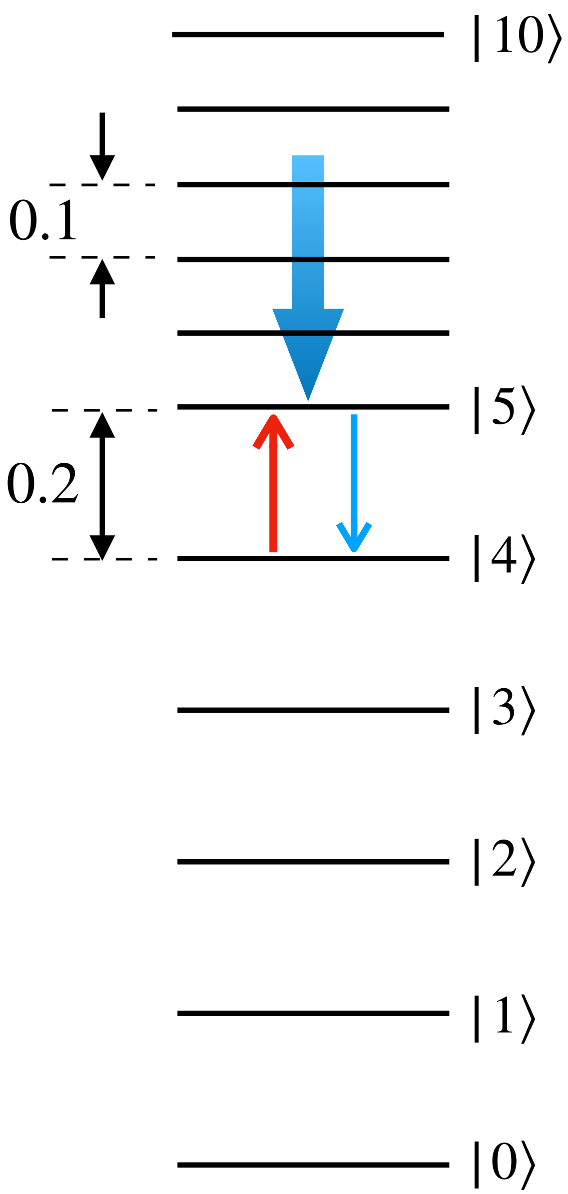


Steady-state occupations



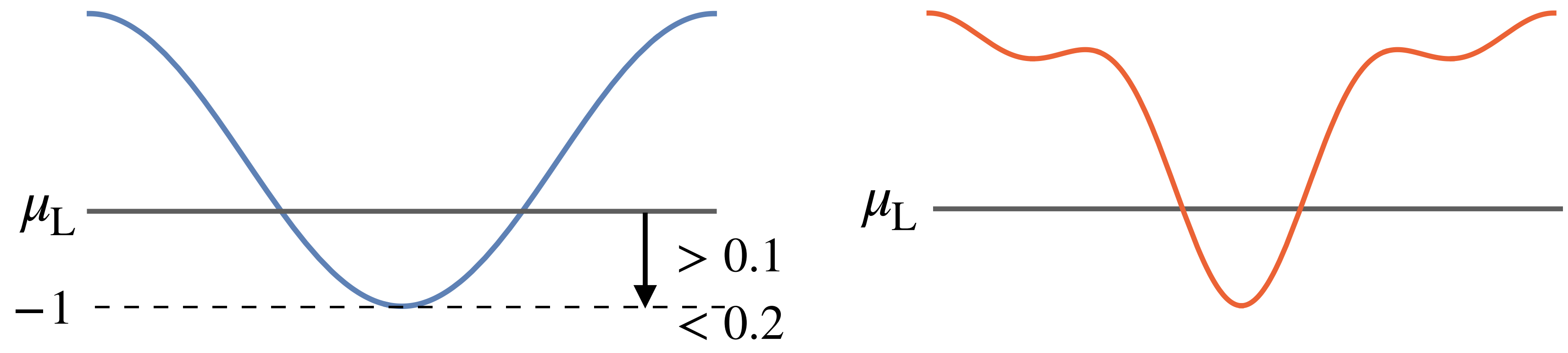
Corollary 1: Mid-spectrum nonclassical steady state

System $|n\rangle$

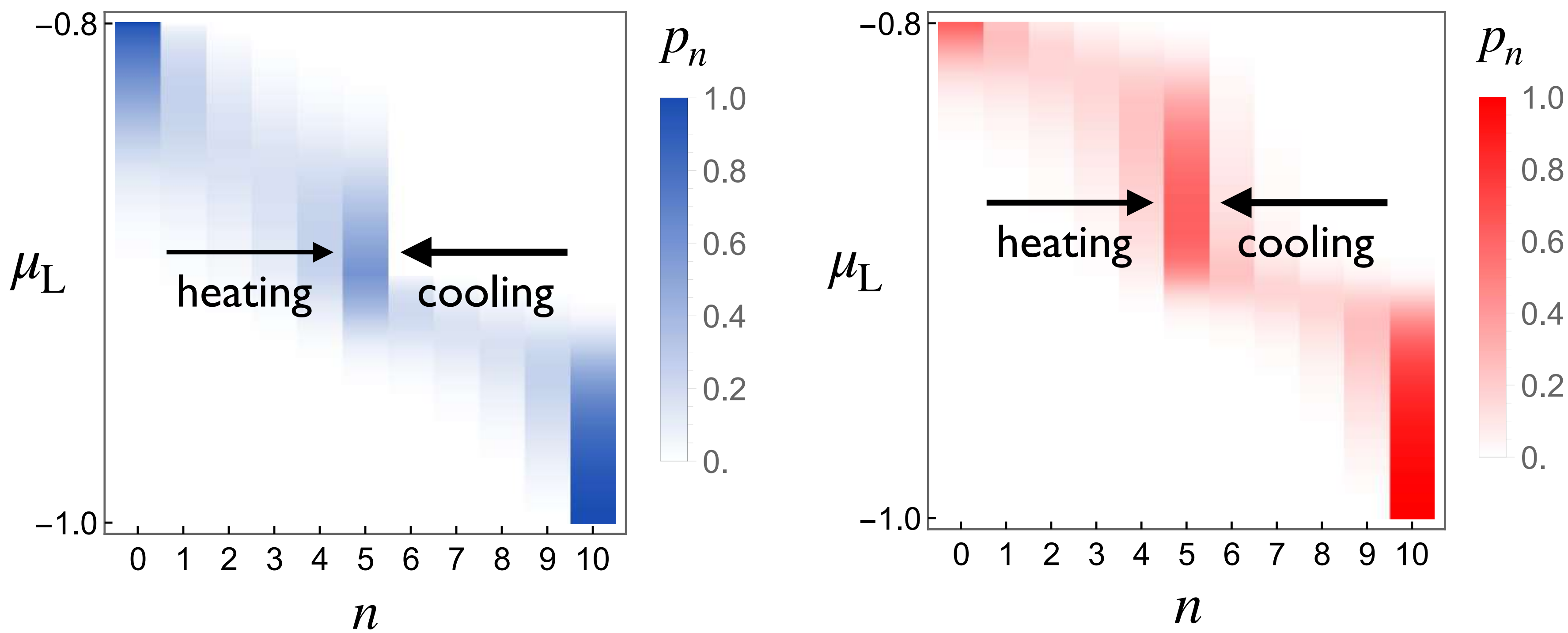


"Nonlinear cavity"

