Tunneling spin and heat transport in ultracold atomic systems

Yuta Sekino, Yuya Ominato, Hiroyuki Tajima, Shun Uchino, & Mamoru Matsuo, arXiv:2312.04280

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In collaboration with
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Shun Uchino (Waseda), Mamoru Matsuo (UCAS, Beijing)

NCTS-iTHEMS Joint Workshop on Matters to Spacetime: Symmetries and Geometry, Aug. 29 2024

Takehome message: Tunneling transport by criticality

Anomalous tunneling spin and heat transport near **magnonic critical points** of ferromagnets

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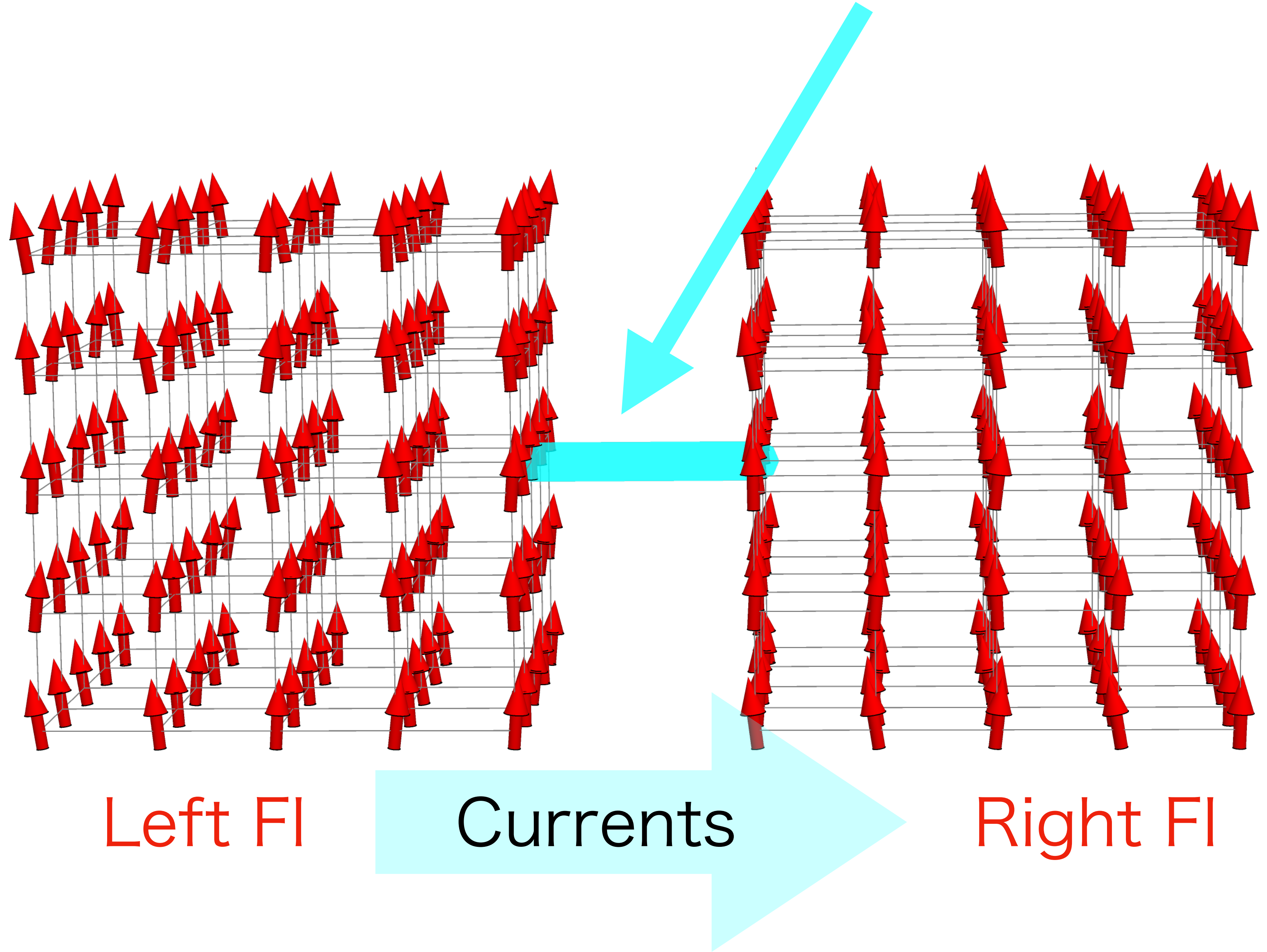
Two ferromagnetic insulators (FIs) realized with **cold atoms** connected via a quantum point contact



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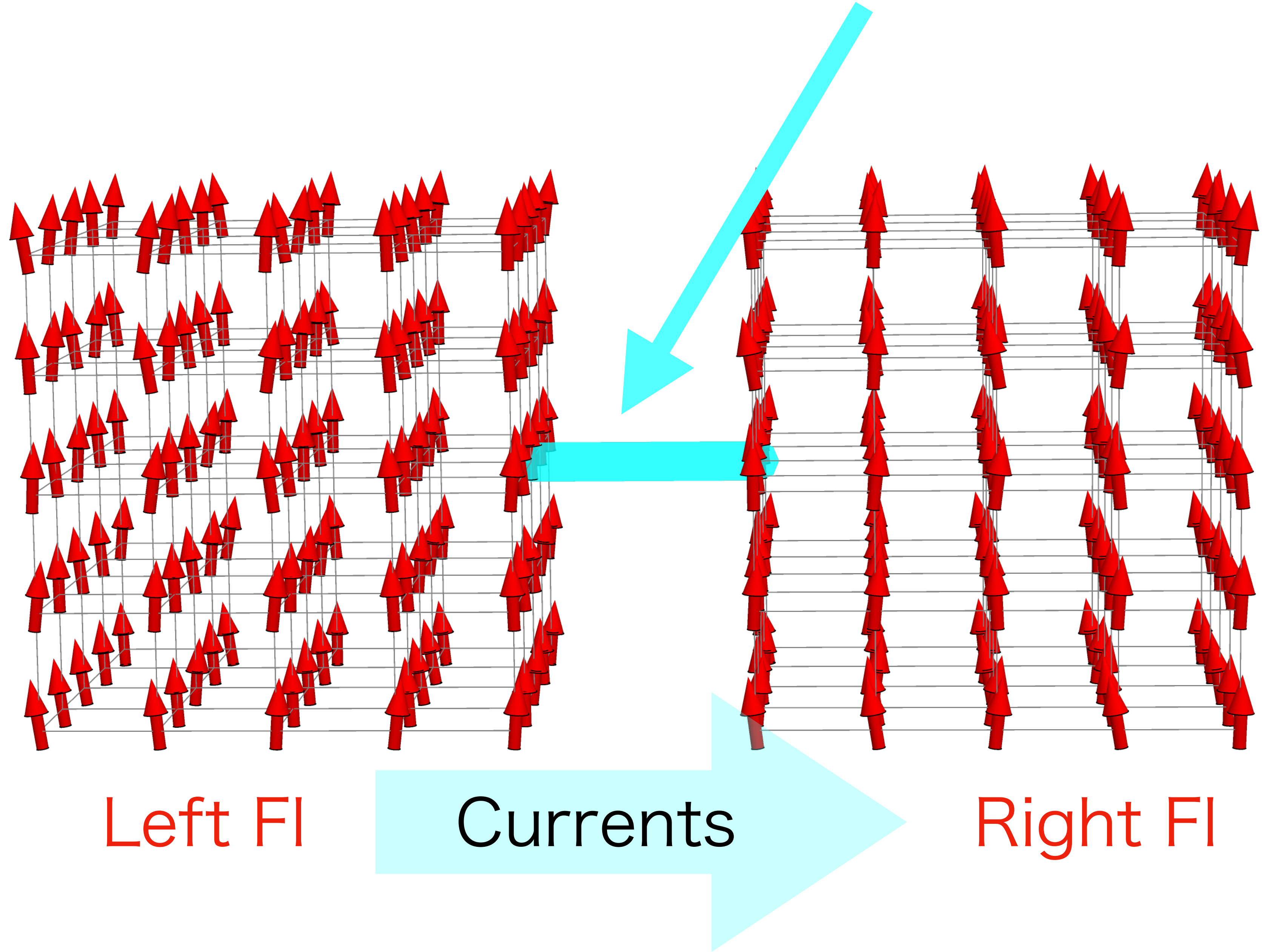
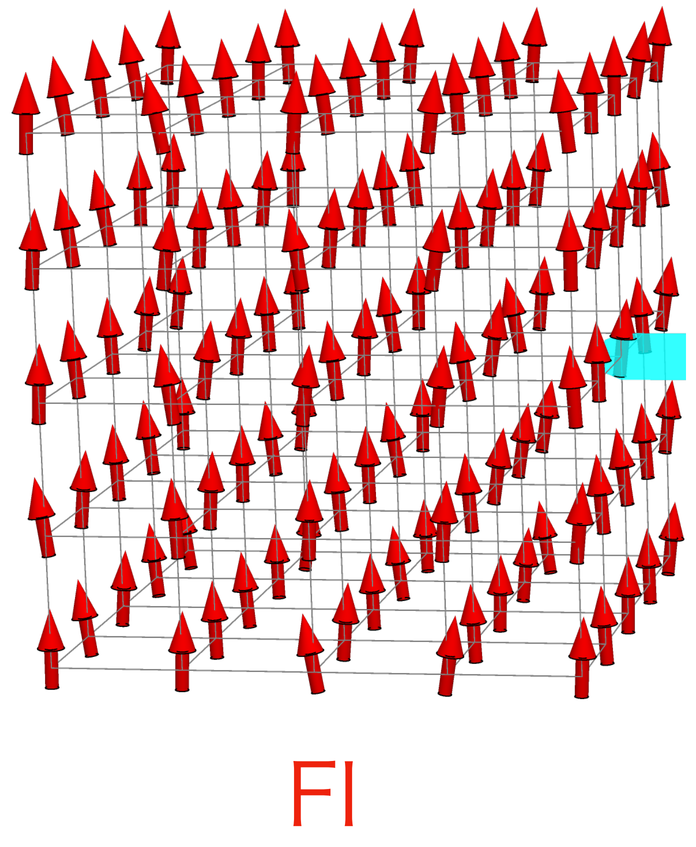
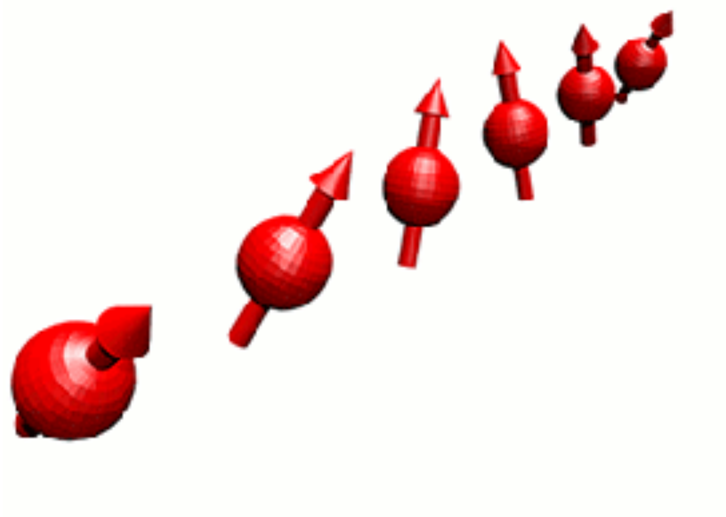


Gapless point of magnons in ferromagnets

Spontaneous breaking of O(3) symmetry in FIs → Magnon as **gapless Nambu-Goldstone mode**





Animation by R. Pradip, KIT.
https://www.ips.kit.edu/2786_Giant-Spin-Phonon-Interaction.php

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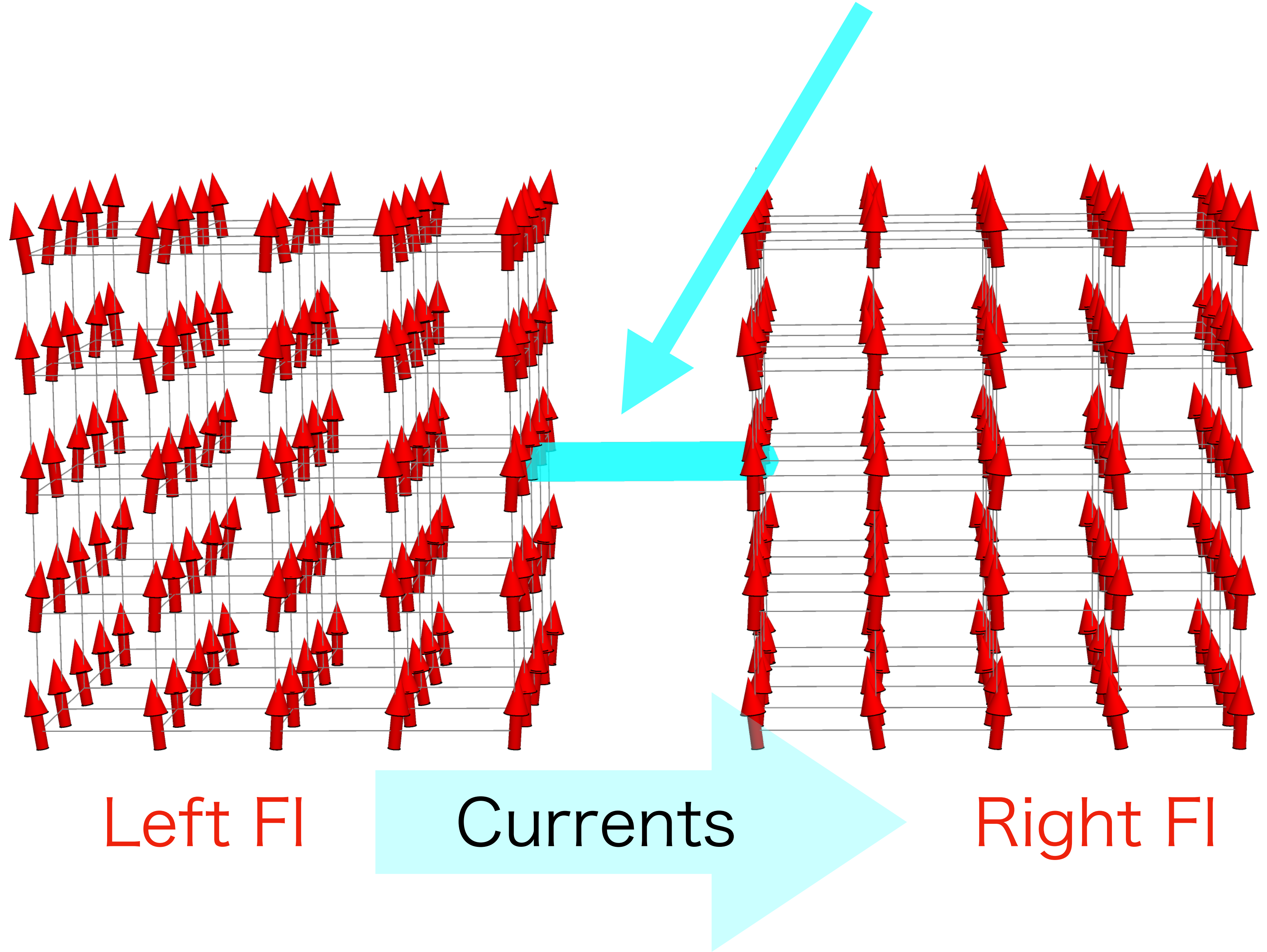

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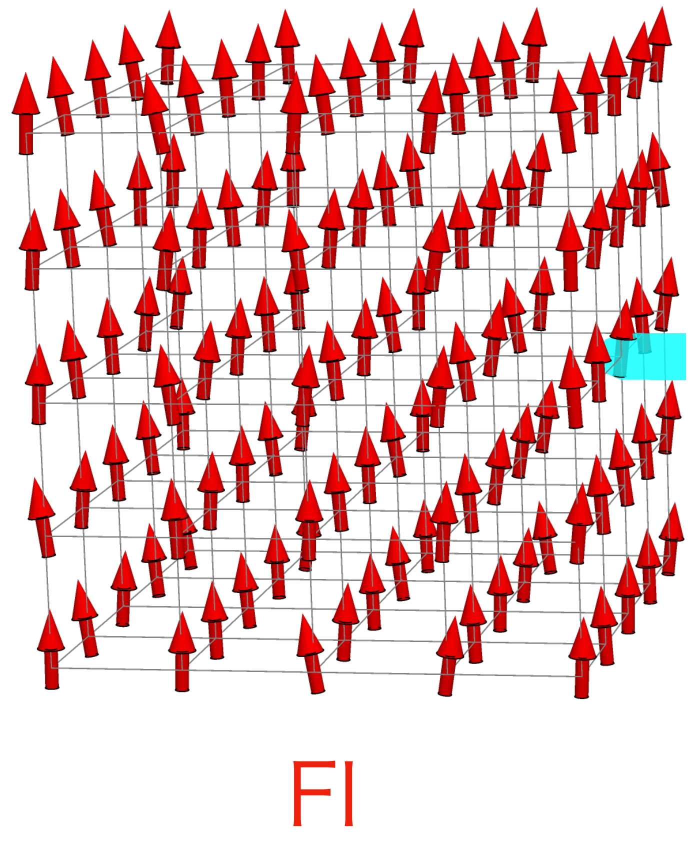

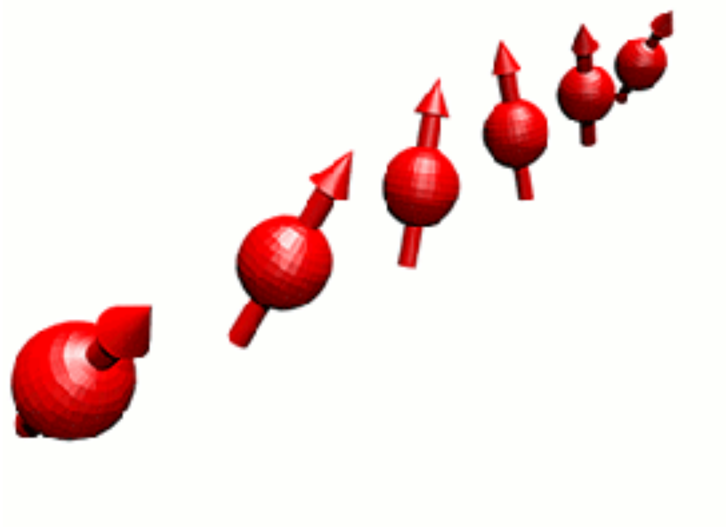

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Anomalous enhancement of spin & heat conductances resulting from **the magnonic criticality**

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Parameters tunable by lasers & magnetic fields → Various many-body systems

- Interactions b/w atoms
- Spatial dimension
- Lattice structure

- **Ferromagnetic Heisenberg spins**
- Antiferromagnetic Heisenberg spins
- Superfluids of Fermi gases

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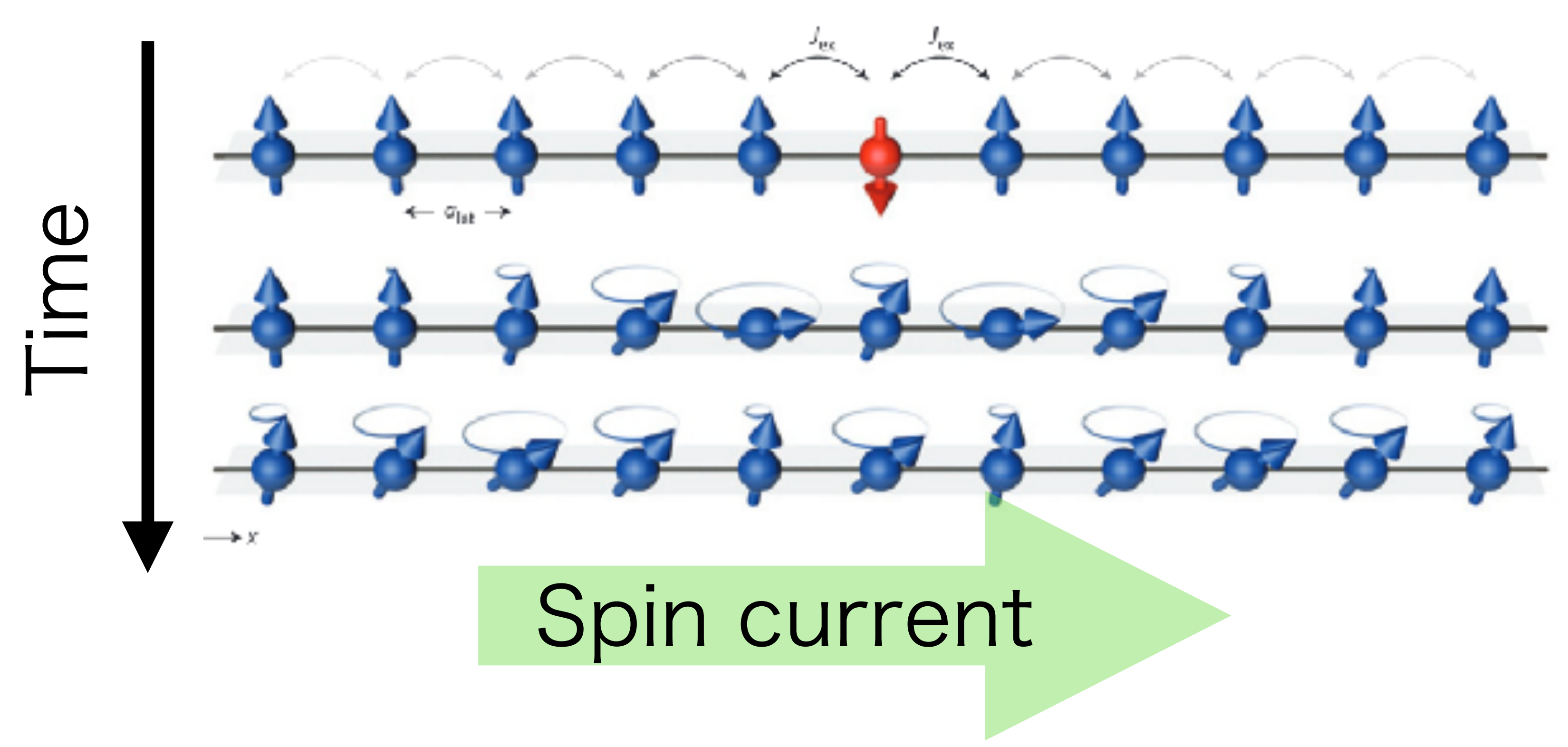
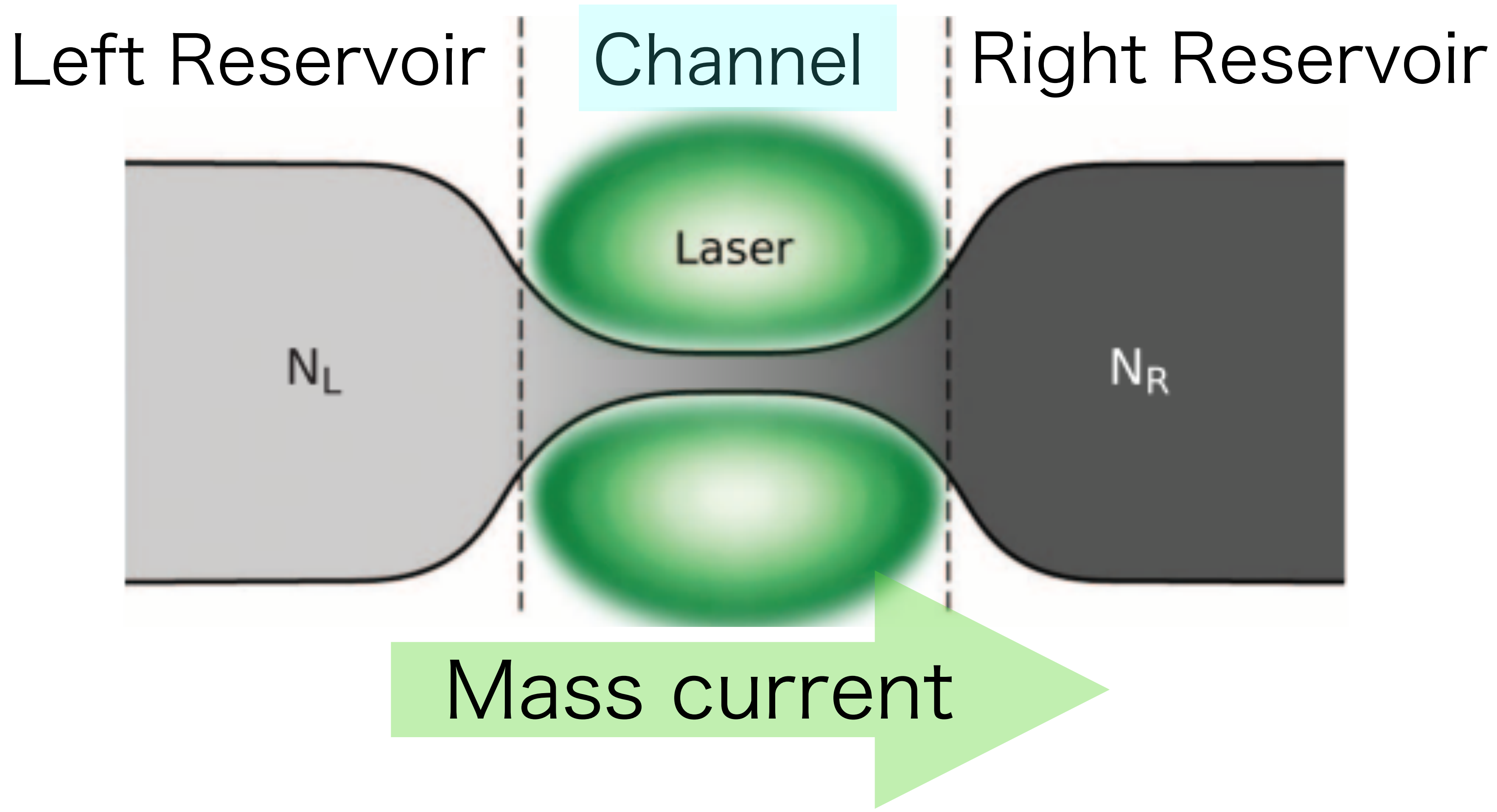
Cold atoms as platforms for **quantum transport**

Bulk spin transport in ferromagnetic Heisenberg spins



MPI: Fukuhara et al., Nat. Phys (2013); Nature (2013);
Hild et al., PRL (2014); Wei et al., Science (2022)
MIT: Jepsen et al., Nature (2020); PRX (2021); Nat. Phys. (2022).

Tunneling mass transport b/w Fermi gases



ETH: Brantut et al., Science **337**,1069-1071(2012); …
LENS: Valtolina et al., Science **350**, 1505-1508(2015); …
Kyoto (w/ synthetic dim): Ono et al., Nat Commun **12**, 6724 (2021)

Extending tunneling transport to spin systems

We propose tunneling transport b/w quantum magnets with ultracold atoms

YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280

Between Fermi atomic gases

ETH: Brantut et al., Science **337**,1069-1071(2012); ⋯

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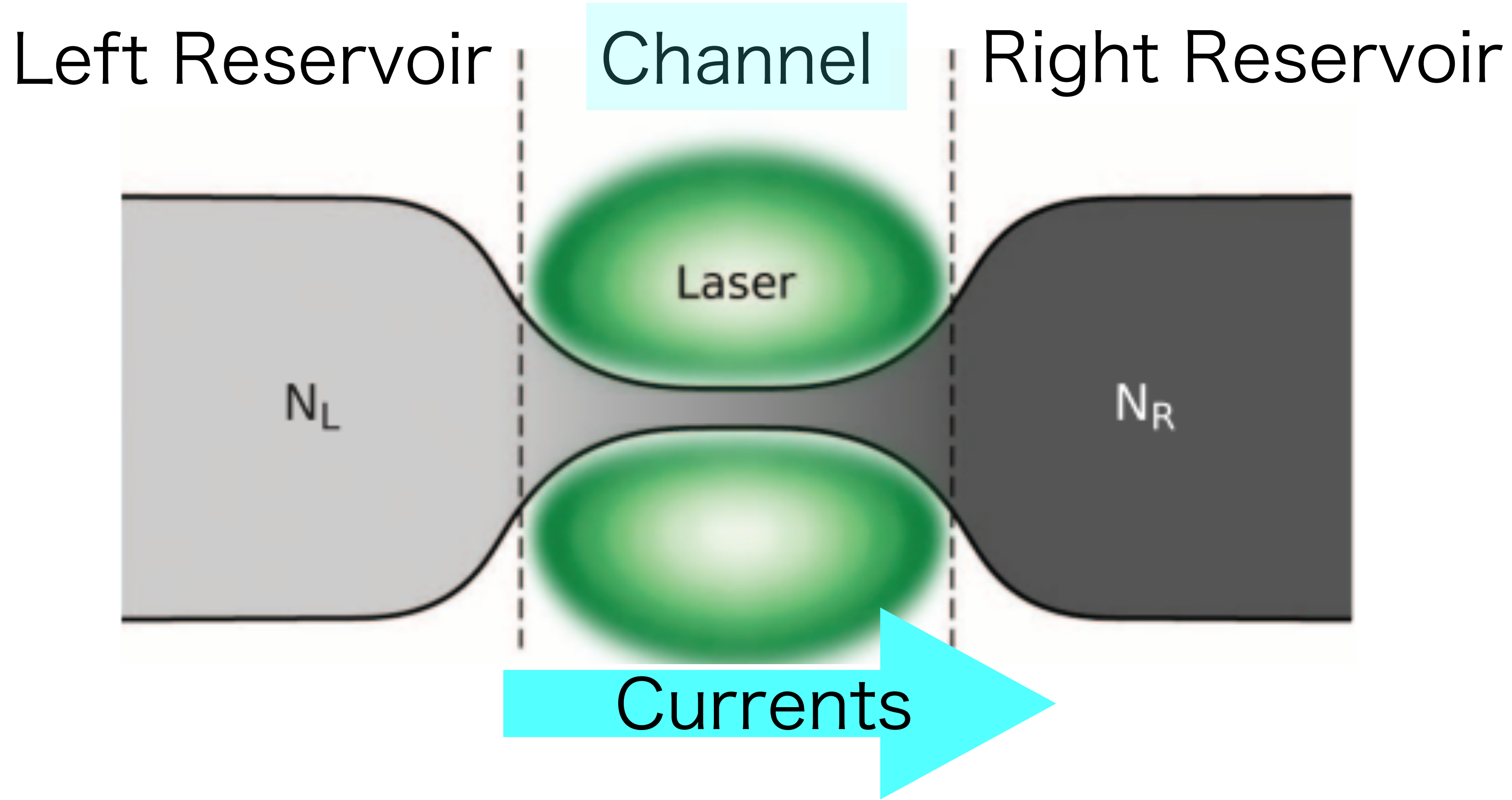
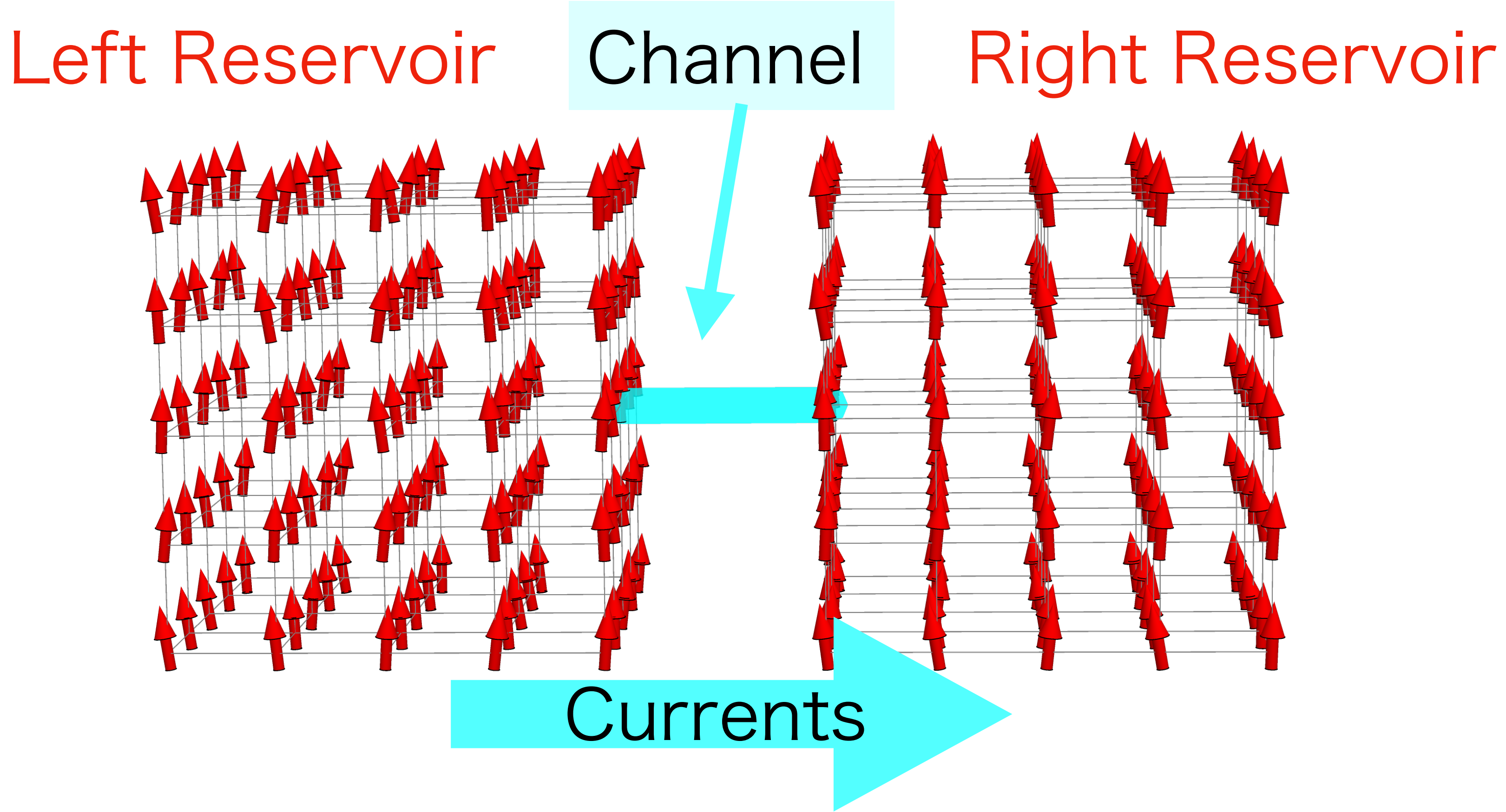


Governed by atoms

Between ferromagnetic Heisenberg spins

YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280



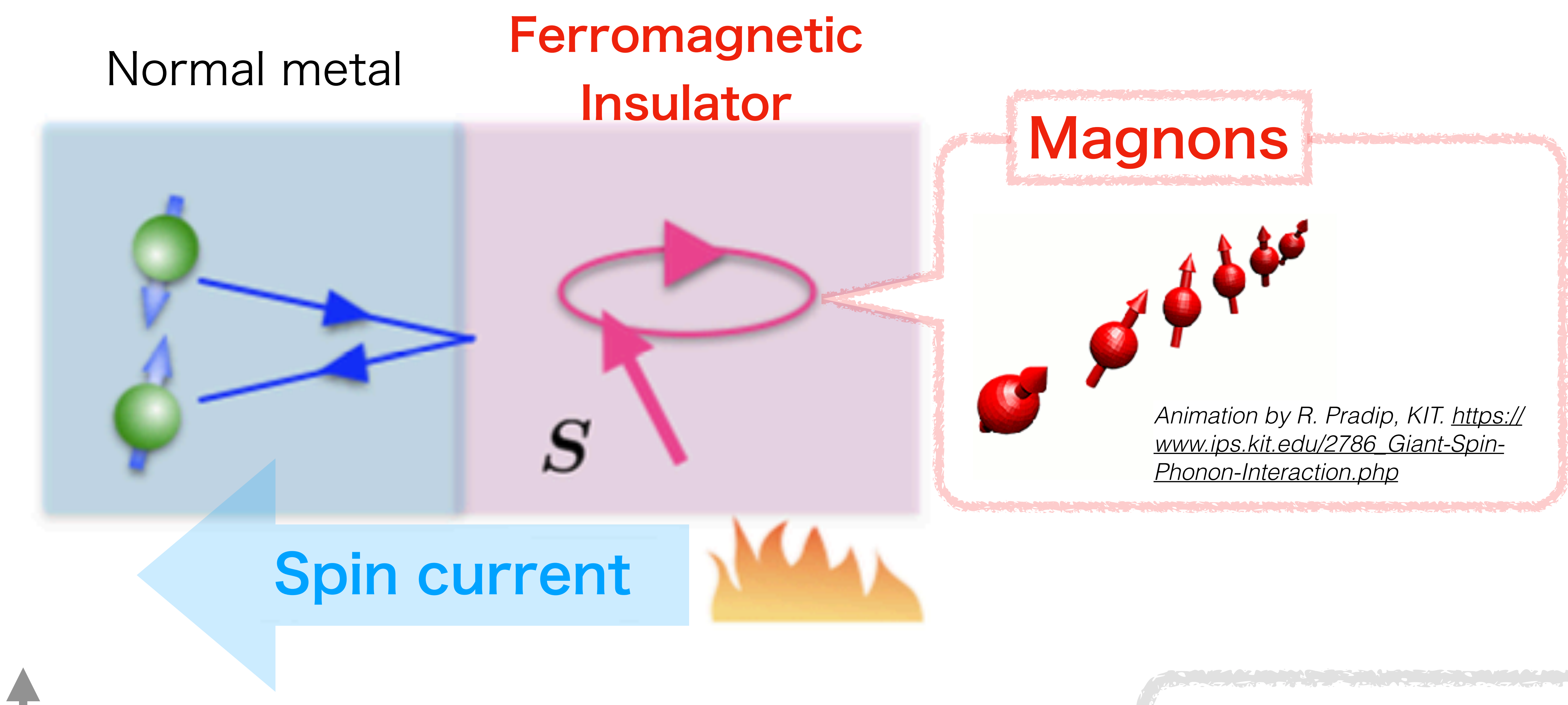
Governed by **magnons !!**

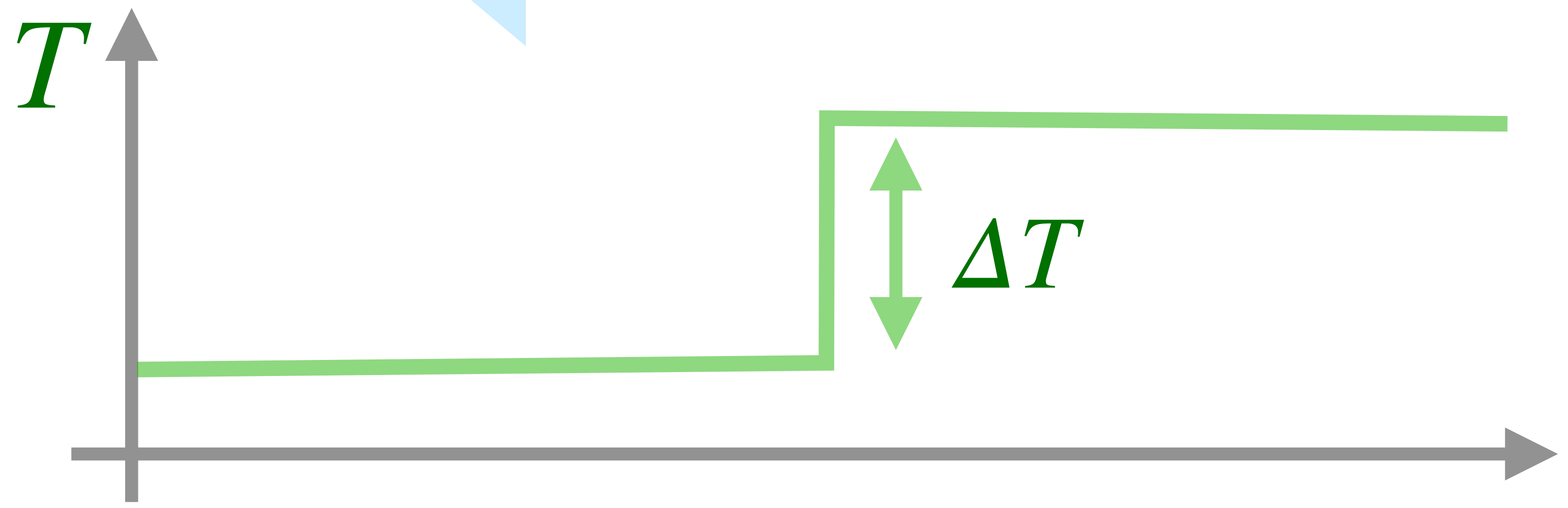
Animation by R. Pradip, KIT.
https://www.ips.kit.edu/2786_Giant-Spin-Phonon-Interaction.php

Motivation from solid-state physics

Spin and heat tunneling transport with magnons is one of the hot topics in spintronics focusing on efficient **spin-heat** conversion for devices applications

- **Spin Seebeck effect:** spin-current generation by **temperature bias ΔT**





Observation:
Uchida et al., Nature **455**, 778–781 (2008)
Review of spin caloritronics:
Bauer et al., Nature Materials **11**, 391–399 (2012)

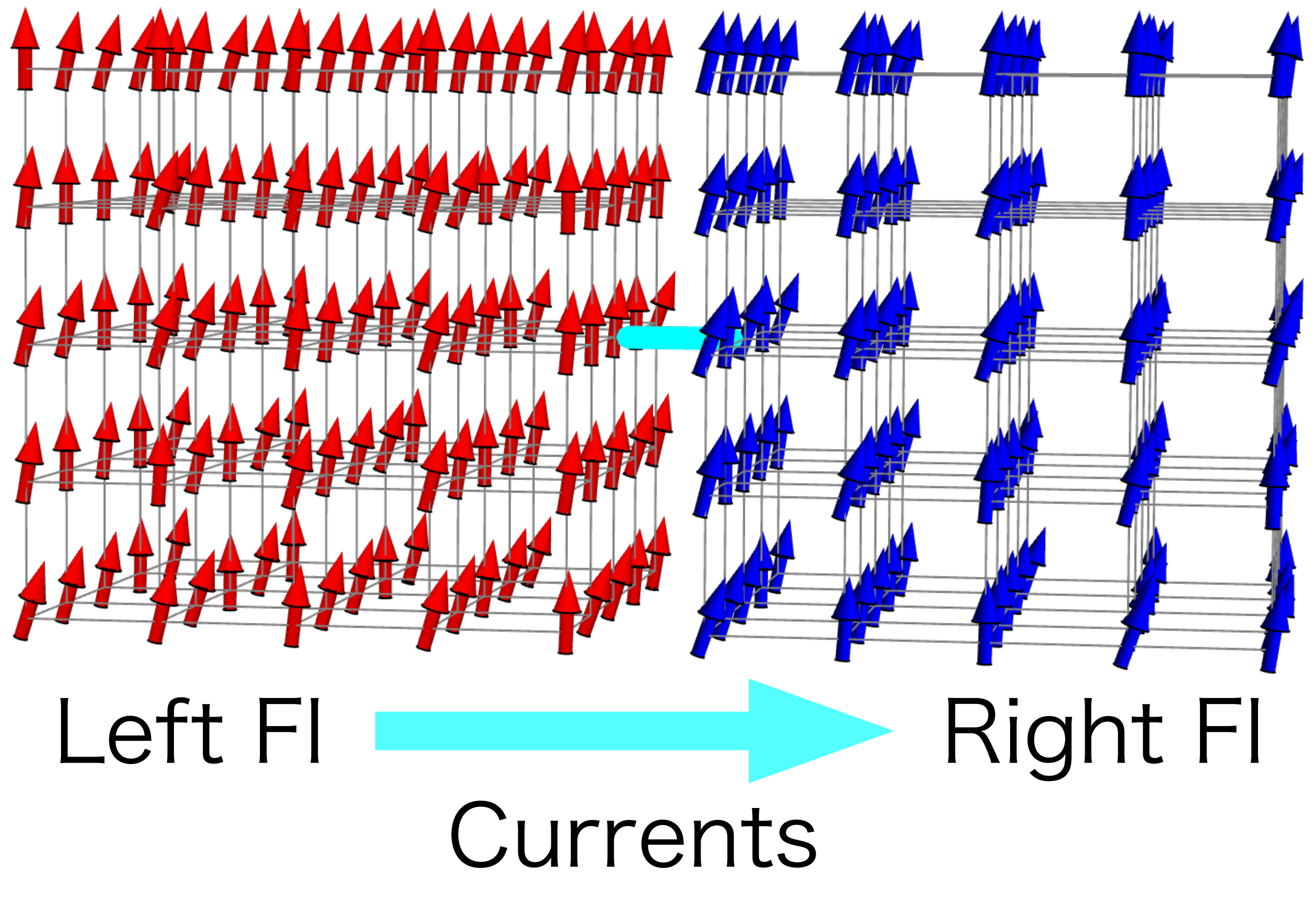
Spin & heat transport is basic, important issues in **both cold-atomic and solid-state physics**

Quantum simulation of magnonic transport

To bridge cold atoms and spintronics, we propose **tunneling spin & heat transport of magnons by utilizing high controllability of cold atoms**

<u>YS</u>, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280

Heisenberg FIs



Cold-atomic physics

Solid-state physics

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Why tunneling spin & heat transport w/ cold atoms?

