Journal Club on 06 January 2015

Interfacial Spin and Heat Transfer between Metals and Magnetic Insulators

arXiv:1409.7128

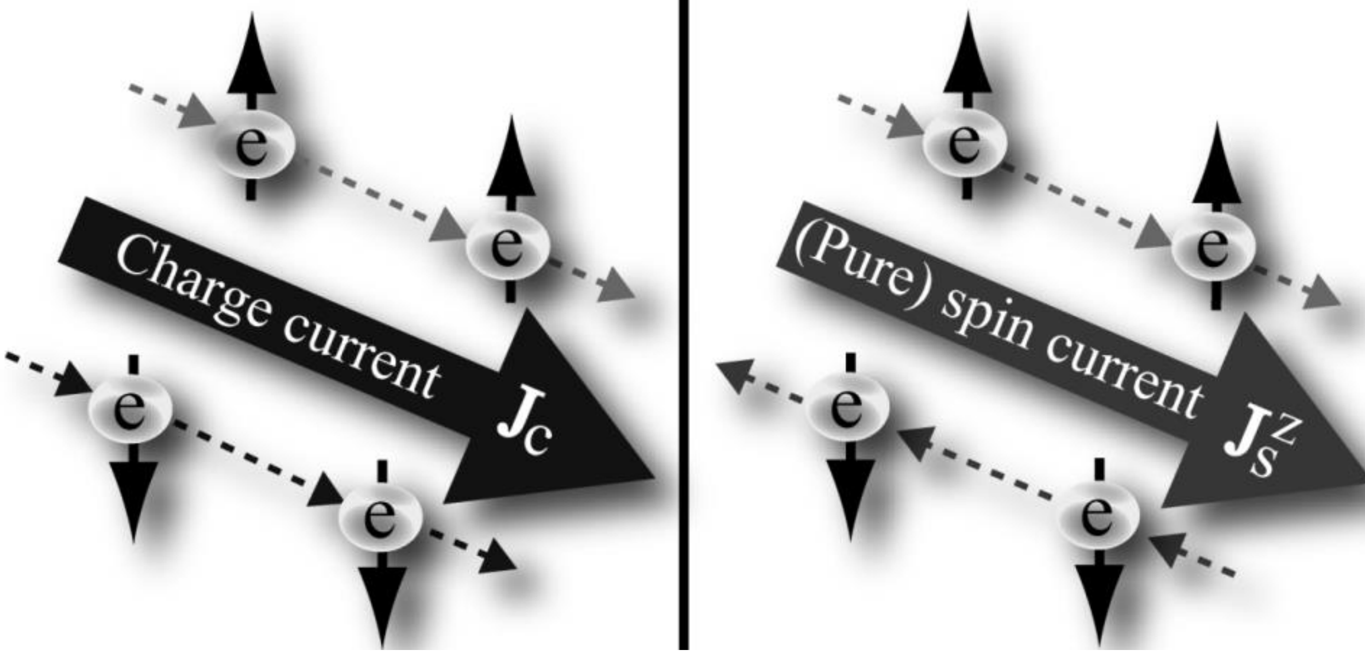
Scott A. Bender & Yaroslav Tserkovnyak

Kouki Nakata

- **BACKGROUND**

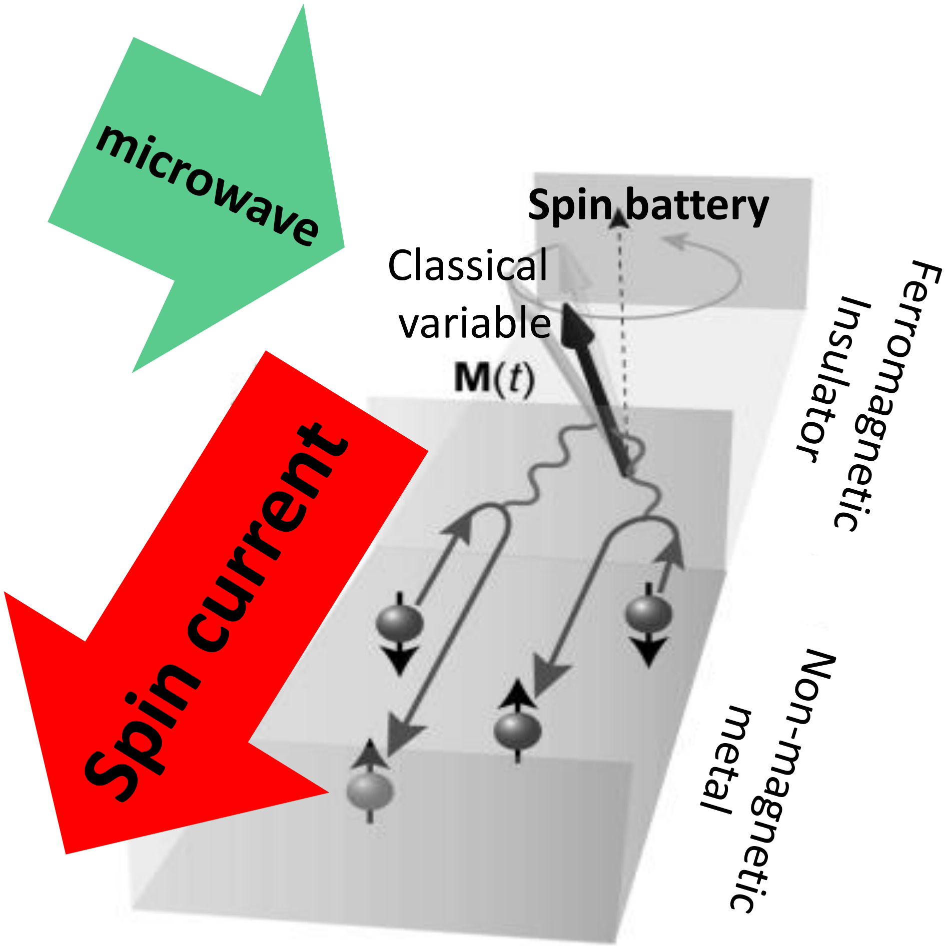
Spin Current

Charge current	Spin current
$\mathbf{J}_C := \sum_\sigma \mathbf{J}^\sigma = \mathbf{J}^\uparrow + \mathbf{J}^\downarrow$	$\mathbf{J}_S^Z := \sum_\sigma \sigma \mathbf{J}^\sigma = \mathbf{J}^\uparrow - \mathbf{J}^\downarrow$