Lead spectrum

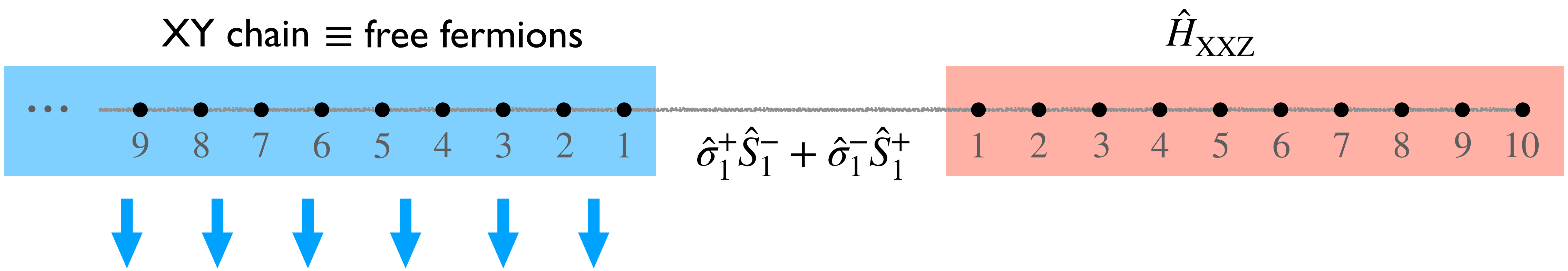


Steady-state occupations



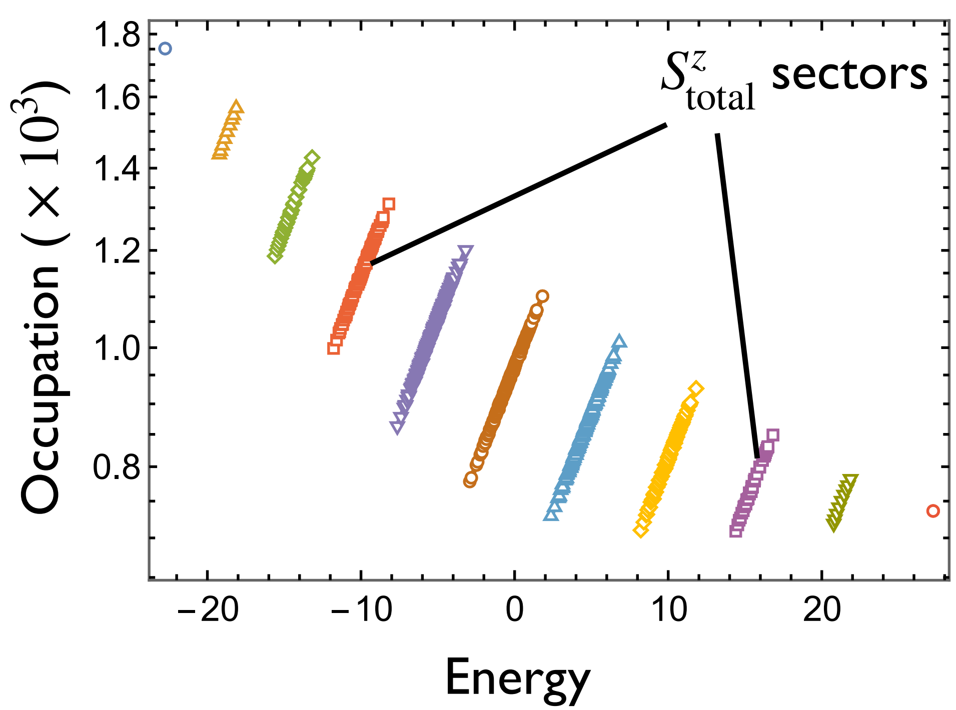
5-photon Fock state

Corollary 2: Global cooling + subsector heating

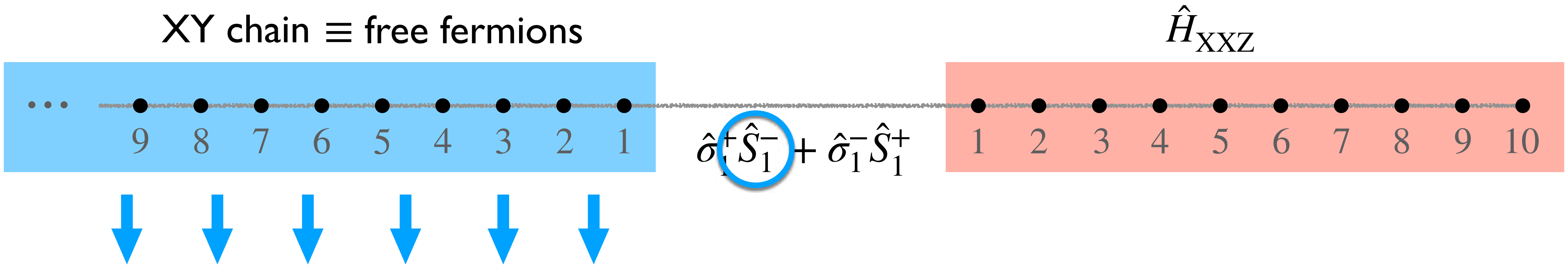


$$\hat{H}_{\mathrm{XXZ}} = \sum_i \left[J_z \hat{S}_i^z \hat{S}_{i+1}^z + J_\perp\left(\hat{S}_i^x \hat{S}_{i+1}^x + \hat{S}_i^y \hat{S}_{i+1}^y\right) - B_z \hat{S}_i^z\right]$$

$J_z = 1,\ J_\perp = 0.5,\ B_z = -5,\ \mu_{\mathrm{L}} + 1 = 0.9$



Corollary 2: Global cooling + subsector heating



$$\hat{H}_{\mathrm{XXZ}} = \sum_i \left[J_z \hat{S}_i^z \hat{S}_{i+1}^z + J_\perp \left(\hat{S}_i^x \hat{S}_{i+1}^x + \hat{S}_i^y \hat{S}_{i+1}^y \right) - B_z \hat{S}_i^z \right]$$