1. Ultraclean systems

   No impurity

   No roughness & lattice mismatch

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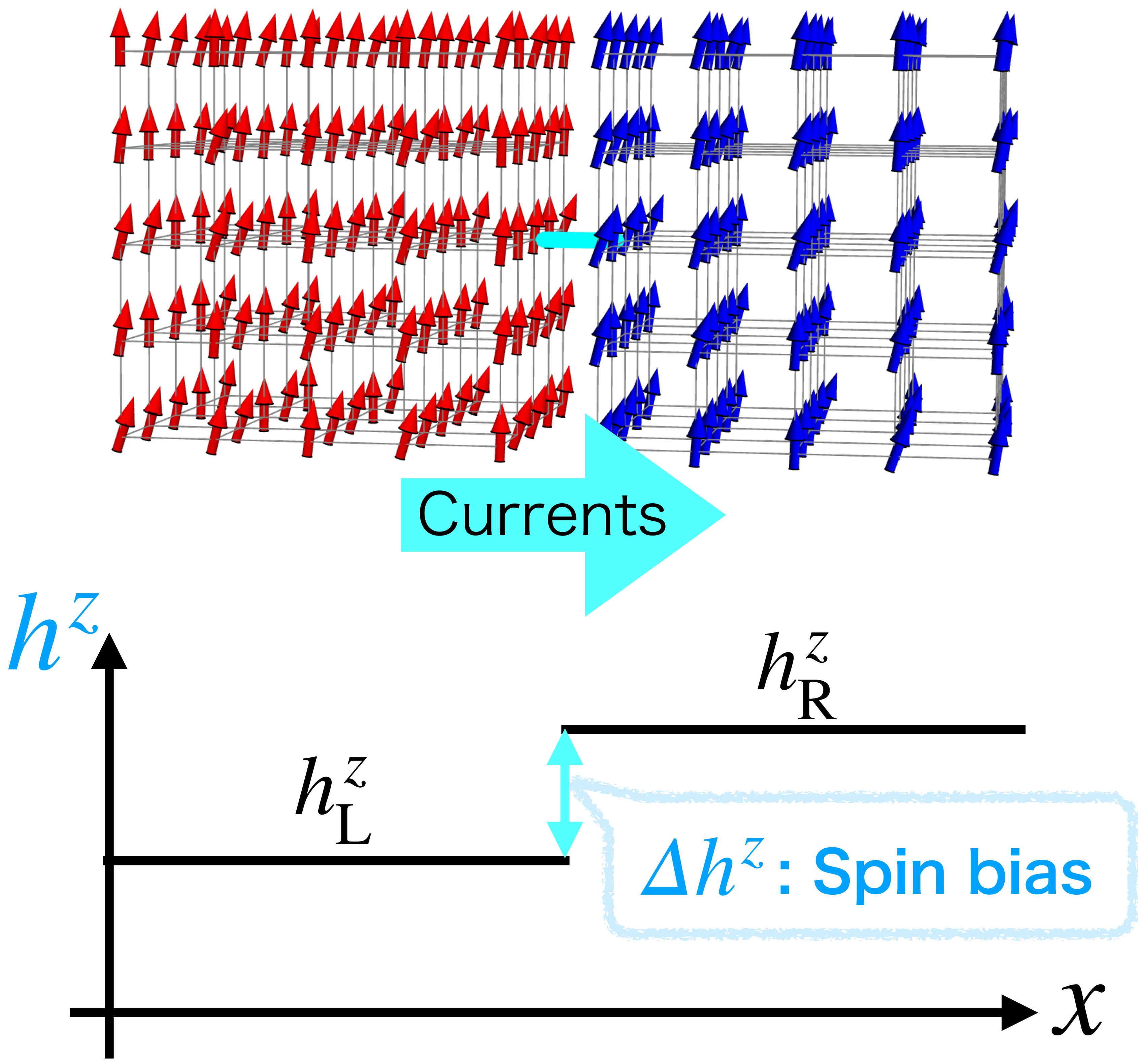
2. Controllability of **effective Zeeman field** $\vec{h}(\vec{r})$ **(= chemical potential of spin)**



$$H_{\mathrm{Zeeman}} = -\int d\vec{r}\,\vec{h}(\vec{r}) \cdot \hat{\vec{s}}(\vec{r})$$

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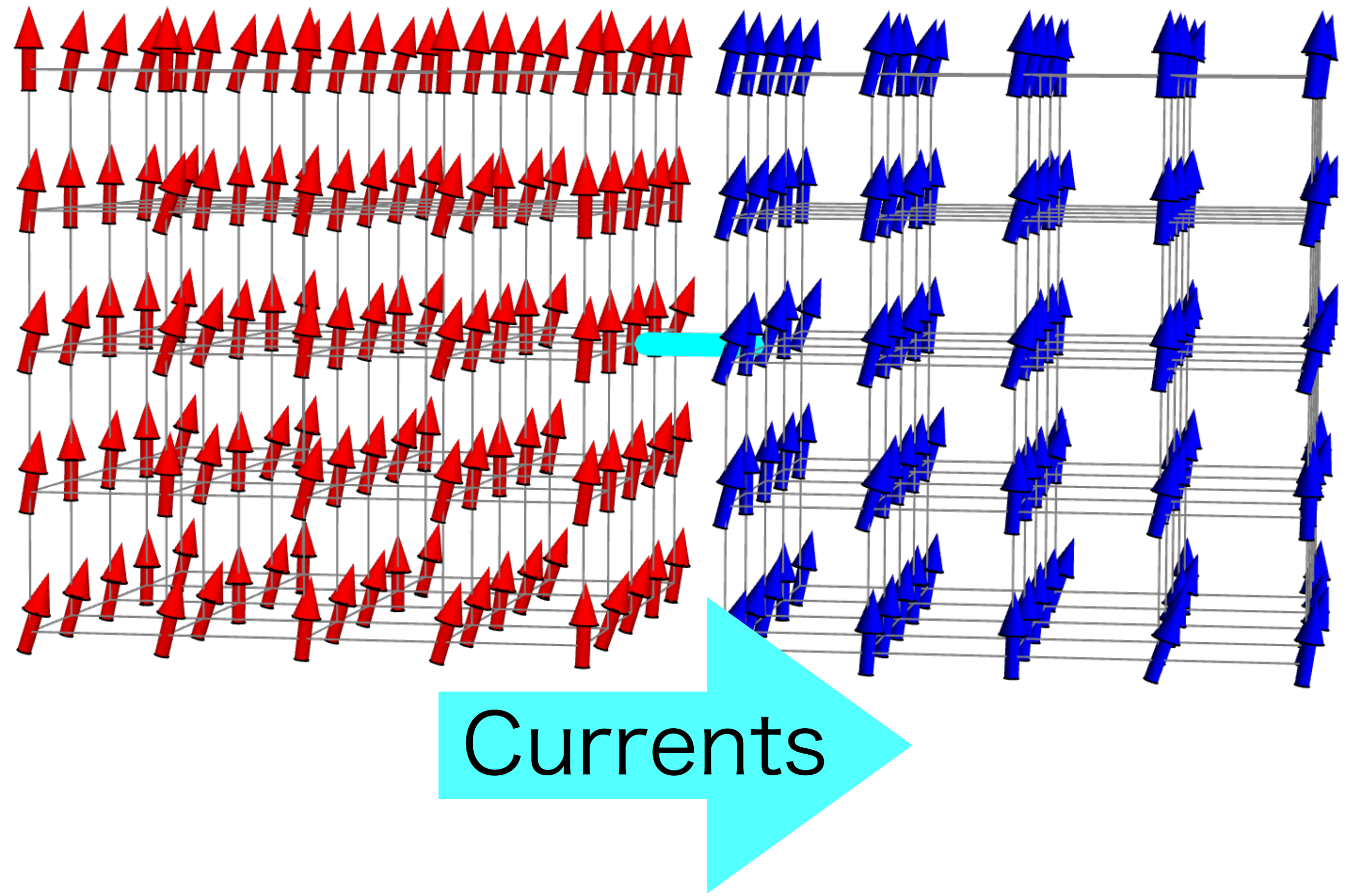

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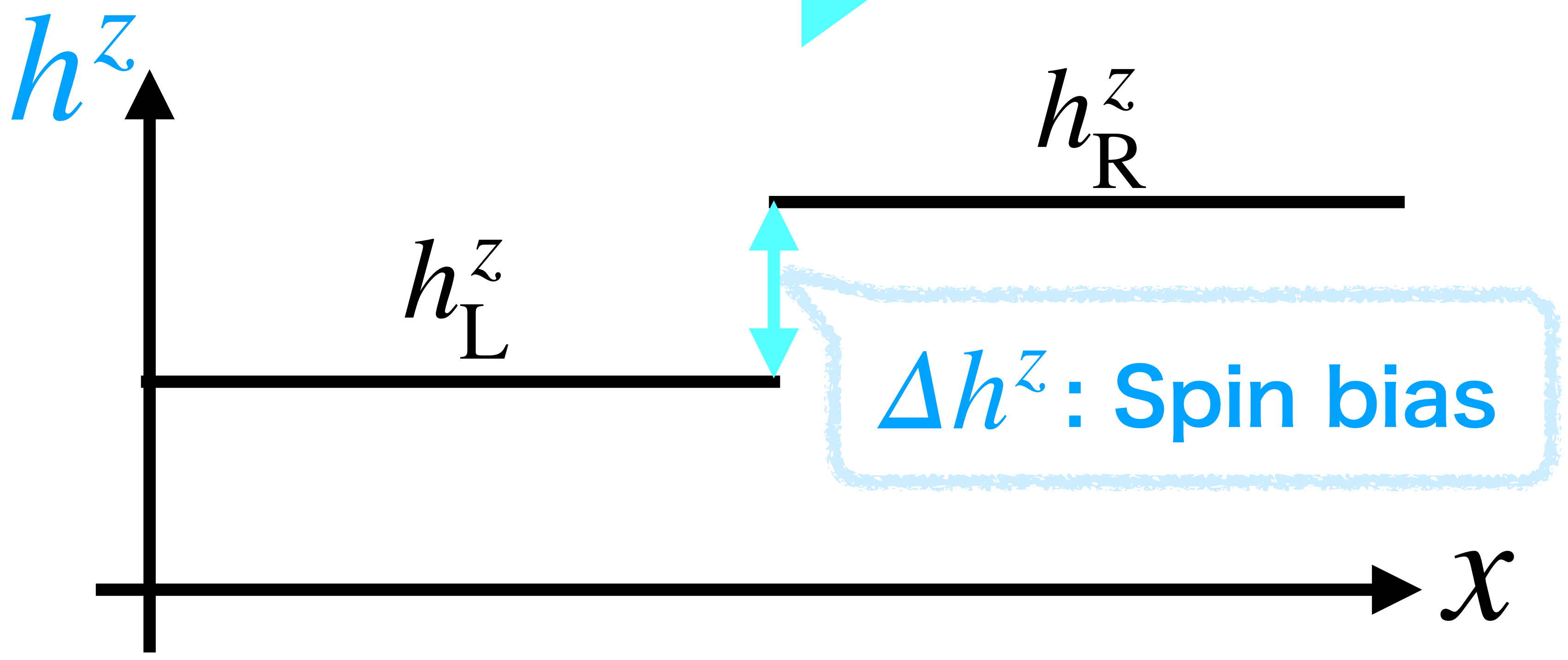

Solid-state experiments:

Gerenration of Δh is challenging

w/ spatially modulated magnetic fields

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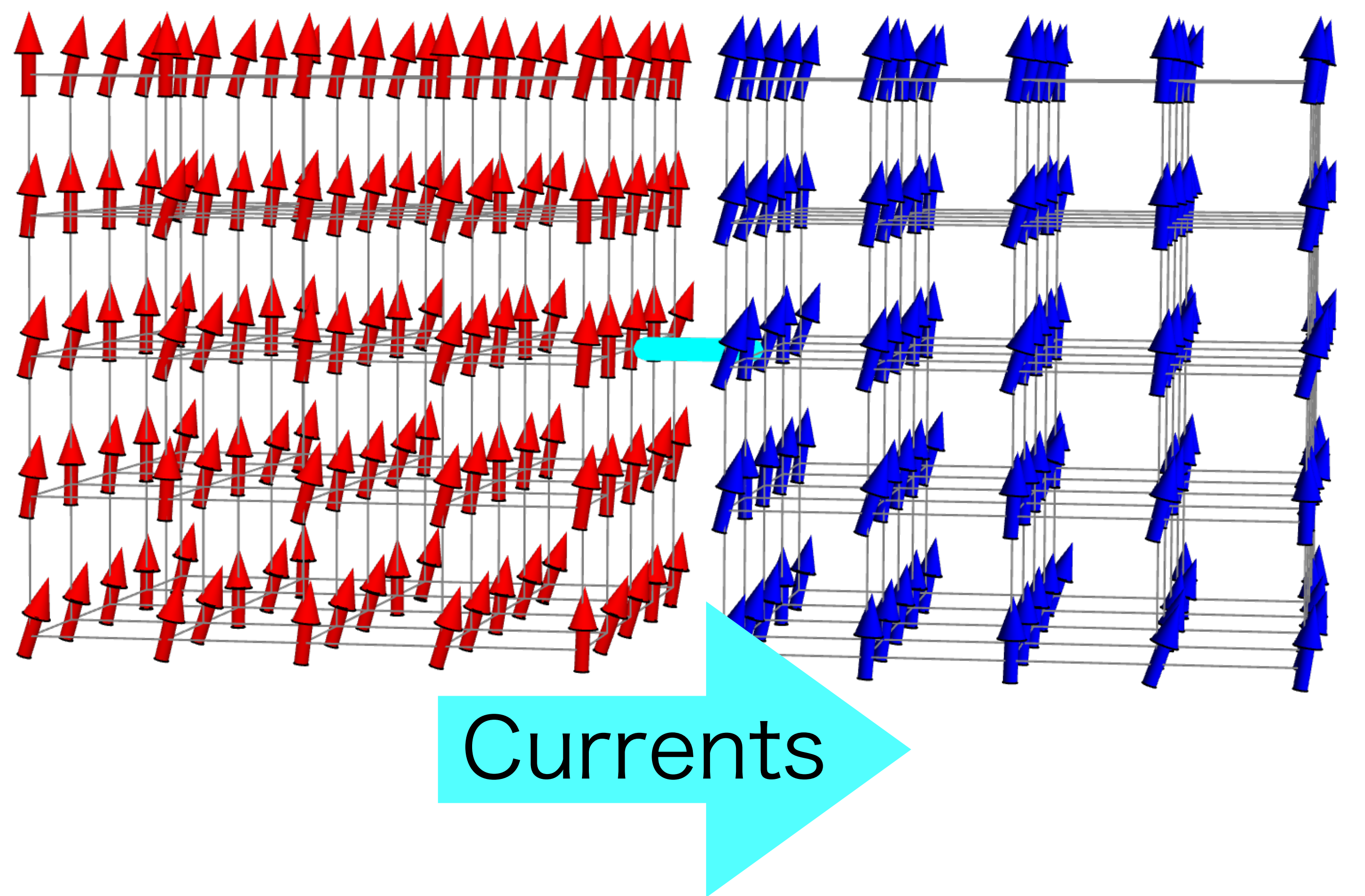

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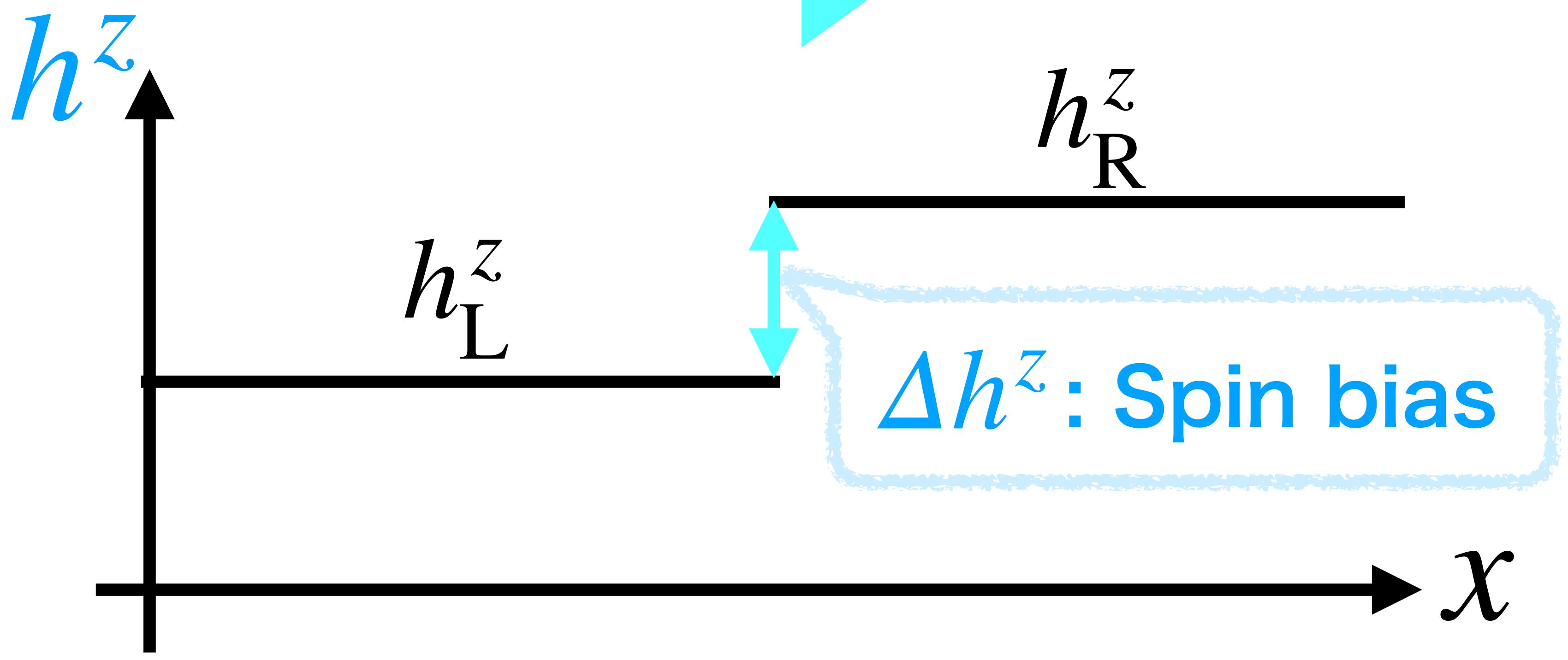

Solid-state experiments:

Gerenration of Δh is challenging

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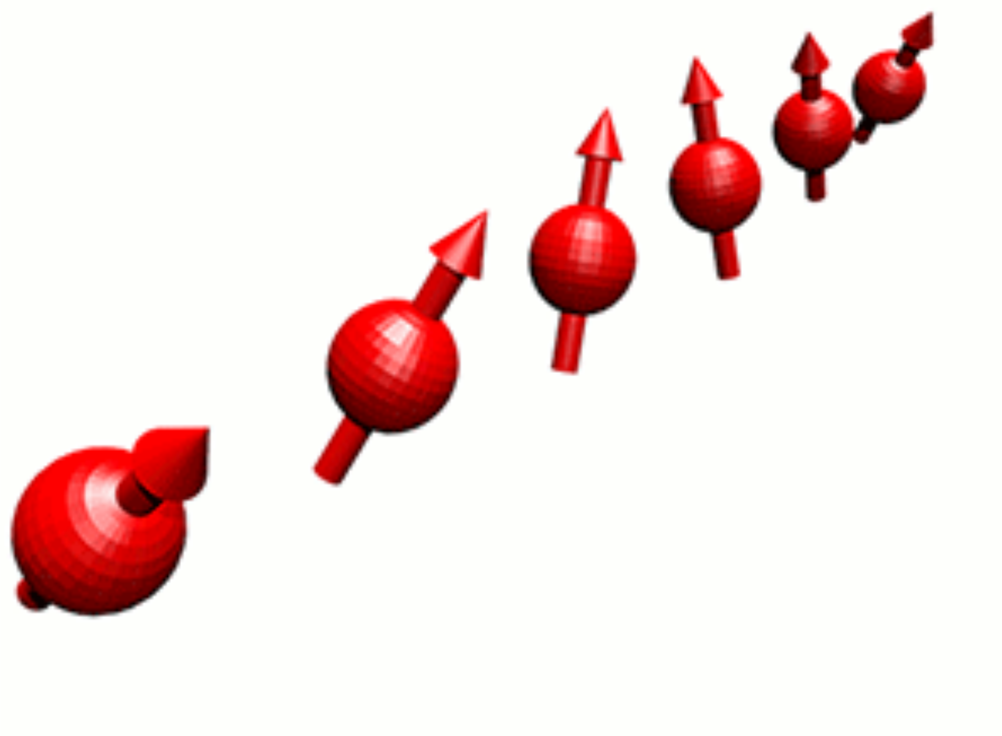
Cold-atom experiments:

Controllable, effective Δh has been achieved by directly manipulating magnetization $M^z_{\mathrm{L}}, M^z_{\mathrm{R}}$ of each reservoir

For Fermi gases
[Kriner et al., PNAS, **113** (29) 8144-8149 (2016)]

Magnons and its criticality in ferromagnetic insulators



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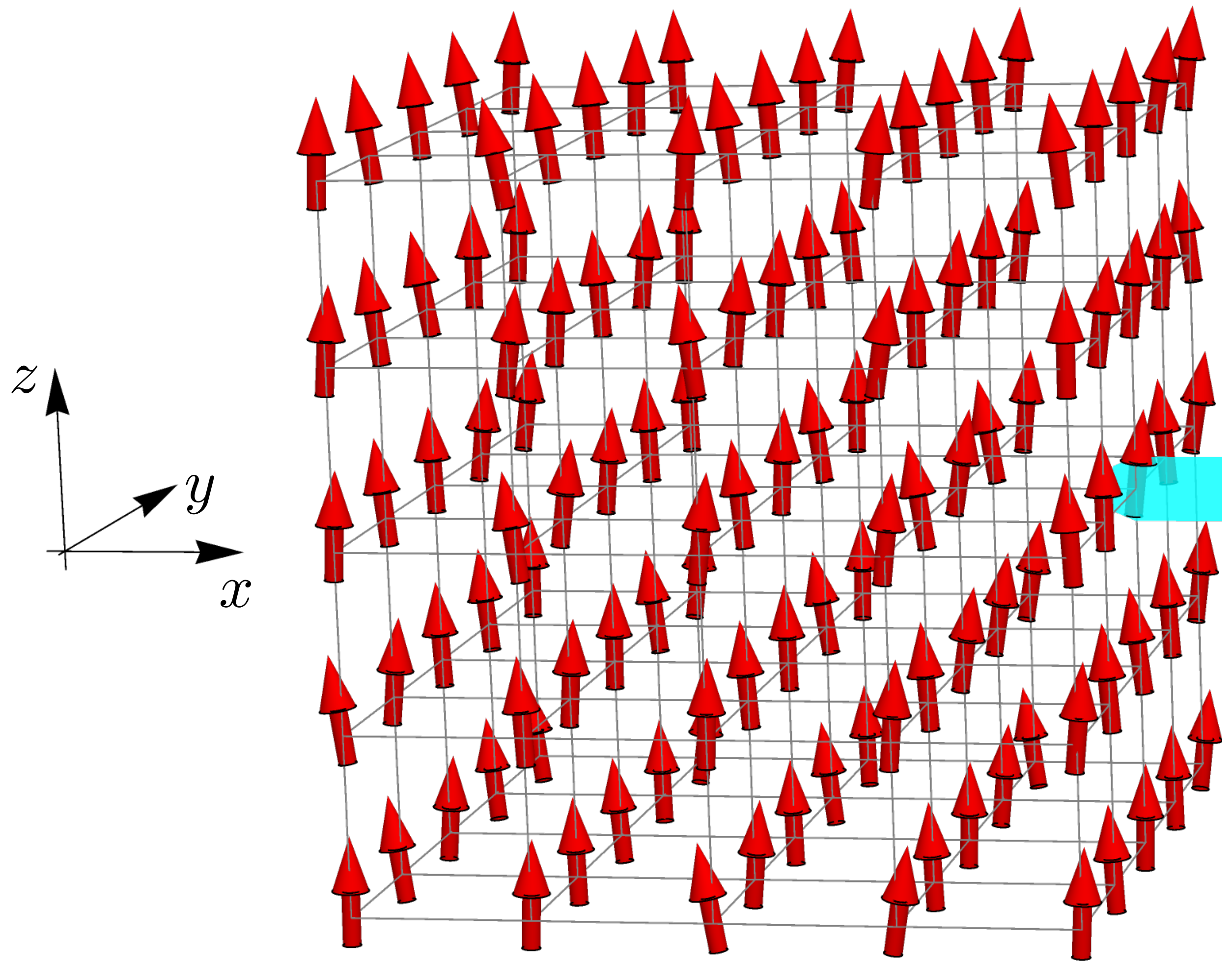
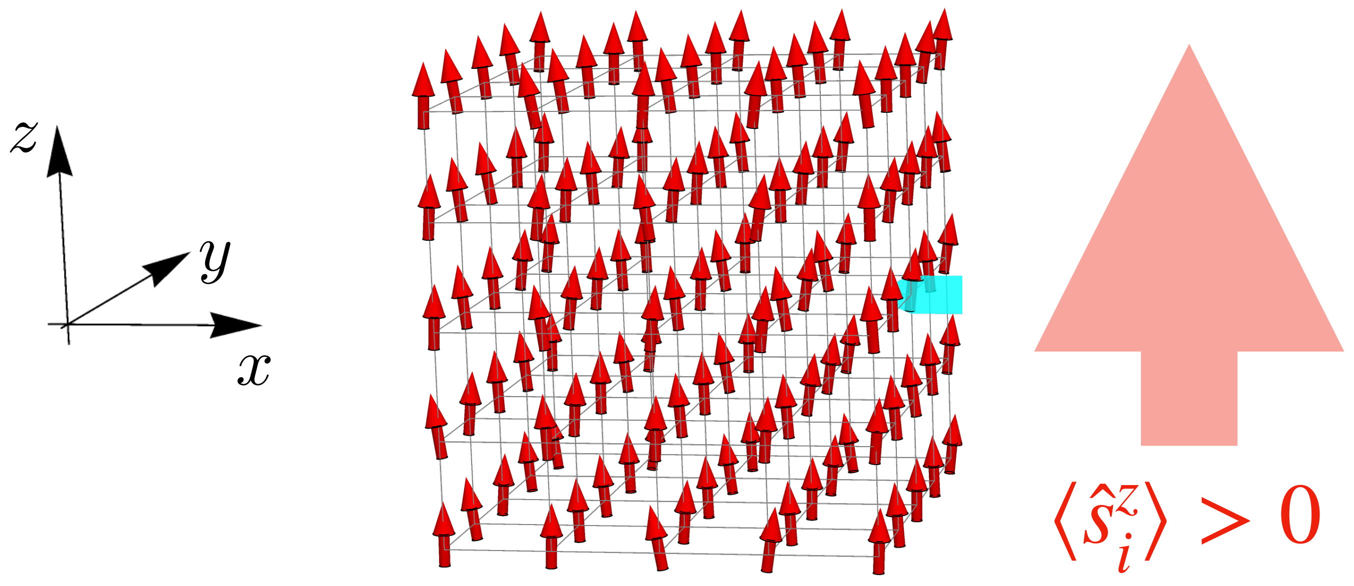


Magnons as quasiparticle in ferromagnets

Ferromagnetic Heisenberg model



$$\hat{H}^{\mathrm{Hei}} = -J \sum_{\langle i,j \rangle} \vec{\hat{s}}_i \cdot \vec{\hat{s}}_j - h \sum_i \hat{s}_i^z$$

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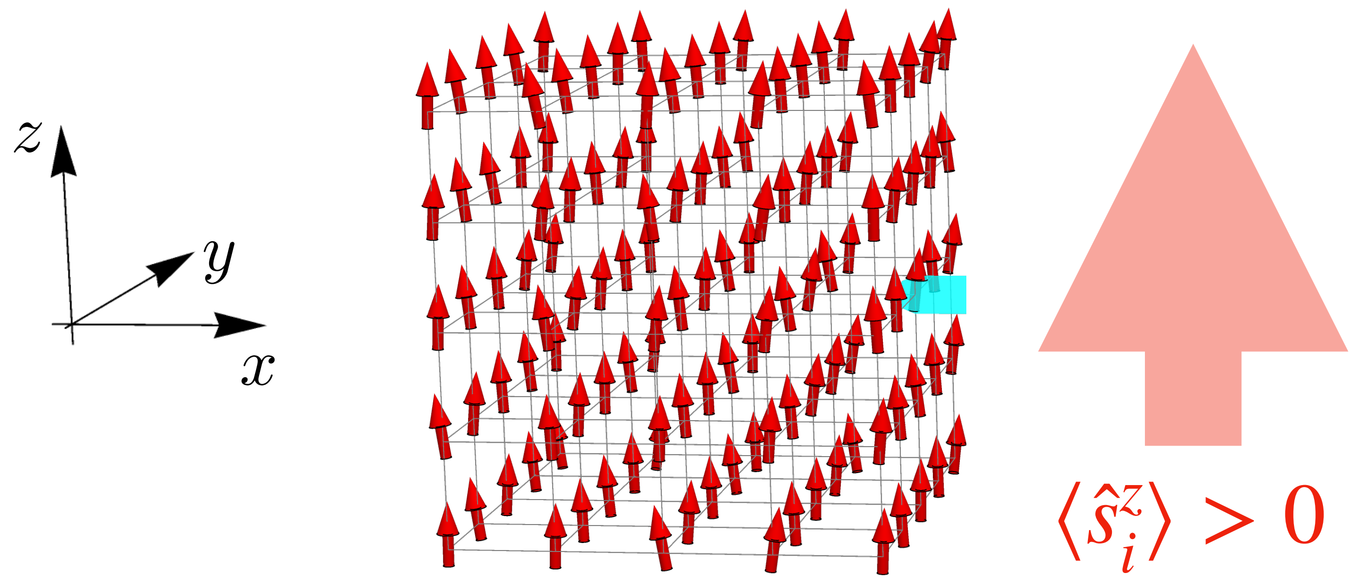

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Holstein-Primakov trans.

$$\hat{s}_i^z = S - \hat{b}_i^\dagger \hat{b}_i$$

$$\hat{s}_i^- = \sqrt{2S - \hat{b}_i^\dagger \hat{b}_i}\,\hat{b}_i^\dagger$$

$$\hat{s}_i^+ = \hat{b}_i \sqrt{2S - \hat{b}_i^\dagger \hat{b}_i}$$

b_i : Bosonic field

$S = 1/2, 1, 3/2, \cdots$

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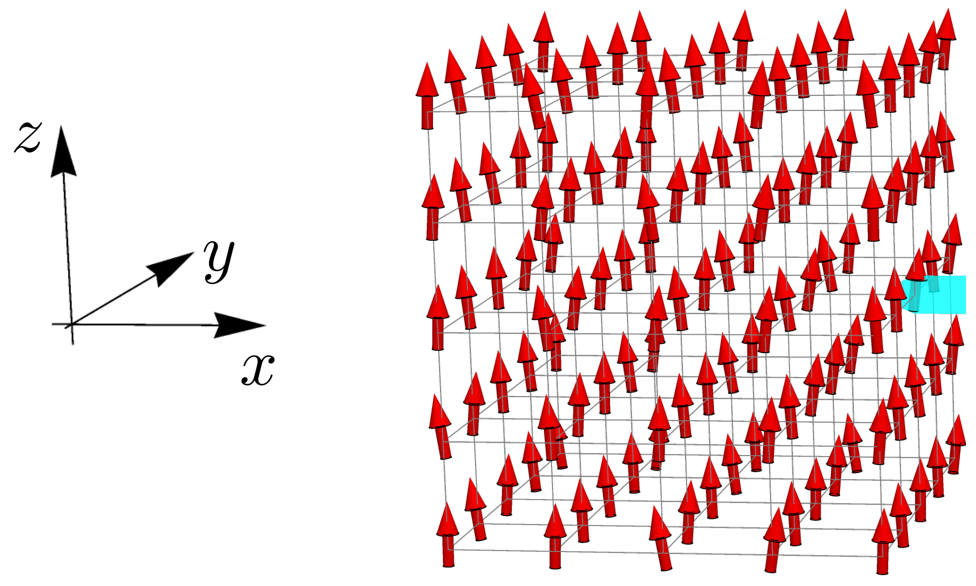

$\langle \hat{s}_i^z \rangle > 0$

High polarization

$\langle \hat{s}_i^z \rangle \approx S$ or $\langle \hat{b}_i^\dagger \hat{b}_i \rangle \ll 1$

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Spin-wave approx.

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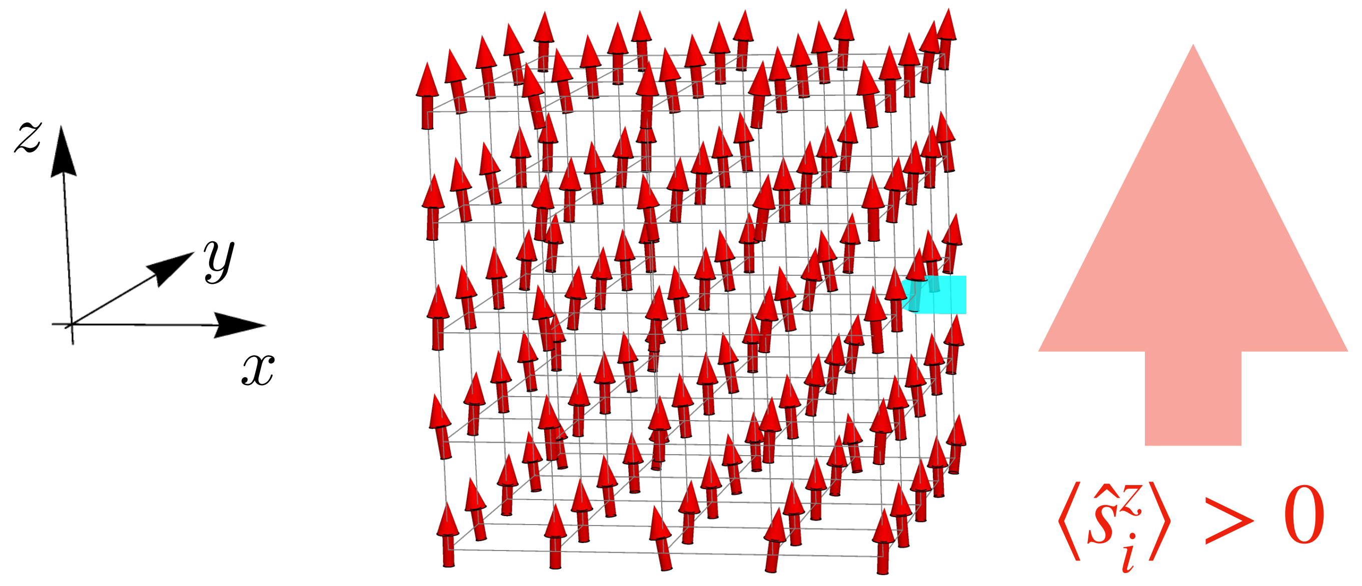

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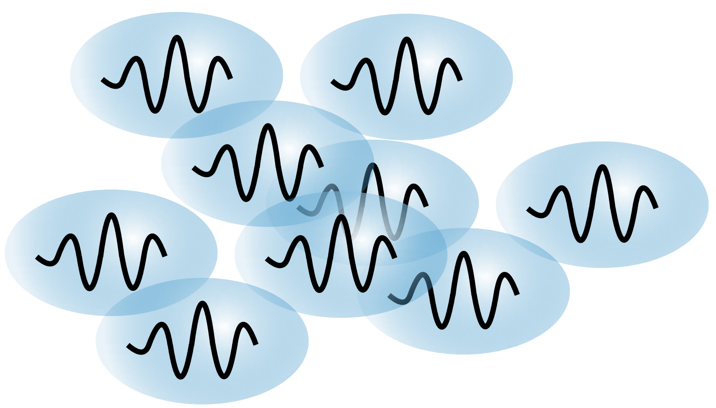
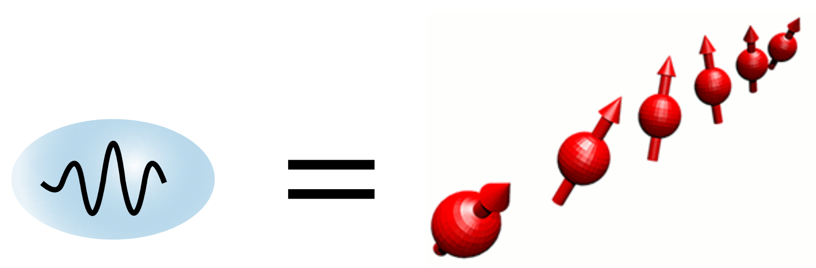
Gas of thermally excited magnons





$$H^{\mathrm{Hei}} \approx \sum_{\vec{k}} E_{\vec{k}} b_{\vec{k}}^\dagger b_{\vec{k}}$$

$b_{\vec{k}}$: field of magnon

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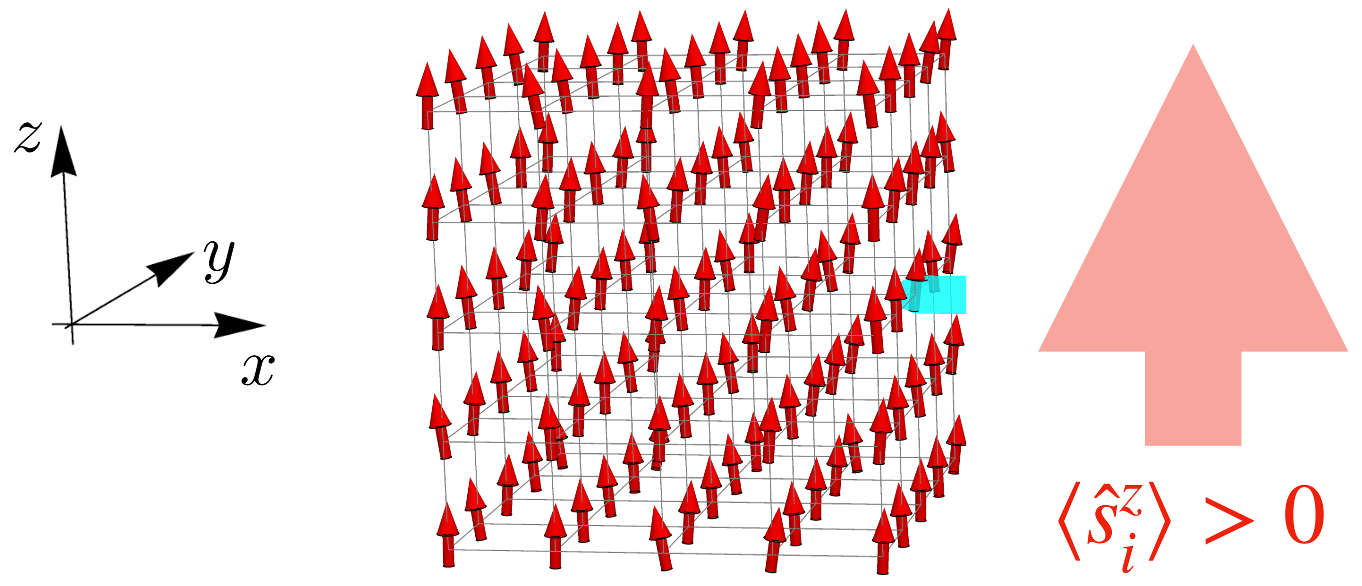

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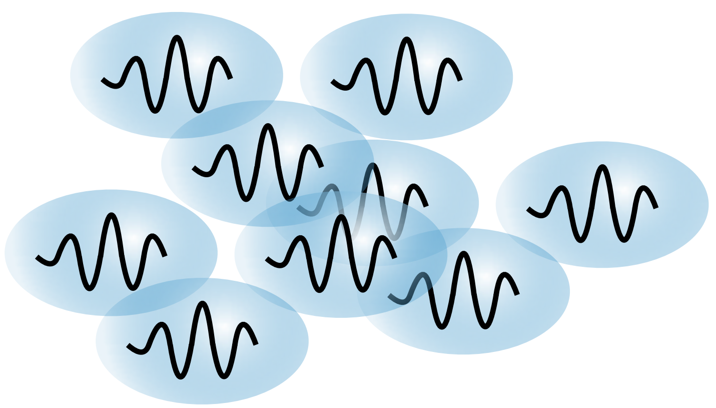
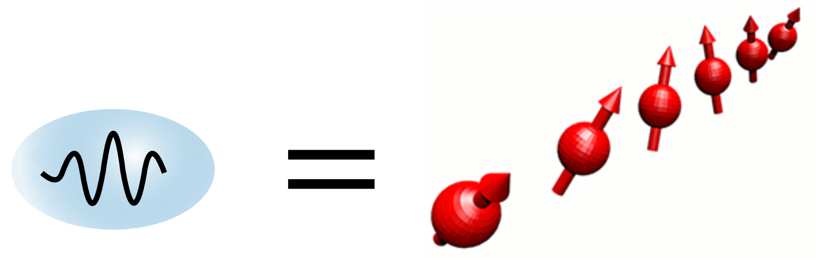