Spin Pumping

A standard (experimentally established) way to generate spin current



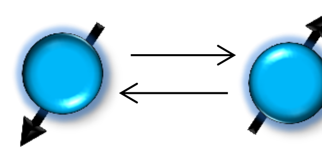
M(t): LLG Eq.

K. Ando *et al.,* Nat. Mater., **10** (2011) 655

Points

✓ ***The exchange interaction***
The key to spin pumping.

✓ ***Interface;***
Spin-flip



✓ ***Ferromagnet (resonance, i.e. FMR)***
→ **Spin battery.**

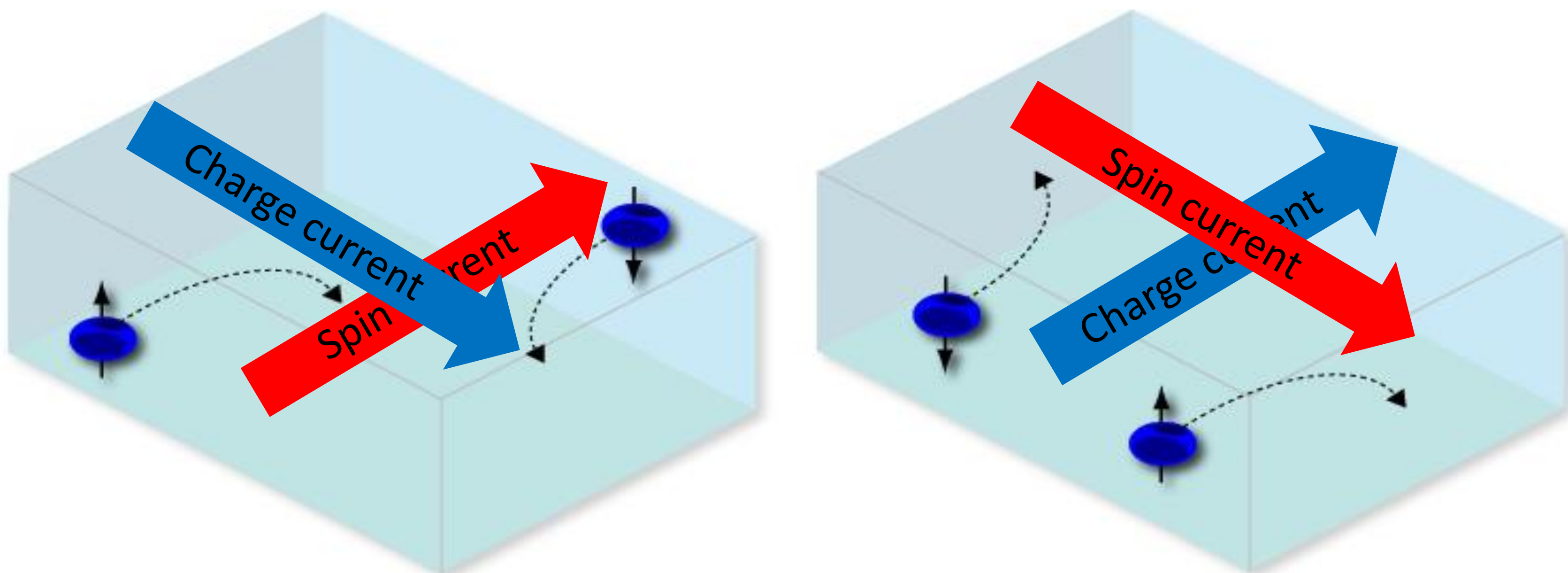
Brataas et al., Phys. Rev. B, **66** (2002) 060404 (R).