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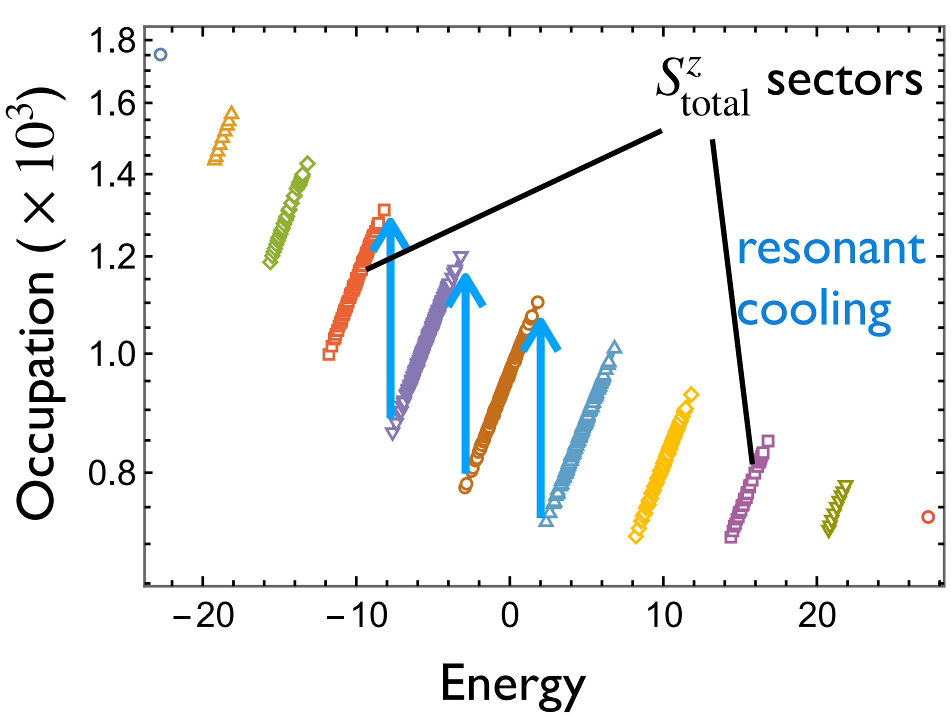
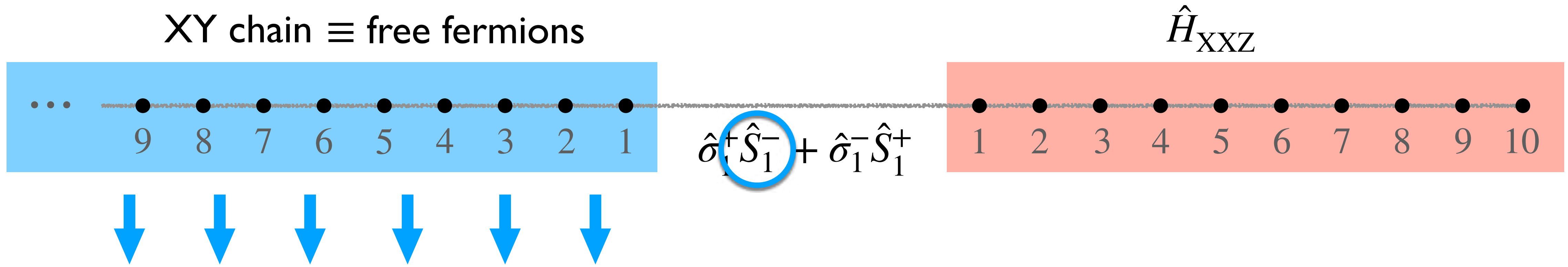


Corollary 2: Global cooling + subsector heating



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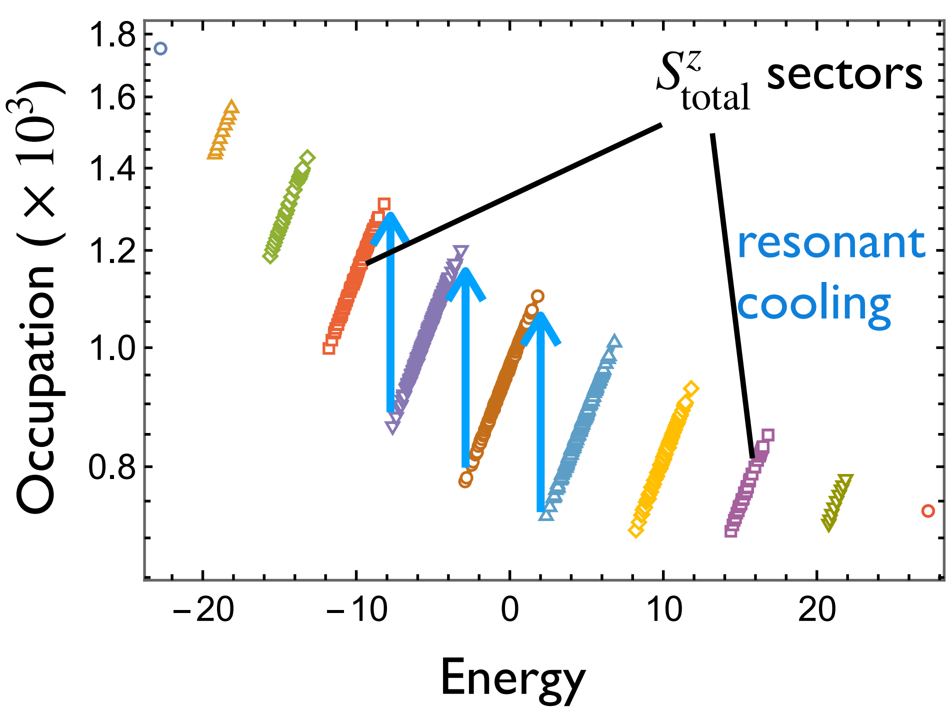
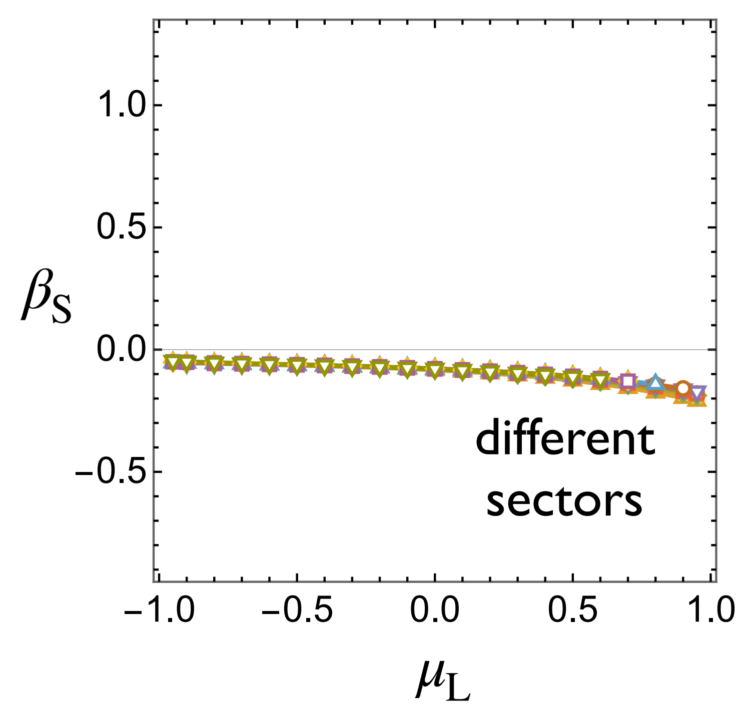
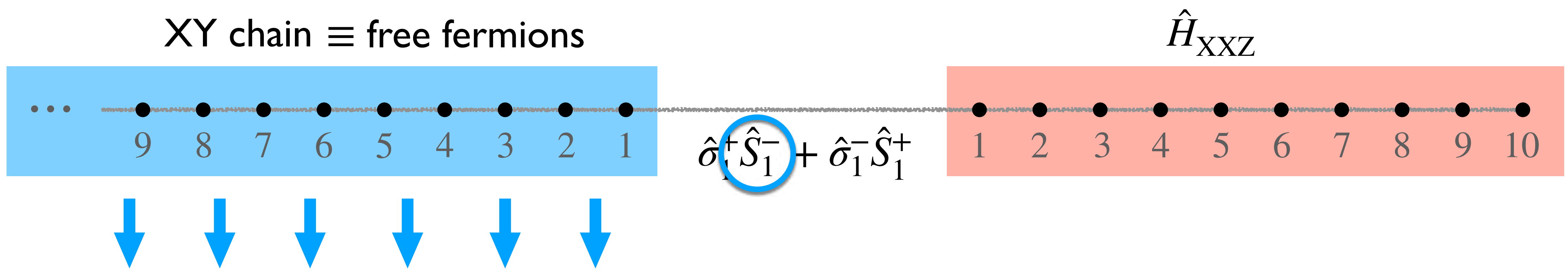