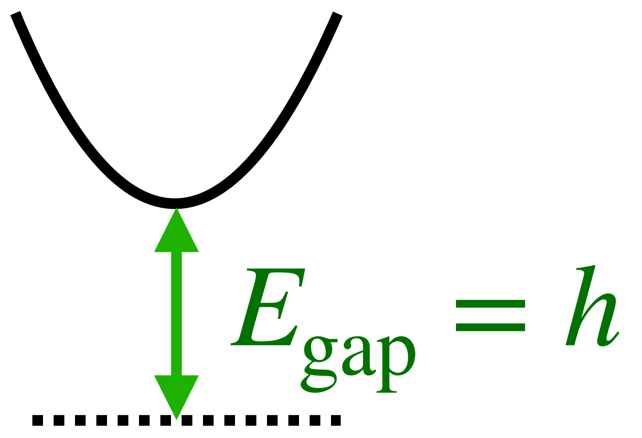


$$H^{\mathrm{Hei}} \approx \sum_{\vec{k}} E_{\vec{k}} b_{\vec{k}}^\dagger b_{\vec{k}}$$

$b_{\vec{k}}$: field of magnon

Magnon energy

$$E_k = 2JSk^2 + h$$



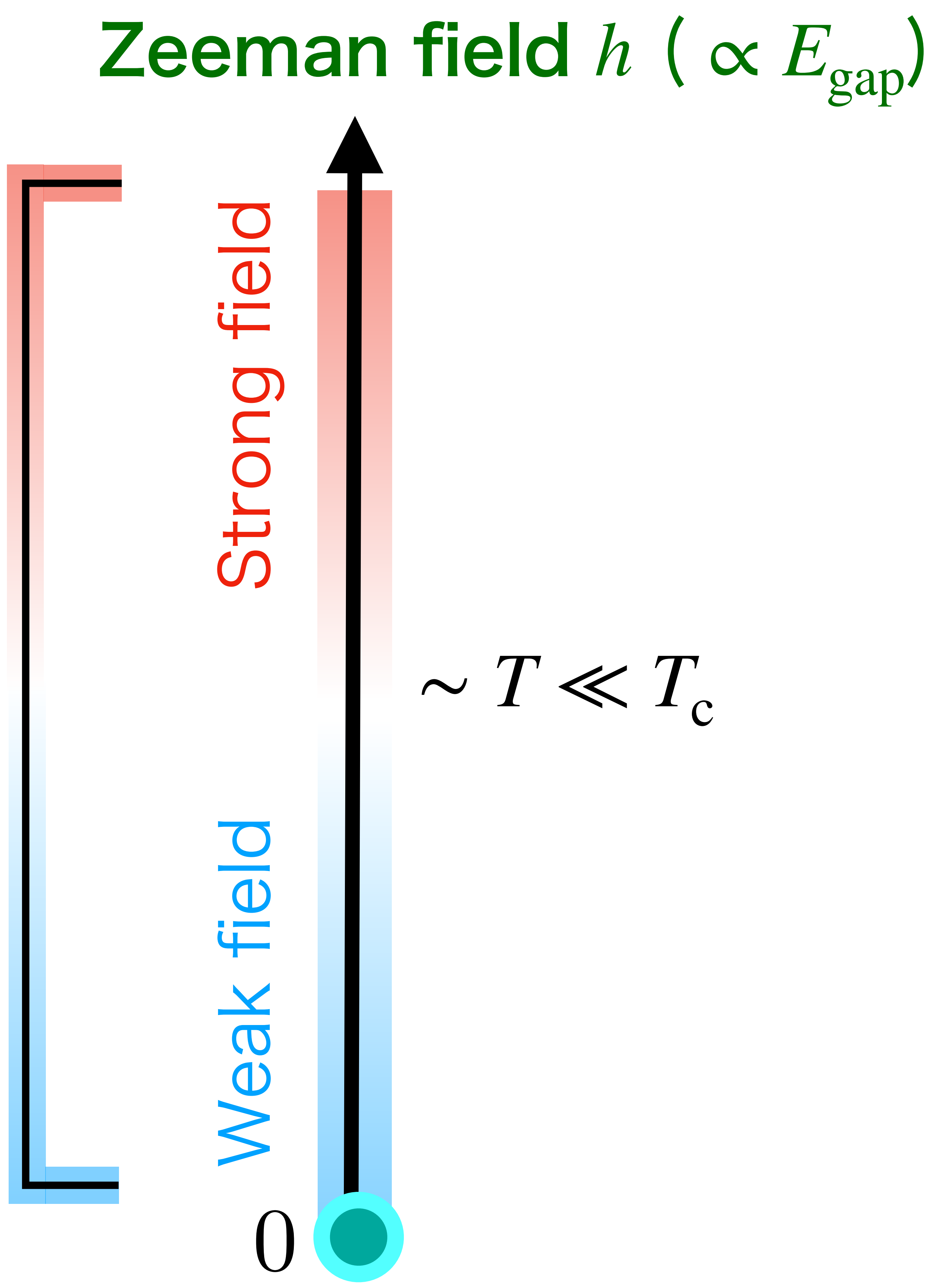
Magnon gap by **Zeeman field** h

Quantum regime of magnons near critical point

Cold atoms

Controllable h

Krinner et al., PNAS **113**, 8144 (2016)



Quantum regime of magnons near critical point

Zeeman field h ($\propto E_{\text{gap}}$)

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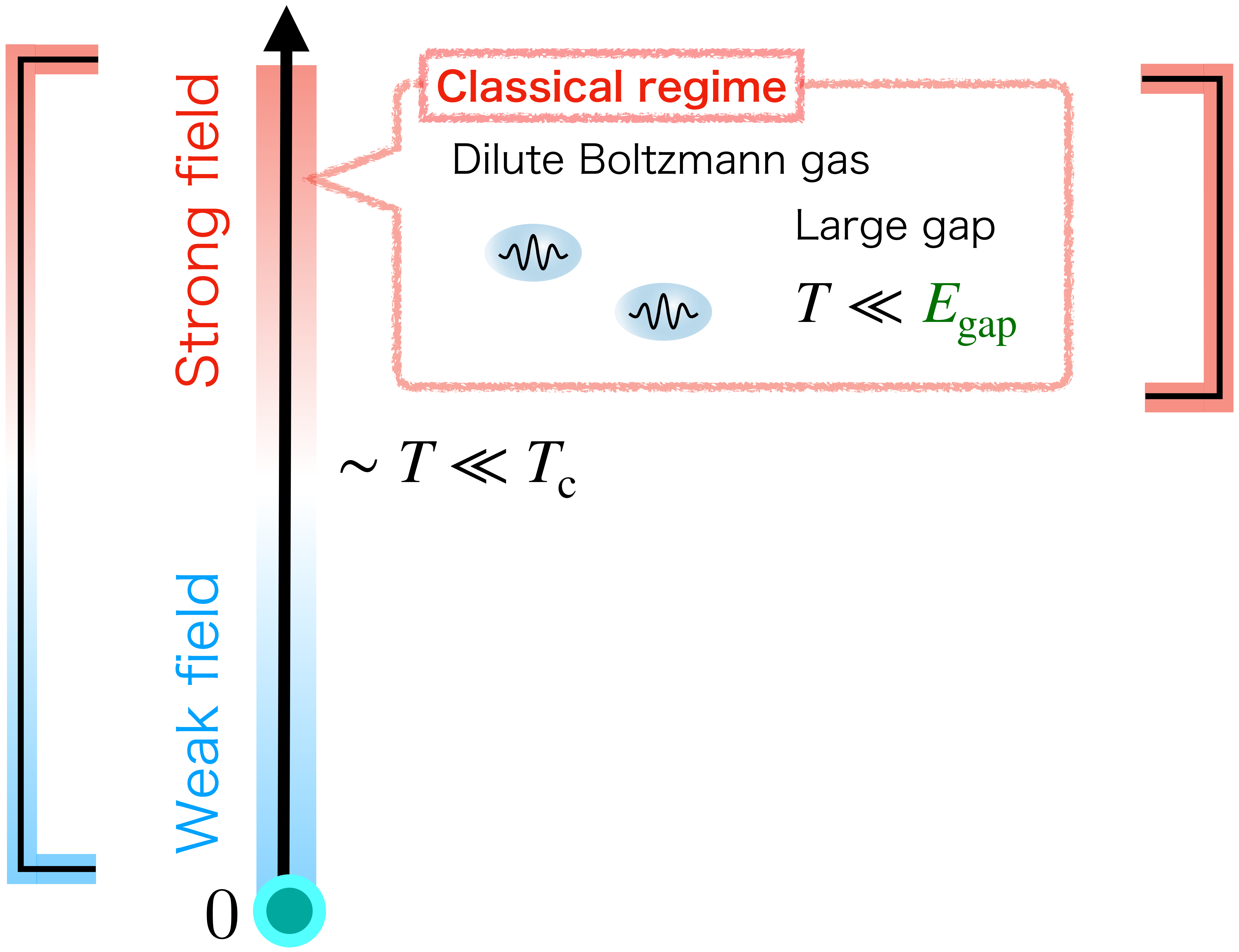
Krinner et al., PNAS **113**, 8144 (2016)



Spintronics w/ solid FI

Tserkovnyak et al., Rev. Mod. Phys. **77**, 1375 (2005)

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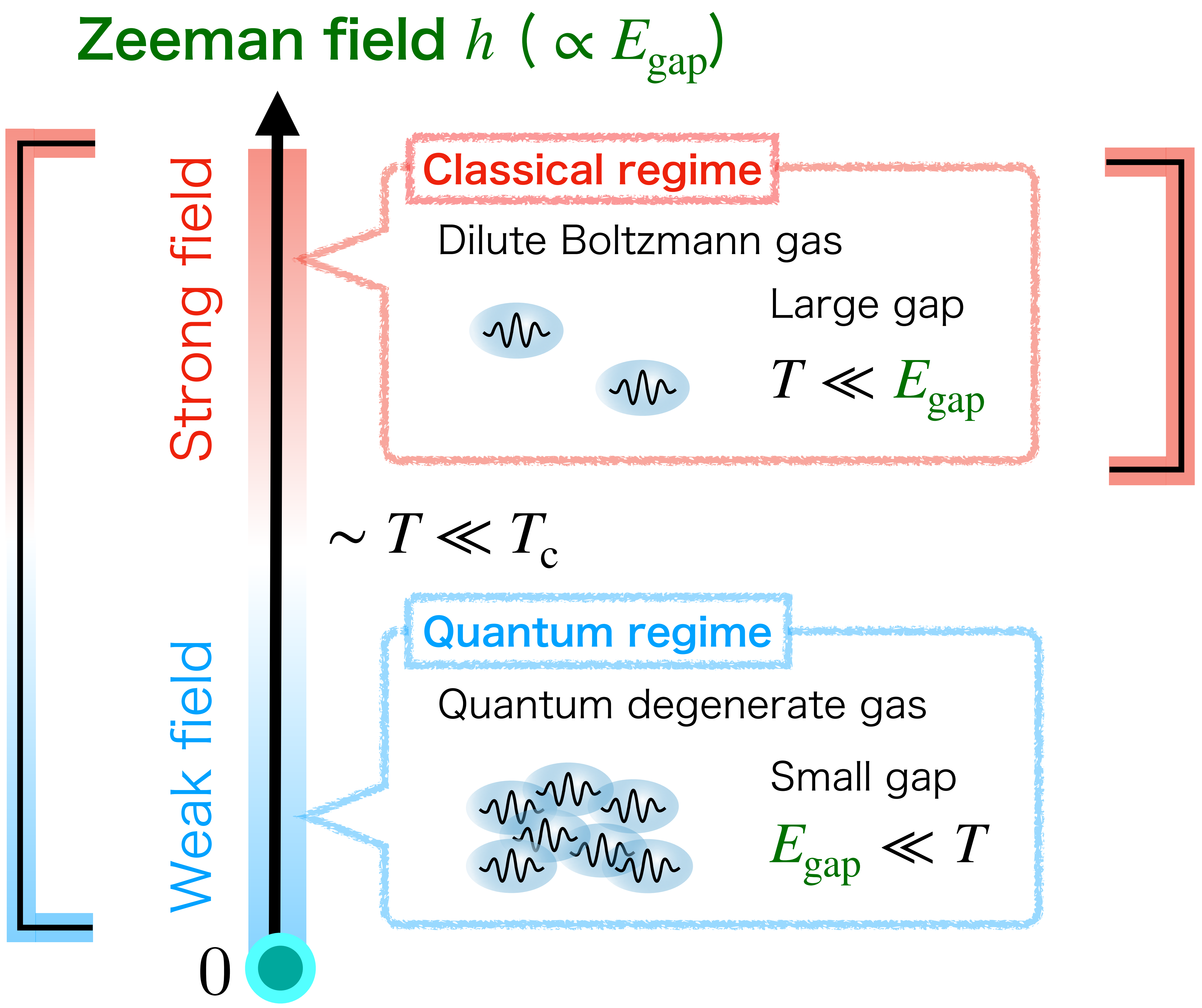

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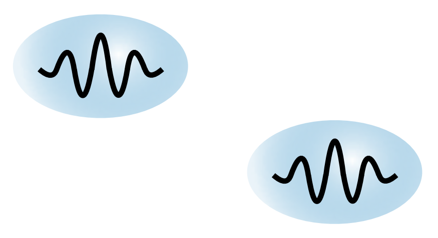
Strong field

Classical regime

Dilute Boltzmann gas



Large gap

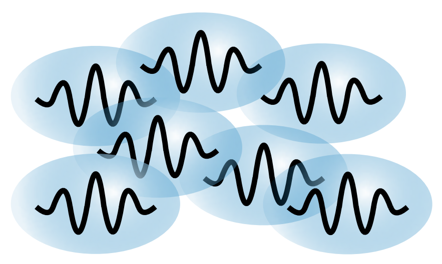
$T \ll E_{gap}$

$\sim T \ll T_c$

Weak field

Quantum regime

Quantum degenerate gas



Small gap

$E_{gap} \ll T$

0

Magnonic critical point

$E_{gap} = h = 0$

Spintronics w/ solid FI

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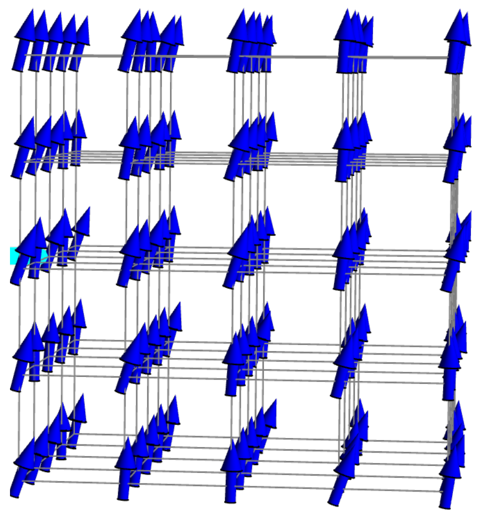
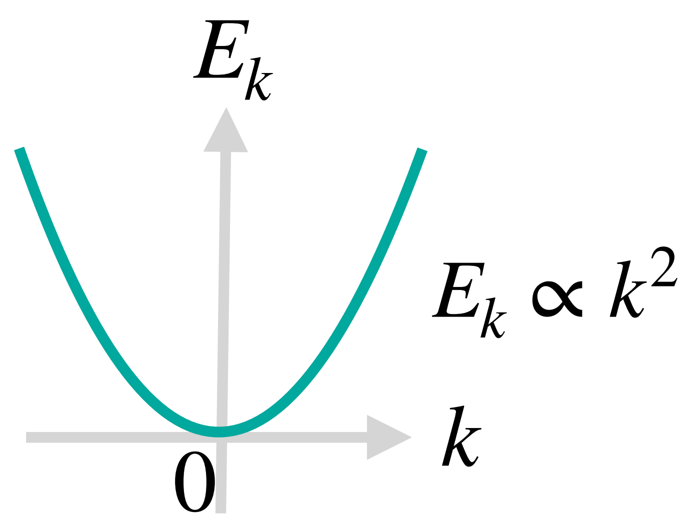
Spontaneous breaking of O(3) symmetry in FIs → **Gapless** magnon as **Nambu-Goldstone mode**



Spontaneous Magnetization



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Spintronics w/ solid FI

Tserkovnyak et al., Rev. Mod. Phys. **77**, 1375 (2005)
W. Bauer et al., Nat. Mater. **11**, 391 (2012)

$\sim T \ll T_{\mathrm{c}}$

Weak field

Quantum regime

Quantum degenerate gas

Small gap

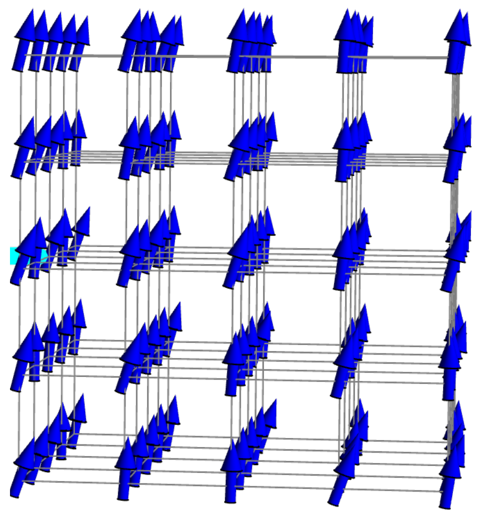
$E_{\mathrm{gap}} \ll T$

0

Magnonic critical point

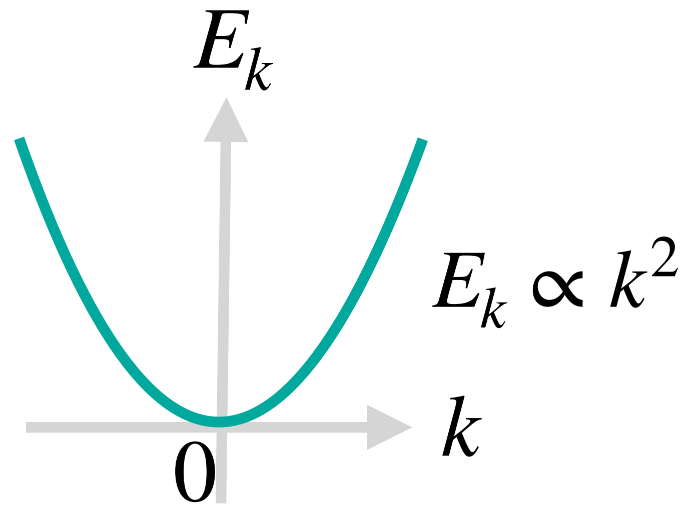
$E_{\mathrm{gap}} = h = 0$

Spontaneous breaking of O(3) symmetry in FIs



Spontaneous Magnetization

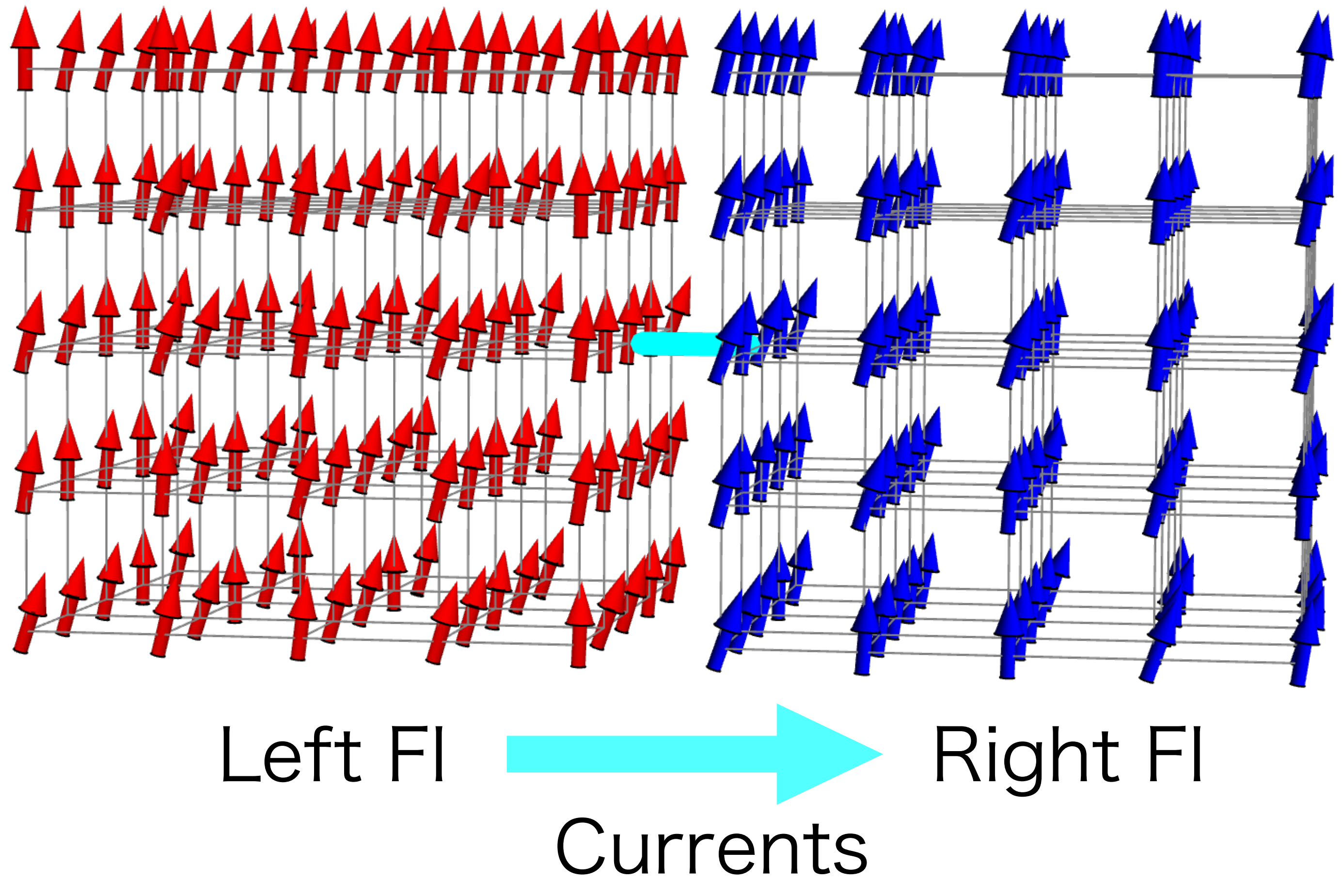
Gapless magnon as **Nambu-Goldstone mode**



Cold atoms allow us to explore **quantum transport** near **the magnonic critical point**

Anomalous tunneling transport of magnons

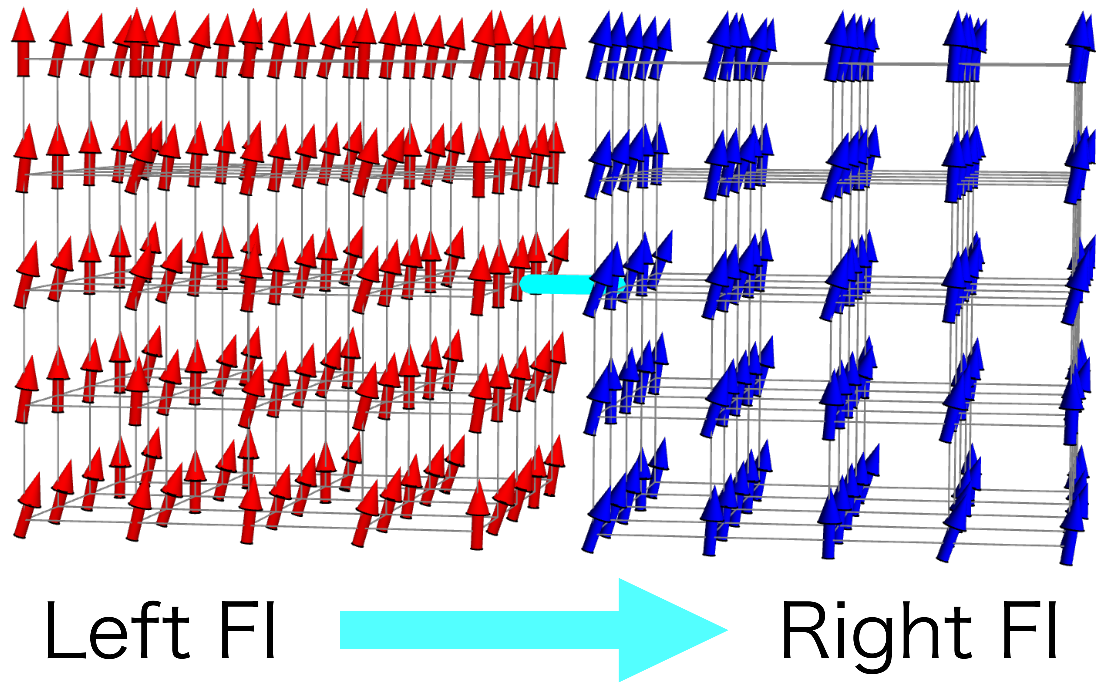
YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280

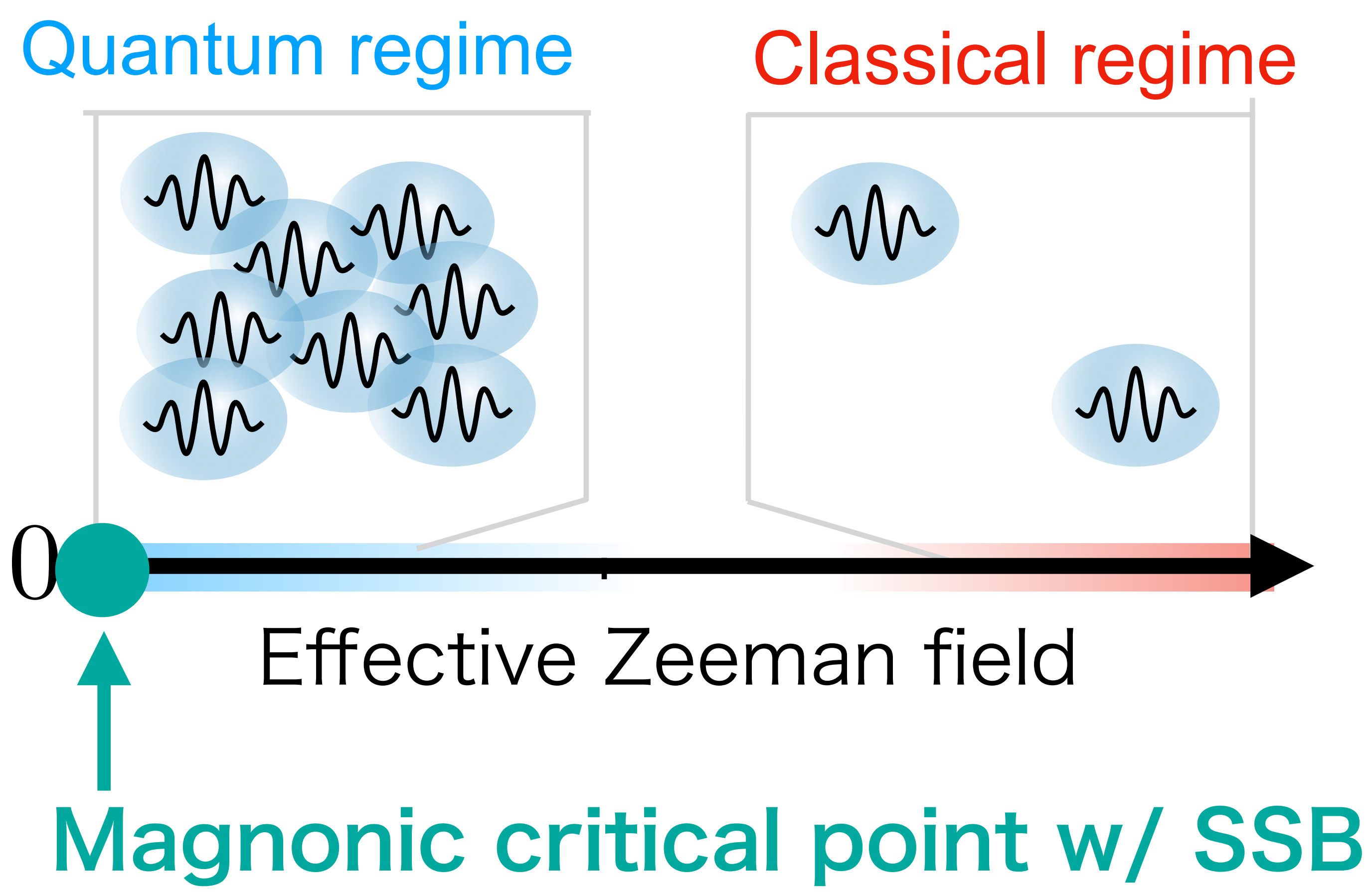


Summary of setup and results

YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280

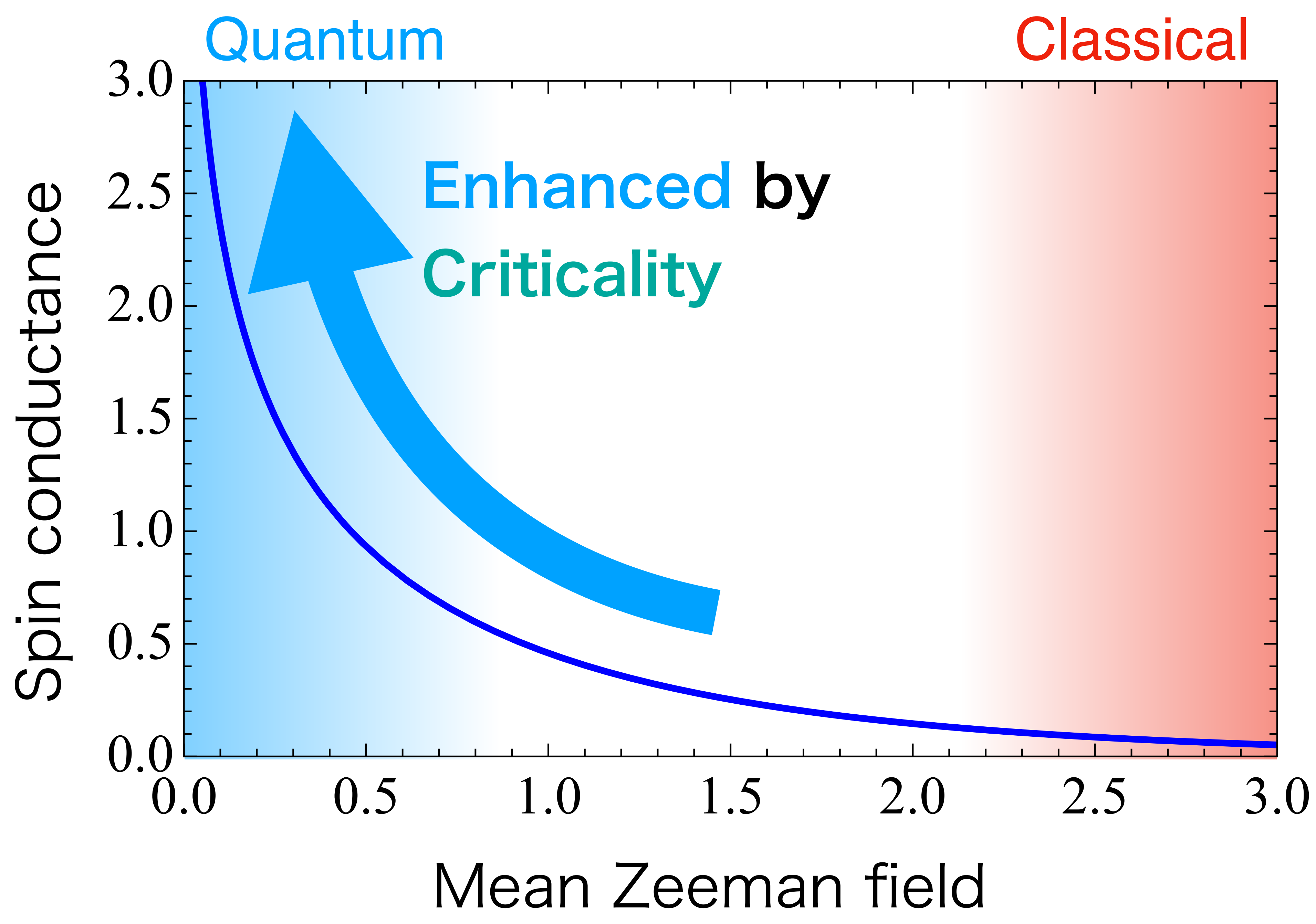
Highly spin-polarized FIs connected with a magnetic quantum point contact





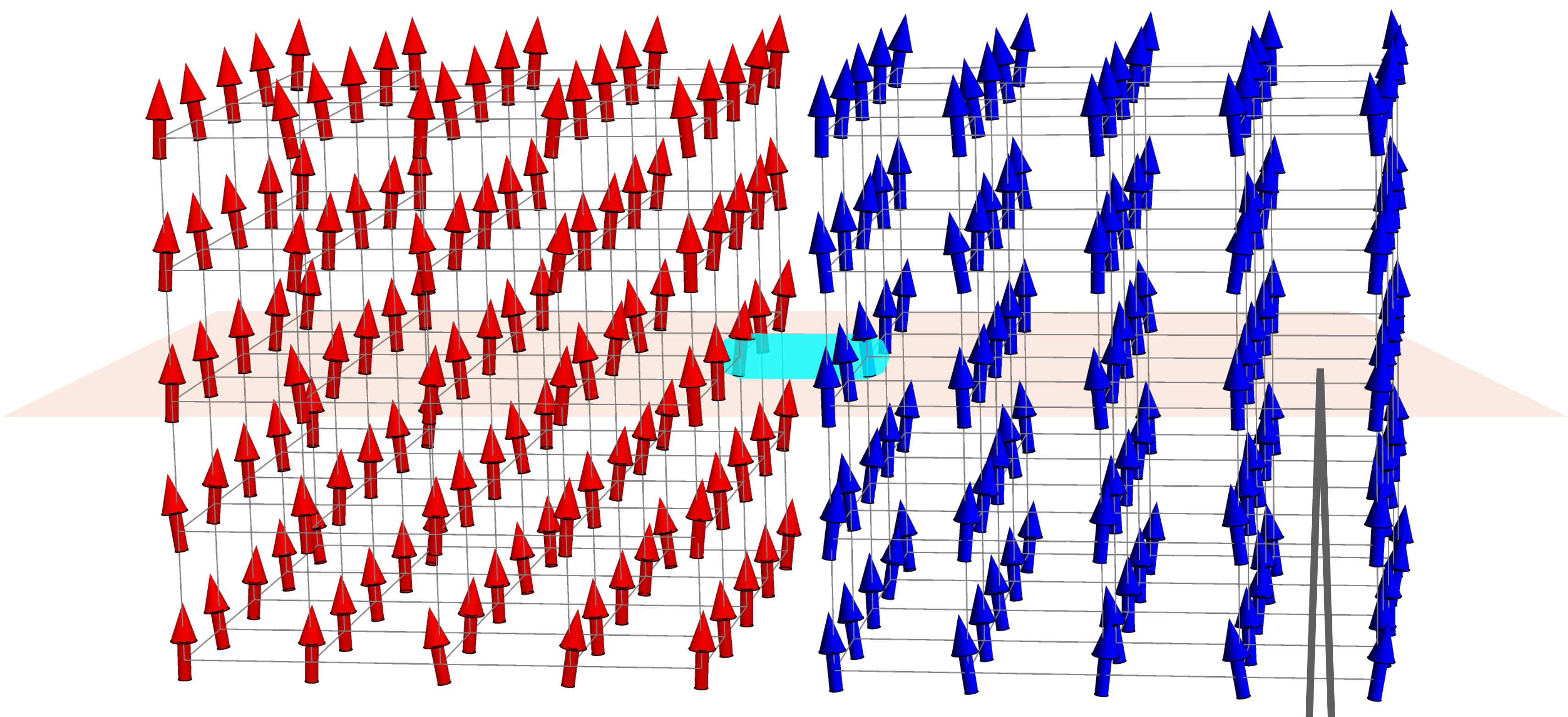
Anomalous thermomagnetic transport by **magnonic criticality**

e.g. **Anomalous enhancement** in spin conductance

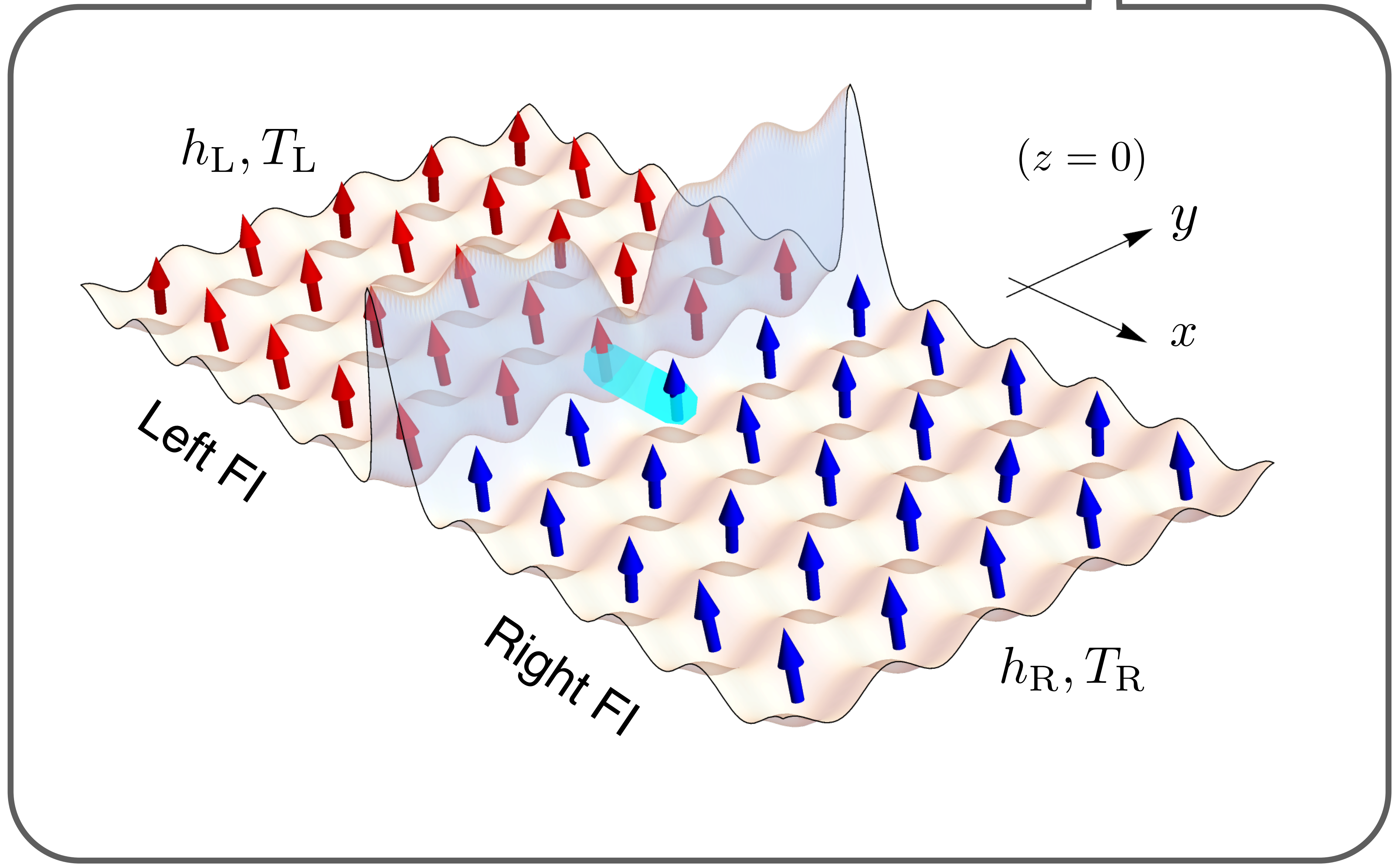


Model for magnonic tunneling transport

YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280



$h_{\mathrm{L}}, T_{\mathrm{L}}$ $h_{\mathrm{R}}, T_{\mathrm{R}}$



Hamiltonian:

$$H = H_{\mathrm{L}} + H_{\mathrm{R}} + H_{\mathrm{T}}$$

$$H_{\alpha=\mathrm{L,R}} = -J \sum_{\langle \vec{r}_\alpha, \vec{r}'_\alpha \rangle} \vec{s}_{\vec{r}_\alpha} \cdot \vec{s}_{\vec{r}'_\alpha} - h_\alpha \sum_{\vec{r}_\alpha} s^z_{\vec{r}_\alpha}$$

$$H_{\mathrm{T}} = -J_{\mathrm{T}} \vec{s}_{\vec{R}_{\mathrm{L}}} \cdot \vec{s}_{\vec{R}_{\mathrm{R}}}$$

Effective magnetic field

1. Weak tunneling coupling

$$J_{\mathrm{T}} \ll J$$

2. Spin-wave theory to analyze the highly spin-polarized case

$$H_\alpha \approx \sum_{\vec{k}} E_{\vec{k}\alpha} b^\dagger_{\vec{k}\alpha} b_{\vec{k}\alpha}$$

Magnon:

$$s^-_{\vec{k}\alpha} \approx b^\dagger_{\vec{k}\alpha}$$

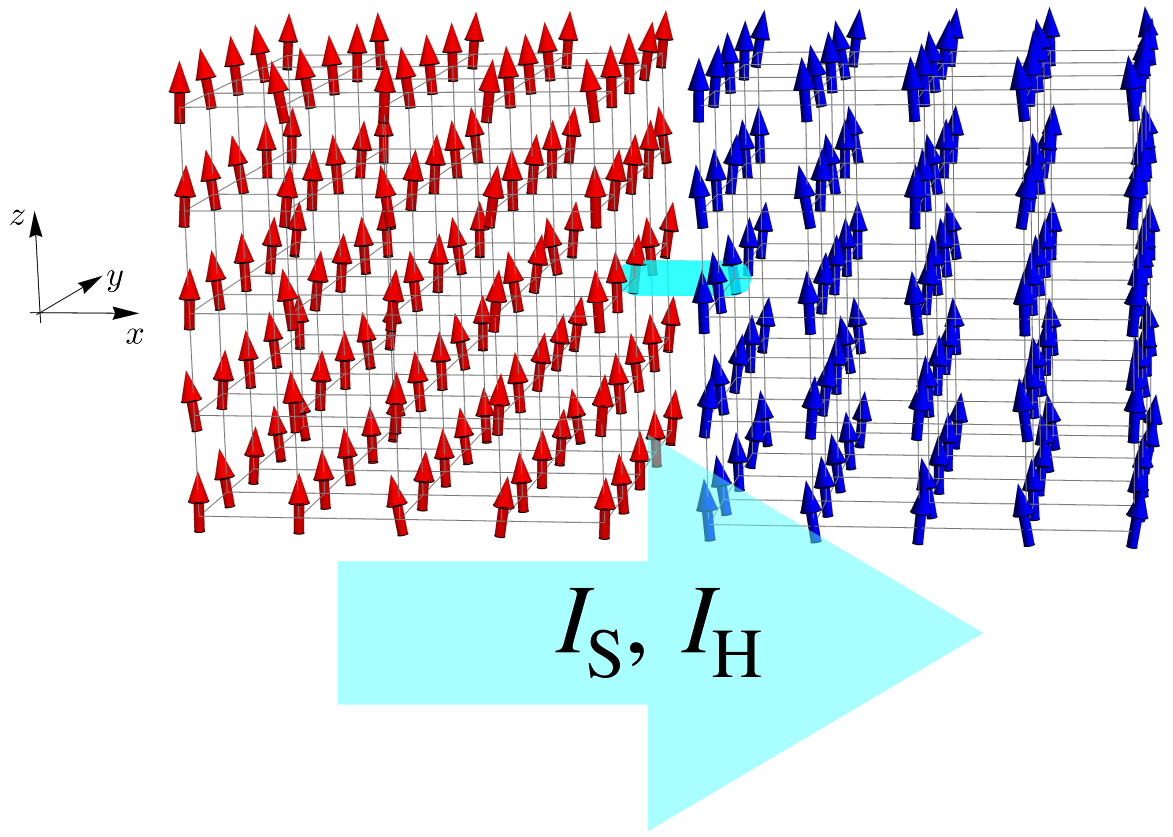
$$E_{\vec{k}\alpha} = h_\alpha + (J/2)k^2$$