✓ ***Microwaves (quantum fluctuations);***

Driving force and resonance
→ Out of equilibrium.

Inverse Spin-Hall Effect

Indirect detection of spin currents



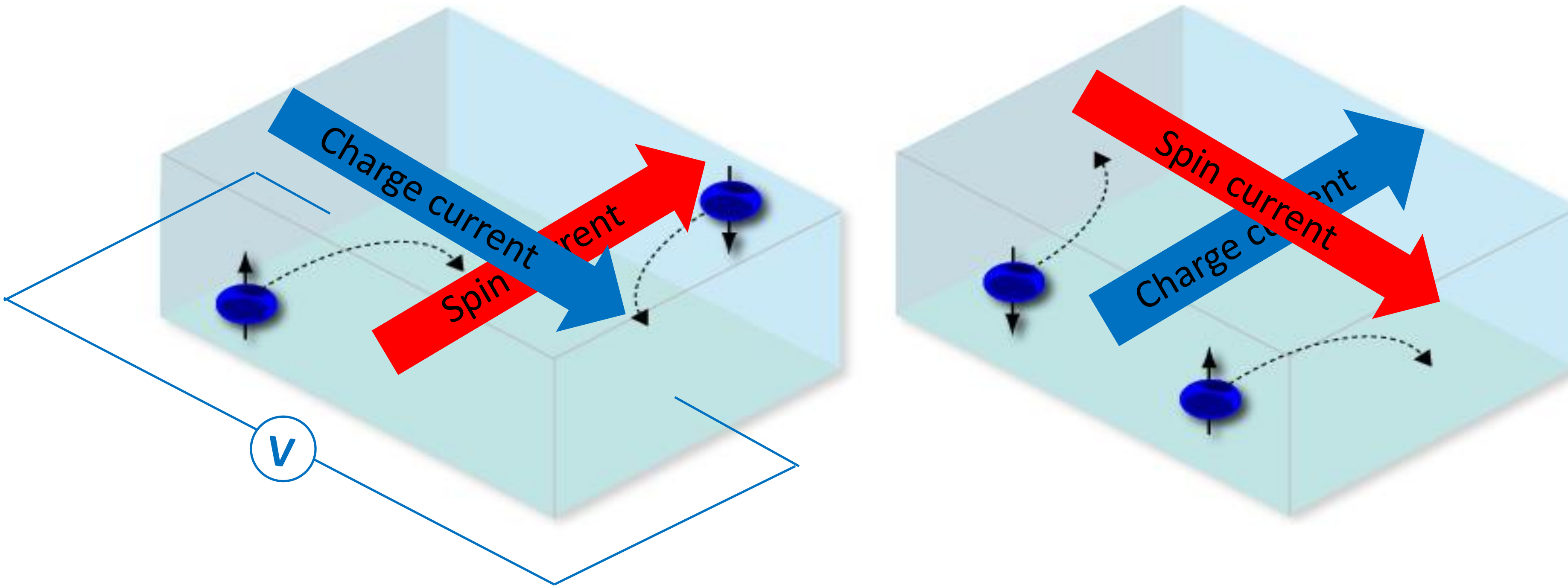
✓ ***Inverse spin-Hall effect*** ← **Spin-orbital interaction** → ✓ ***Spin-Hall effect***