Corollary 2: Global cooling + subsector heating



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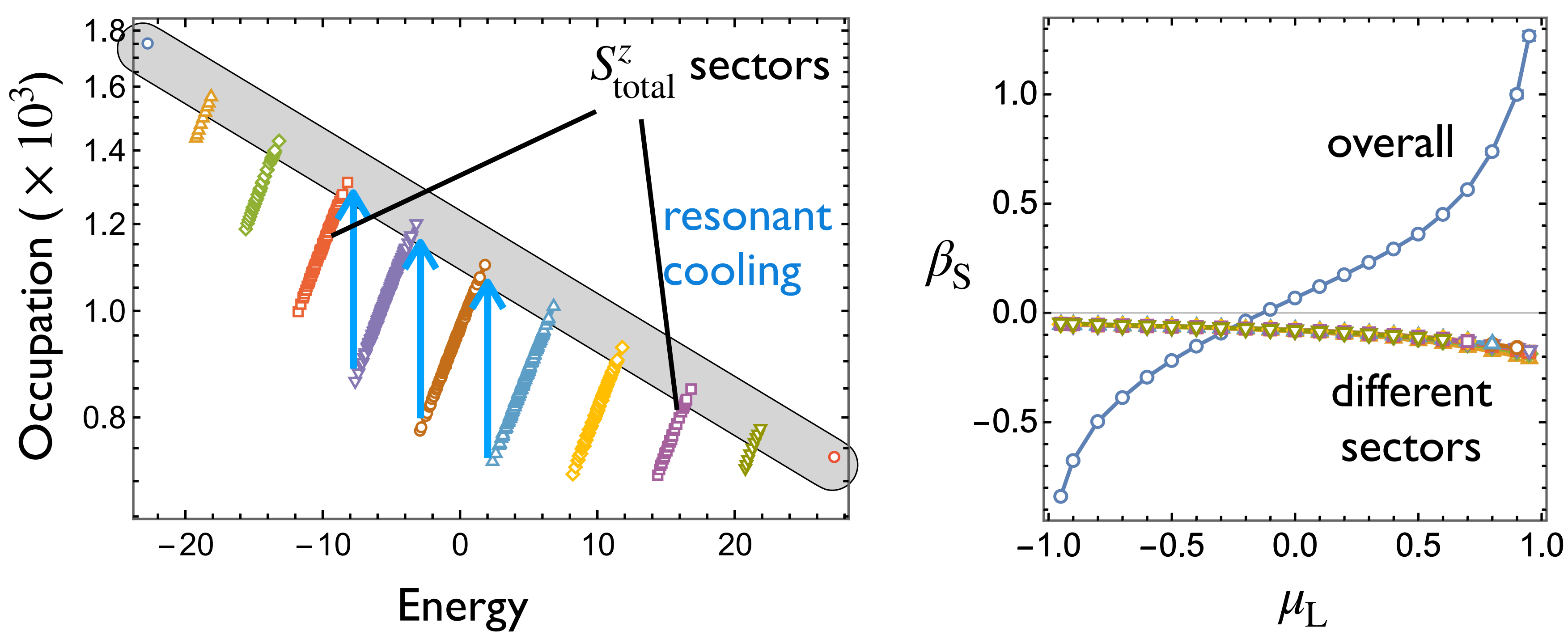

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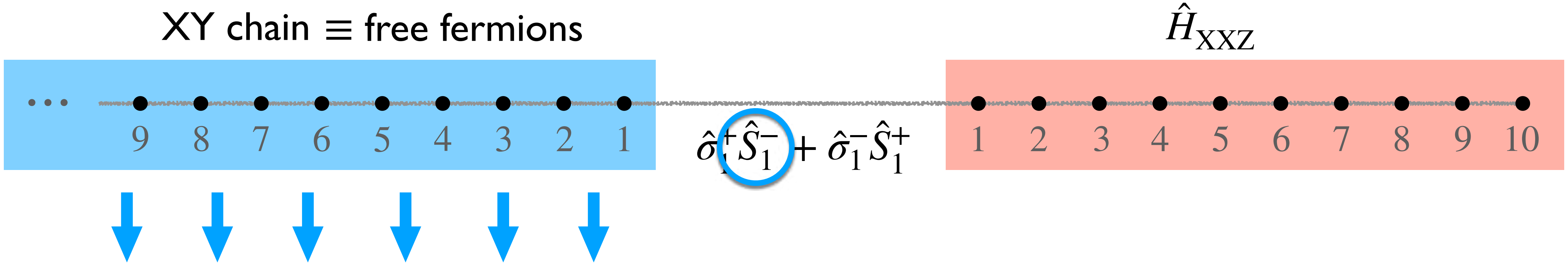