Magnon energy gap

Tunneling Hamiltonian formalism

Evaluating the spin and heat currents I_S, I_H up to $O(J_\mathrm{T}^2)$ w/ Schwinger-Keldysh formalism

Electron systems : Meir & Wingreen PRL **68**, 2512 (1992)
Bosonic atoms : Meier and Zwerger, PRA **64**, 033610 (2001)



$$H = H_\mathrm{L} + H_\mathrm{R} + H_\mathrm{T}$$

$$H_\mathrm{T} = -J_\mathrm{T} \vec{s}_{\vec{R}_\mathrm{L}} \cdot \vec{s}_{\vec{R}_\mathrm{R}}$$

YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280

Spin current: $$I_\mathrm{S} = \left\langle \frac{d\hat{M}_\mathrm{L}^z}{dt} \right\rangle \sim (J_\mathrm{T})^2 \int_{-\infty}^{\infty} d\omega\, \rho_\mathrm{L}(\omega)\rho_\mathrm{R}(\omega)\Delta n_\mathrm{B}(\omega)$$

Heat current: $$I_\mathrm{H} = -\left\langle \frac{d\hat{H}_\mathrm{L}}{dt} \right\rangle \sim (J_\mathrm{T})^2 \int_{-\infty}^{\infty} d\omega\, (\omega + h_\mathrm{L})\rho_\mathrm{L}(\omega)\rho_\mathrm{R}(\omega)\Delta n_\mathrm{B}(\omega)$$

Magnetization: $\hat{M}_\alpha^z = \sum_{\vec{r}_\alpha} s_{\vec{r}_\alpha}^z$

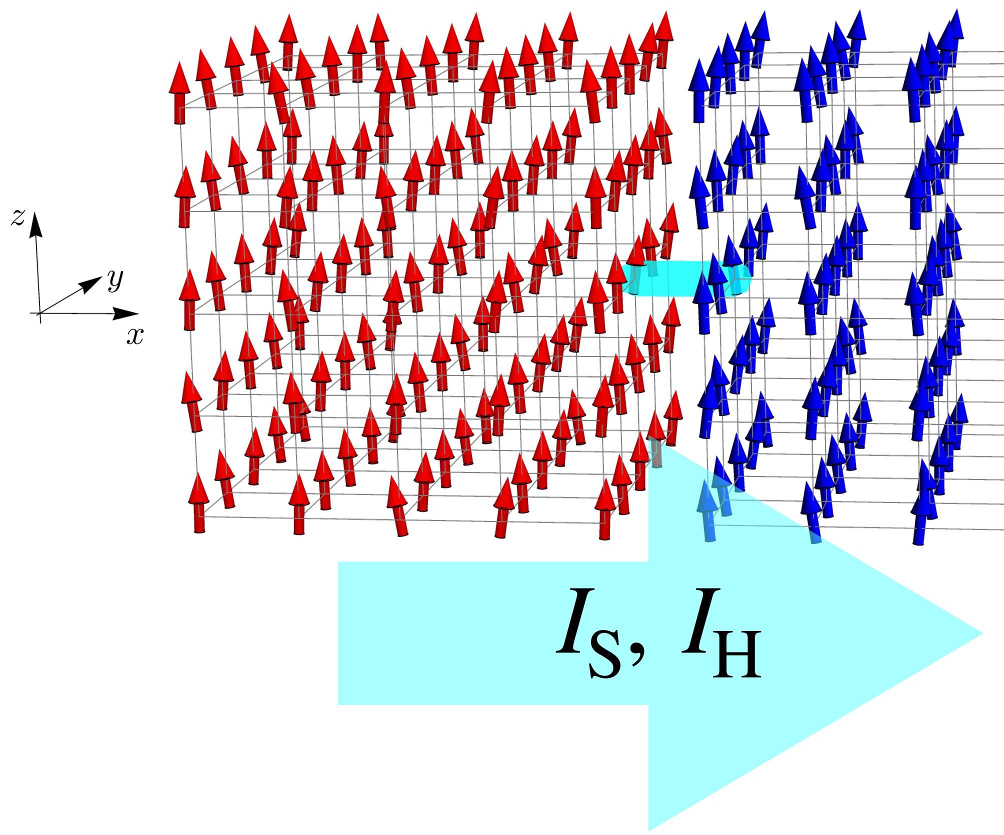
Magnon DoS: $\rho_\mathrm{L/R}(\omega) \propto \sqrt{\omega}\,\theta(\omega)$

Difference of magnon distribution:

$$\Delta n_\mathrm{B}(\omega) = n_\mathrm{B,L}(\omega) - n_\mathrm{B,R}(\omega)$$

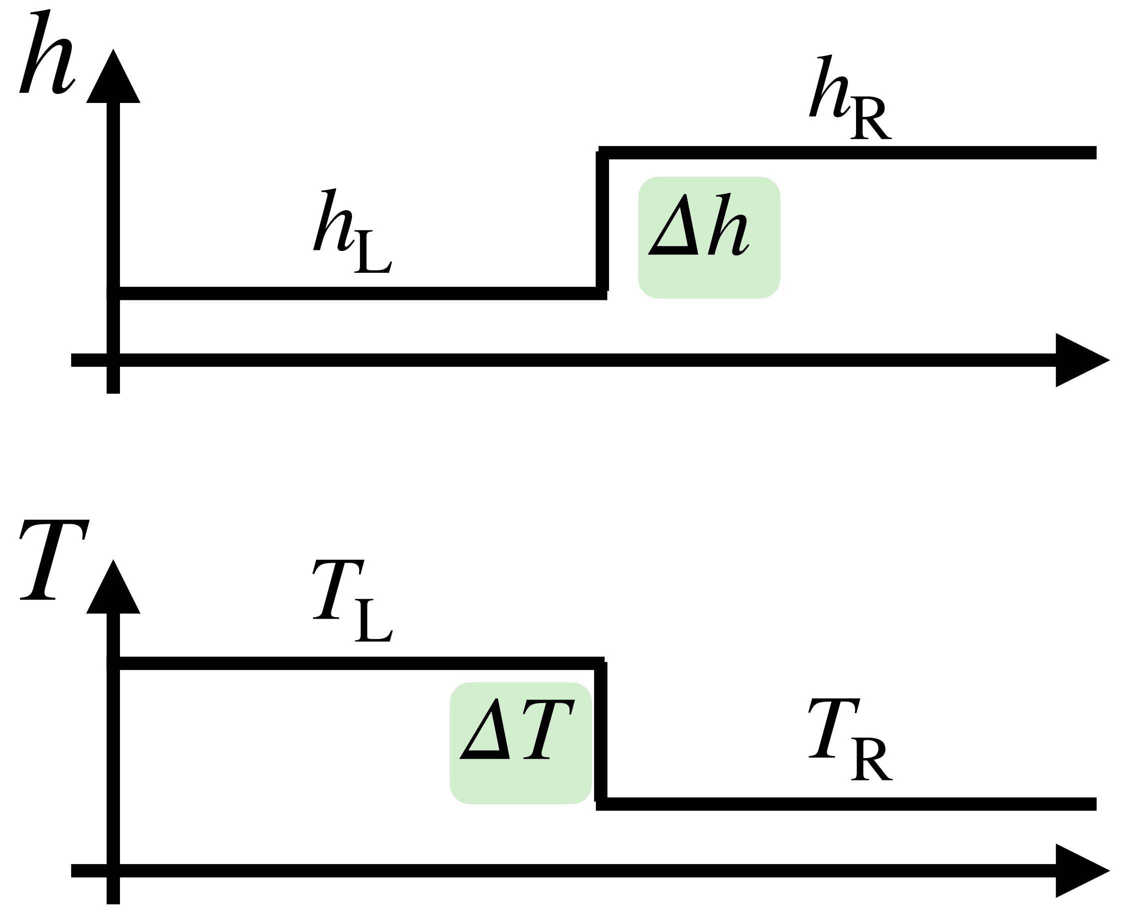
Conductances of spin and heat

Expanding currents to small spin & temperature biases $\Delta h, \Delta T$



$$\begin{pmatrix} I_S \\ I_H \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} \begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix} + O((\Delta h)^2, (\Delta T)^2, \Delta h \Delta T)$$

Conductance Bias



$$\frac{L_{11}}{AT} = F_1(x),$$

$$\frac{L_{12}}{AT} = \frac{L_{21}}{AT^2} = 2\,F_2(x) + x\,F_1(x),$$

$$\frac{L_{22}}{AT^2} = 6\,F_3(x) + 4x\,F_2(x) + x^2\,F_1(x),$$

$$x = \frac{(h_L + h_R)/2}{(T_L + T_R)/2} = \frac{\text{averaged field}}{\text{averaged temp}}$$

Bose-Einstein integral:

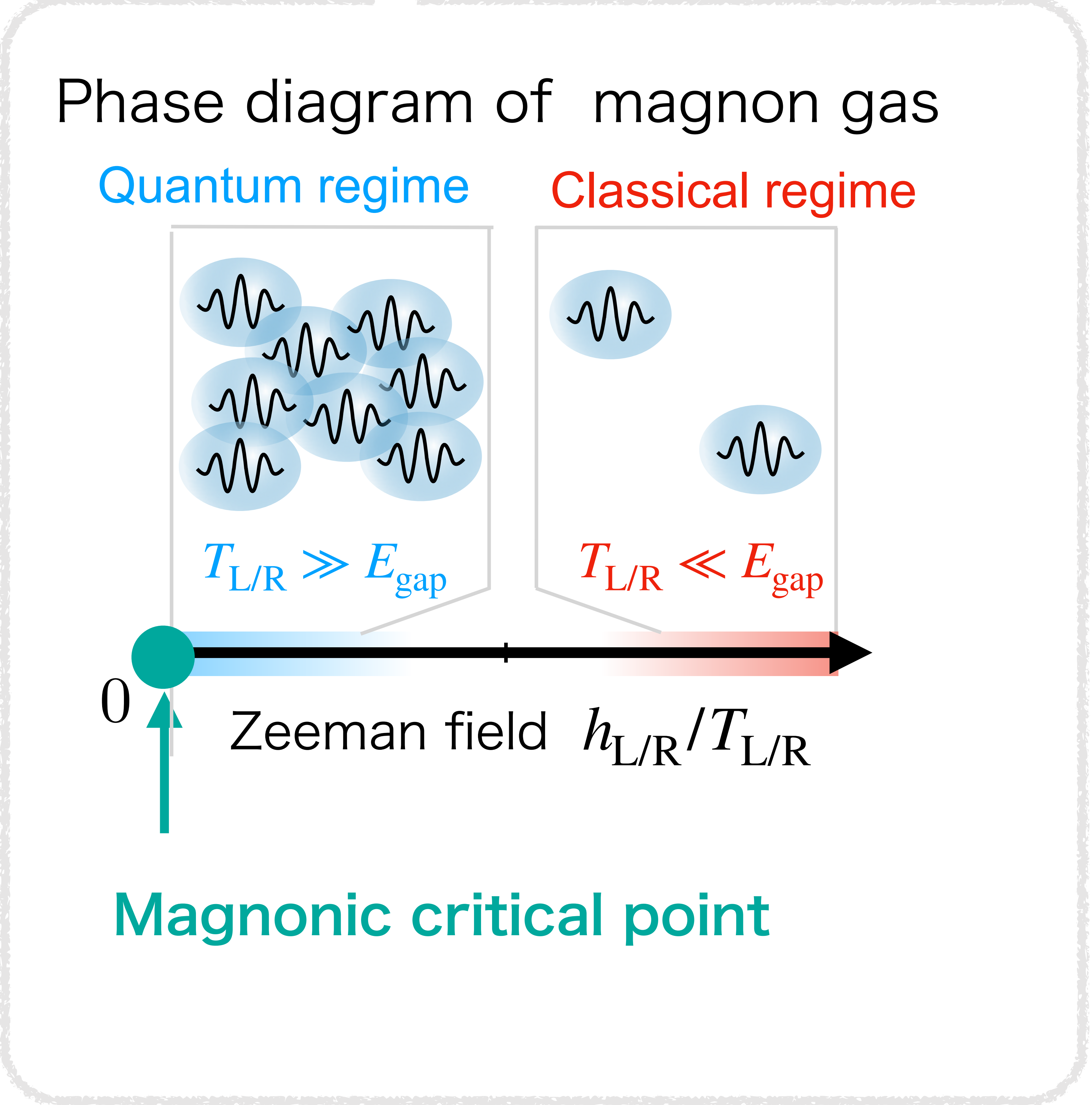
$$F_d(x) \propto \int_0^\infty d\omega \, \frac{\omega^{d-1}}{e^{\omega + x} - 1}$$

Critical behavior of transport coefficients

YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280

Magnonic criticality enhances **conductances L_{ij} in quantum regime**

$$\begin{pmatrix} I_S \\ I_H \end{pmatrix} = \begin{pmatrix} L_{11} L_{12} \\ L_{21} L_{22} \end{pmatrix} \begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix}$$



Critical behavior of transport coefficients

YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280

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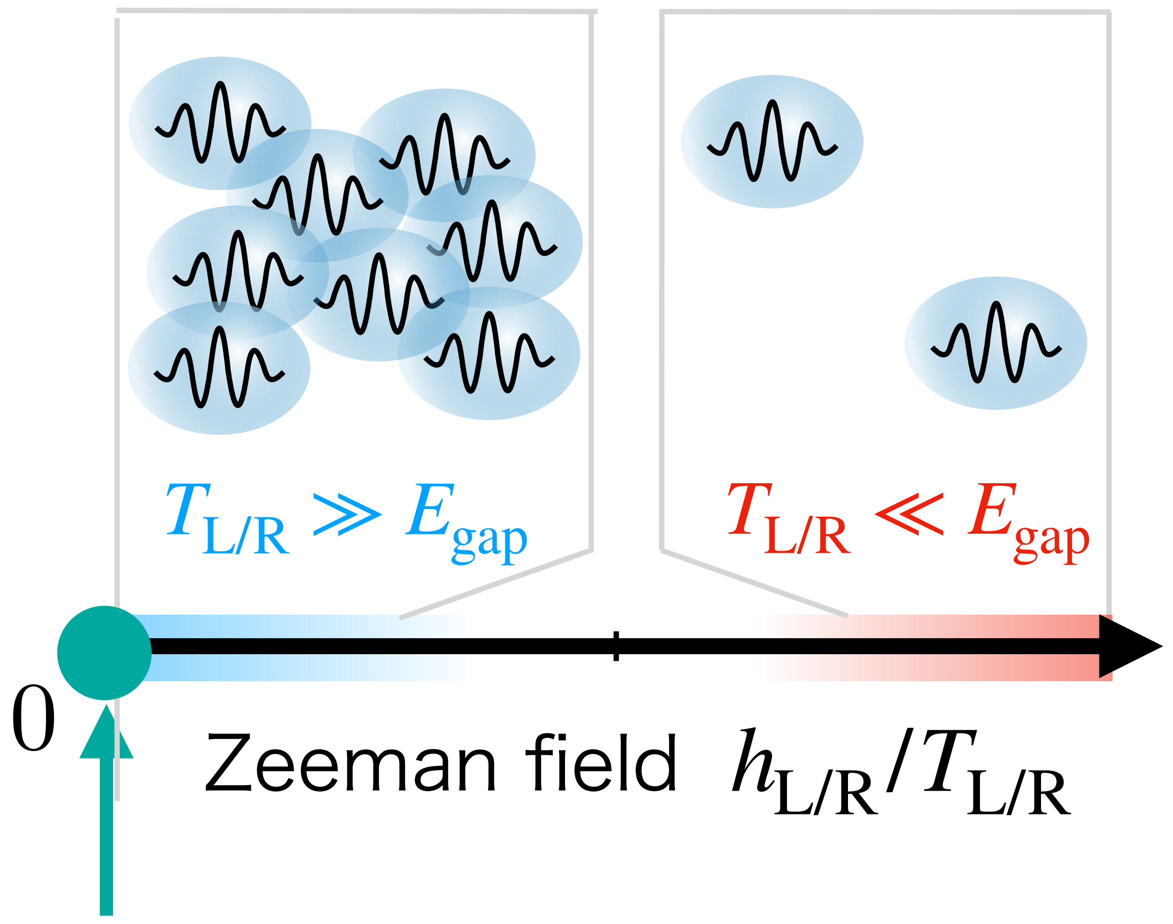
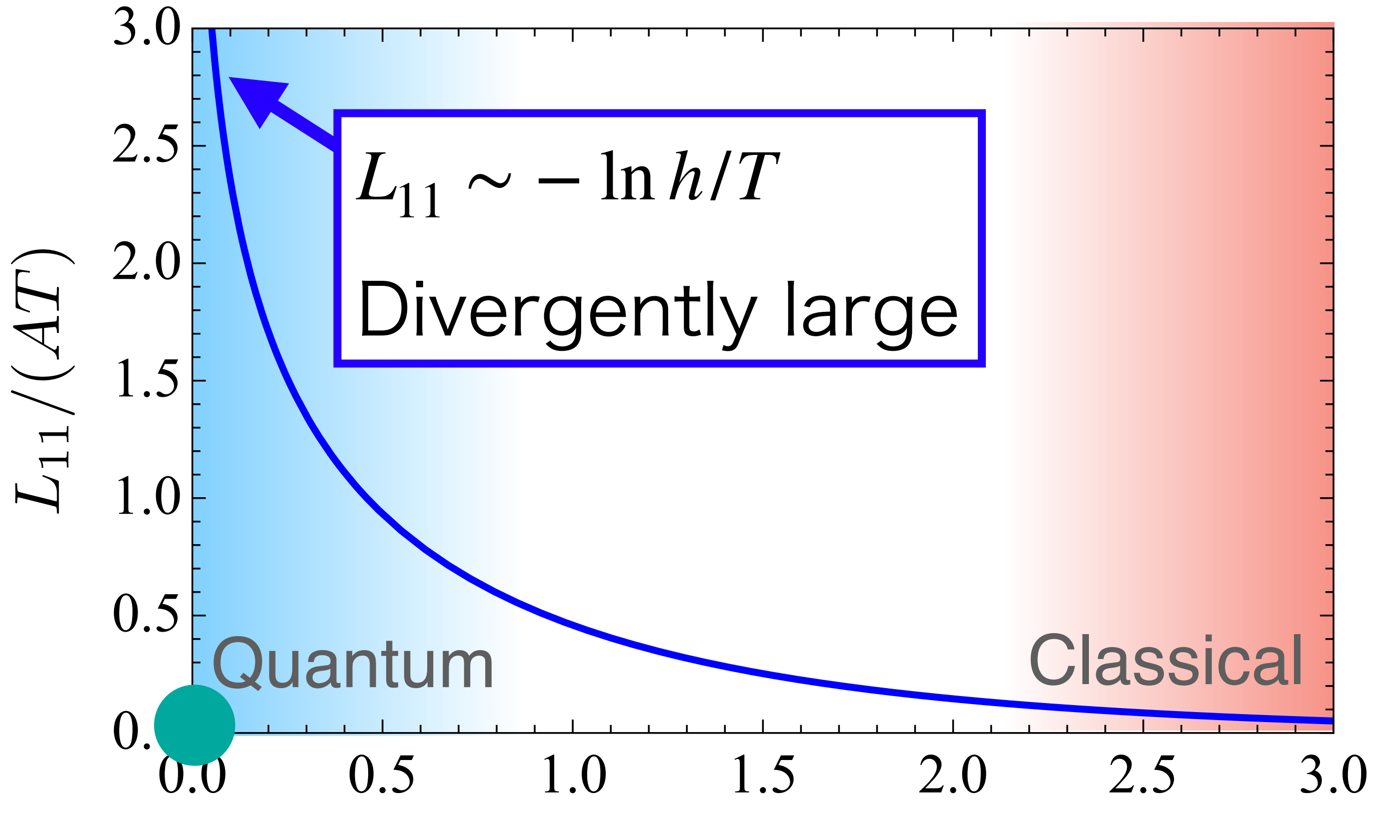
Phase diagram of magnon gas



Magnonic critical point

Spin conductance L_{11}



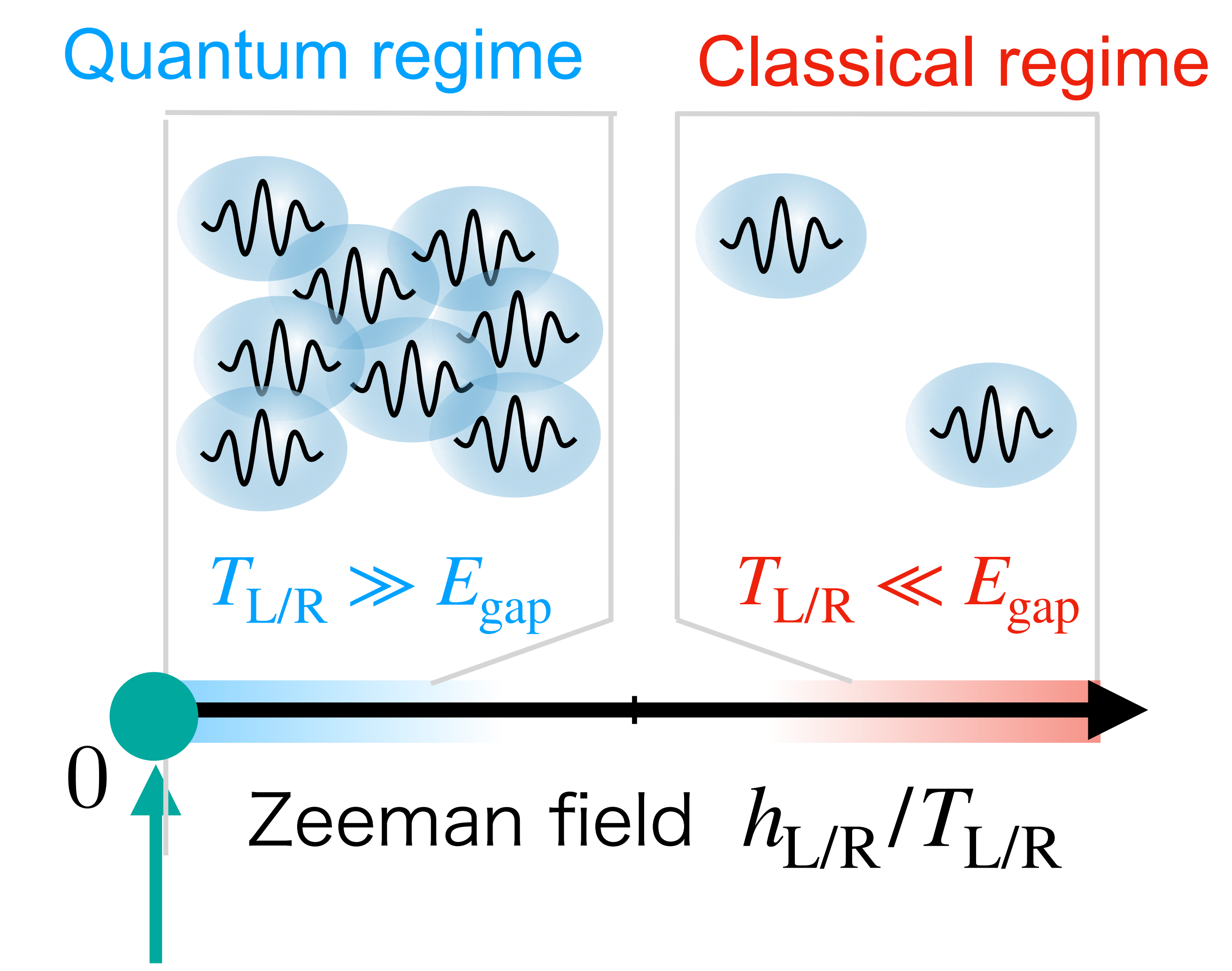
Critical enhancement of conductances L_{ij} in the quantum regime

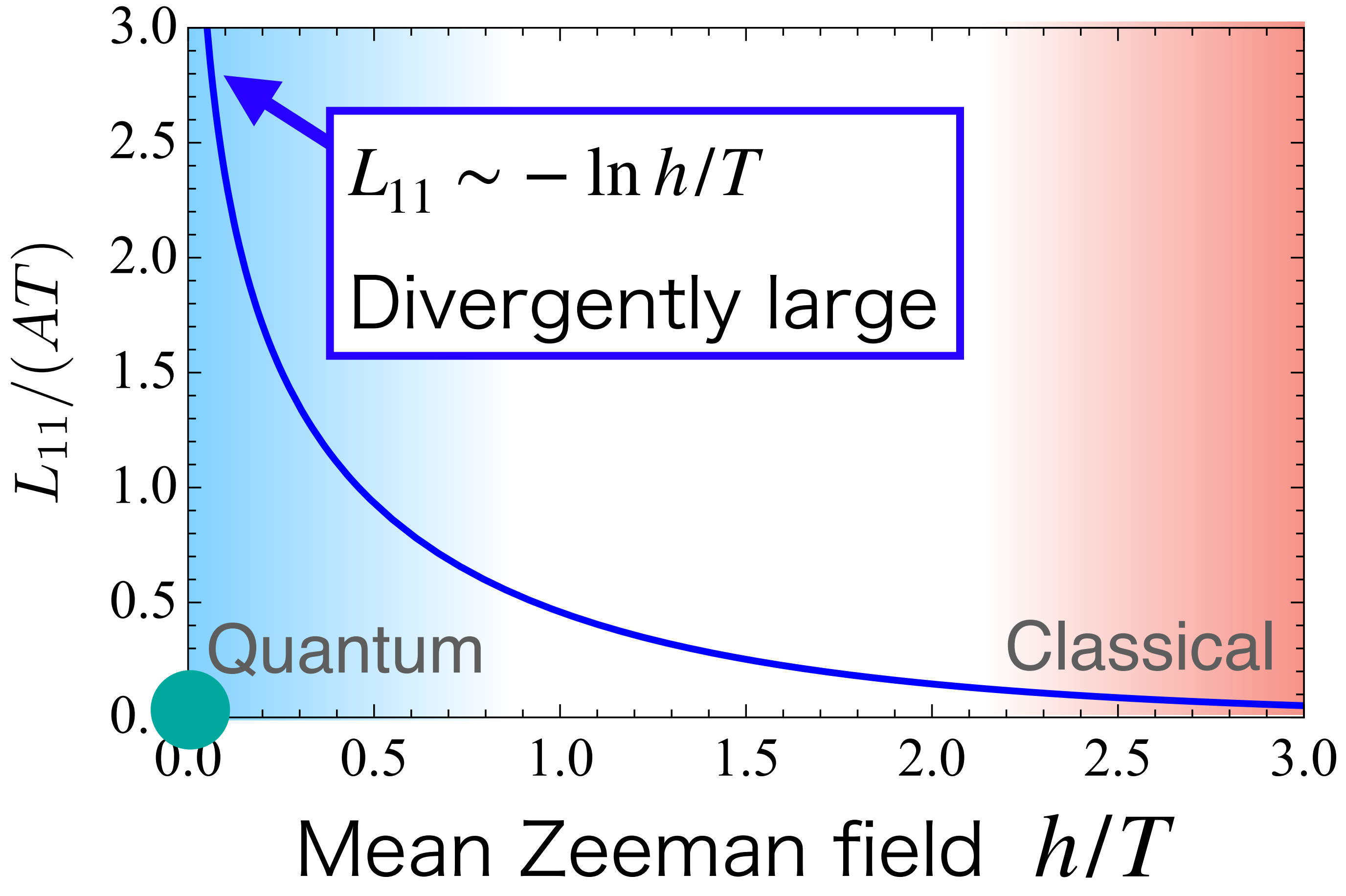
Critical behavior of transport coefficients

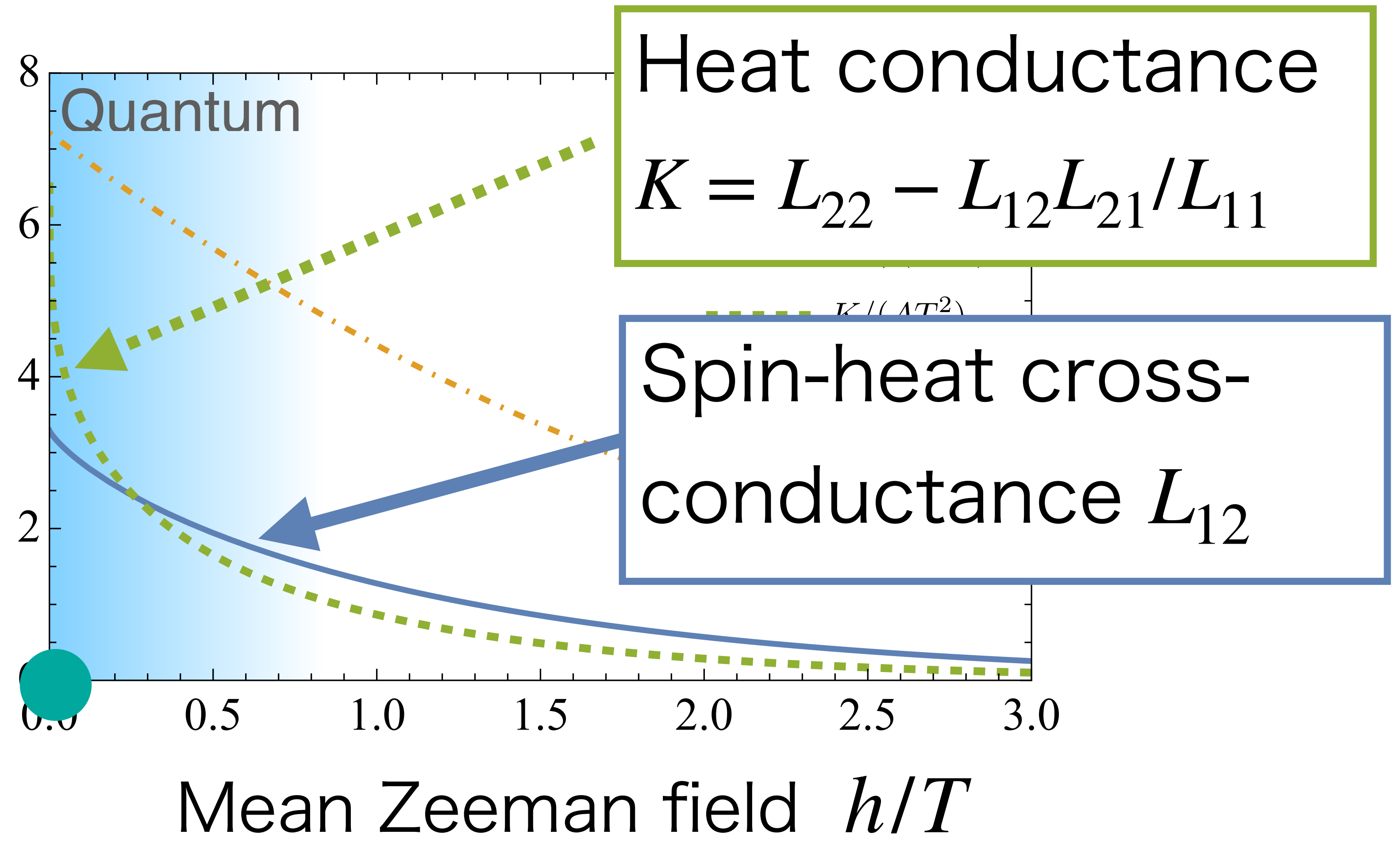
YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280

Magnonic criticality enhances **conductances L_{ij} in quantum regime**

$$\begin{pmatrix} I_S \\ I_H \end{pmatrix} = \begin{pmatrix} L_{11} L_{12} \\ L_{21} L_{22} \end{pmatrix} \begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix}$$



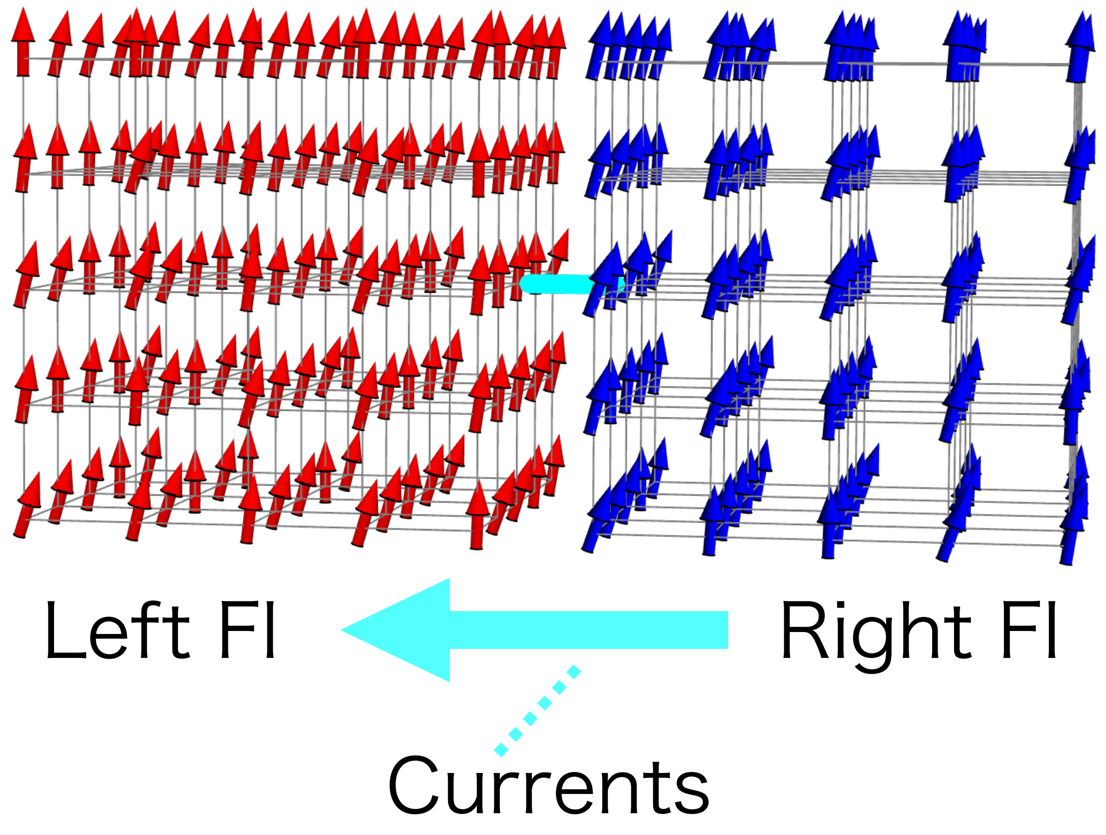




Critical enhancement of conductances L_{ij} in the quantum regime

Summary of this talk

Anomalous tunneling spin and heat transport near the magnonic critical point

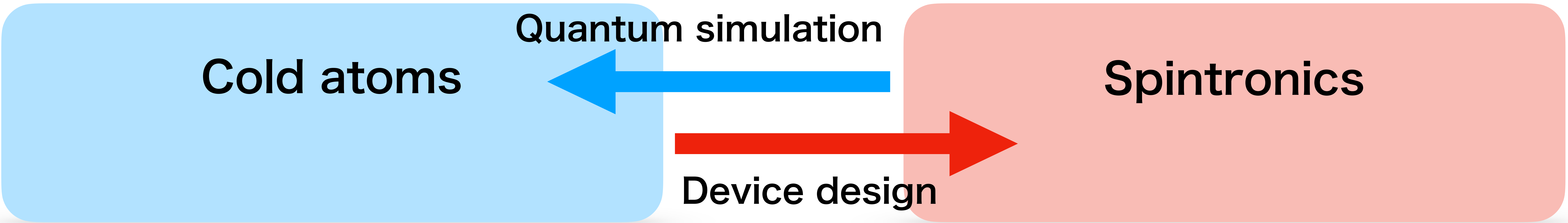


Critical enhancement of spin & heat conductances

Originating from the magnonic critical point corresponding to spontaneous symmetry breaking of O(3) spin rotation

New mechanism for efficient spin & heat transport by criticality

Accelerating interdisciplinary communications b/w Cold atom & Spintronics



Backup slides

Phase diagram of ferromagnetic Heisenberg model

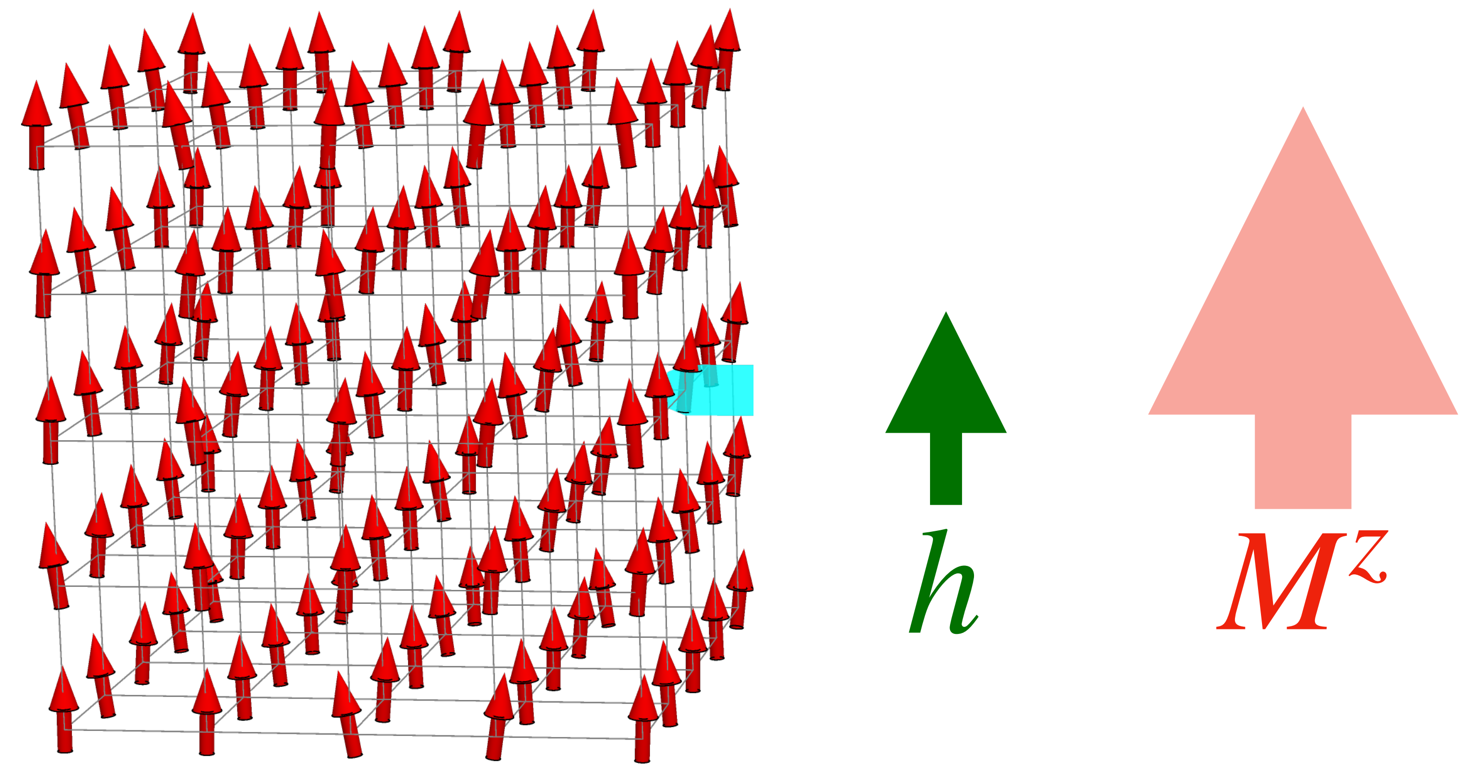
$$\hat{H}^{\mathrm{Hei}} = -J\sum_{\langle i,j\rangle} \hat{\vec{s}}_i \cdot \hat{\vec{s}}_j - h\sum_i \hat{s}_i^z$$

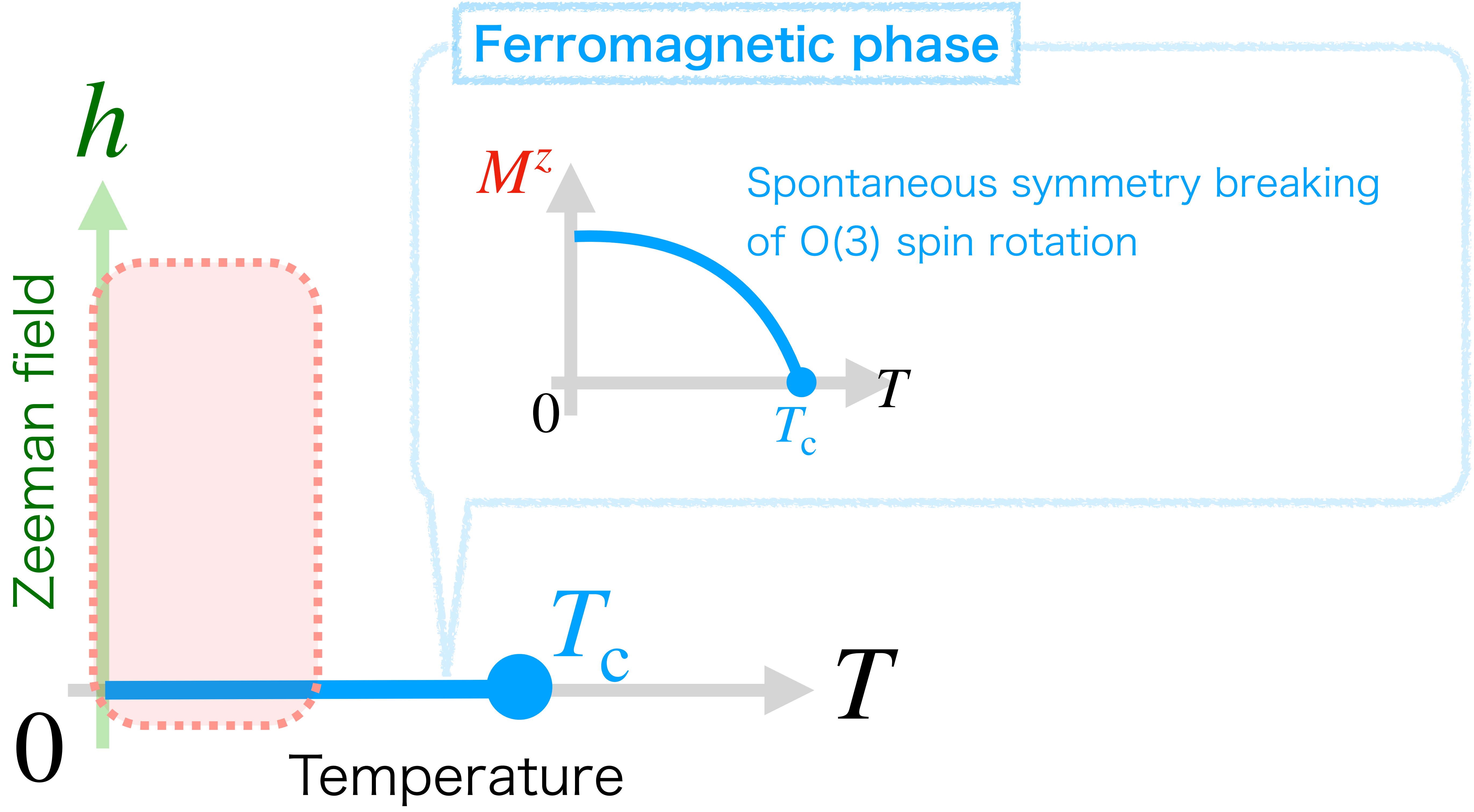
Zeeman field

$h \geq 0$

Magnetization

$M^z = \sum_i \langle \hat{s}_i^z \rangle$





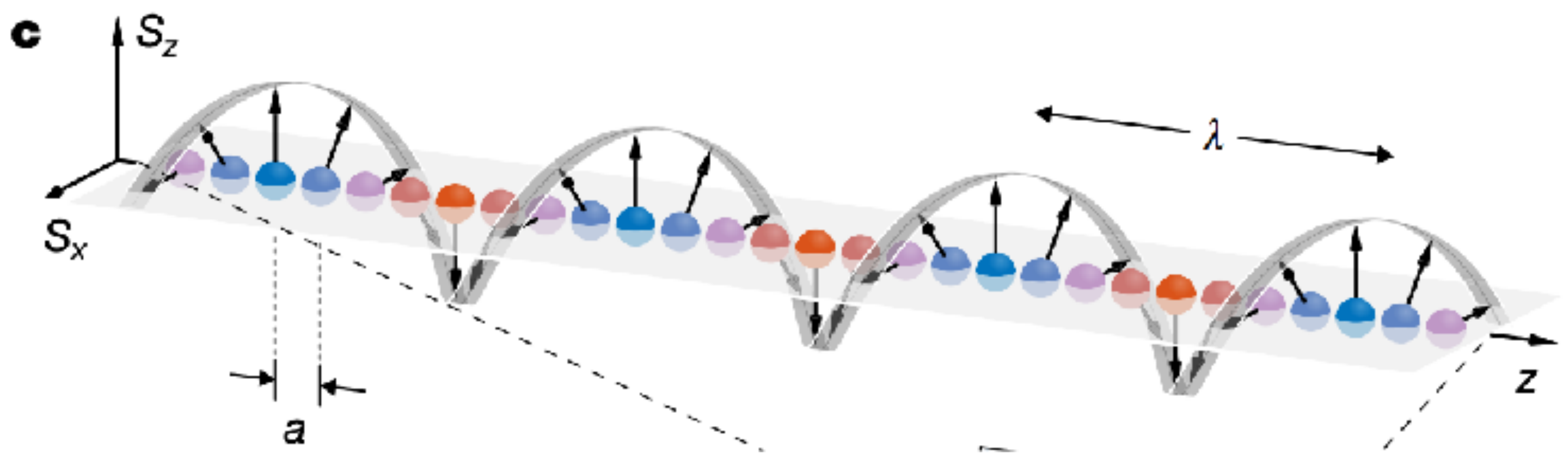
We focus on a low-temp region $T \ll T_c$ with large M^z,

where **magnons** appear

Quantum simulation of ferromagnets: bulk vs tunneling

Cold-atomic experiments on spin dynamics in Heisenberg ferromagnets

Previous experiments



MPI: Fukuhara et al., Nat. Phys (2013); Nature (2013);
Hild et al., PRL (2014); Wei et al., Science (2022)
MIT: Jepsen et al., Nature (2020); PRX (2021); Nat. Phys. (2022).