Spin current → charge current

Charge current → spin current

Inverse Spin-Hall Effect

Indirect detection of spin currents



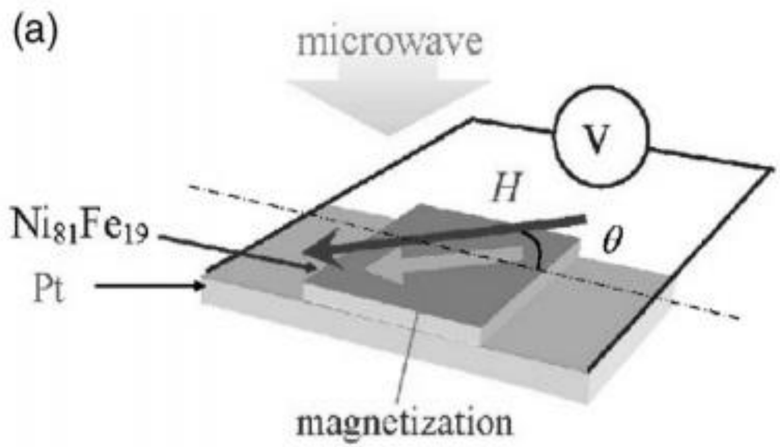
✓ ***<u>Inverse spin-Hall effect</u>*** ← **Spin-orbital interaction** → ✓ ***<u>Spin-Hall effect</u>***

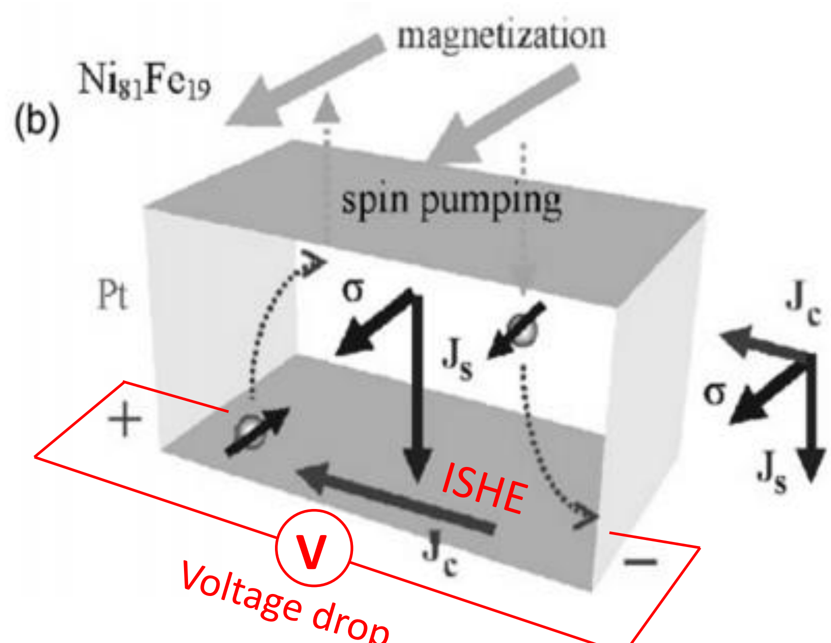
Spin current → charge current
→ ***Voltage drop*: V**