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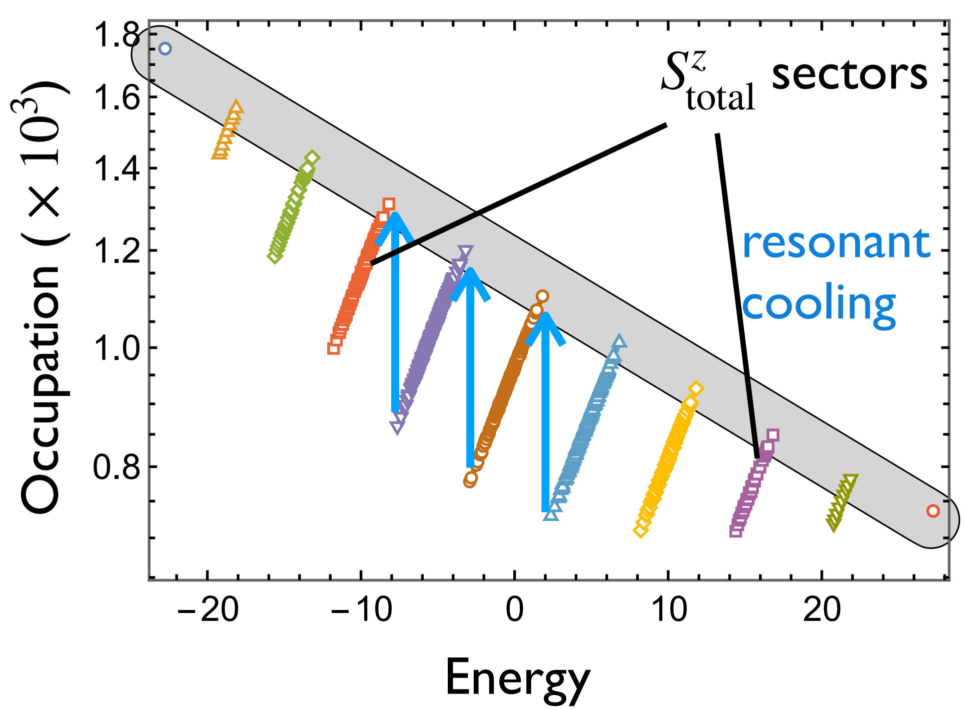
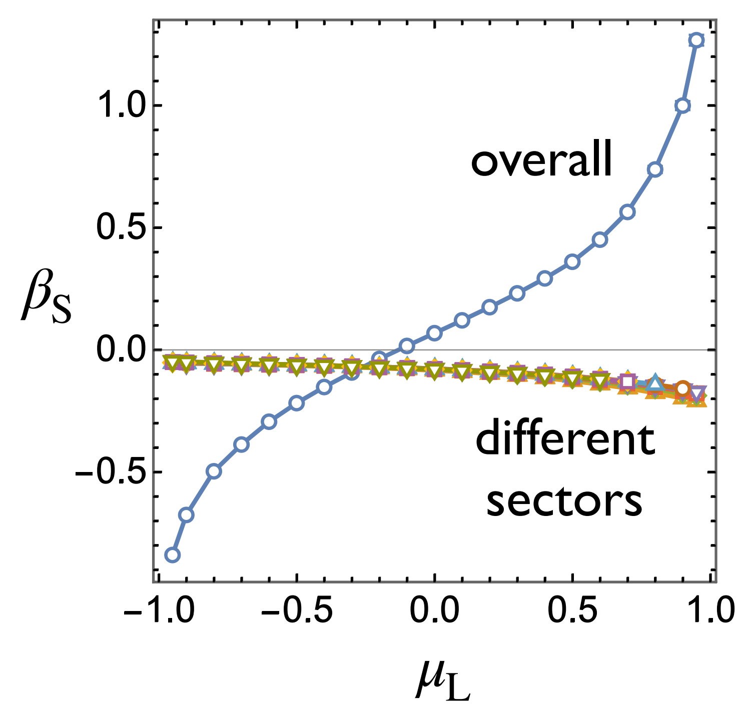
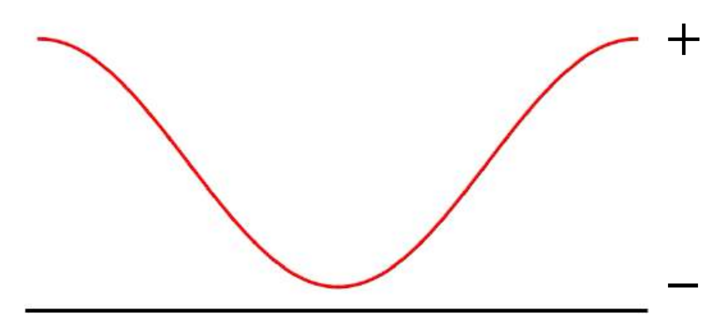
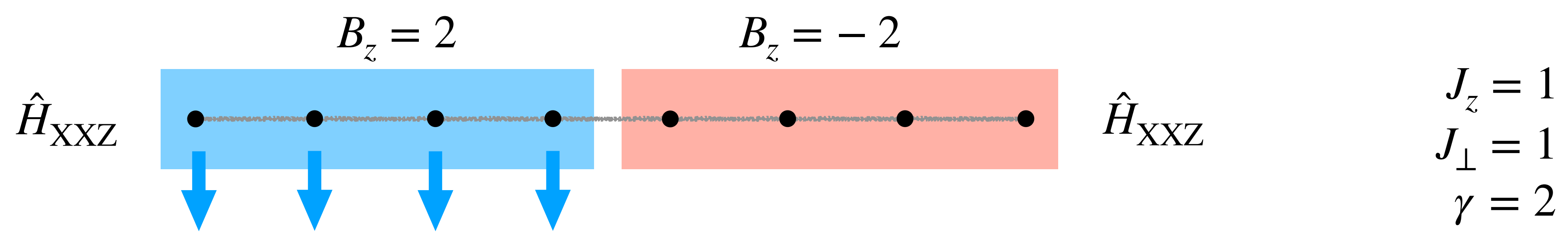
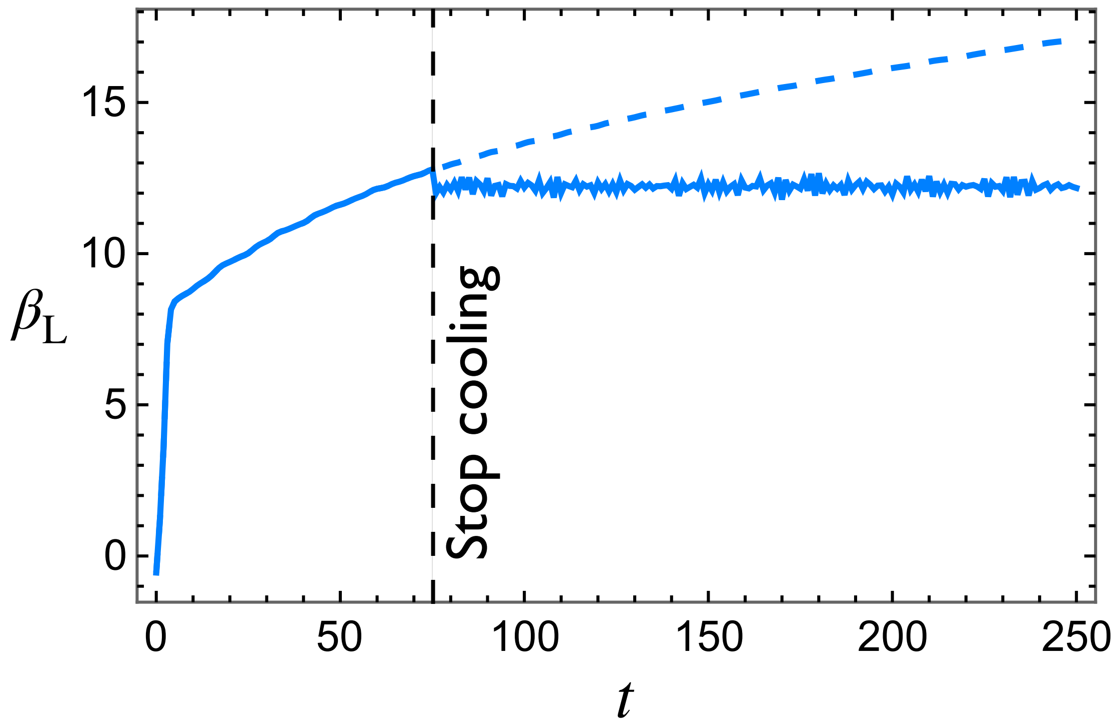
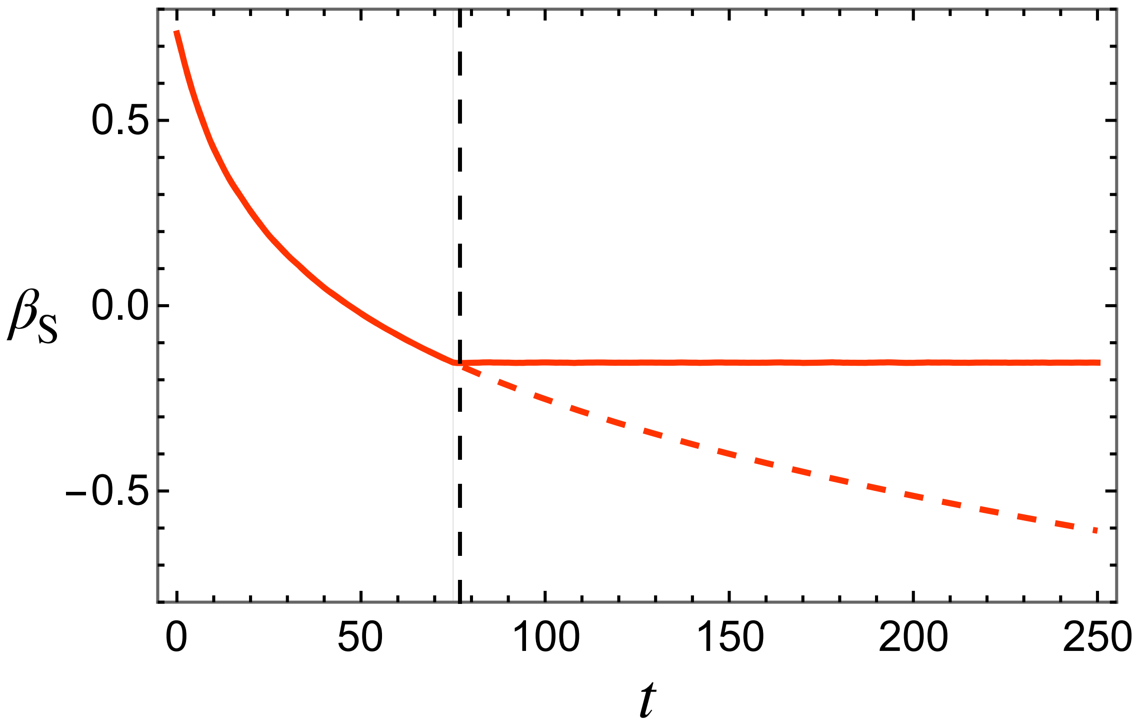