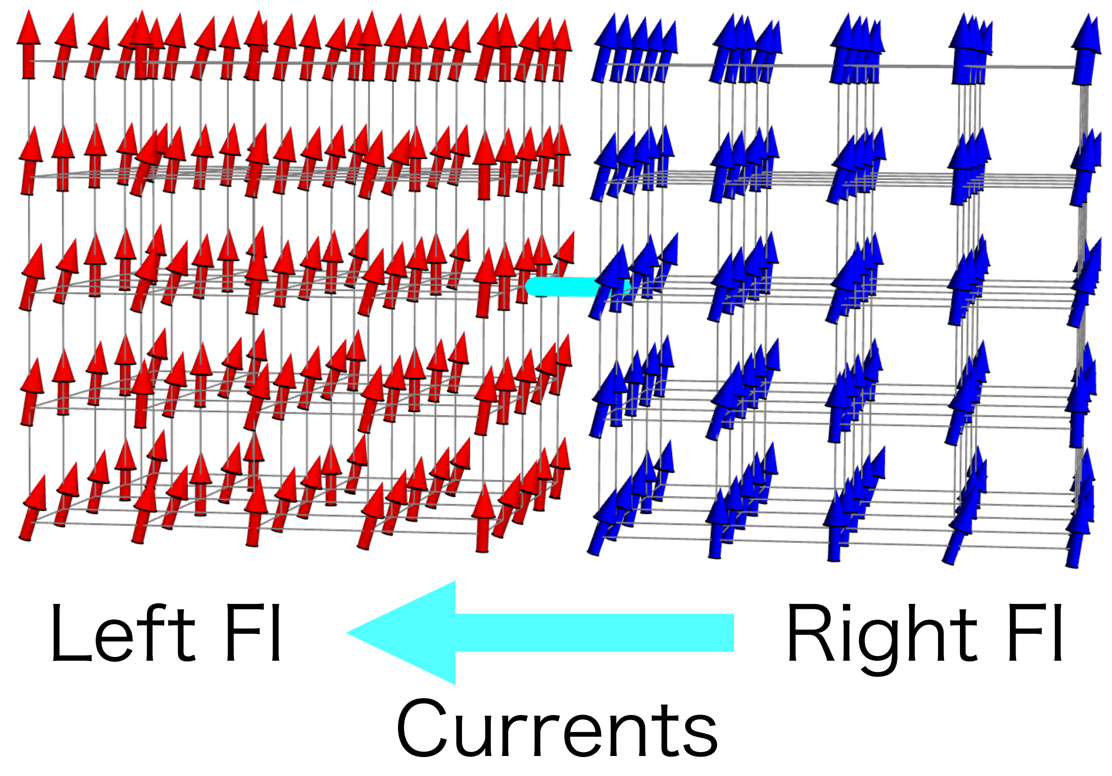
Bulk transport

Mainly 1D   Integrable

Far-from equilibrium

Sometimes complex physical picture

Our proposal



Tunneling transport

3D   Most relevant to spintronics
Spontaneous symmetry breaking

Near equilibrium

Clear physical picture from equilibrium states

Anomalous transport ↔ Magnonic critical point

Expression of Currents

$$I_S = \int_{-\infty}^{\infty} d\omega\, \mathcal{T}(\omega) \Delta n_B(\omega)$$

$$I_H = \int_{-\infty}^{\infty} d\omega\, (\omega + h_L) \mathcal{T}(\omega) \Delta n_B(\omega)$$

$$\begin{pmatrix} I_S \\ I_H \end{pmatrix} = \begin{pmatrix} L_{11} L_{12} \\ L_{21} L_{22} \end{pmatrix} \begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix} + O((\Delta h)^2, (\Delta T)^2)$$

Transmittance $\mathcal{T}(\omega) \propto (J_T)^2 \rho_L(\omega + h_L) \rho_R(\omega + h_R)$

Magnon DoS $\rho_{\alpha=L,R}(\omega) = \sum_{\vec{k}} \delta(\omega - E_{\vec{k}\alpha}) \propto \sqrt{\omega - h_\alpha}$

Magnon energy $E_{\vec{k}\alpha} = h_\alpha + (J/2)k^2$

Difference of magnon distribution:

$$\Delta n_B(\omega) = n_{B,L}(\omega + h_L) - n_{B,R}(\omega + h_R)$$

$$n_{B,L/R}(\omega) = \frac{1}{1 + e^{\omega/T_{L/R}}}$$

Conductance:

$$\frac{L_{11}}{AT} = F_1(x),$$

$$\frac{L_{12}}{AT} = \frac{L_{21}}{AT^2} = 2\,F_2(x) + x\,F_1(x),$$

$$\frac{L_{22}}{AT^2} = 6\,F_3(x) + 4x\,F_2(x) + x^2\,F_1(x),$$

Bose-Einstein integral:

$$F_d(x_\alpha = h_\alpha/T_\alpha) \propto \int_0^{\infty} d\omega\, \frac{\omega^{d-1}}{e^{(\omega+h_\alpha)/T_\alpha} - 1}$$

Conductance

Expansion in small bias

$$\Delta h = -(h_{\rm L} - h_{\rm R})$$
$$\Delta T = T_{\rm L} - T_{\rm R}$$

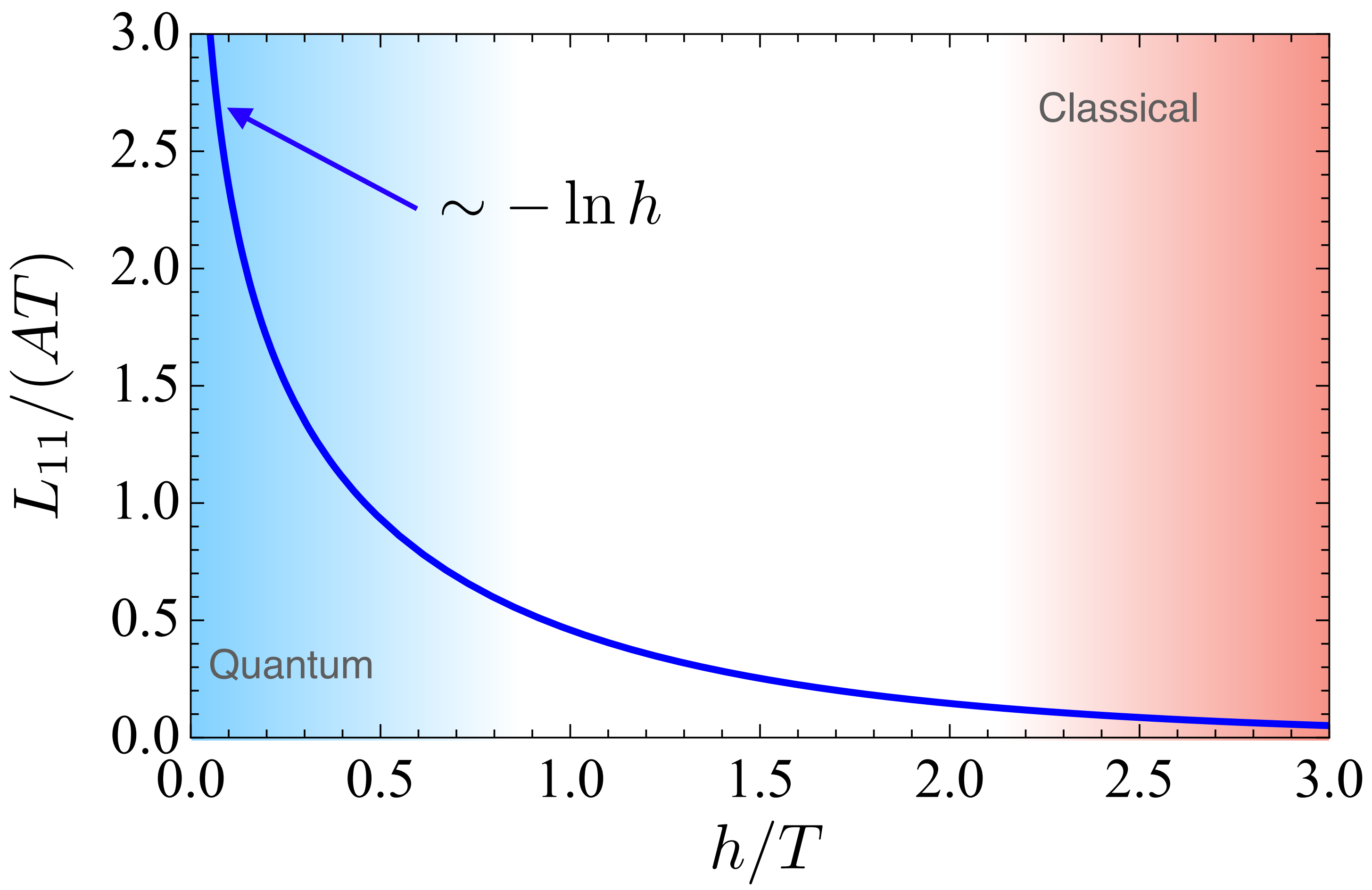
$$\begin{pmatrix} I_{\rm S} \\ I_{\rm H} \end{pmatrix} = \begin{pmatrix} L_{11} L_{12} \\ L_{21} L_{22} \end{pmatrix} \begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix}$$

Conductance:

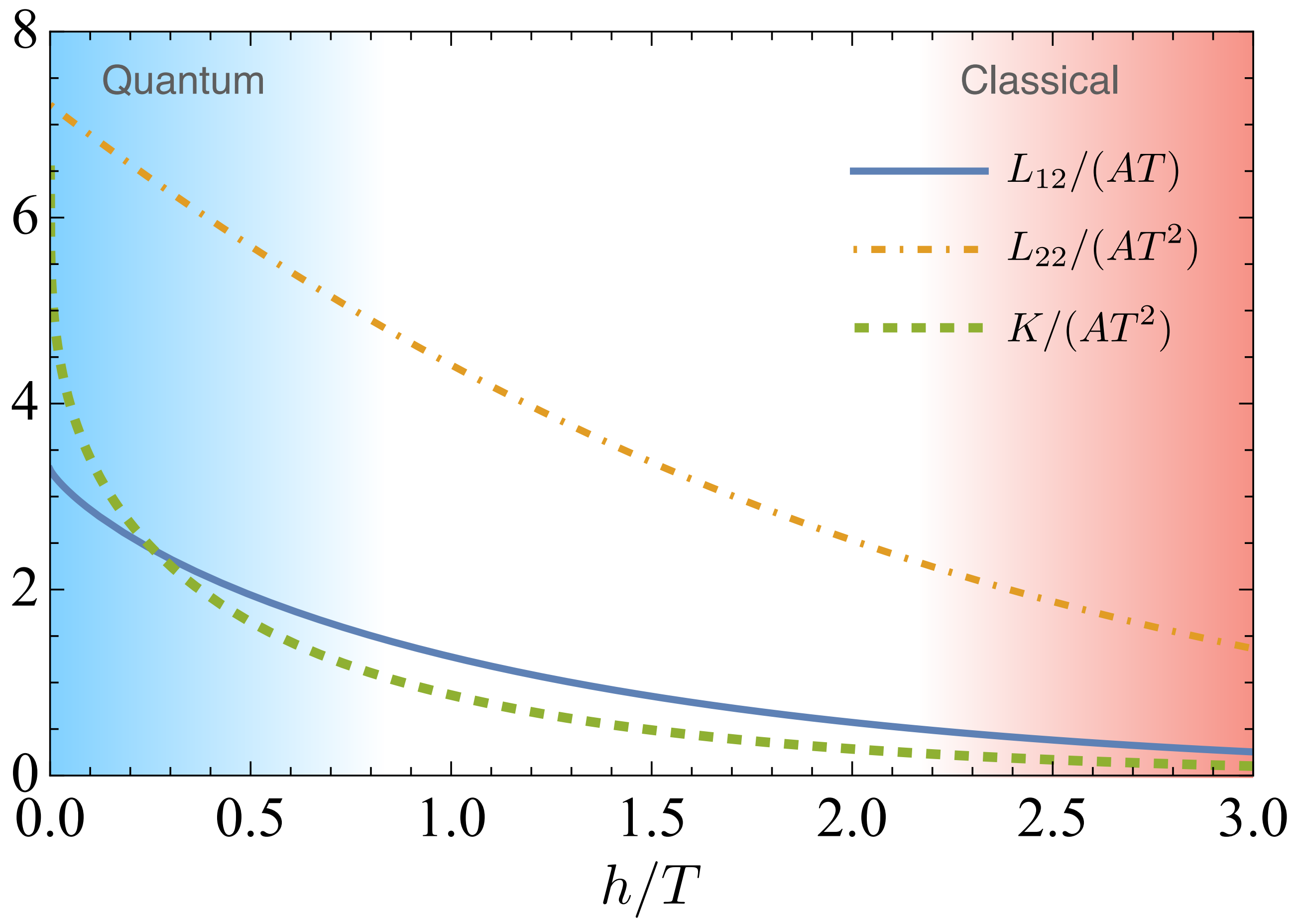
$$\frac{L_{11}}{AT} = F_1(x),$$
$$\frac{L_{12}}{AT} = \frac{L_{21}}{AT^2} = 2\,F_2(x) + x\,F_1(x),$$
$$\frac{L_{22}}{AT^2} = 6\,F_3(x) + 4x\,F_2(x) + x^2\,F_1(x),$$

$$x = h/T, \quad h = (h_{\rm L} + h_{\rm R})/2, \quad T = (T_{\rm L} + T_{\rm R})/2$$

Divergent L_{11}



Convergent L_{12}, L_{21}, L_{22}



$$F_d(x_\alpha = h_\alpha/T_\alpha) \propto \int_0^\infty d\omega\, \frac{\omega^{d-1}}{e^{(\omega+h_\alpha)/T_\alpha} - 1}$$

How to experimentally determine conductances?

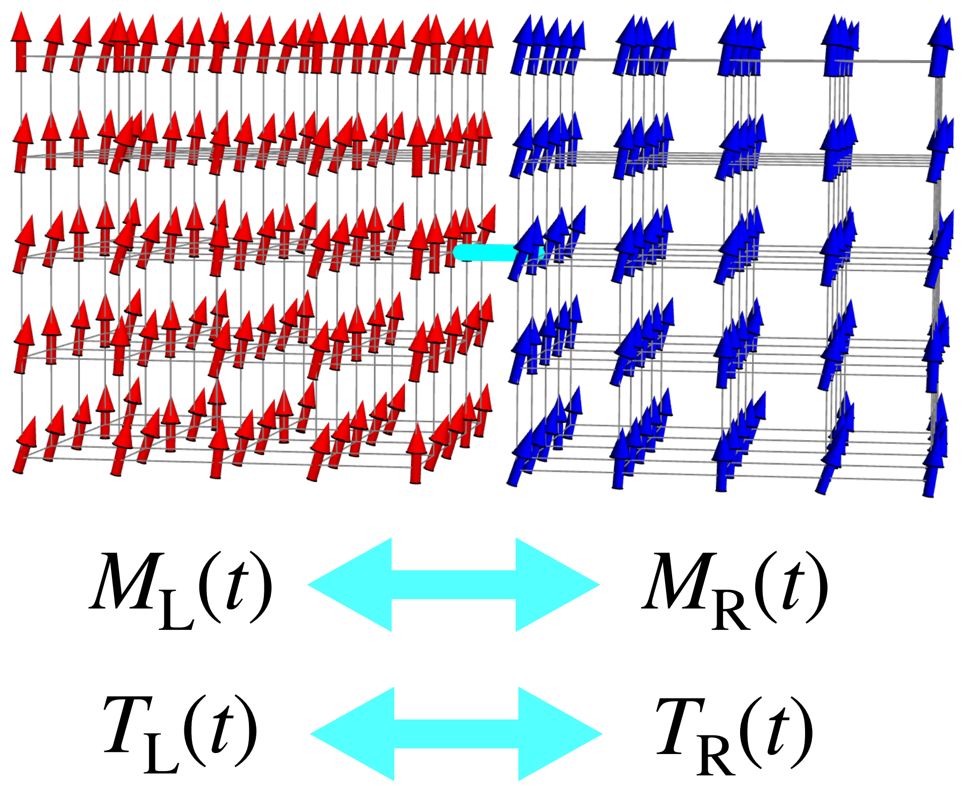
YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280

Following the scheme proposed for Fermi-gas cases [ETH: Brantut et al., Science (2013)],

we can experimentally determine conductances L_{ij} by measuring

A. Near-equilibrium relaxation dynamics of $\Delta M(t) = M_L(t) - M_R(t)$, $\Delta T(t) = T_L(t) - T_R(t)$ **b/w FIs from a thermal initial state**

Fit observed $\Delta M(t), \Delta T(t)$ with Quasi-stationary model



$$\begin{pmatrix} \Delta M(t) \\ \Delta T(t) \end{pmatrix} = \mathbf{\Lambda}(t\,; \mathbf{K}, \mathbf{L}) \begin{pmatrix} \Delta M(0) \\ \Delta T(0) \end{pmatrix}$$

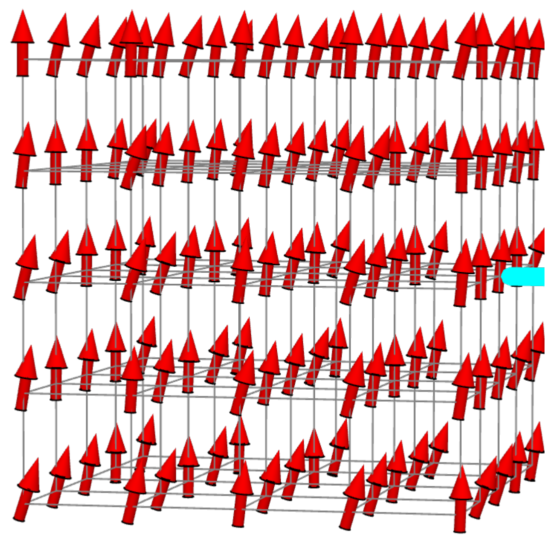
$$\mathbf{K} = \begin{pmatrix} \left(\frac{\partial M}{\partial h}\right)_T & -\left(\frac{\partial M}{\partial T}\right)_h \\ -\left(\frac{\partial S}{\partial h}\right)_T & \left(\frac{\partial S}{\partial T}\right)_h \end{pmatrix}$$

Thermodynamic quantities

$$\mathbf{L} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix}$$

Conductances

B. Thermodynamic quantities of one FI at equilibrium



$h = [h_L(0) + h_R(0)]/2$

$T = [T_L(0) + T_R(0)]/2$

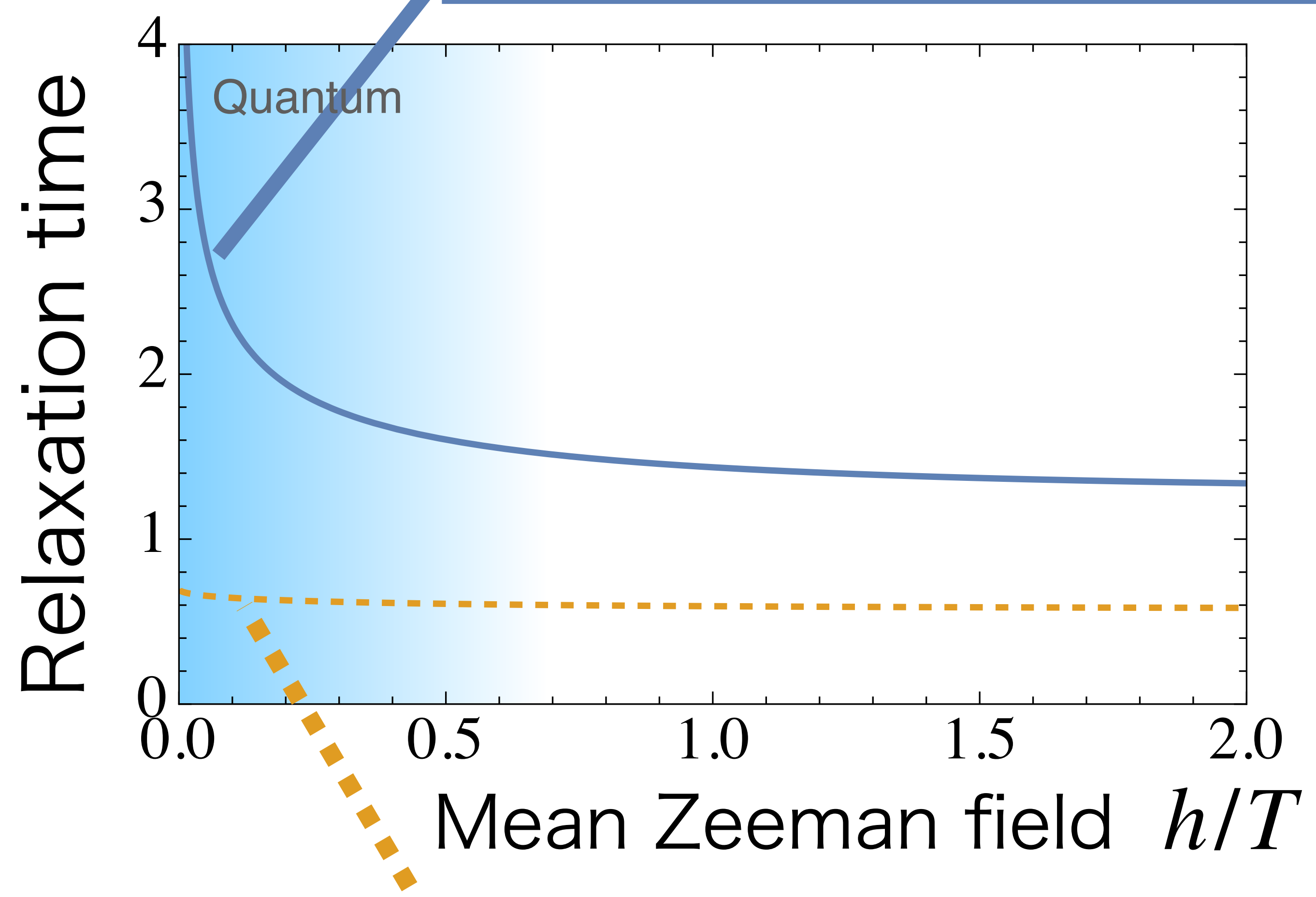
Conductances is determined!!

Slowing down of magnetization relaxation

Extremely slow spin relaxation by **critical behavior of magnon compressibility**

Spin relaxation time

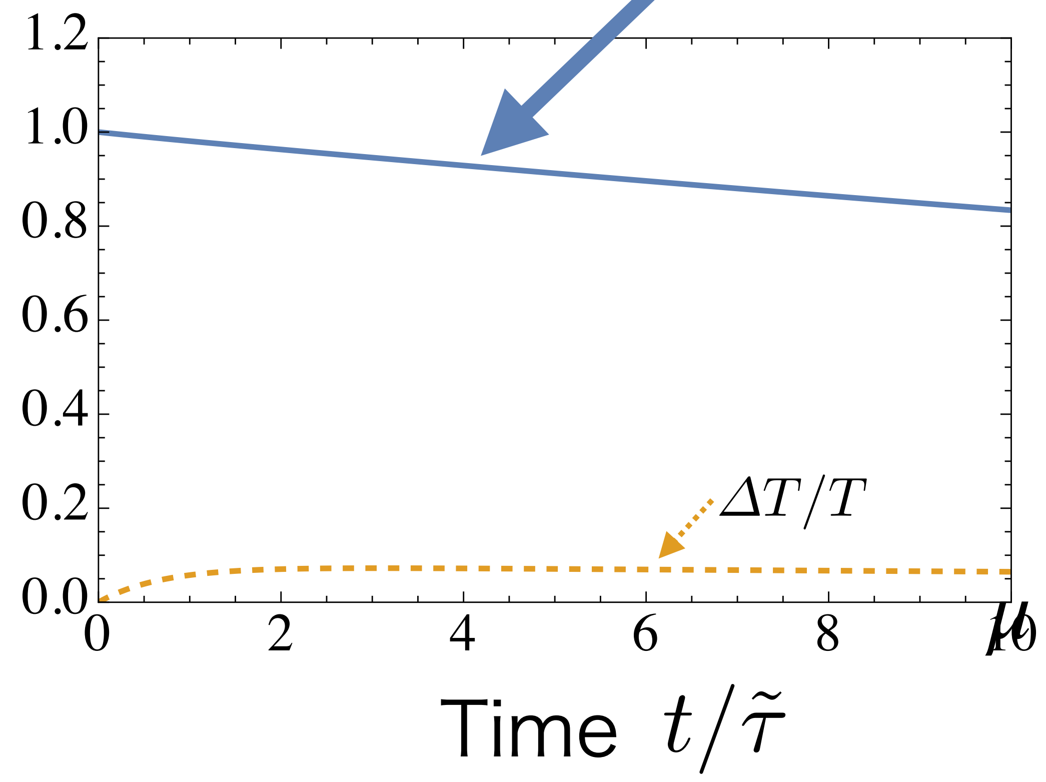
τ_M for $\Delta M = M_{\mathrm{L}} - M_{\mathrm{R}}$



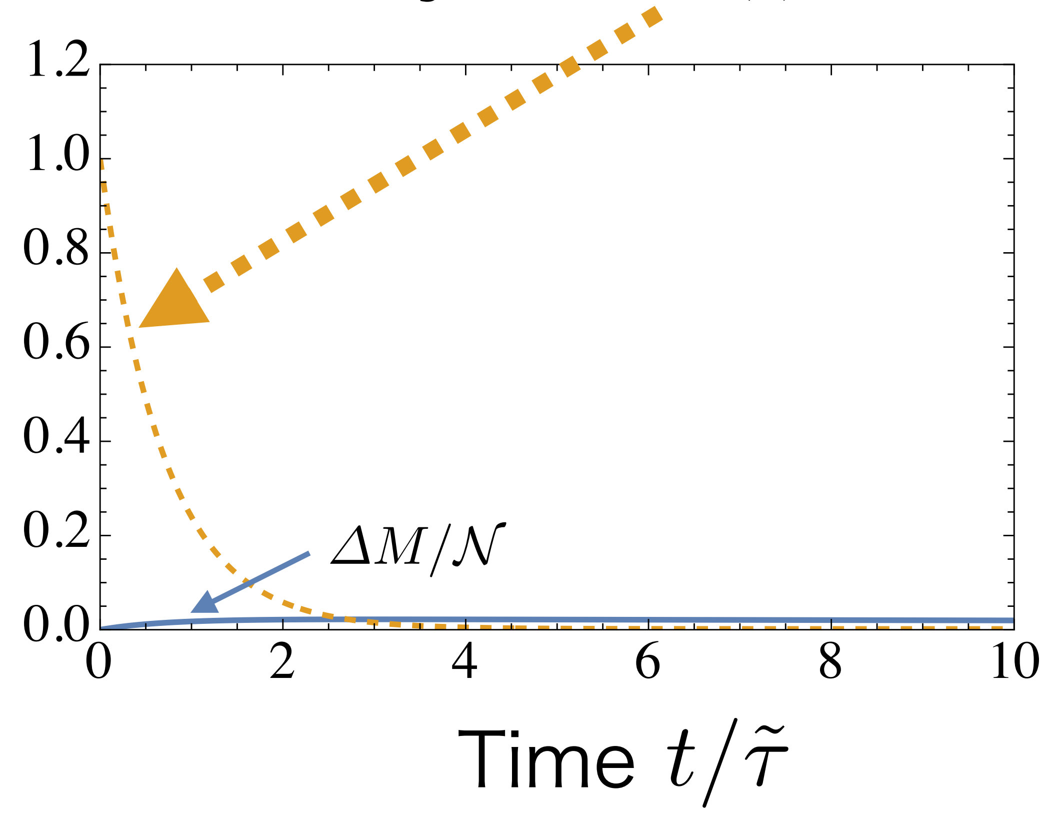
τ_T for $\Delta T = T_{\mathrm{L}} - T_{\mathrm{R}}$

Temp. relaxation time

Slow decay of $\Delta M(t) \sim \exp(-t/\tau_M)$



Fast decay of $\Delta T(t) \sim e^{-t/\tau_T}$



$$\tau_M \sim \frac{\kappa}{L_{11}} \sim \frac{1/\sqrt{h}}{-\log h} \to \infty \qquad (h \to +0)$$

L_{11} : Spin conductance

Diverging magnon compressibility by criticality

$$\kappa = \left(\frac{\partial M}{\partial h}\right)_T \sim 1/\sqrt{h} \to \infty \qquad (h \to +0)$$

Magnonic critical point = **BEC transition point for magnons**

$h \to +0$ $\qquad$ $\mu_{\text{magnon}} \to -0$

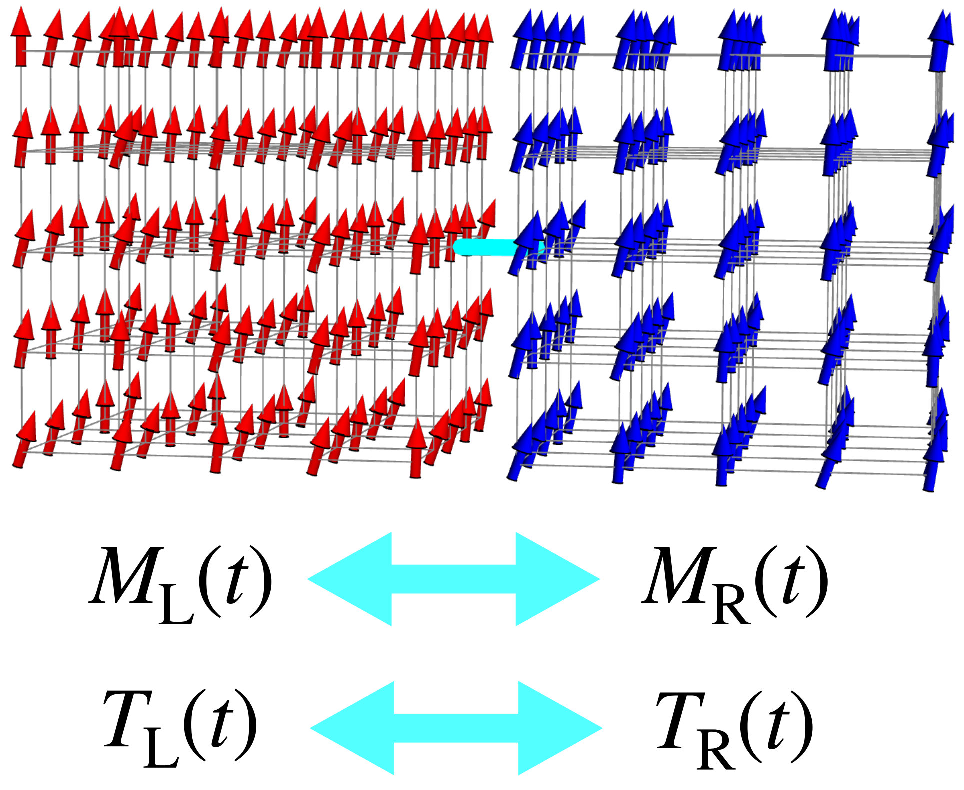
$$-h = \mu_{\text{magnon}}$$

c.f. divergent κ at BEC transition

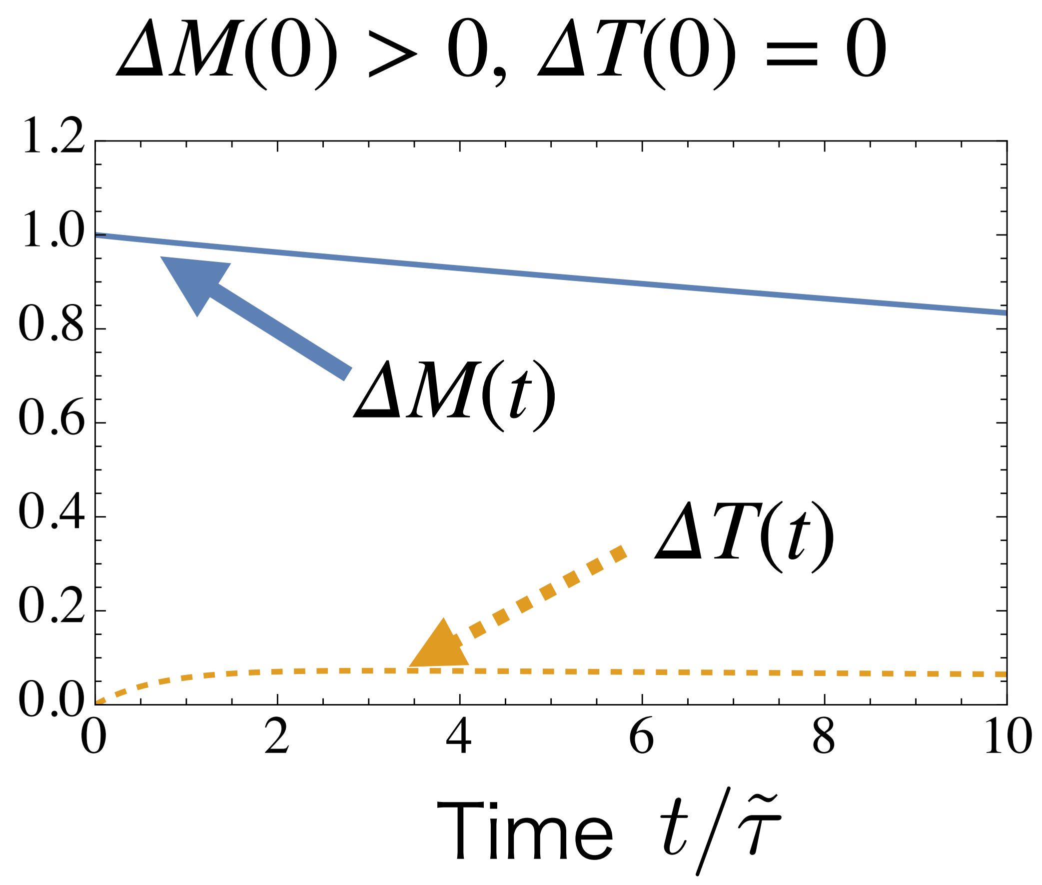
Relaxation dynamics

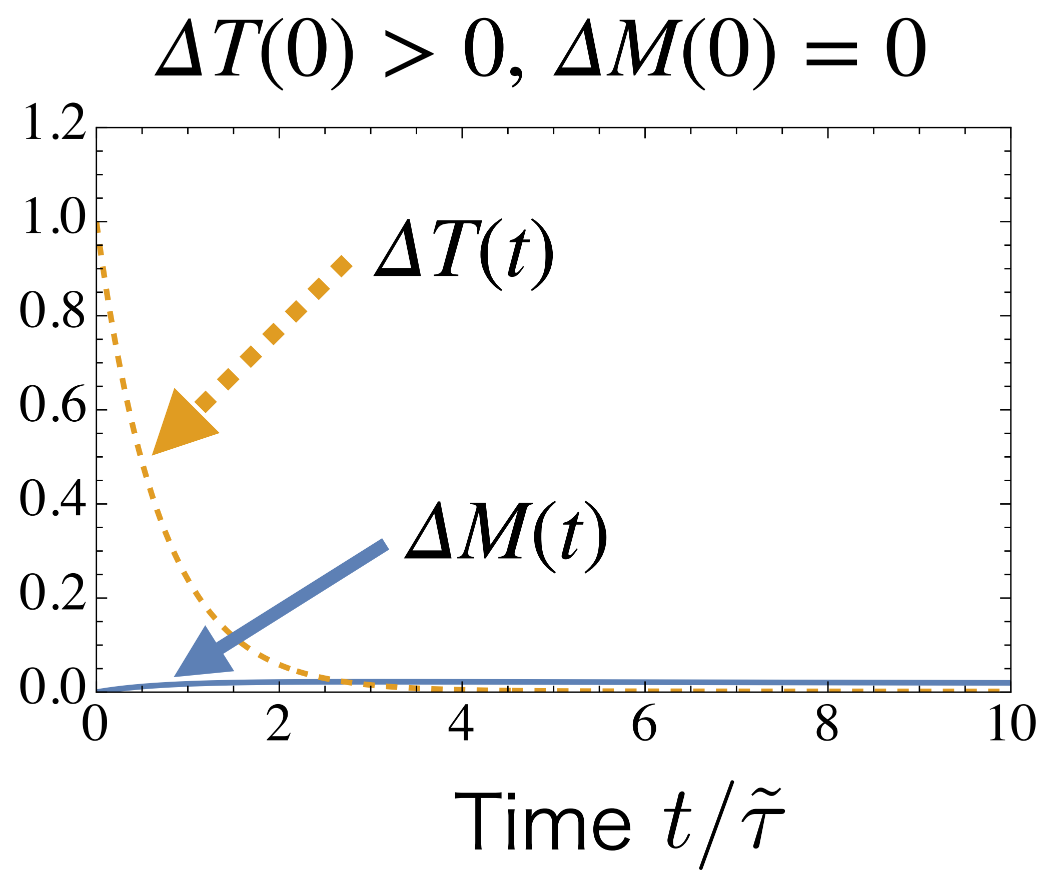
Fermi-gas cases [ETH: Brantut et al., Science (2013)],

A. Near-equilibrium relaxation dynamics of $\Delta M(t) = M_{\mathrm{L}}(t) - M_{\mathrm{R}}(t)$, $\Delta T(t) = T_{\mathrm{L}}(t) - T_{\mathrm{R}}(t)$ b/w FIs from a thermal initial state



1. Close the channel and prepare thermal states with $M_{\mathrm{L/R}}(0)$, $T_{\mathrm{L/R}}(0)$
2. At $t=0$, open the channel so that $M_{\mathrm{L/R}}(t)$, $T_{\mathrm{L/R}}(t)$ start time evolution
3. Observe $\Delta M(t) = M_{\mathrm{L}}(t) - M_{\mathrm{R}}(t)$ $\Delta T(t) = T_{\mathrm{L}}(t) - T_{\mathrm{R}}(t)$ at time t



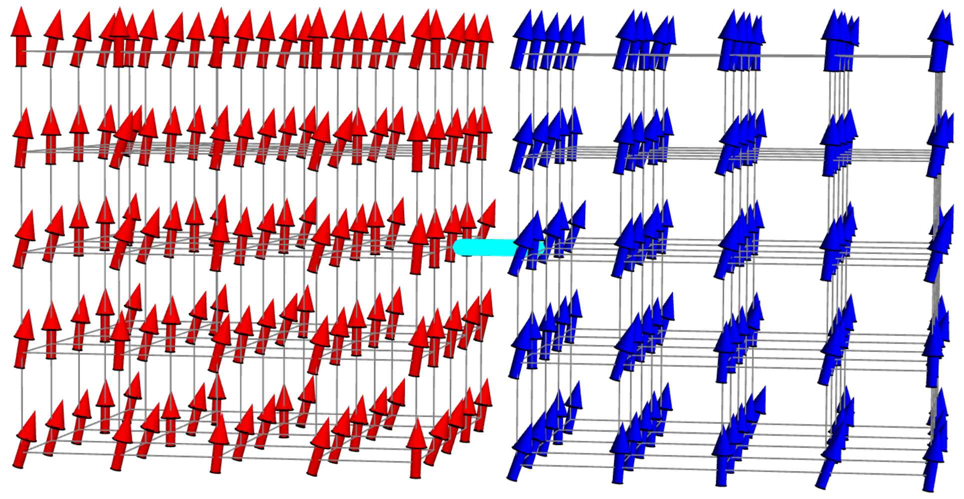


4. Fit obtained $\Delta M(t)$ and $\Delta T(t)$ with solutions of the quasi-stationary model

$$\begin{pmatrix} \Delta M(t)/\mathcal{N} \\ \Delta T(t)/T \end{pmatrix} = \begin{pmatrix} \Lambda_{11}(t) & \Lambda_{11}(t) \\ \Lambda_{11}(t) & \Lambda_{22}(t) \end{pmatrix} \begin{pmatrix} \Delta M(0)/\mathcal{N} \\ \Delta T(0)/T(0) \end{pmatrix}$$

Quasi-stationary model

Fermi-gas cases [ETH: Brantut et al., Science (2013)],



$$\begin{pmatrix} \Delta M(t)/\mathcal{N} \\ \Delta T(t)/T \end{pmatrix} = \mathbf{\Lambda}(t\,;\mathbf{L},\,\mathbf{K}) \begin{pmatrix} \Delta M(0)/\mathcal{N} \\ \Delta T(0)/T(0) \end{pmatrix}$$