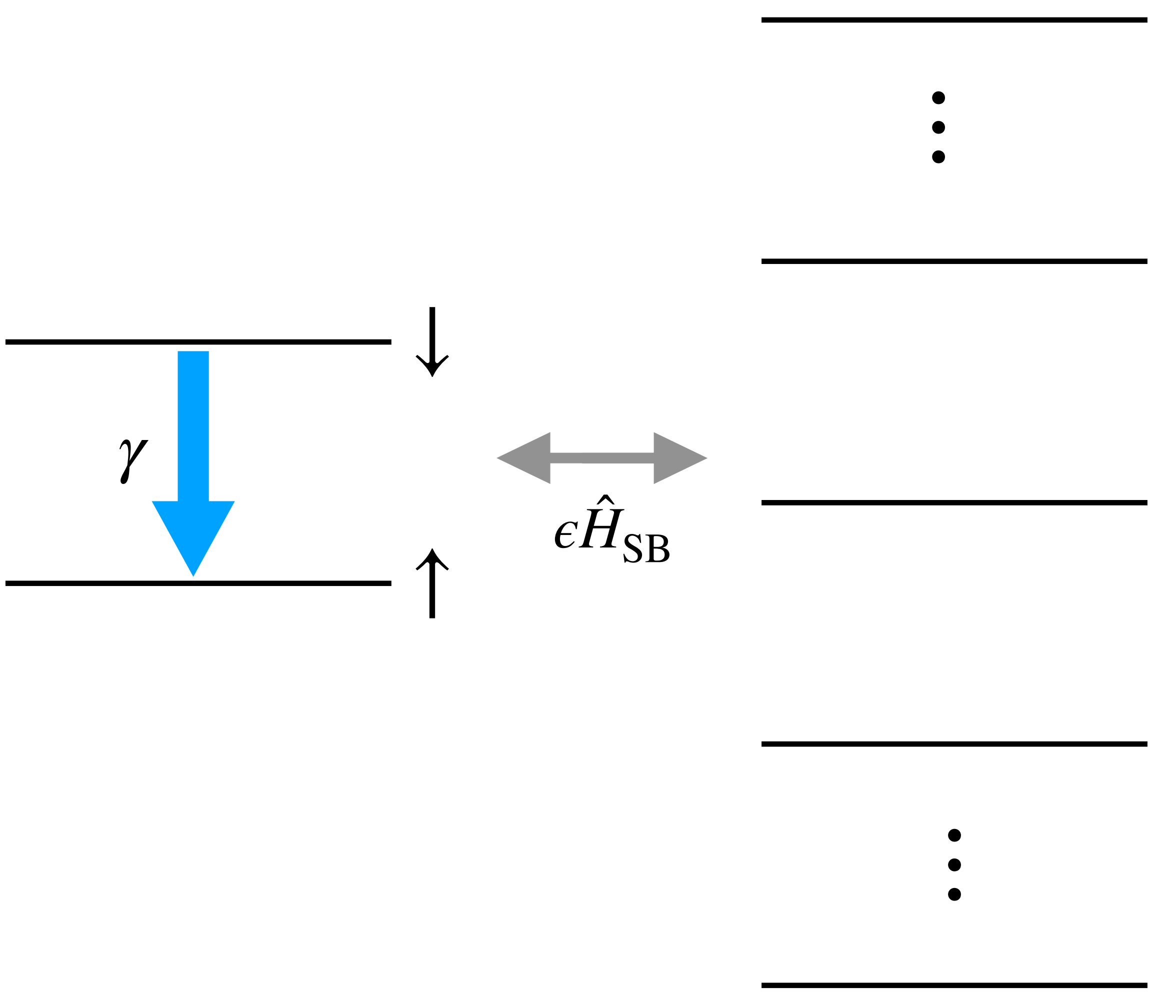




No energy exchange $\Longrightarrow$ temperature difference remains

Symmetry breaking in the coupling

$\hat{H}_{\mathrm{L}} = -\,\hat{\sigma}^z$ $\qquad$ $\hat{H}_{\mathrm{S}} = \Delta_{\mathrm{S}} \hat{S}^z$ $\qquad$ $\hat{H}_{\mathrm{SL}} = \hat{\sigma}^x \hat{S}^x + \eta\, \hat{\sigma}^y \hat{S}^y$



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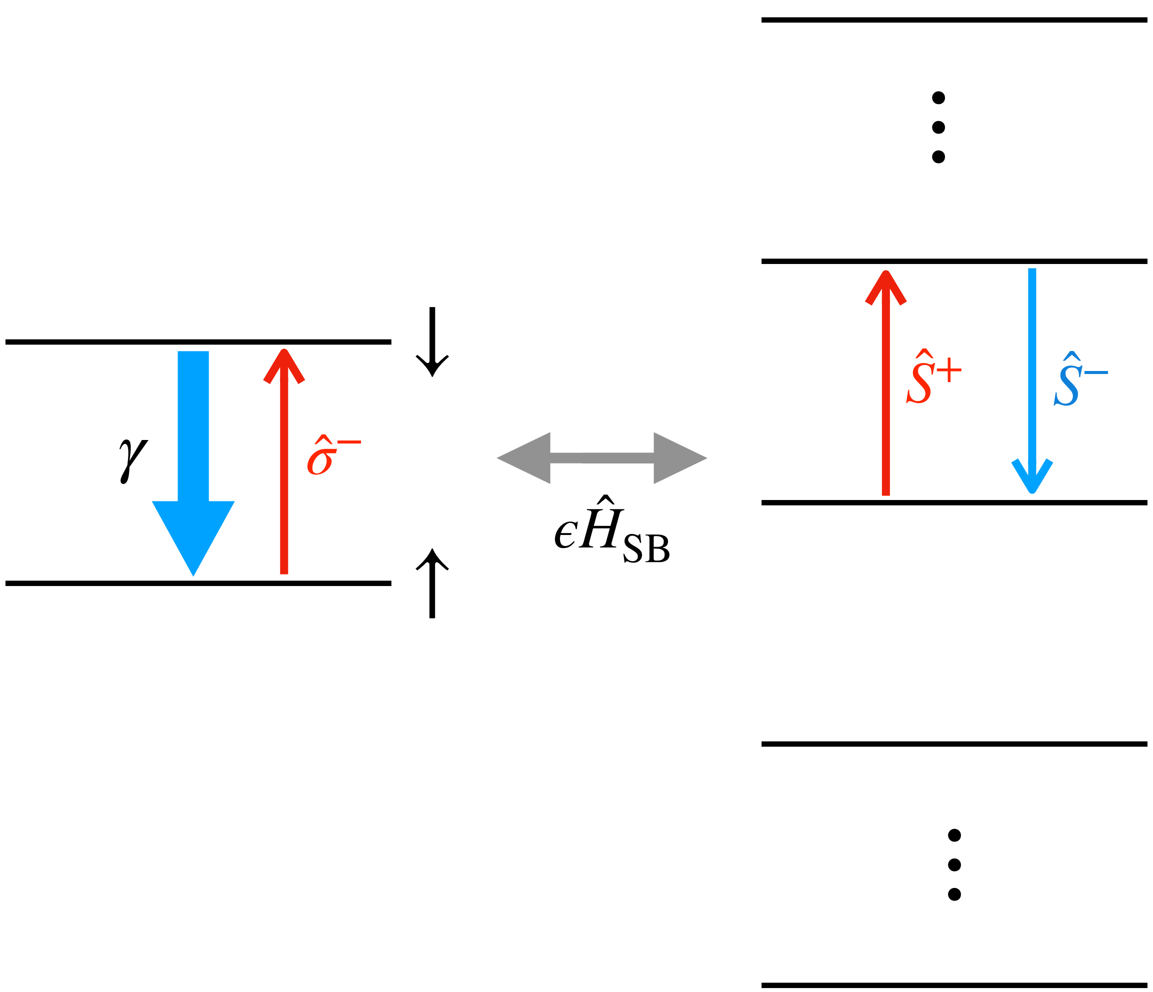
$\hat{H}_{\mathrm{S}} = \Delta_{\mathrm{S}}\hat{S}^z$

$$\hat{H}_{\mathrm{SL}} = \hat{\sigma}^x\hat{S}^x + \eta\,\hat{\sigma}^y\hat{S}^y$$

$$= \frac{1+\eta}{2}\left(\hat{\sigma}^+\hat{S}^- + \hat{\sigma}^-\hat{S}^+\right) + \frac{1-\eta}{2}\left(\hat{\sigma}^+\hat{S}^+ + \hat{\sigma}^-\hat{S}^-\right)$$



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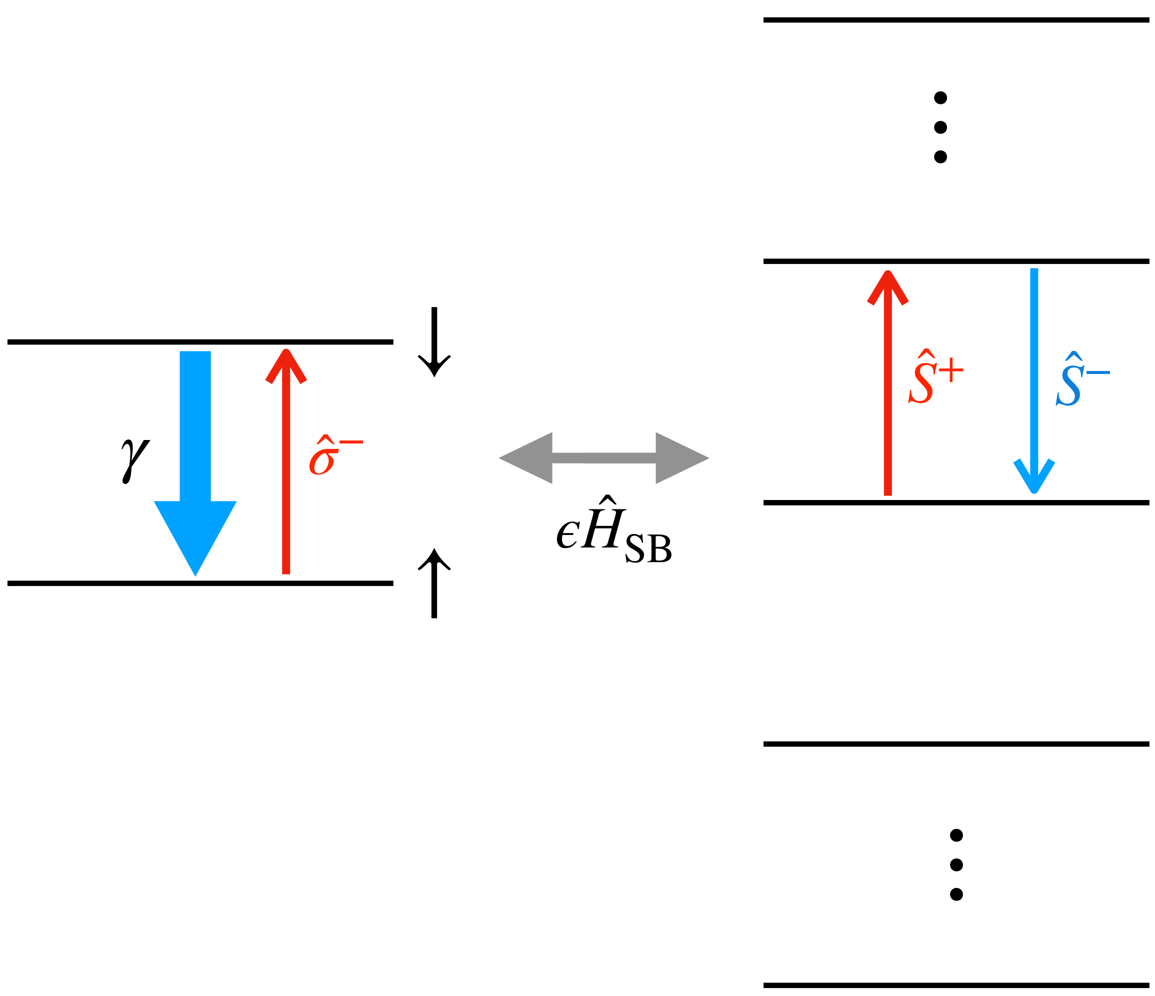
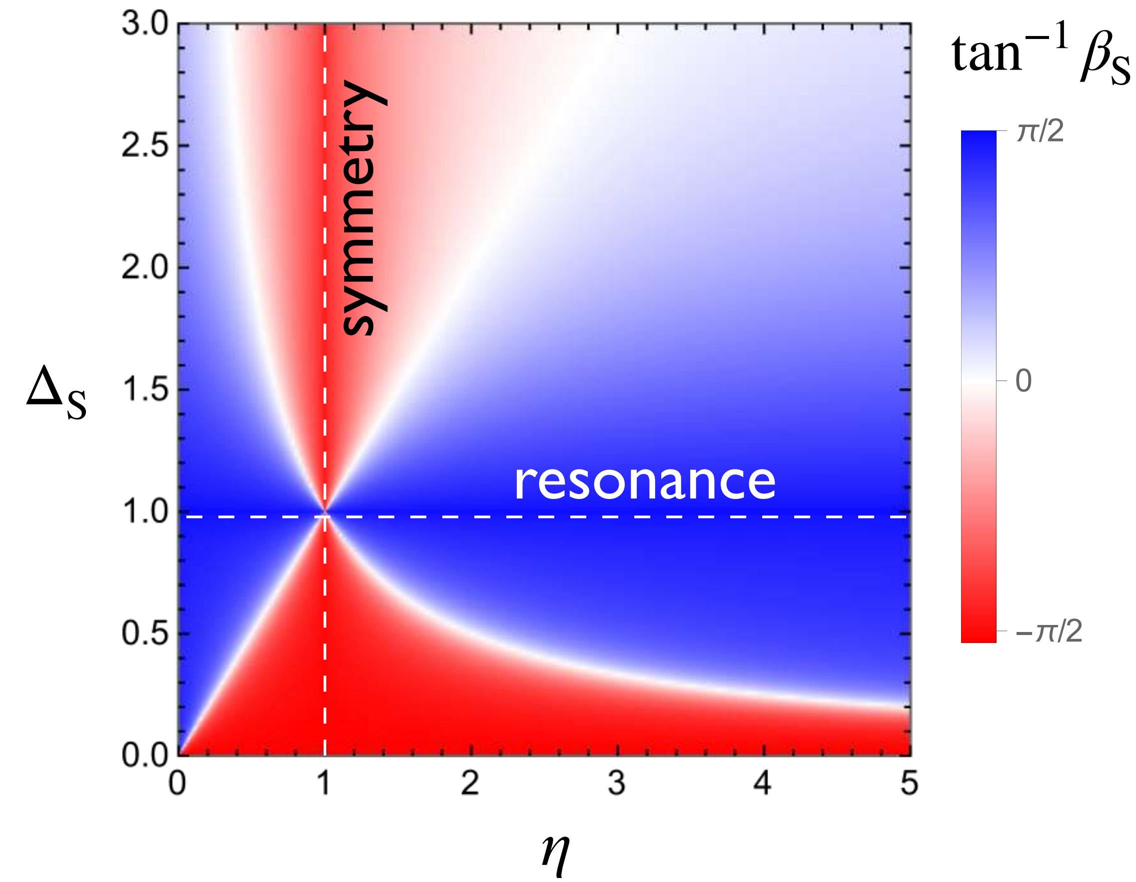
$$= \frac{1+\eta}{2}\left(\hat{\sigma}^+\hat{S}^- + \hat{\sigma}^-\hat{S}^+\right) + \frac{1-\eta}{2}\left(\hat{\sigma}^+\hat{S}^+ + \hat{\sigma}^-\hat{S}^-\right)$$