Matrix $\mathbf{\Lambda}(t\,;\mathbf{L},\,\mathbf{K})$ depend on conductances and thermodynamic quantities

$$\mathbf{L} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} \qquad \mathbf{K} = \begin{pmatrix} \left(\frac{\partial M}{\partial h}\right)_T & -\left(\frac{\partial M}{\partial T}\right)_h \\ -\left(\frac{\partial S}{\partial h}\right)_T & \left(\frac{\partial S}{\partial T}\right)_h \end{pmatrix}$$

Because $\begin{pmatrix} \Delta M(t)/\mathcal{N} \\ \Delta T(t)/T \end{pmatrix}$ is the solution of the following equations:

Transport relation: $$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} -\Delta M \\ T\Delta S \end{pmatrix} = -2\begin{pmatrix} I_{\mathrm{S}} \\ I_{\mathrm{H}} \end{pmatrix} = -2\begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix}\begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix}$$

Thermodynamic relation: $$\begin{pmatrix} -\Delta M \\ \Delta S \end{pmatrix} = \begin{pmatrix} \left(\frac{\partial M}{\partial h}\right)_T & -\left(\frac{\partial M}{\partial T}\right)_h \\ -\left(\frac{\partial S}{\partial h}\right)_T & \left(\frac{\partial S}{\partial T}\right)_h \end{pmatrix}\begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix}$$

Form of $\Lambda(t; L, K)$

$$\boldsymbol{\Lambda}(t;\,\mathbf{L},\,\mathbf{K}) = \begin{pmatrix} \Lambda_{11}(t) & \Lambda_{12}(t) \\ \Lambda_{21}(t) & \Lambda_{22}(t) \end{pmatrix}$$

$$\Lambda_{11/22}(t) = \frac{1}{2}(e^{-t/\tau_-} + e^{-t/\tau_+}) \pm \frac{1}{2}\frac{\frac{L+\alpha^2}{l} - 1}{\lambda_+ - \lambda_-}(e^{-t/\tau_-} - e^{-t/\tau_+})$$

$$\Lambda_{12}(t) = \left(\frac{T\kappa}{\mathcal{N}}\right)^2 l\Lambda_{21}(t) = -\frac{T}{\mathcal{N}}\frac{\alpha\kappa}{\lambda_+ - \lambda_-}(e^{-t/\tau_-} - e^{-t/\tau_+})$$

$$\tau_\pm = \tau_0/\lambda_\pm \qquad \lambda_\pm = \frac{1}{2}\left(1 + \frac{L+\alpha^2}{l}\right) \pm \sqrt{\frac{\alpha^2}{l} + \frac{1}{4}\left(1 - \frac{L+\alpha^2}{l}\right)^2}, \qquad \tau_0 = \frac{\kappa}{2L_{11}}, \qquad \alpha = \alpha_r - \alpha_{ch}.$$

$$\mathbf{K} = \begin{pmatrix} \left(\frac{\partial M}{\partial h}\right)_T & -\left(\frac{\partial M}{\partial T}\right)_h \\ -\left(\frac{\partial S}{\partial h}\right)_T & \left(\frac{\partial S}{\partial T}\right)_h \end{pmatrix} = \kappa\begin{pmatrix} 1 & -\alpha_r \\ -\alpha_r & l+\alpha_r^2 \end{pmatrix} \qquad \mathbf{L} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} = L_{11}\begin{pmatrix} 1 & \alpha_{ch} \\ \alpha_{ch} & L+\alpha_{ch}^2 \end{pmatrix}$$

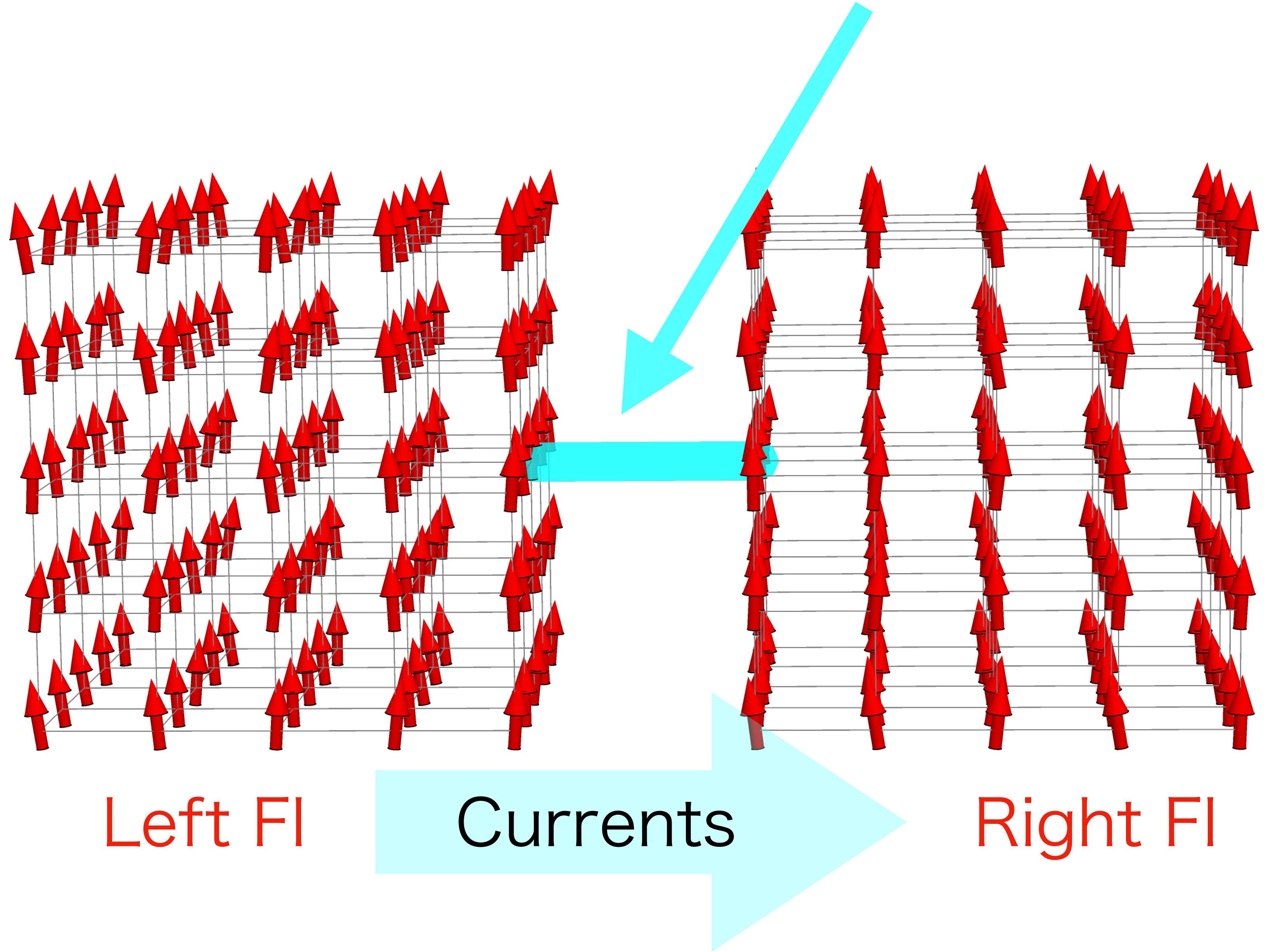
$$\kappa = \left(\frac{\partial N}{\partial \mu}\right)_T, \qquad \alpha_r = \left(\frac{\partial S}{\partial N}\right)_T, \qquad l = \frac{C_N}{\kappa T} = \frac{1}{\kappa}\left(\frac{\partial S}{\partial T}\right)_N \qquad G = 2L_{11}, \qquad \alpha_{ch} = \frac{L_{12}}{L_{11}}, \qquad L = \frac{L_{22}}{TL_{11}} - \left(\frac{L_{12}}{L_{11}}\right)^2.$$

OLD slides

Takehome message: Tunneling transport by criticality

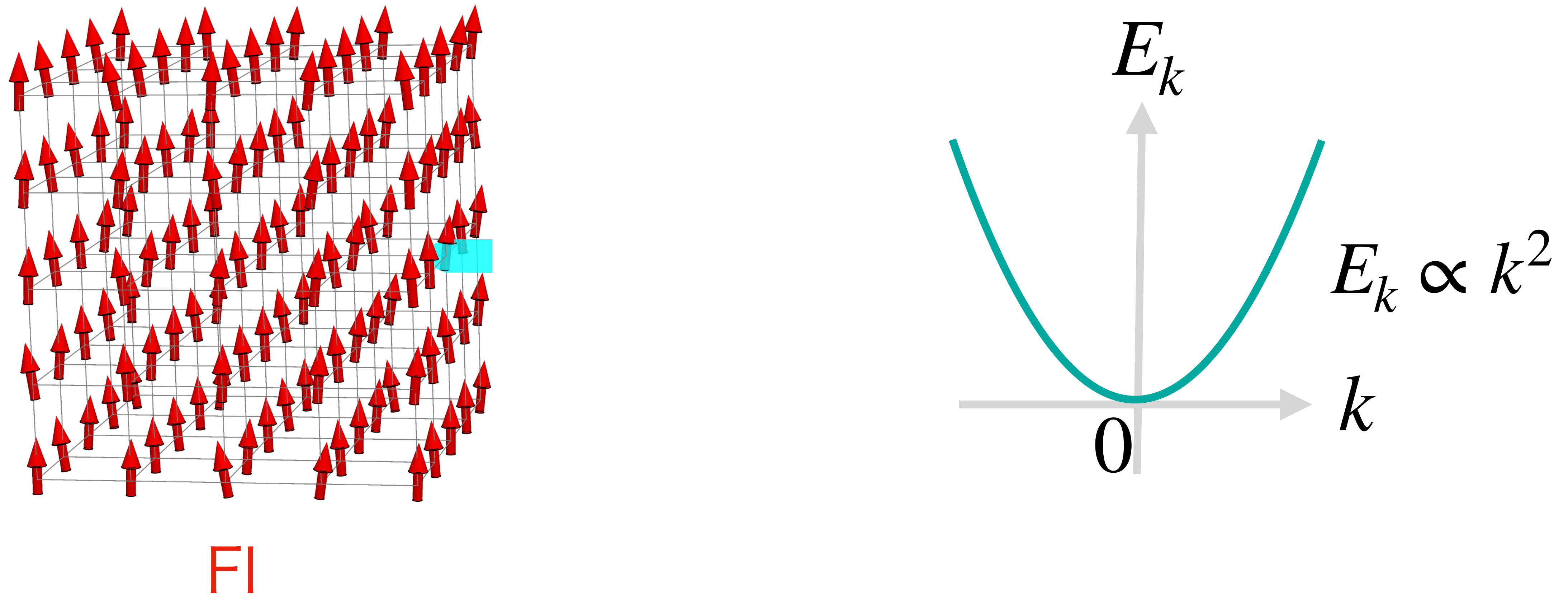
Anomalous tunneling spin and heat transport near **magnonic critical points** of ferromagnets

Two ferromagnetic insulators (FIs) realized with **cold atoms** connected via a quantum point contact



Gapless point of magnons in ferromagnets

Spontaneous breaking of O(3) symmetry in FIs → Magnon as **gapless Nambu-Goldstone mode**

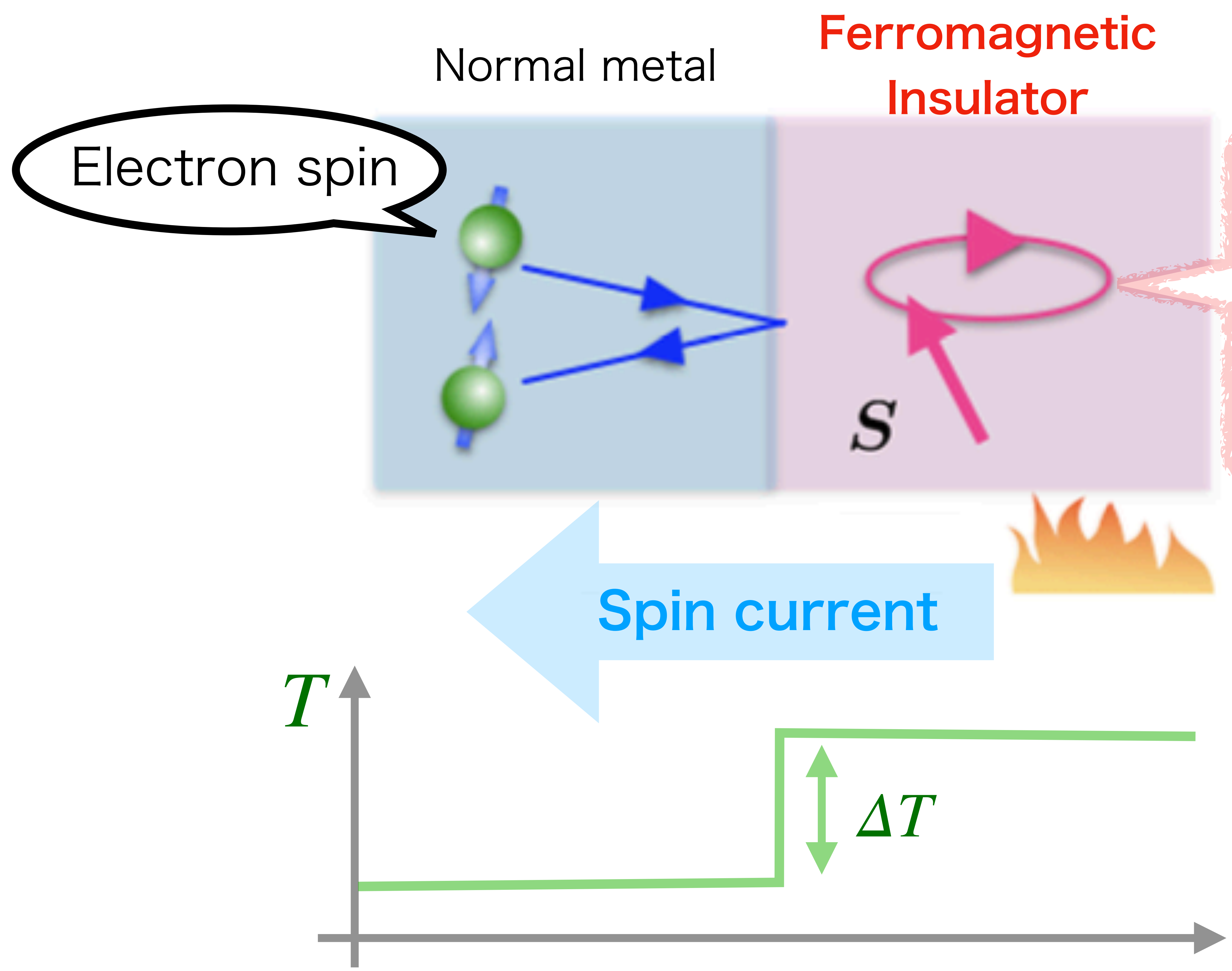


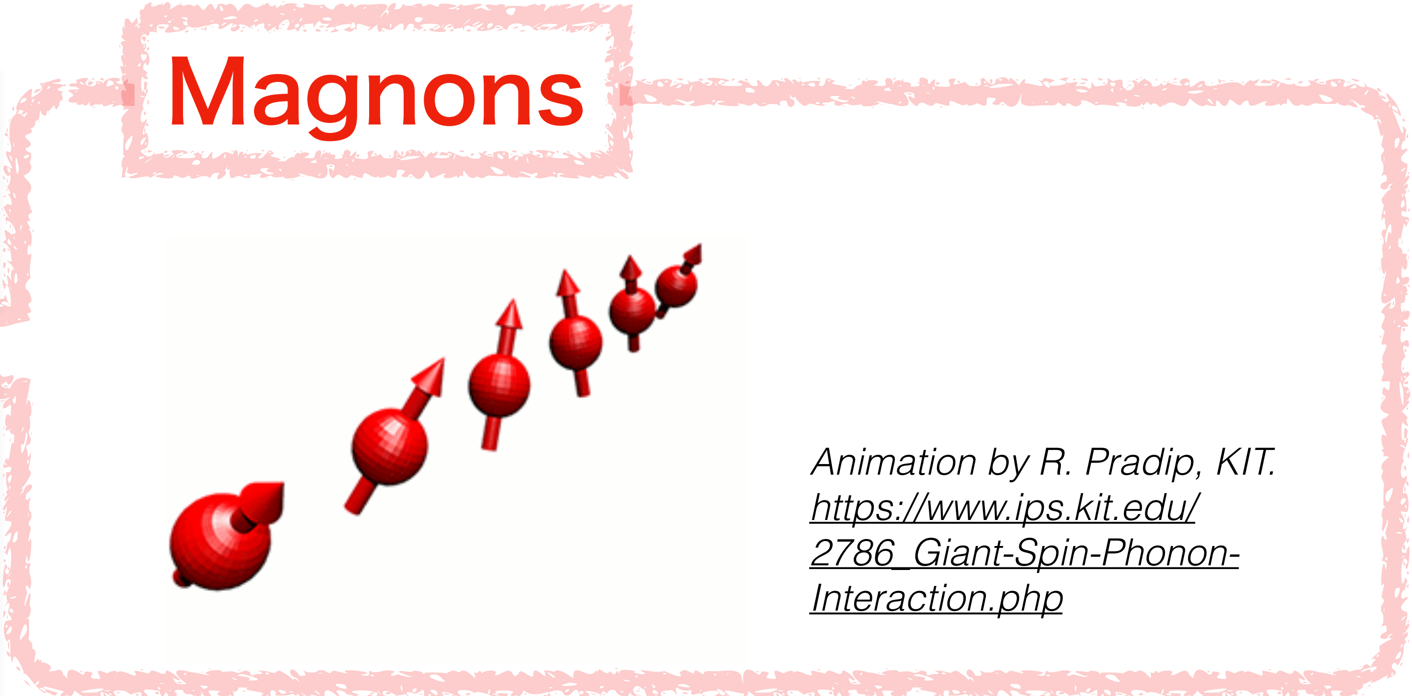
Anomalous enhancement of spin & heat conductances resulting from **the magnonic criticality**

Motivation from solid-state physics

Spin and heat tunneling transport with magnons is one of the hot topics in spintronics focusing on efficient spin-heat conversion for devices applications

- **Spin Seebeck effect:** spin-current generation by temperature bias ΔT



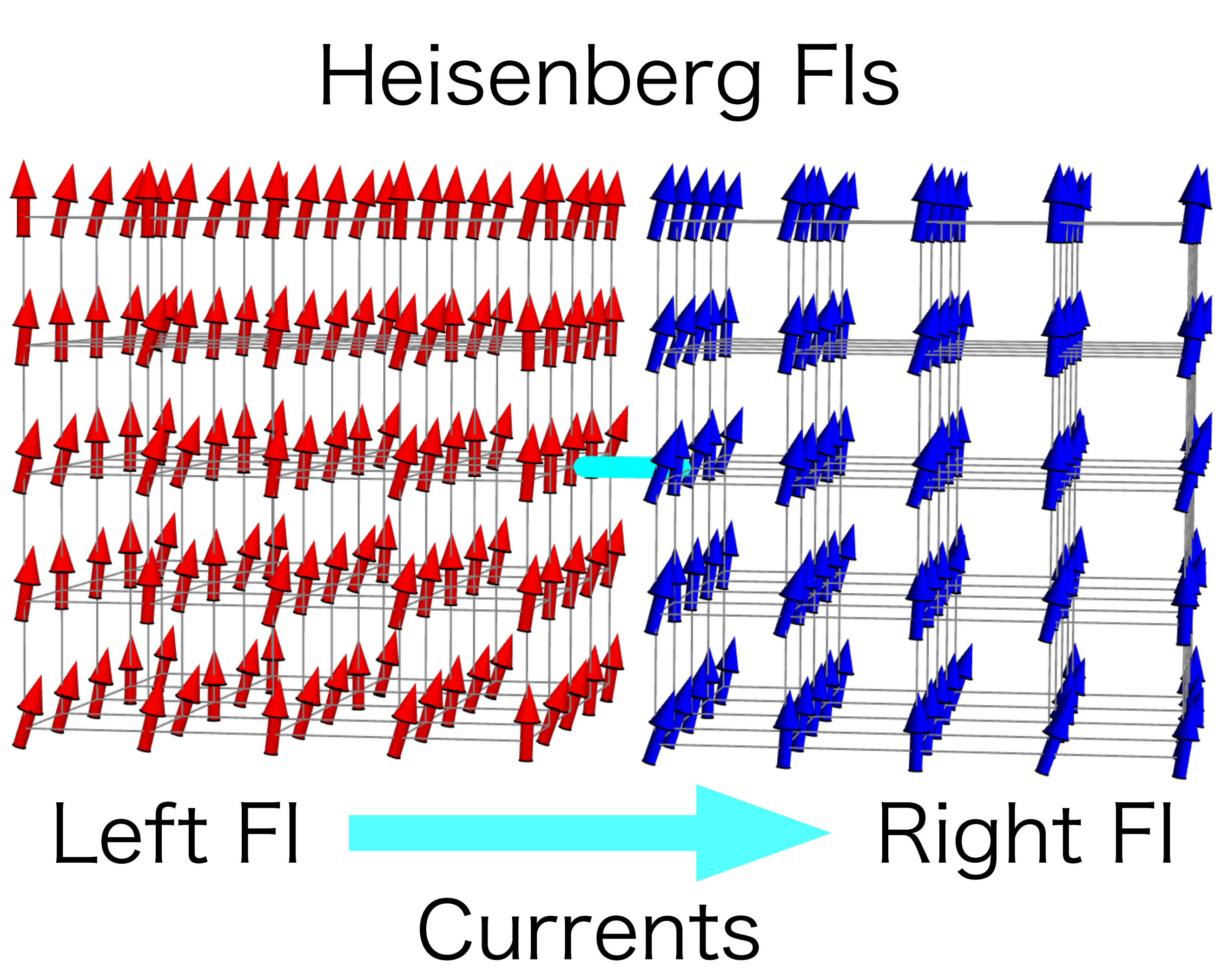


Observation spin Seebeck effect:
Uchida et al., Nature **455**, 778–781 (2008)
Spin caloritronics (review):
Bauer et al., Nature Materials **11**, 391–399 (2012)

Quantum simulation of magnonic transport

To bridge cold atoms and spintronics, we propose **a quantum simulation of spin & heat tunneling transport of magnons b/w ferromagnets**

YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280



Cold-atomic physics

Y. Sekino
RIKEN

H. Tajima
U. Tokyo

S. Uchino
Waseda Univ.

Solid-state physics

Y. Ominato
Waseda Univ.

M. Matsuo
UCAS, China

Why tunneling spin & heat transport w/ cold atoms?

1. Ultraclean systems

   No impurity

   No roughness & lattice mismatch

2. Quantum controllability of **effective Zeeman fields** Similarly to Fermi gases [Kriner et al., PNAS, **113** (29) 8144-8149 (2016)]

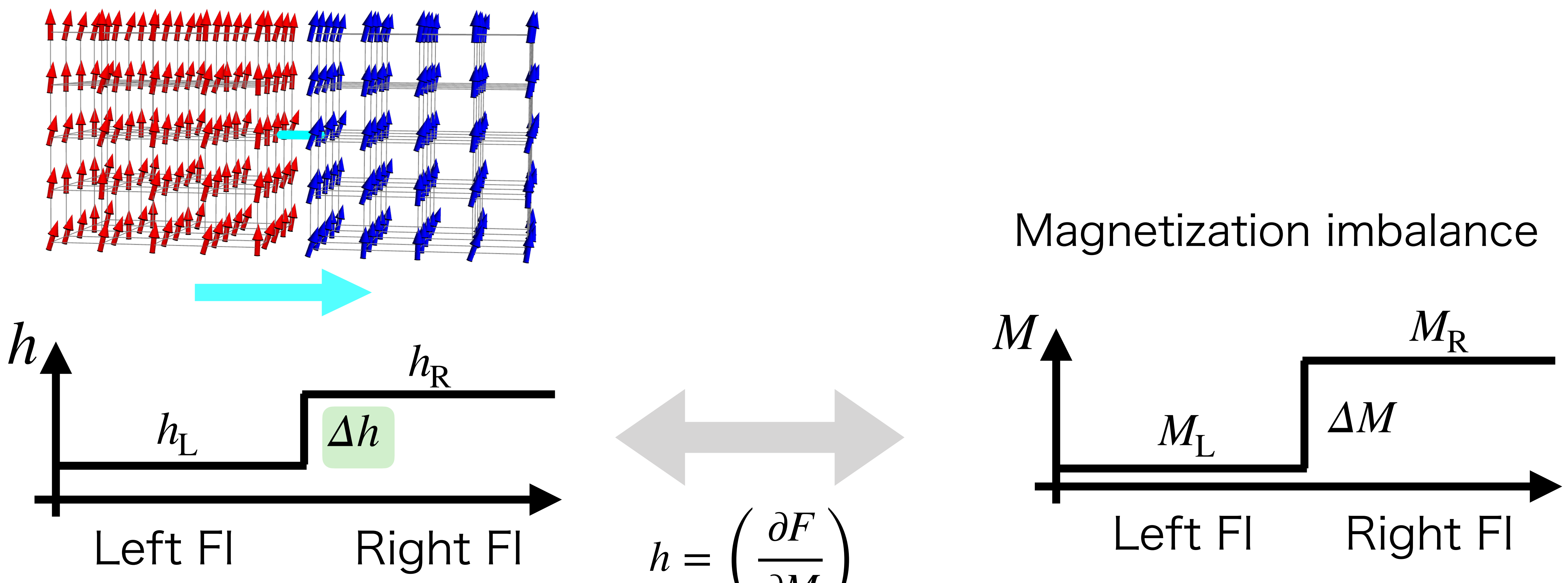
   Control of spin bias Δh to generate spin & heat currents

No solid-state experiment b/w FIs

because inducing Δh by

spatially-modulated magnetic field is difficult

Magnetization imbalance



$$h = \left(\frac{\partial F}{\partial M}\right)_T$$

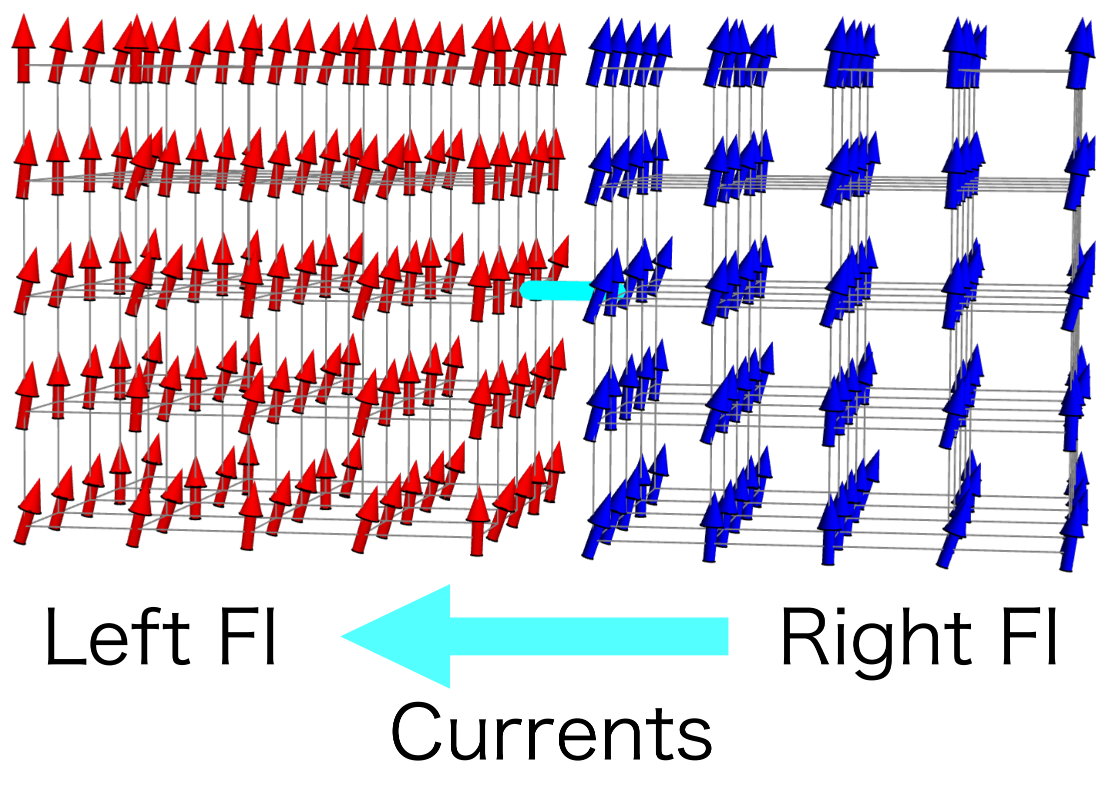
Effective Zeeman fields can be tuned by optically controlling $M_{\mathrm{L/R}} = (N_\uparrow^{\mathrm{L/R}} - N_\downarrow^{\mathrm{L/R}})/2$

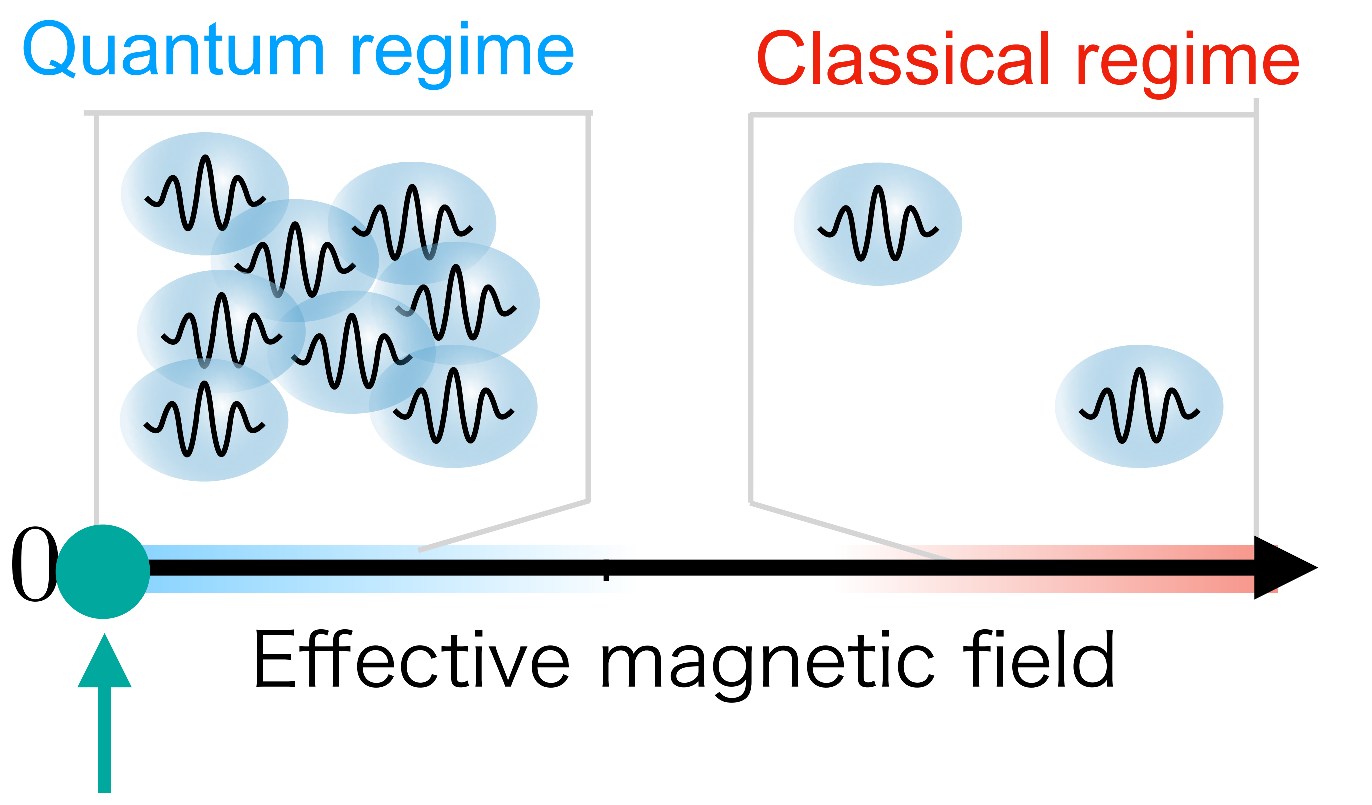
$h_{\mathrm{L/R}}$

Summary of setup and results

YS, Ominato, Tajima, Uchino, & Matsuo, arXiv:2312.04280

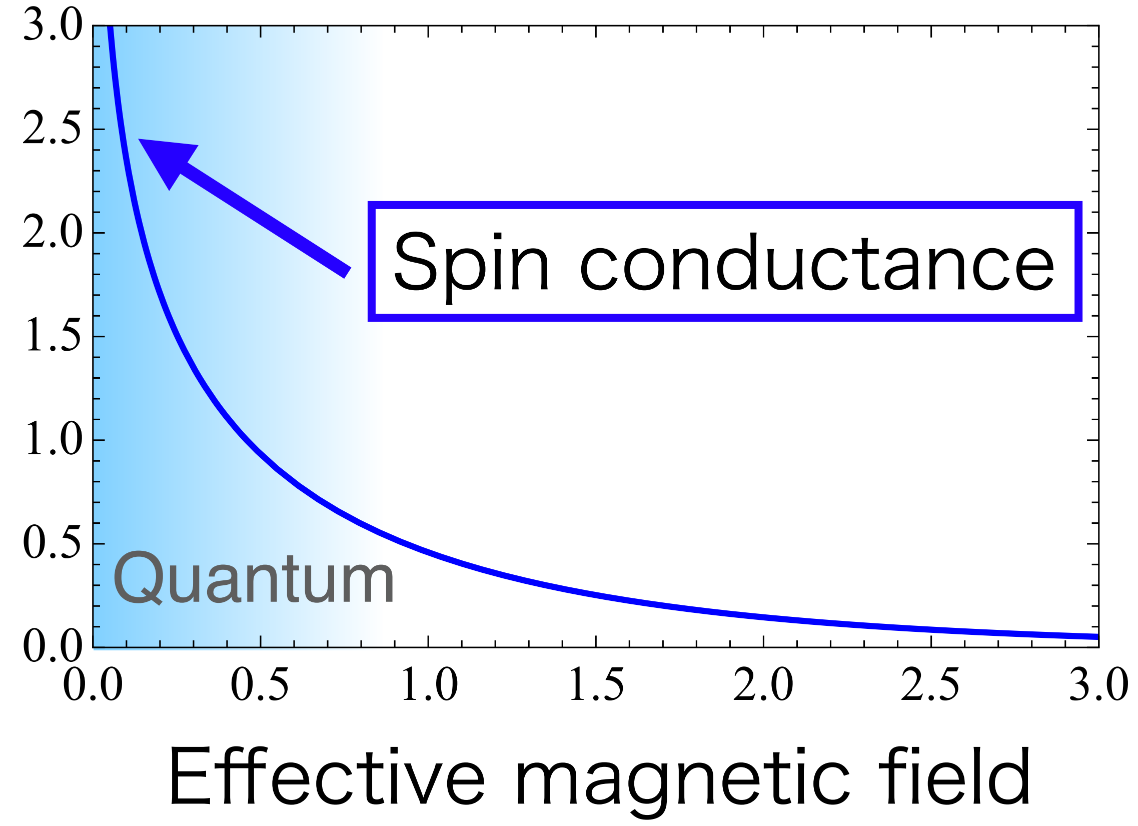
Highly spin-polarized FIs connected with a magnetic quantum point contact

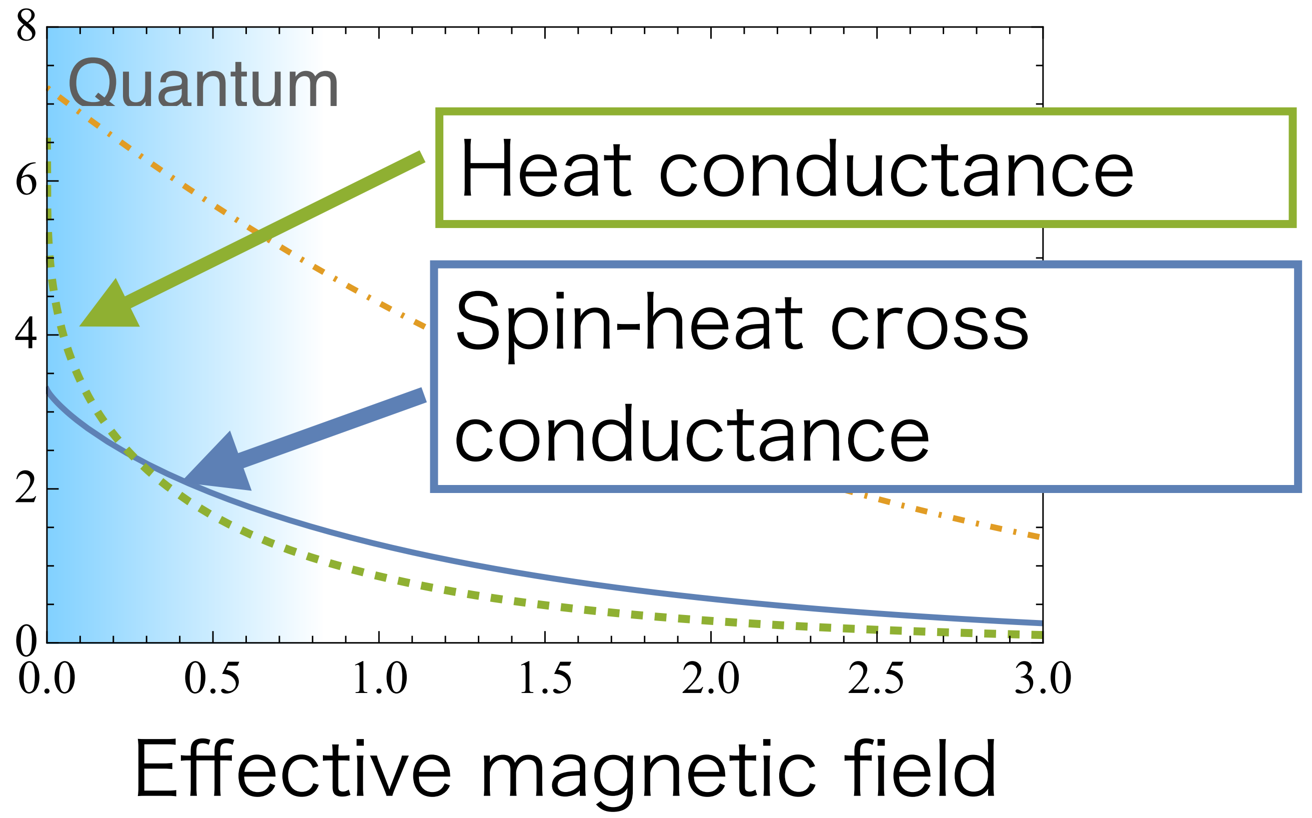




Anomalous thermomagnetic transport by magnonic criticality

Enhancement in spin & heat conductances





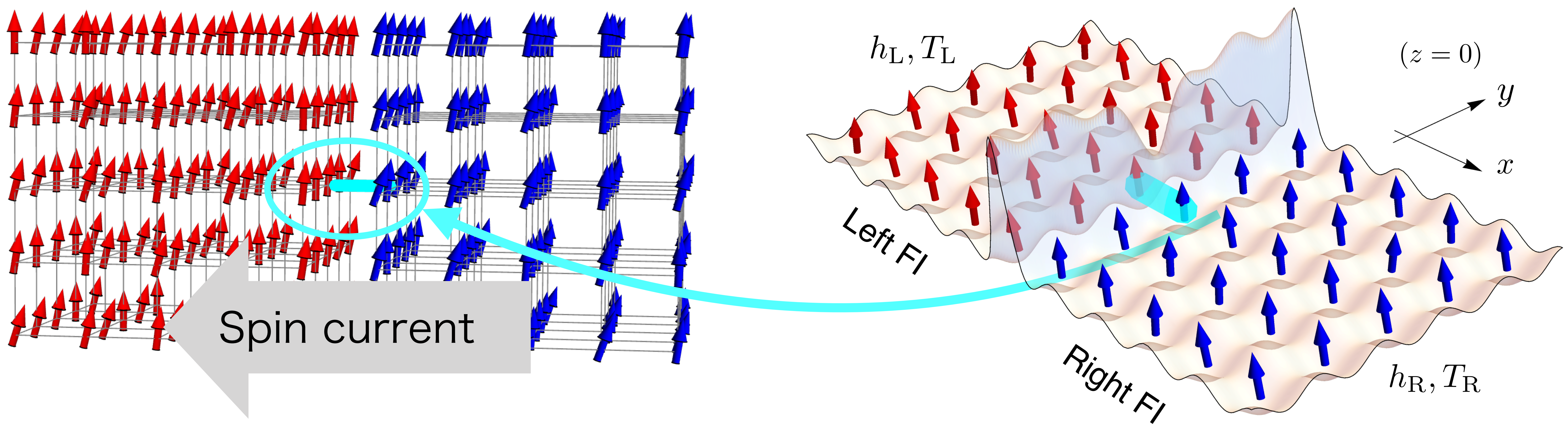
Large-scale optical lattice

Timelyness:
巨大な系を用意できる => 輸送をやれるよね

アボガドロ数での固体系での、スピントロニクス応用できるよね

Takehome message: Tunneling transport by magnonic criticality

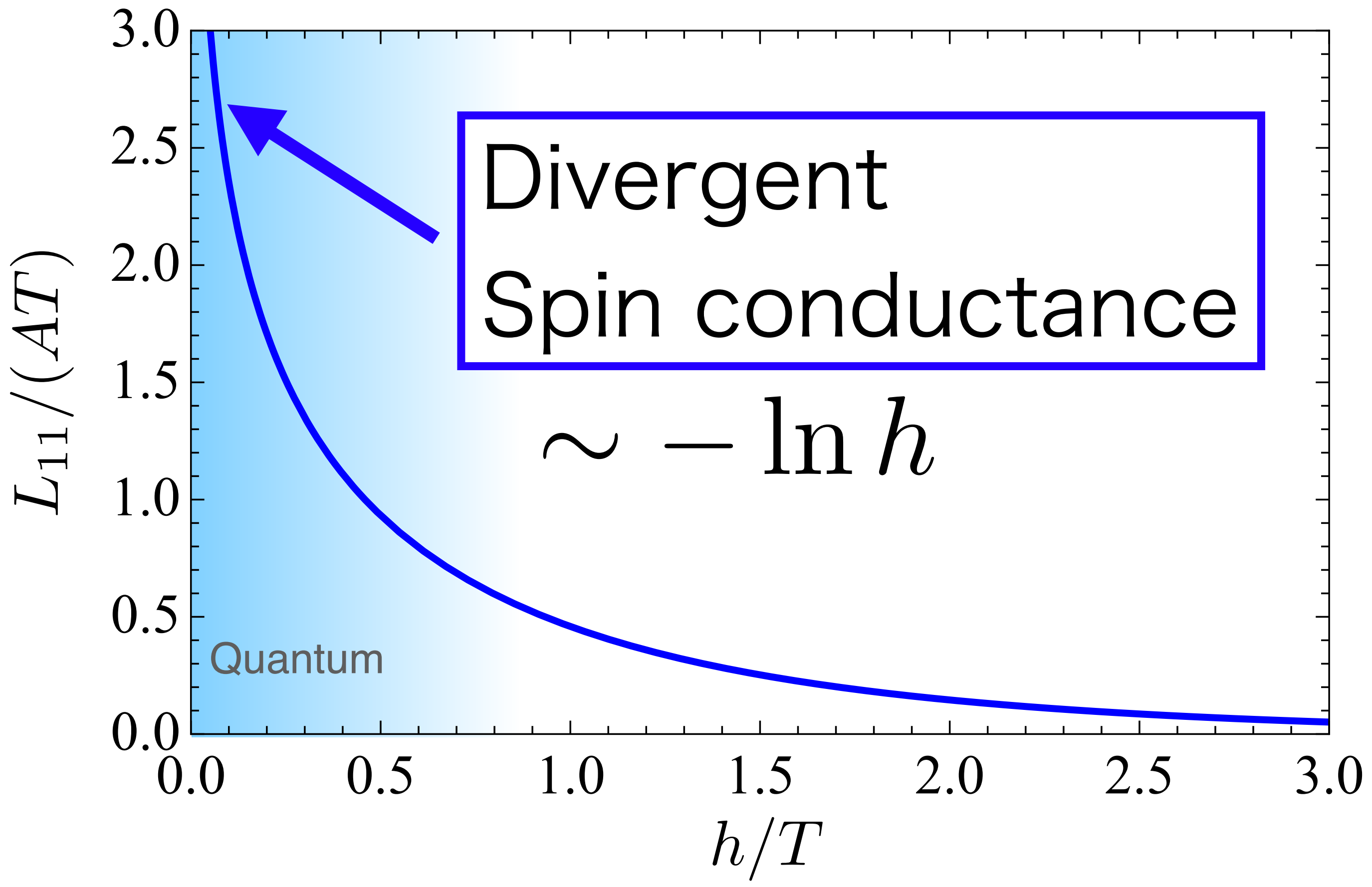
Anomalous tunneling transport due to gapless magnons at the magnonic critical point