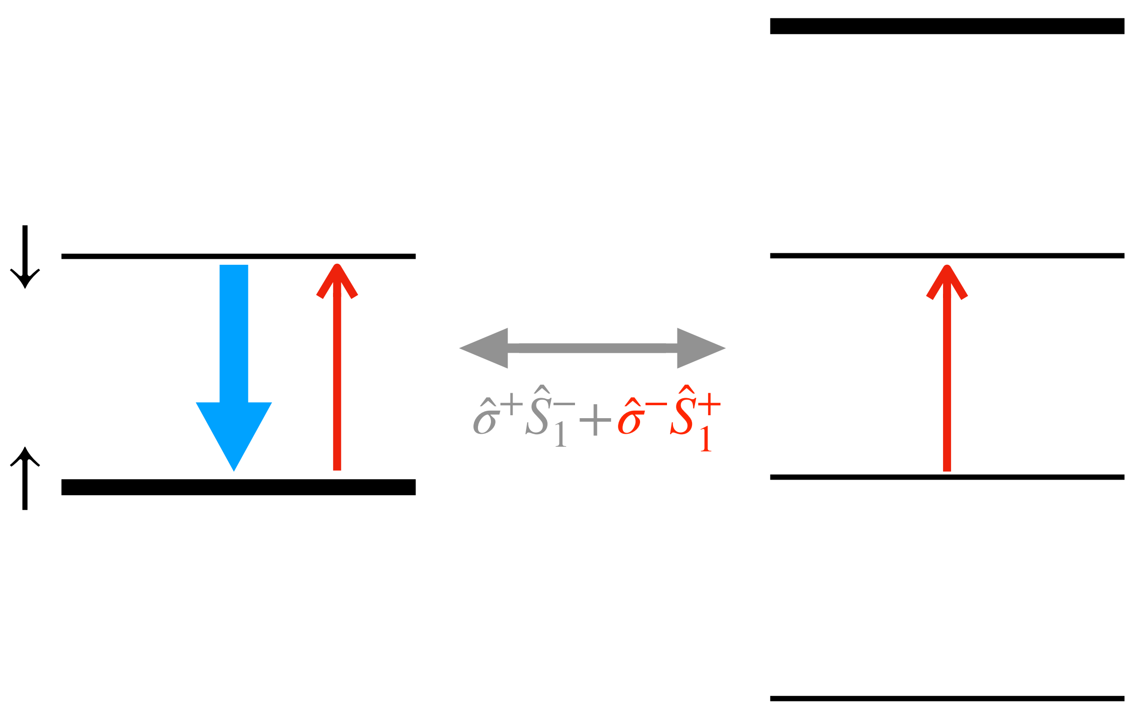


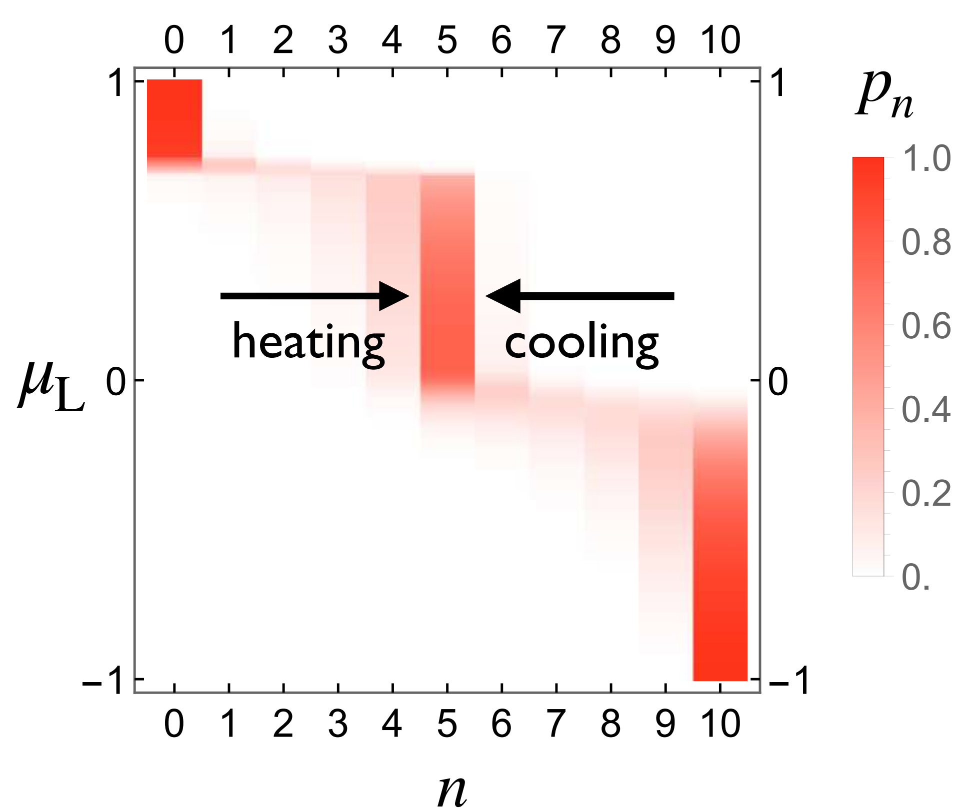
Steady state has detailed balance: $\beta_{\mathrm{S}} = \dfrac{2}{\Delta_{\mathrm{S}}} \ln \left| \dfrac{1-\eta}{1+\eta} \cdot \dfrac{1+\Delta_{\mathrm{S}}}{1-\Delta_{\mathrm{S}}} \right|$

Summary

Thank you :)

- “Anti-thermalization” due to conserved quantum number related to energy
- N-photon Fock state & other non-thermal steady states
- Realize in circuit/cavity QED, Rydberg array, cold atoms/ions…





J Uppalapati, M Haque, P McClarty, SD, arXiv:2412.07630