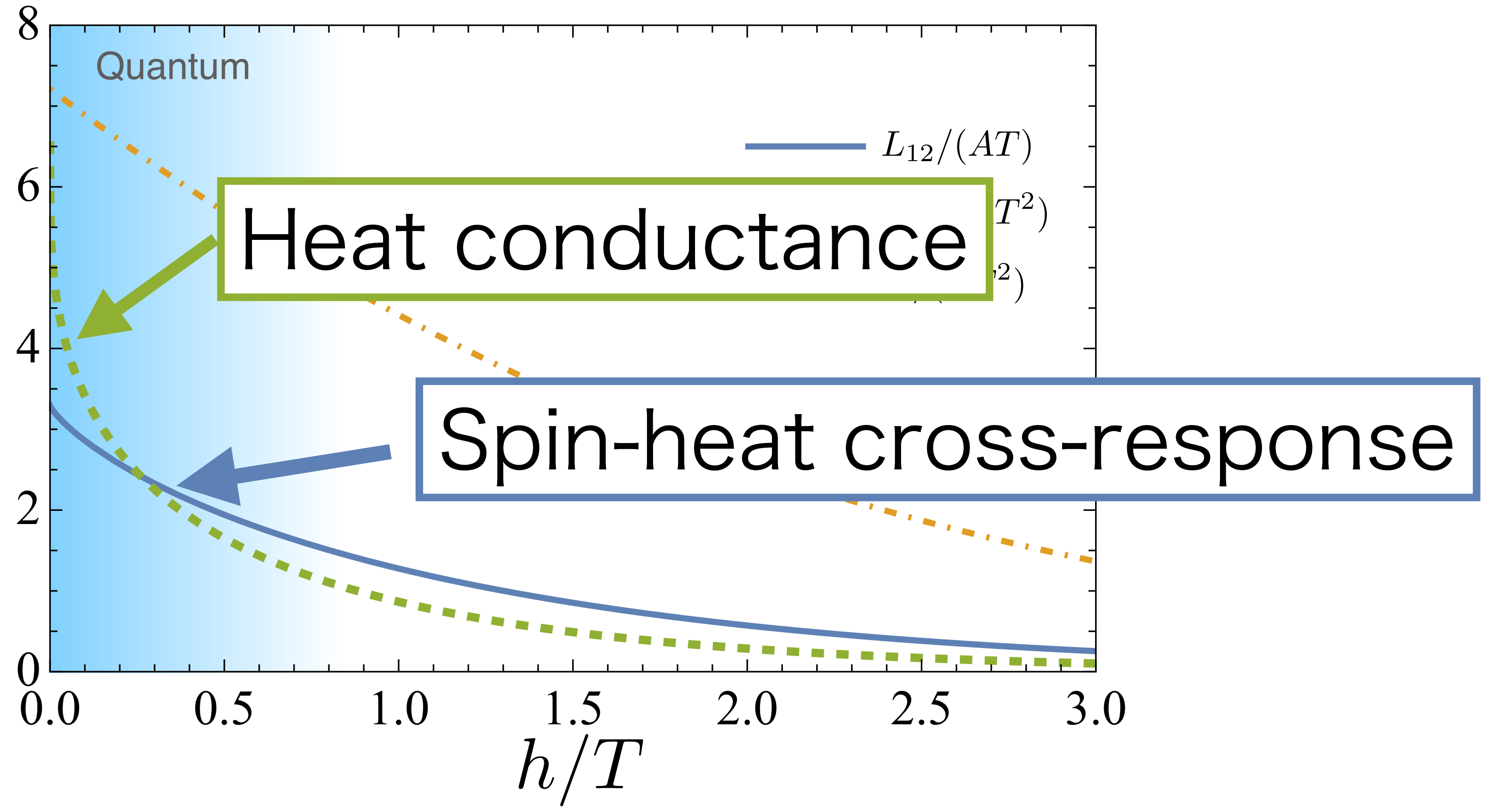


Two Heisenberg ferromagnets co
via a quantum point contact

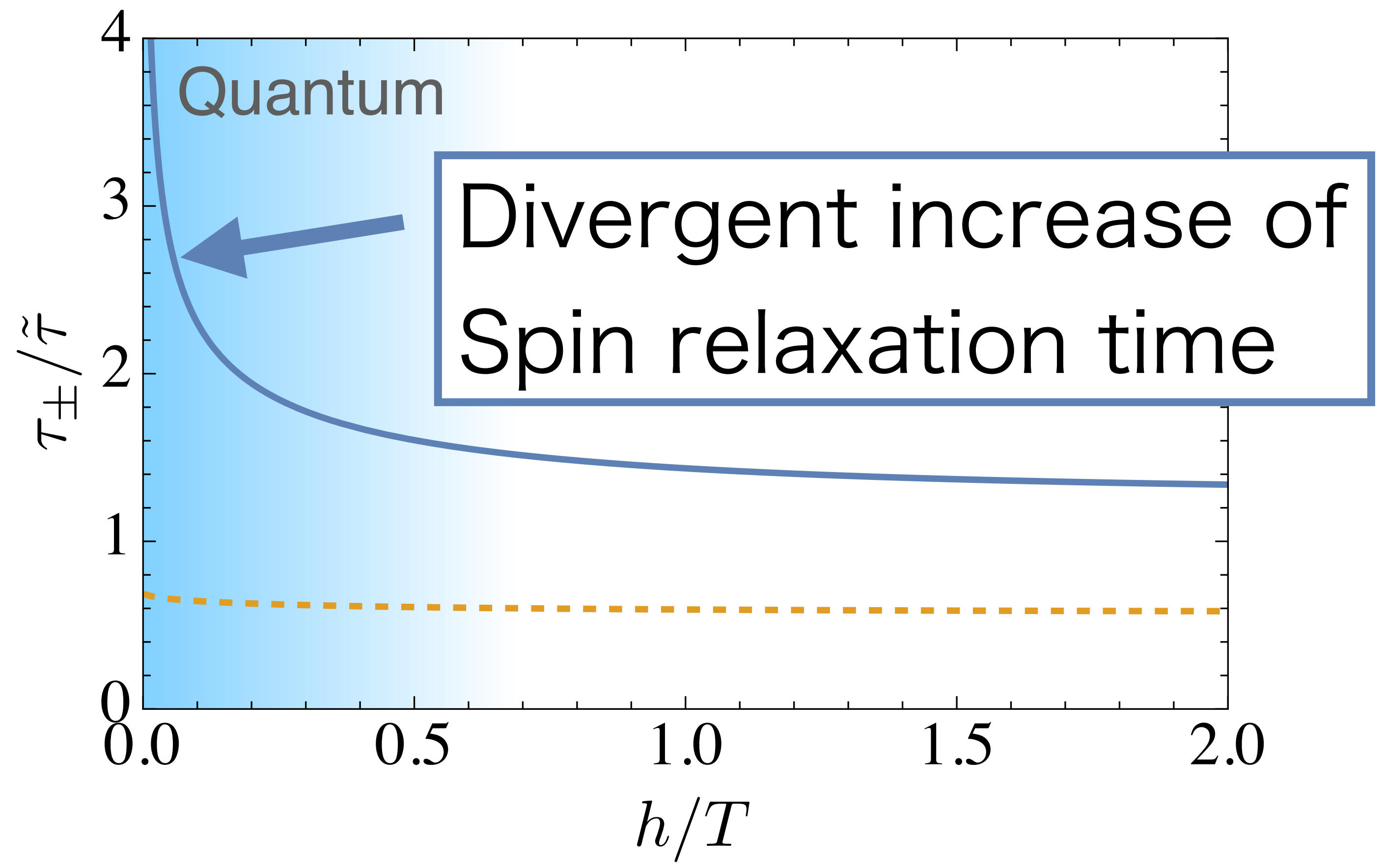
Anomalous spin & heat transport properties

1. Anomalous enhancement in spin & heat transport coefficients





2. Extremely slow spin relaxation

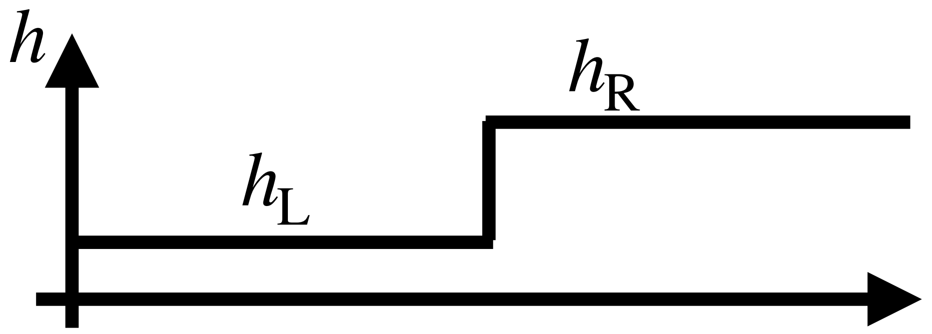


Advantage of cold atoms to investigate tunnel transport

冷却原子のメリットをともかくおす（結論を先に言う）
固体はどうかということを比較はあまりしない
その一方で、固体では、無理

Quantum controllability

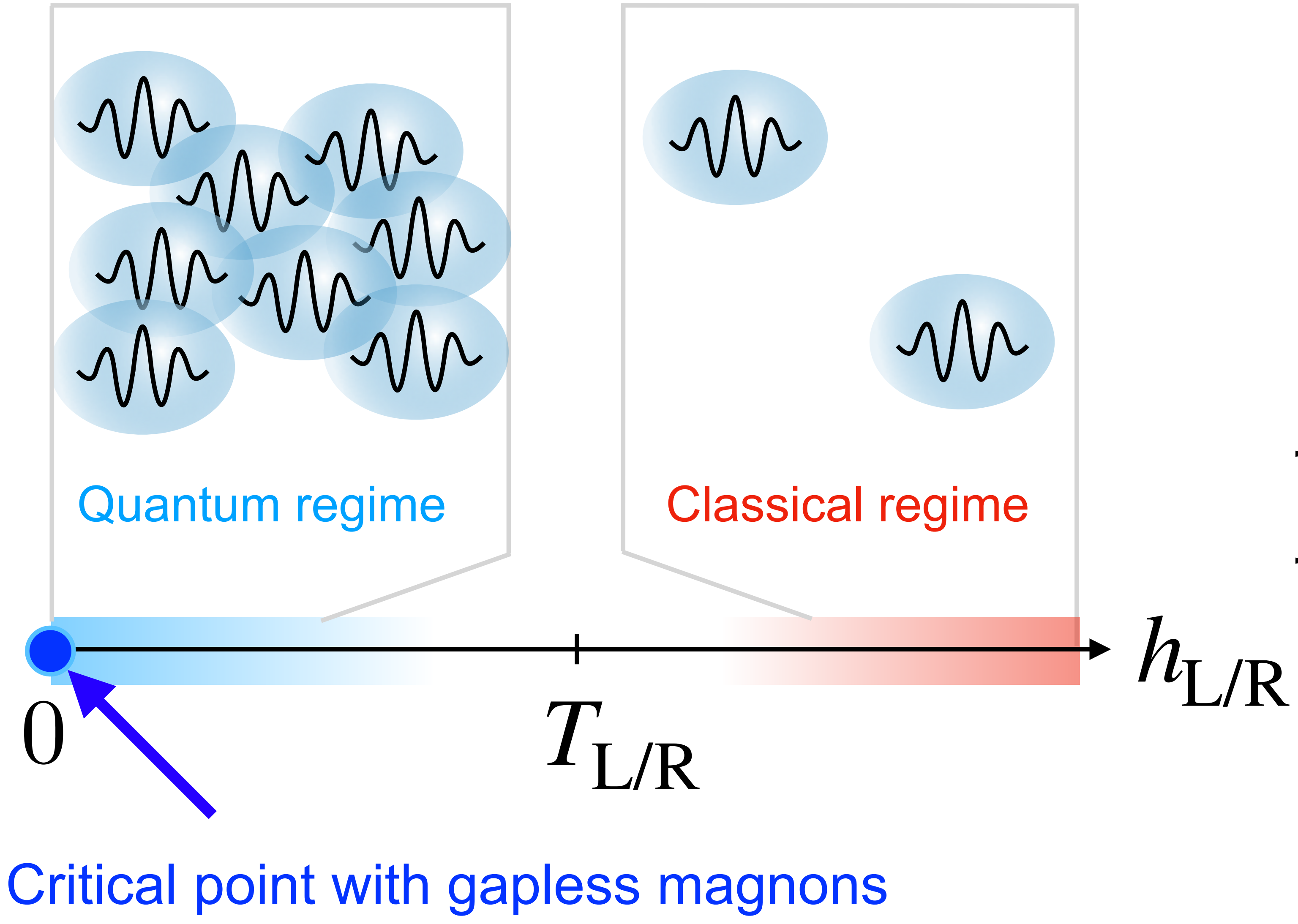
1. Control of spin bias to induce spin current



2. Ultraclean systems

No impurity, lattice defect, & lattice vibration
Interfering spin currents （整合性を後で考える）

Roughness, lattice mismatch も追加しても良いかも



Previous proposal for solids
Nakata et al., PRB (2015);
PRB (2018); …

3. Control of interface by lasers

To avoid the emergence of magnetic domains
To avoid the emergence of magnetic domains

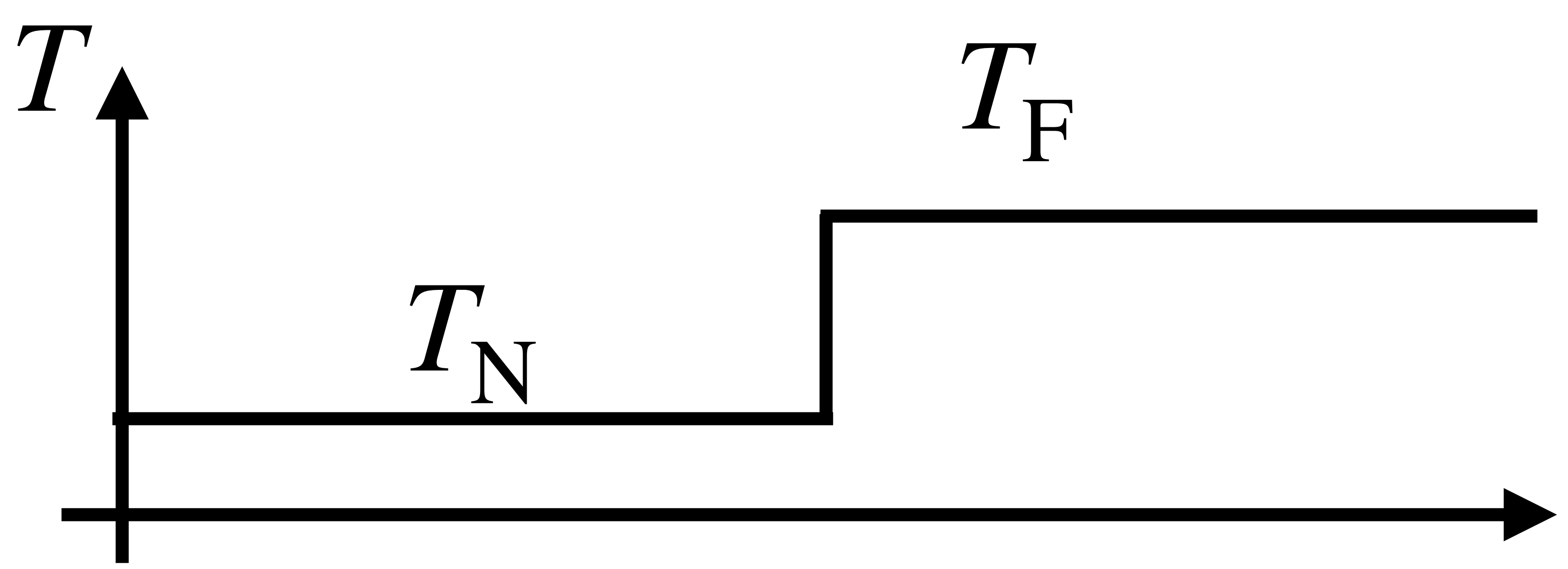
2つの大きな困難がある：
1. 磁場勾配を定量性が出るように制御するのが困難（古典ですら難しい）
2. 弱磁場での実験が難しい

Advantage of cold atoms to investigate tunnel transport

Quantum controllability

Solids

1. Control of magnetic field to induce spin current



2. Uncontrollable elements

Impurity
Lattice defect
Lattice vibration (phonon)

Cold atoms

Effective Zeeman field controlled by spin imbalance

$$h_{\alpha=L/R} = \left(\frac{\partial E_\alpha}{\partial M_\alpha}\right)_{S_\alpha}$$

$$M = (N_\uparrow - N_\downarrow)/2$$

Total internal energy E_α

Equilibrium:

Measured in the single-comp case
Taksasu et al., ⋯

平衡状態の場

Clean spin systems

Nothing

Advantage of cold atoms to investigate tunnel transport

Solids

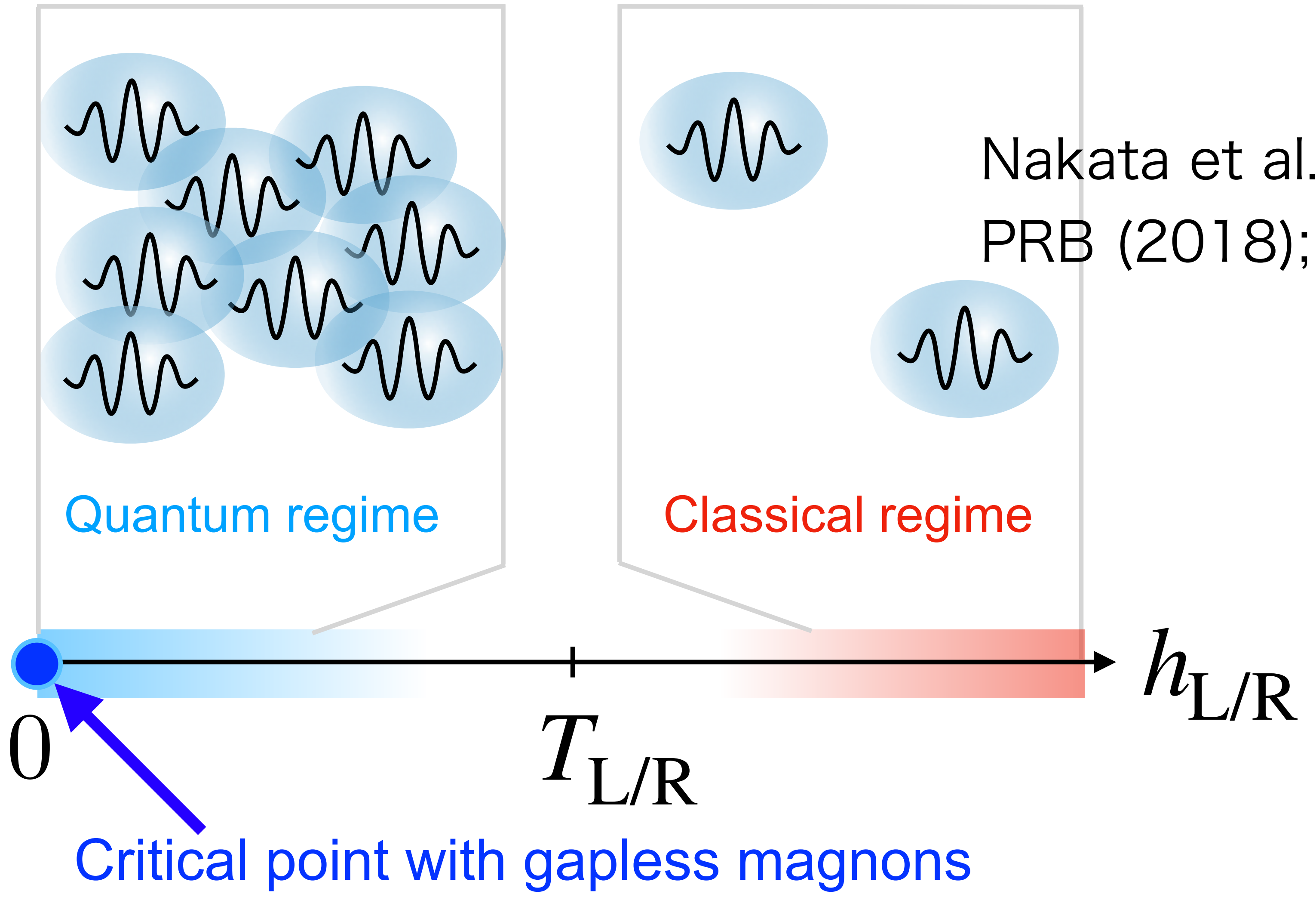
3. Interface control

Difficult to fabricate clean interface

Lattice mismatch

Change of Electron state near the surface

4. Magnon criticality

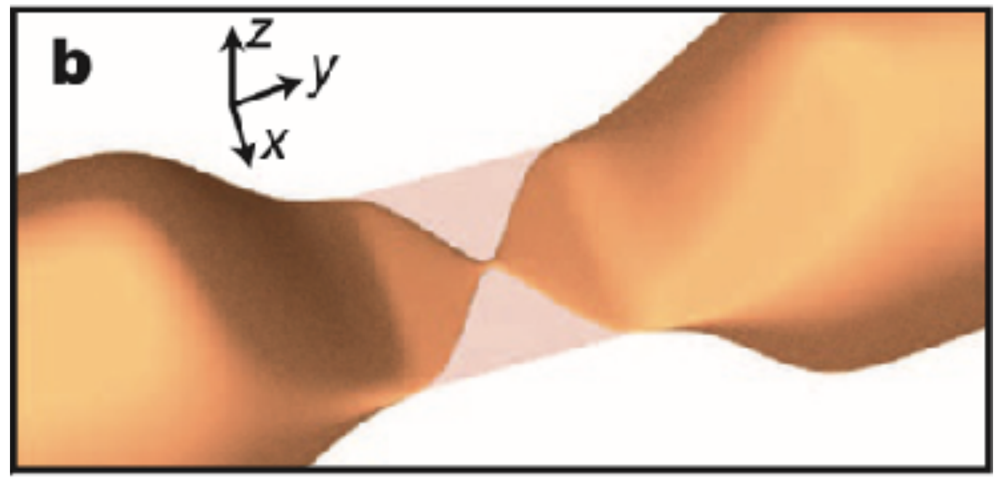


Nakata et al., PRB (2015); PRB (2018); …

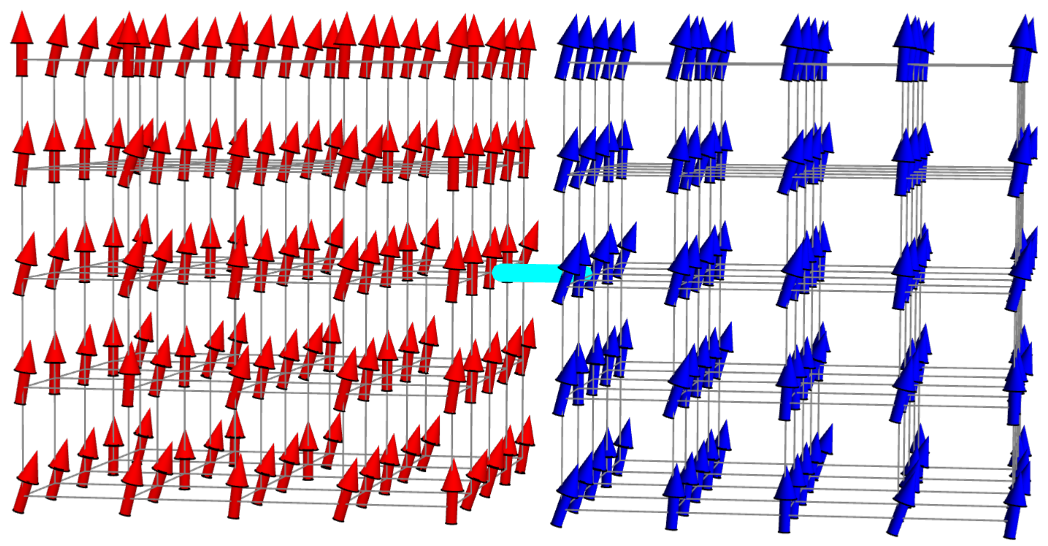
Cold atoms

3. Control of potential profile by lasers

Quantum point contact



Krinner et al., Nature (2015)



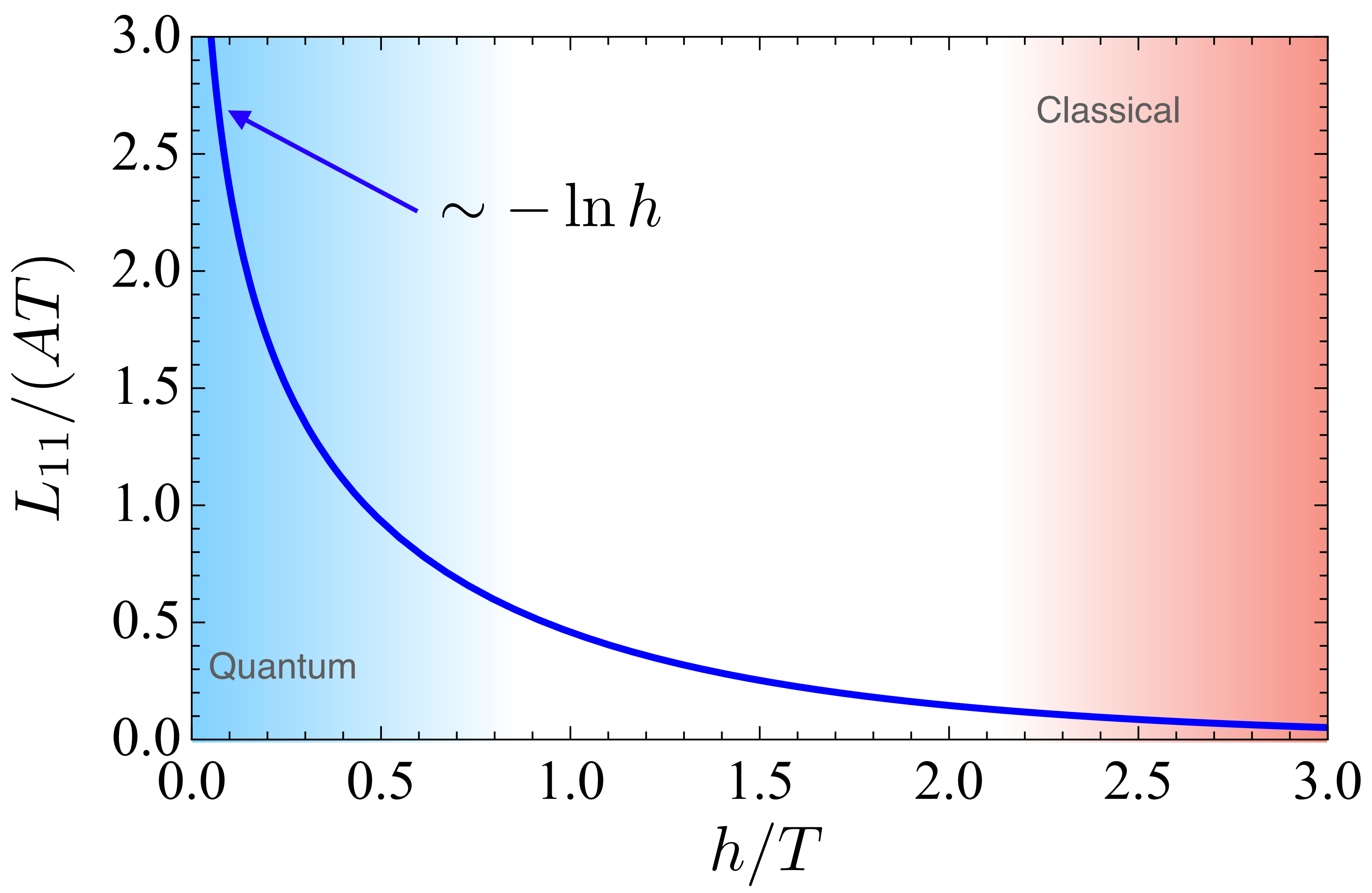
Critical behavior of Spin Conductance

Divergent behavior of spin conductance resulting from magnon criticality

L_{11}

Spin conductance

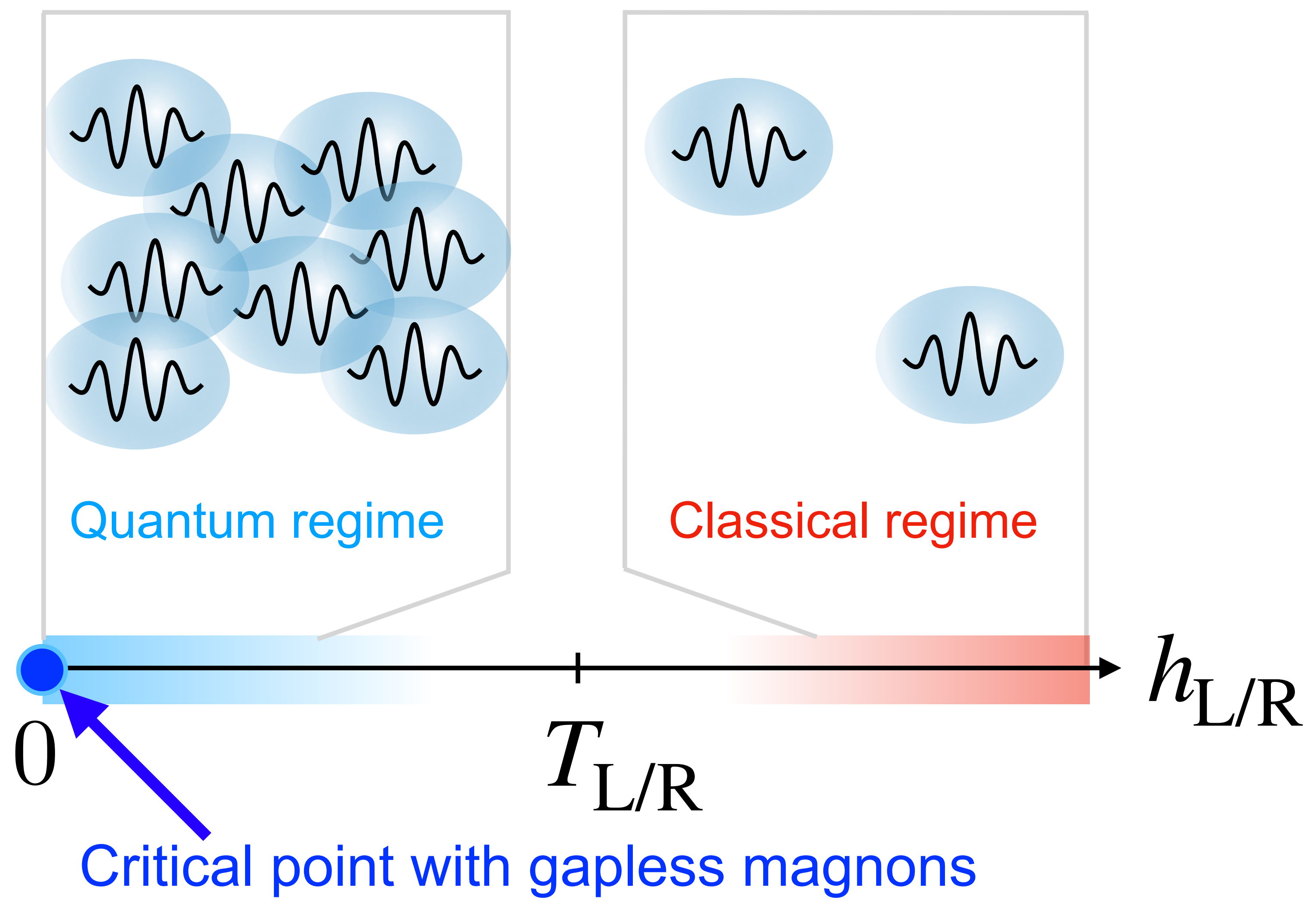
$$I_S = L_{11}\Delta h + O(\Delta h^2)$$



$T_L = T_R$

$\Delta h = h_R - h_L, h = (h_L + h_R)/2$

Criticality of magnons



$$E_{gap} = h_{L/R}$$

Gapless magnon as a Goldstone mode due to spontaneous magnetization

Critical behavior of transport coefficients

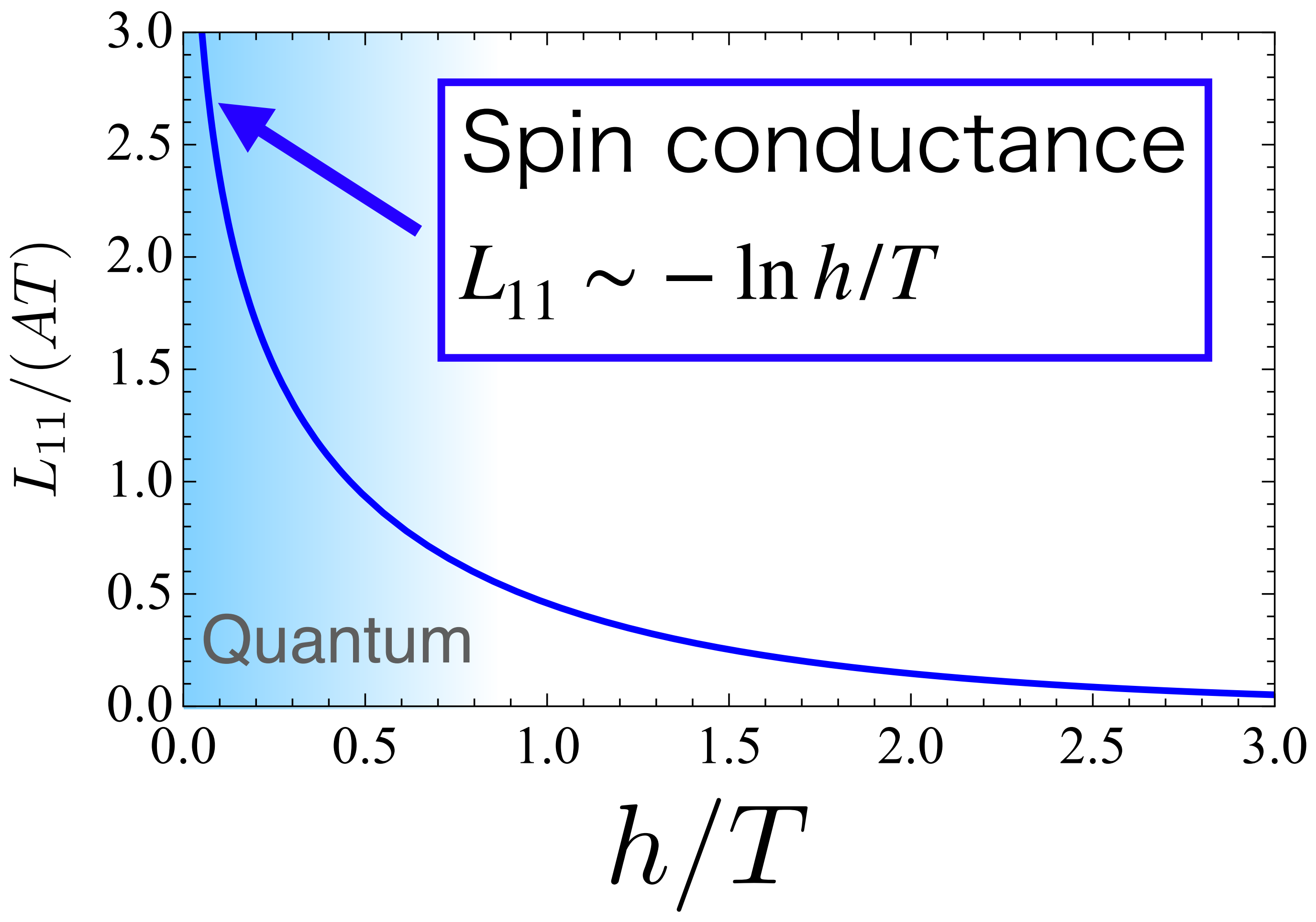
Enhancement of transport coefficients **resulting from** magnon criticality

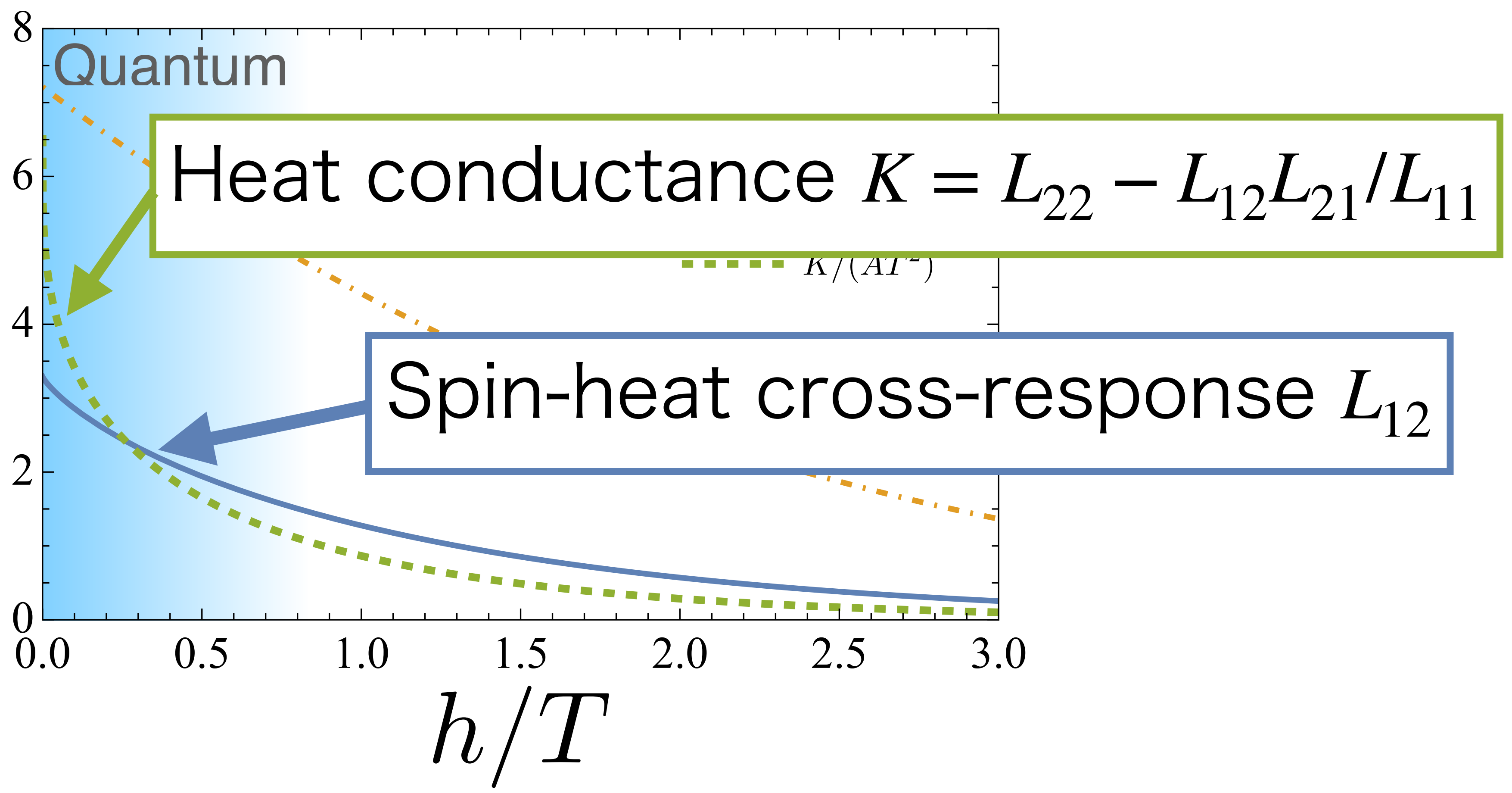
Transport coefficients L_{ij}

$$\begin{pmatrix} I_S \\ I_H \end{pmatrix} = \begin{pmatrix} L_{11} L_{12} \\ L_{21} L_{22} \end{pmatrix} \begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix} + O(\Delta T^2, \Delta h^2)$$

$\Delta h = h_R - h_L, h = (h_L + h_R)/2$

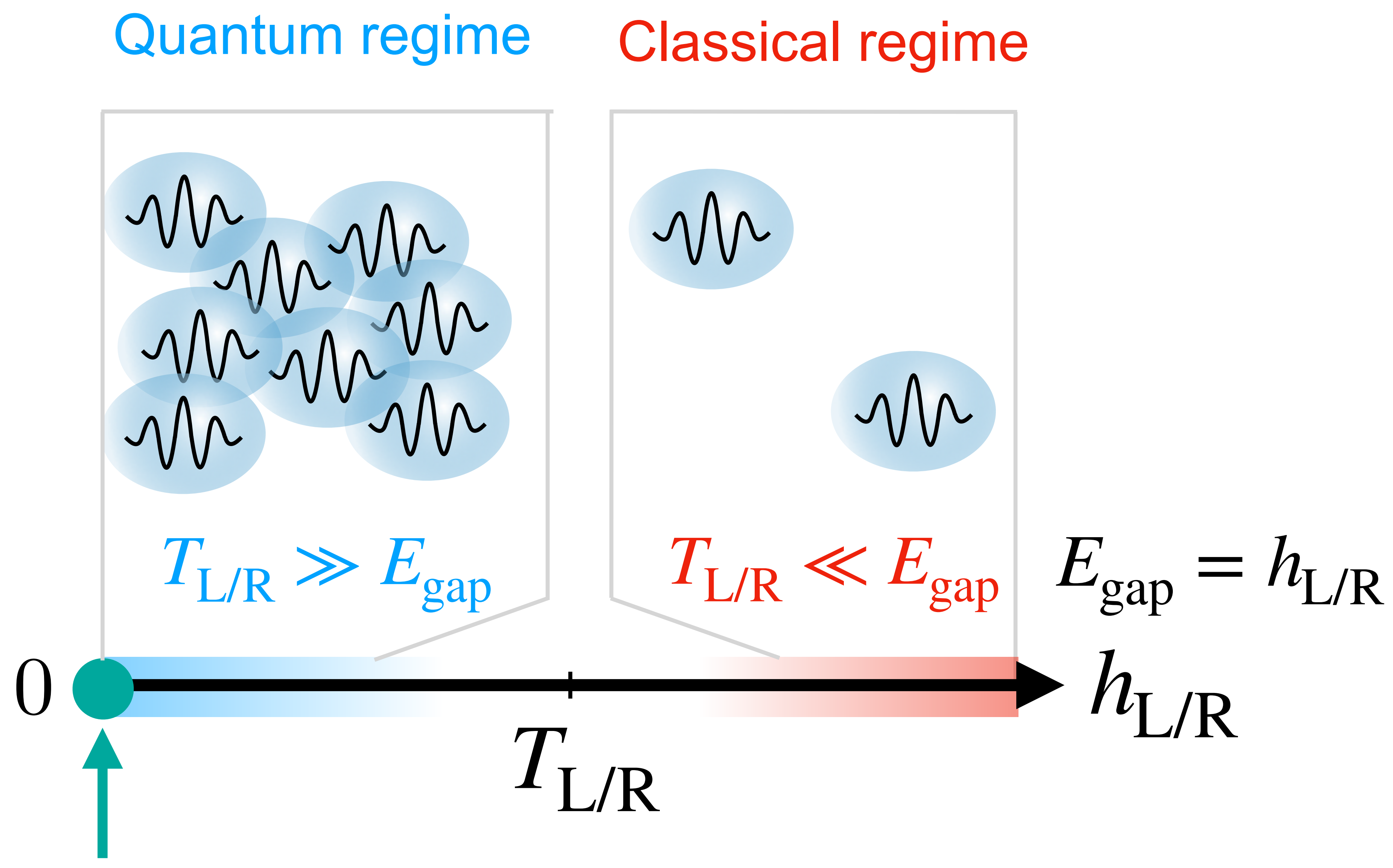
$\Delta T = T_L - T_R, T = (T_L + T_R)/2$





Transport coefficients are enhanced neat the magnonic critical point

Phase diagram of magnons at $T_{L/R} > 0$



Magnonic critical point at $E_{gap} = 0$

Gapless magnon as a Goldstone mode due to **spontaneous magnetization**

Slowing down of magnetization relaxation

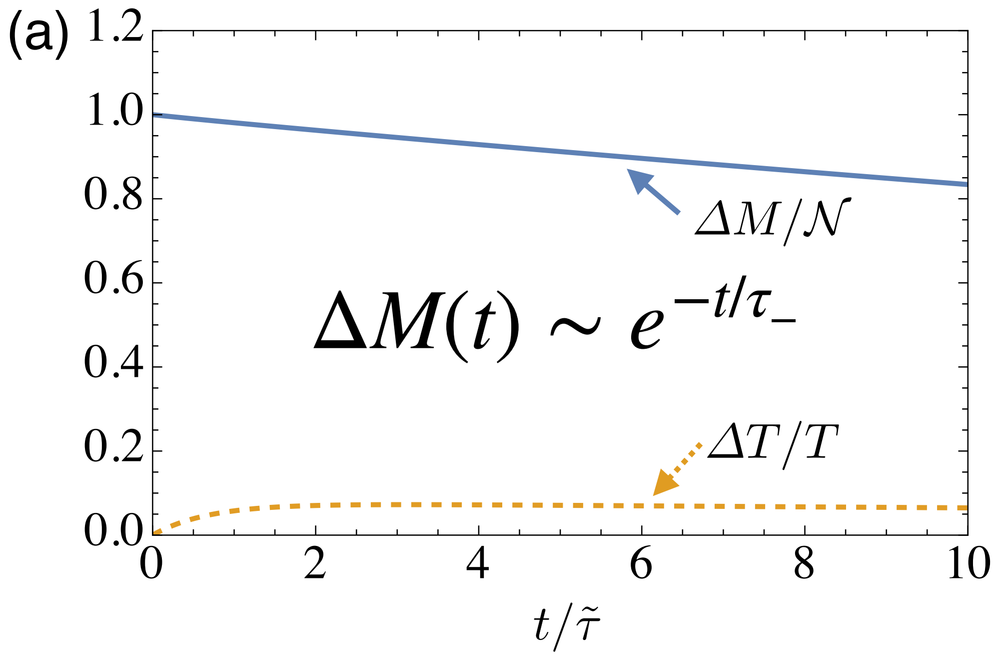
Critical behavior of magnon compressibility causes slowing down in two-terminal spin relaxation

Two-terminal relaxation in quasi-stationary case
similar to Fermi-gas cases

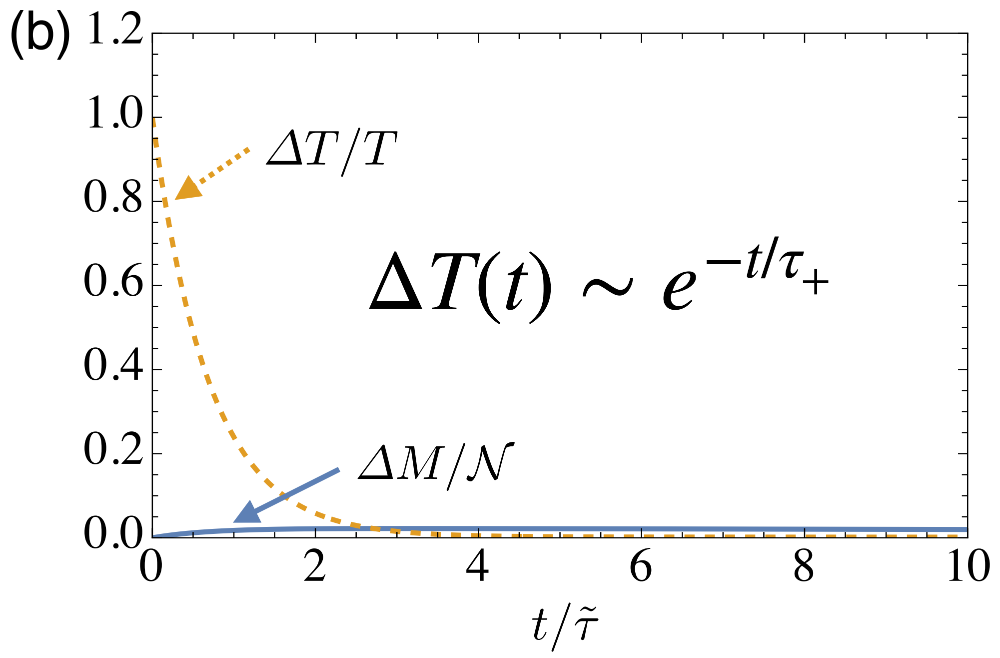
$$\Delta M(t) = M_{\mathrm{L}}(t) - M_{\mathrm{R}}(t)$$
$$\Delta T(t) = T_{\mathrm{L}}(t) - T_{\mathrm{R}}(t)$$

Relevant to extract trans. properties

$(\Delta M(0) > 0,\ \Delta T(0) = 0)$



$(\Delta M(0) = 0,\ \Delta T(0) > 0)$



Decay of magnetization is very slow

$\tau_- = 56\tilde{\tau}$ Relaxation time of M

$\tau_+ = 0.70\tilde{\tau}$ Relaxation time of T

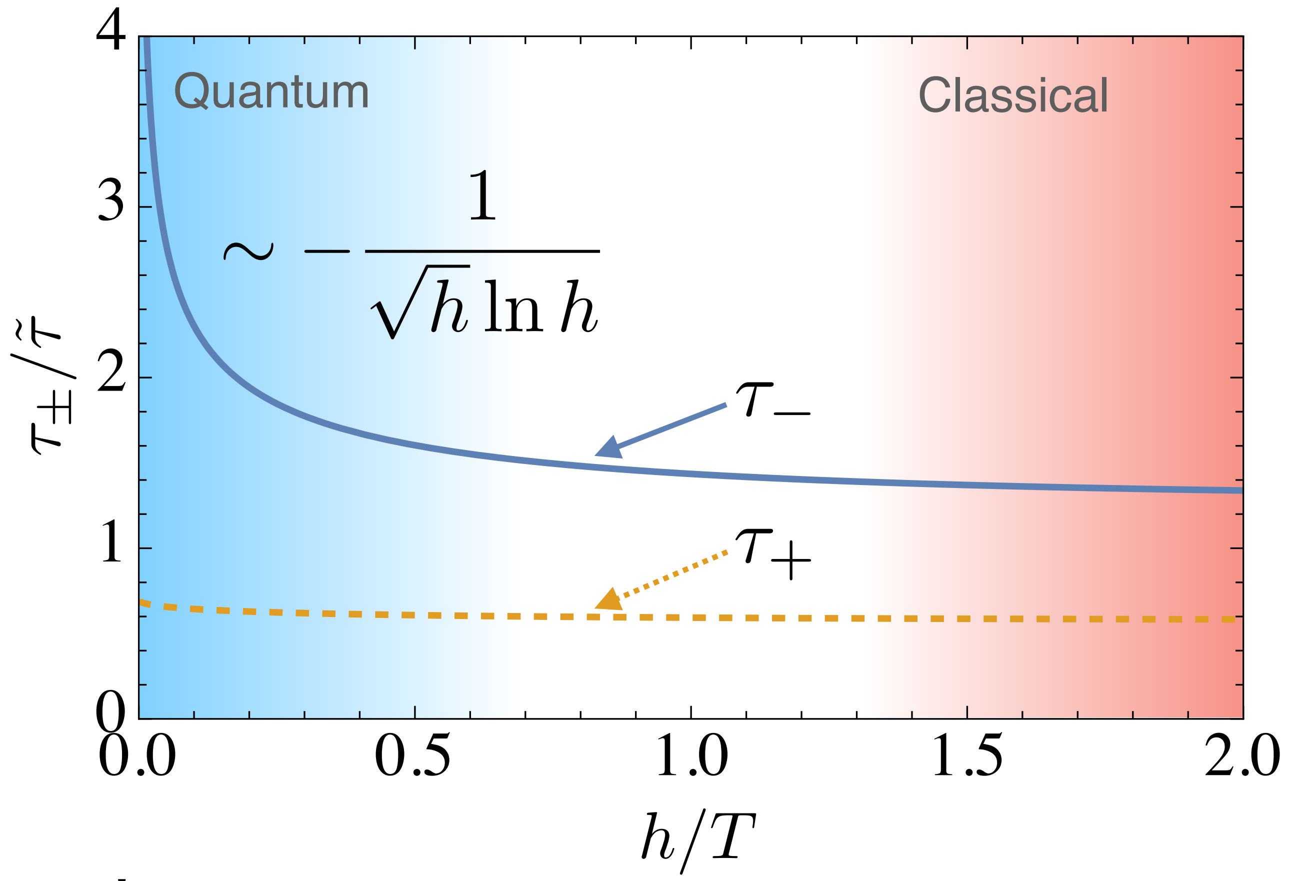
Transport coefficients + Therm

Spin conductance, ⋯

Differential sus

$$\kappa = \left(\frac{\partial M}{\partial h}\right)_T$$

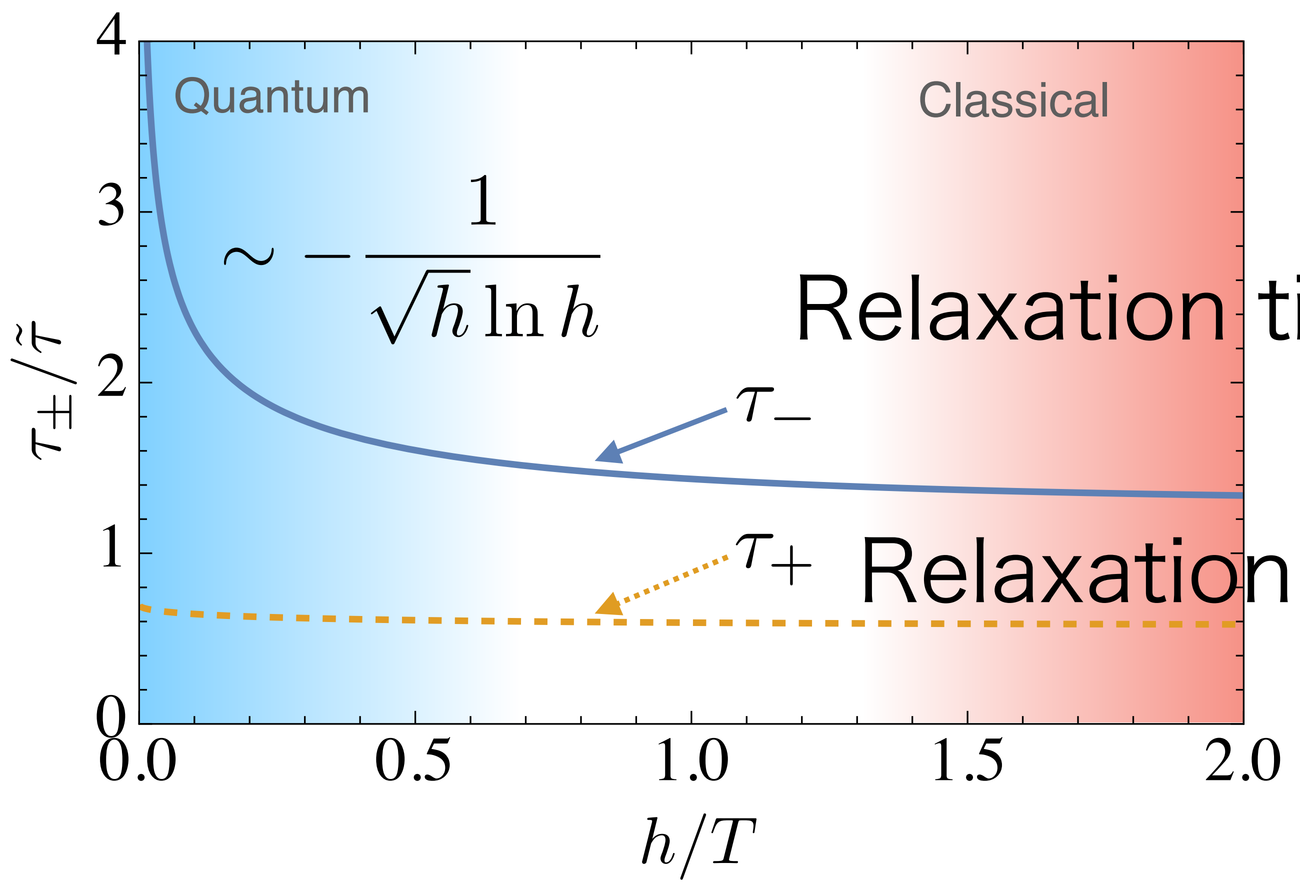
Compressibility



$$\tau_- \sim \frac{\kappa}{L_{11}} \sim \frac{1/\sqrt{h}}{-\log h}$$

Slowing down of magnetization relaxation

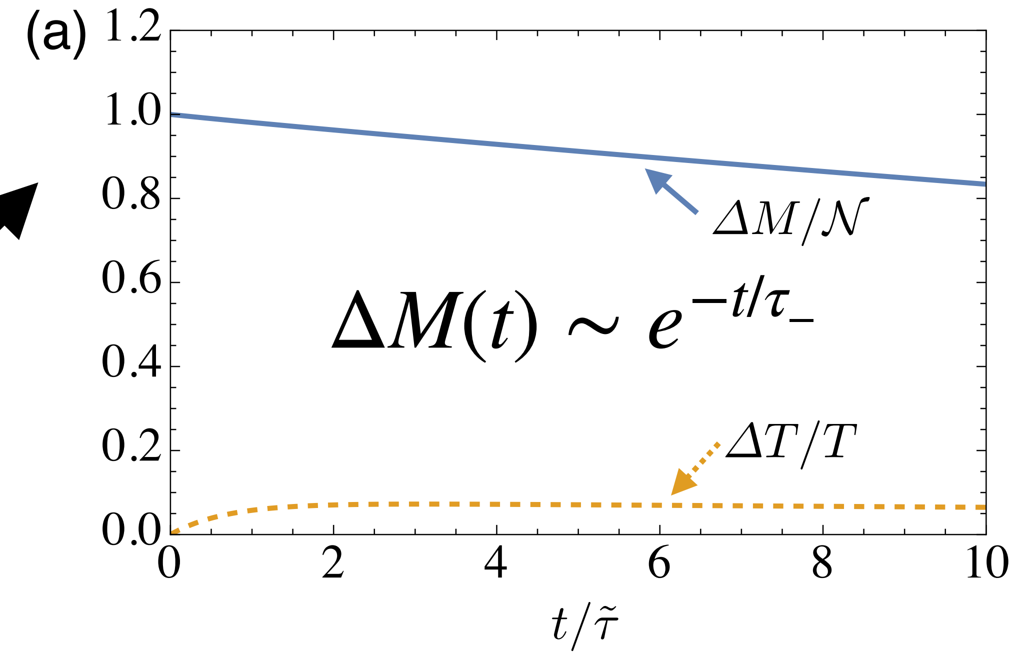
Critical behavior of magnon compressibility causes slowing down in two-terminal spin relaxation

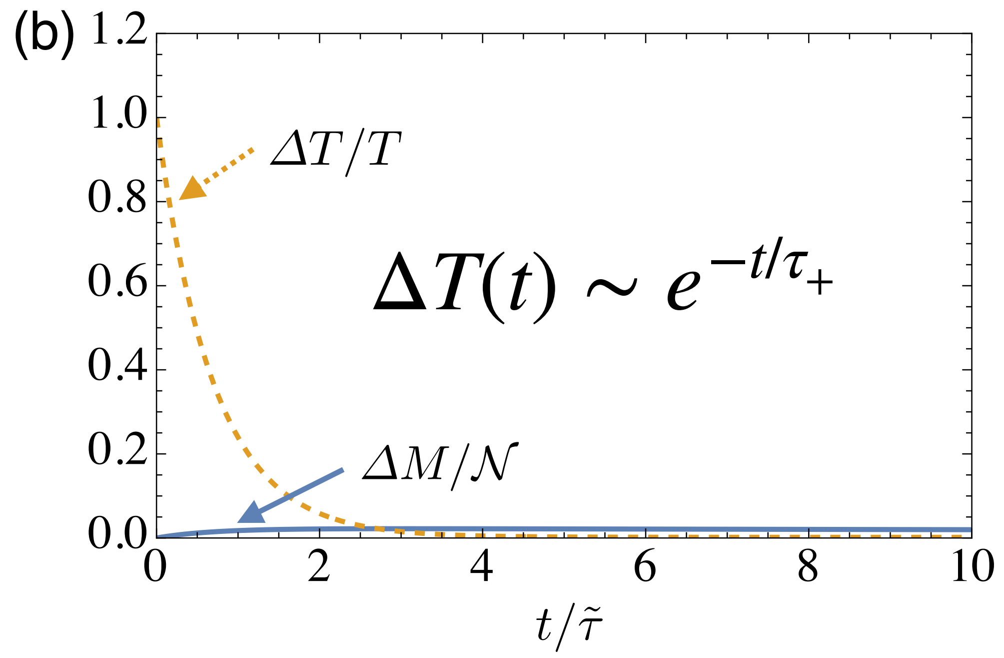


Relaxation time of M

Relaxation time of T

$(\Delta M(0) > 0,\ \Delta T(0) = 0)$





Compressibility of magnons

Differential susceptibility, ⋯

$$\kappa = \left(\frac{\partial M}{\partial h}\right)_T$$

$$\tau_- \sim \frac{\kappa}{L_{11}} \sim \frac{1/\sqrt{h}}{-\log h}$$

Spin conductance, ⋯

Magnon criticality <=> BEC transition point

Magnon criticality <=> BEC transition point

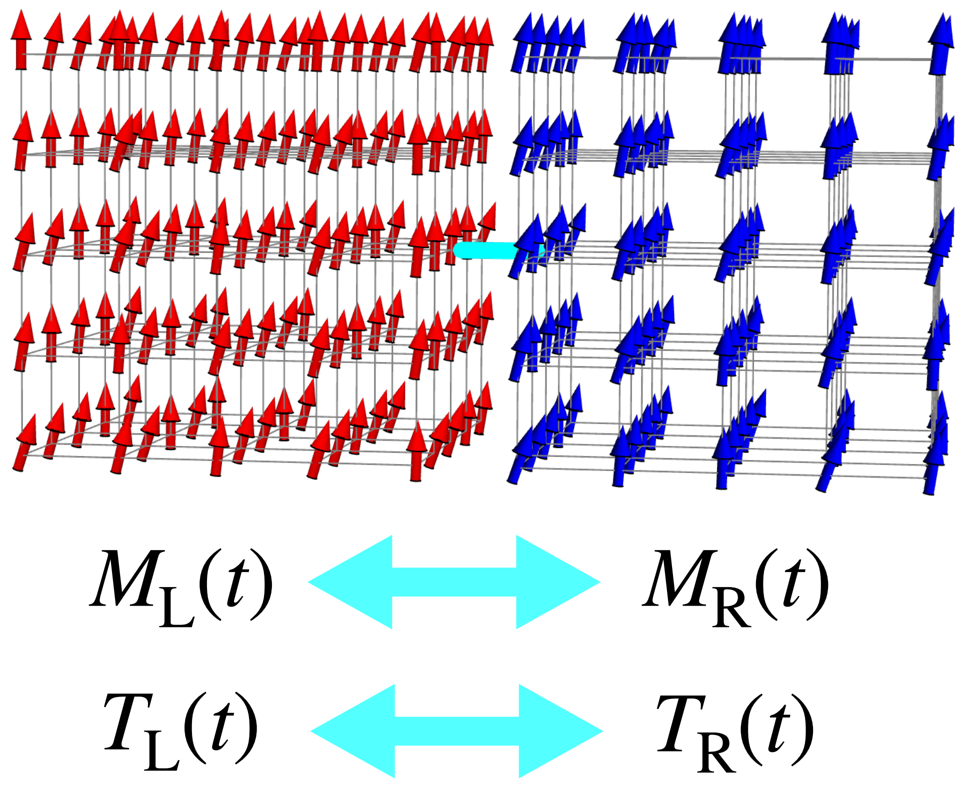
How to experimentally determine conductances?

Following the scheme proposed for Fermi-gas cases [ETH: Brantut et al., Science (2013)],
we can experimentally determine transport properties L_{ij} by measuring

A. Relaxation dynamics of $\Delta M(t) = M_{\mathrm{L}}(t) - M_{\mathrm{R}}(t)$, $\Delta T(t) = T_{\mathrm{L}}(t) - T_{\mathrm{R}}(t)$ b/w FIs near equilibrium

B. Thermodynamic quantities of one FI at equilibrium

A. Relaxation dynamics b/w FIs



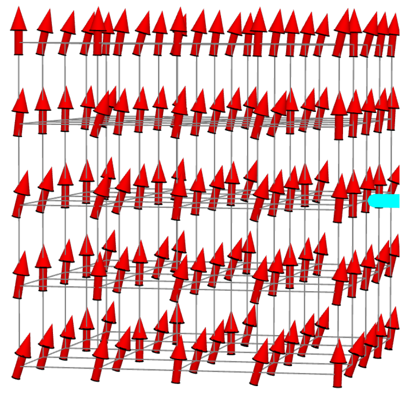
1. Close the channel and prepare thermal states with $M_{\mathrm{L/R}}(0)$, $T_{\mathrm{L/R}}(0)$
2. At $t = 0$, open the channel so that $M_{\mathrm{L/R}}(t)$, $T_{\mathrm{L/R}}(t)$ start time evolution
3. Observe $\Delta M(t) = M_{\mathrm{L}}(t) - M_{\mathrm{R}}(t)$ $\Delta T(t) = T_{\mathrm{L}}(t) - T_{\mathrm{R}}(t)$ at time t
4. Fit obtained $\Delta M(t)$ and $\Delta T(t)$ with solutions of the quasi-stationary model

Transport relation: $$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} -\Delta M \\ T\Delta S \end{pmatrix} = -2\begin{pmatrix} I_{\mathrm{S}} \\ I_{\mathrm{H}} \end{pmatrix} = -2\begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix}\begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix}$$

Thermodynamic relation: $$\begin{pmatrix} -\Delta M \\ \Delta S \end{pmatrix} = \begin{pmatrix} \left(\frac{\partial M}{\partial h}\right)_T & -\left(\frac{\partial M}{\partial T}\right)_h \\ -\left(\frac{\partial S}{\partial h}\right)_T & \left(\frac{\partial S}{\partial T}\right)_h \end{pmatrix}\begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix}$$

Fitting parameters consist of L_{ij} and thermodynamic quantities

B. Measuring thermodynamic quantities of one FI at equilibrium



$$h = [h_{\mathrm{L}}(0) + h_{\mathrm{R}}(0)]/2$$
$$T = [T_{\mathrm{L}}(0) + T_{\mathrm{R}}(0)]/2$$

Why tunneling magnon transport in cold atoms?

1. Ultraclean systems

   No impurity

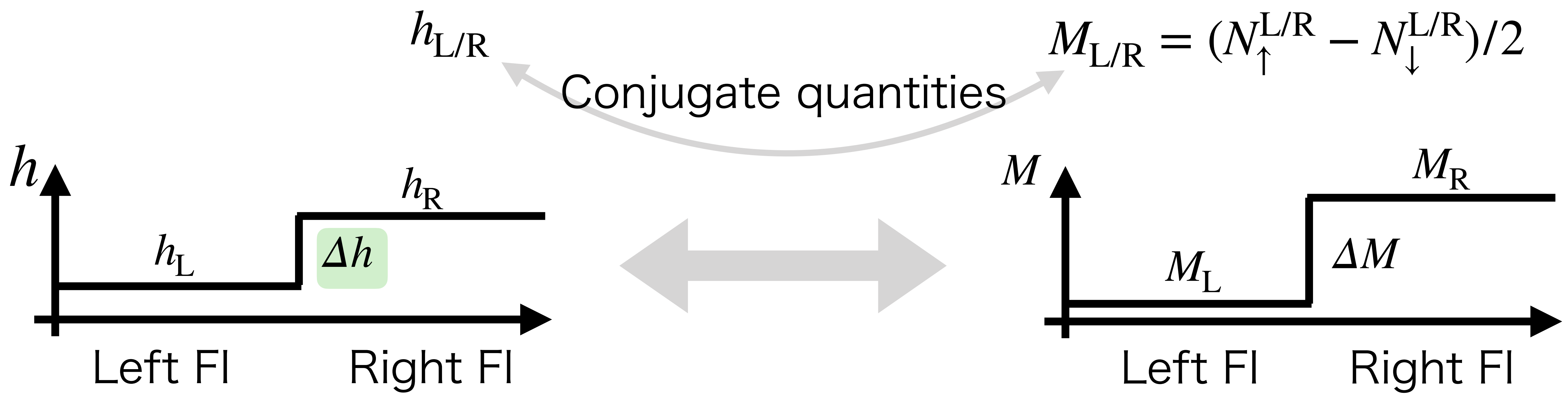
   Roughness & lattice mismatch

2. Quantum controllability of **effective Zeeman fields**

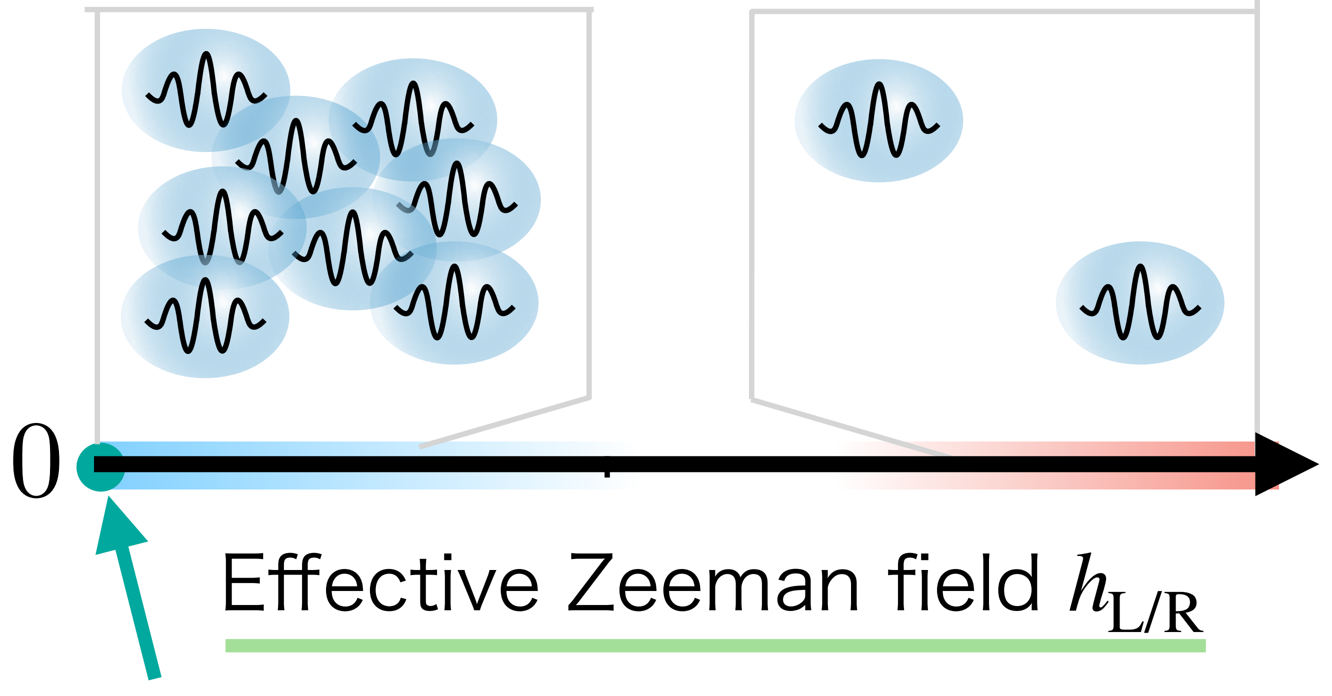
Similarly to the Fermi gases [Kriner et al., PNAS, **113** (29) 8144-8149 (2016)]

Control of spin bias Δh to generate tunneling currents

Effective Zeeman fields can be tuned by spin imbalance

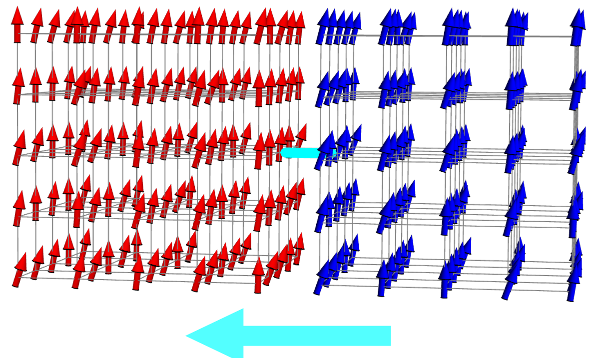


Access to quantum critical regime



No tunneling experiment b/w FIs in solid-state systems Theoretical proposal: Nakata et al., PRB (2015); PRB (2018)

Focusing on Classical regime



Hard to generate Δh by spatial modulation of magnetic field

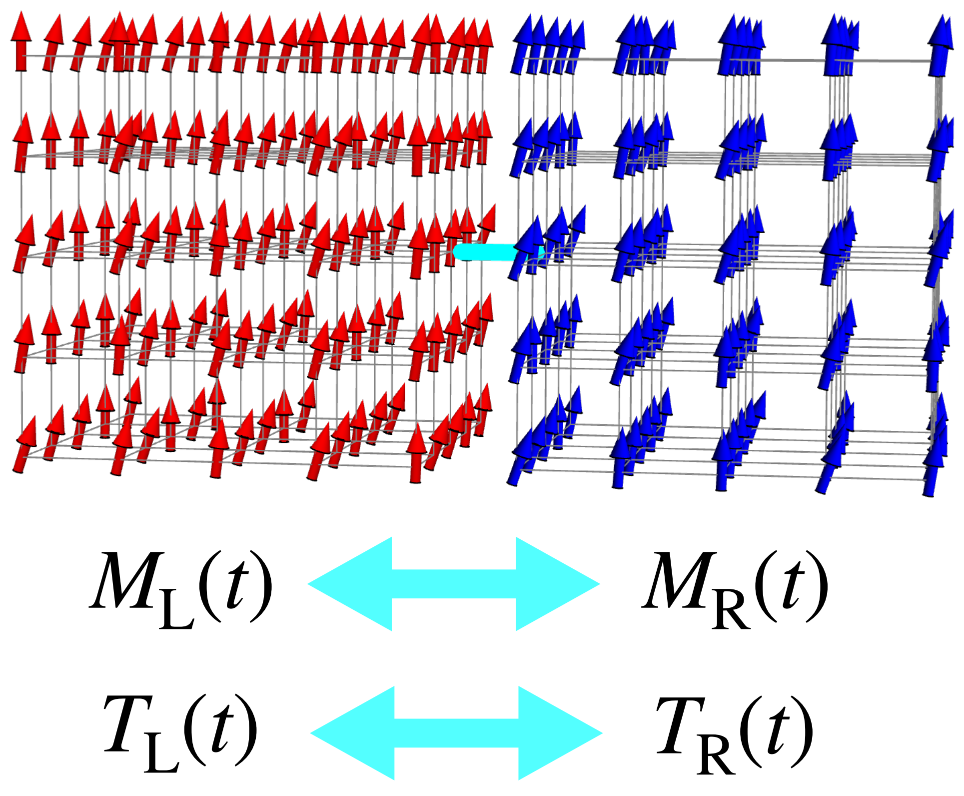
Difficult to access **magnonic quantum regime** because of magnetic domains by dipole interactions

How to experimentally determine conductances?

Following the scheme proposed for Fermi-gas cases [ETH: Brantut et al., Science (2013)],

we can experimentally determine transport properties L_{ij} by measuring

A. Near-equilibrium relaxation dynamics of $\Delta M(t) = M_\mathrm{L}(t) - M_\mathrm{R}(t)$, $\Delta T(t) = T_\mathrm{L}(t) - T_\mathrm{R}(t)$ b/w FIs from a thermal initial state



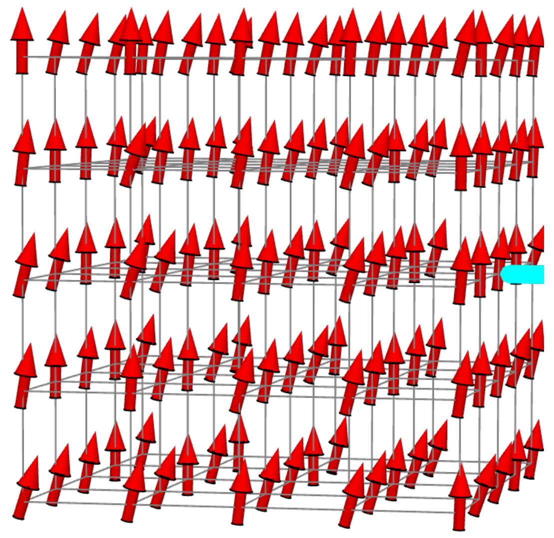
1. Observe $\Delta M(t)$ and $\Delta T(t)$ at time t
2. Fit obtained $\Delta M(t)$ and $\Delta T(t)$ with solutions of the quasi-stationary model

Transport relation: $$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} -\Delta M \\ T\Delta S \end{pmatrix} = -2\begin{pmatrix} I_\mathrm{S} \\ I_\mathrm{H} \end{pmatrix} = -2\begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix}\begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix}$$

Thermodynamic relation: $$\begin{pmatrix} -\Delta M \\ \Delta S \end{pmatrix} = \begin{pmatrix} \left(\frac{\partial M}{\partial h}\right)_T & -\left(\frac{\partial M}{\partial T}\right)_h \\ -\left(\frac{\partial S}{\partial h}\right)_T & \left(\frac{\partial S}{\partial T}\right)_h \end{pmatrix}\begin{pmatrix} \Delta h \\ \Delta T \end{pmatrix}$$

Fitting parameters consist of L_{ij} and thermodynamic quantities

B. Thermodynamic quantities of one FI at equilibrium



$$h = [h_\mathrm{L}(0) + h_\mathrm{R}(0)]/2$$
$$T = [T_\mathrm{L}(0) + T_\mathrm{R}(0)]/2$$

Why quantum simulation of magnon transport w/ cold atoms?

1. Ultraclean systems

   No impurity

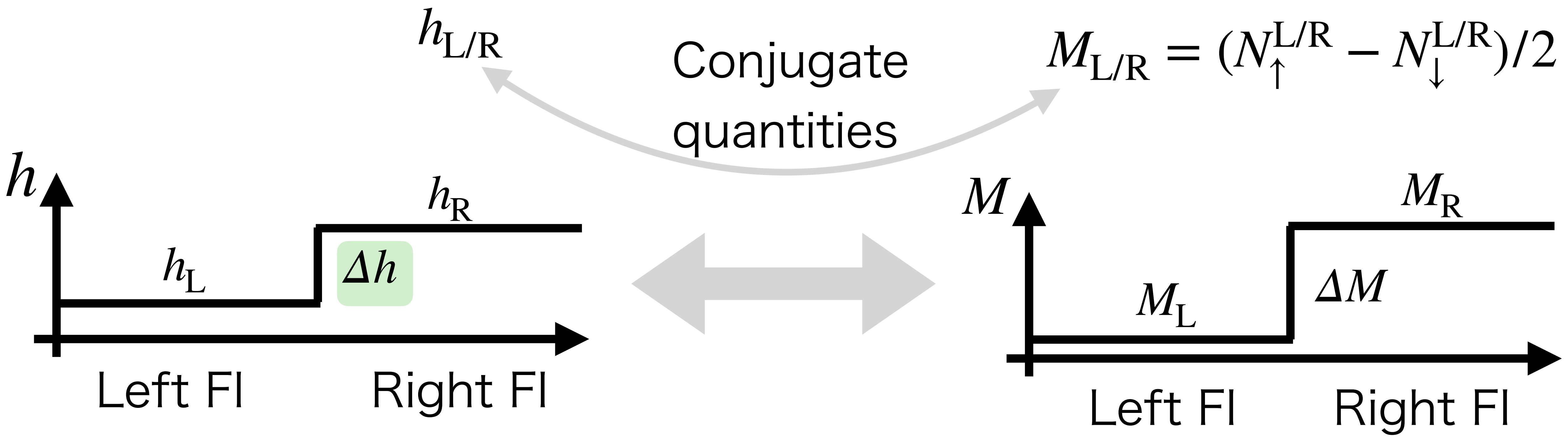
   No roughness & lattice mismatch

2. Quantum controllability of **effective Zeeman fields**

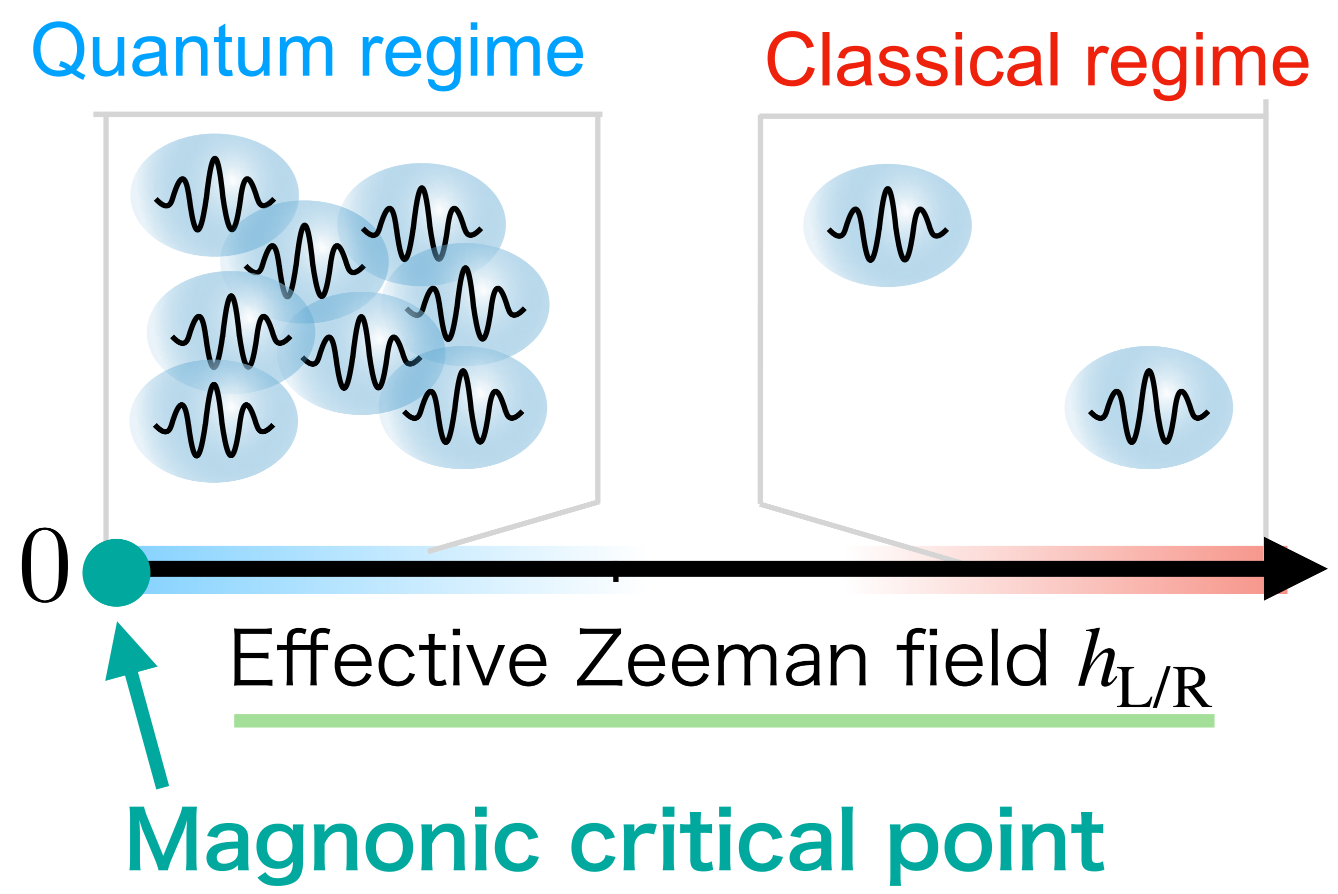
Similarly to the Fermi gases [Kriner et al., PNAS, **113** (29) 8144-8149 (2016)]

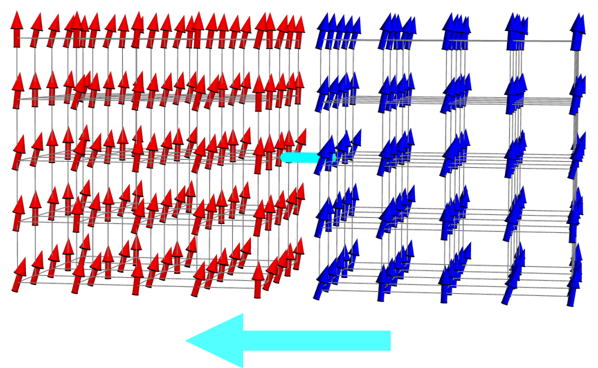
Control of spin bias Δh to generate tunneling currents

Effective Zeeman fields can be tuned by spin imbalance



Access to quantum critical regime





No solid-state experiment b/w FIs

because inducing Δh by spatially-modulated magnetic field is difficult

Theoretical proposal for **solid FIs** focusing on classical regime [Nakata et al., PRB (2015); PRB (2018)]

Difficult to experimentally access **magnonic quantum regime** because of magnetic domains by dipole interactions