Charge current → spin current

Experiment

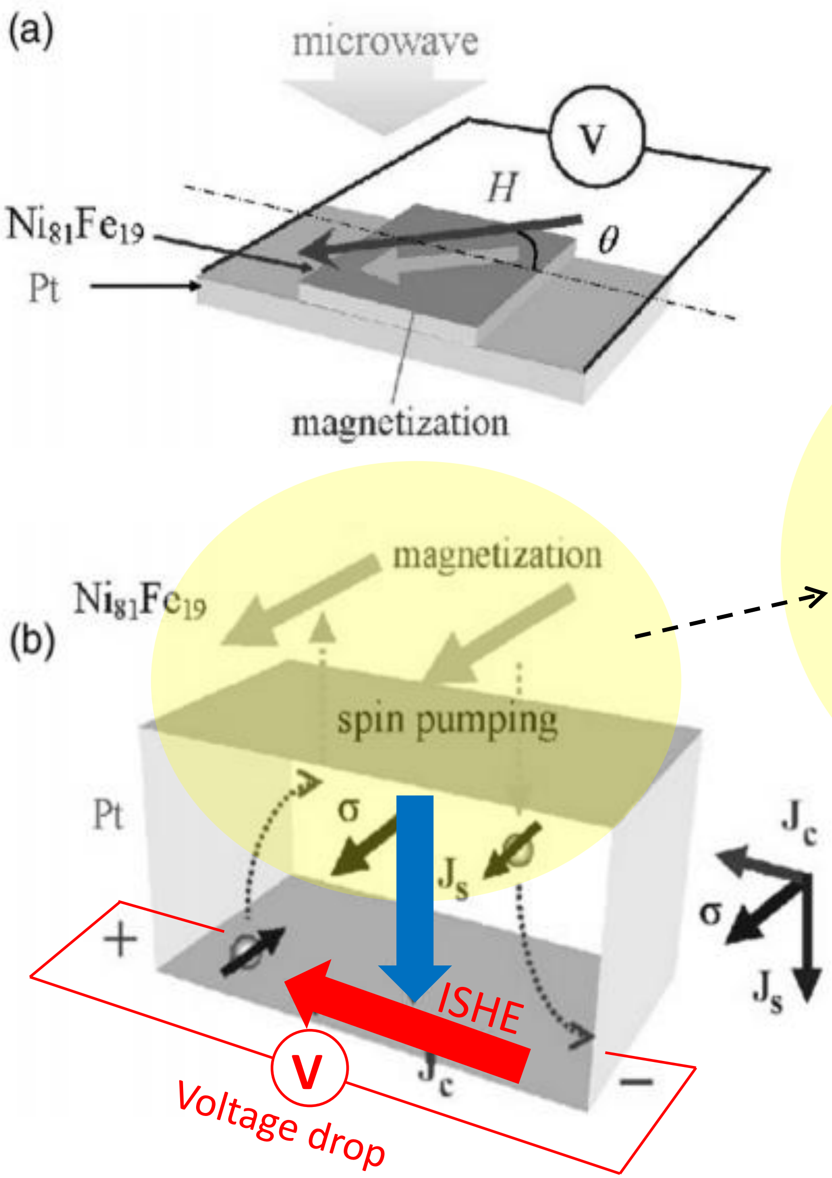
E. Saitoh et al., *Appl. Phys. Lett.*, **88**,182509, (2006).

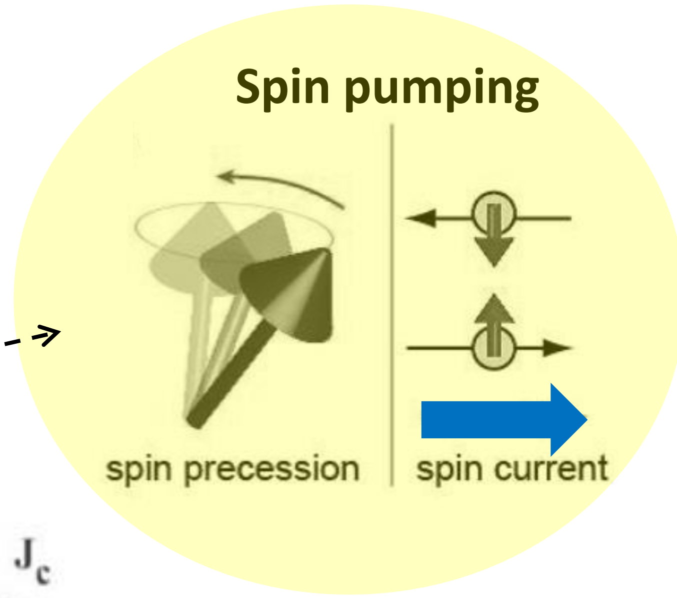




Experiment

E. Saitoh et al., *Appl. Phys. Lett.*, **88**,182509, (2006).





➢ THEIR WORK

"Interfacial Spin Transfer between Metals/Magnetic Insulators"

arXiv:1409.7128

Scott A. Bender and Yaroslav Tserkovnyak

SYSTEM:
Metal/Ferromagnetic Insulator

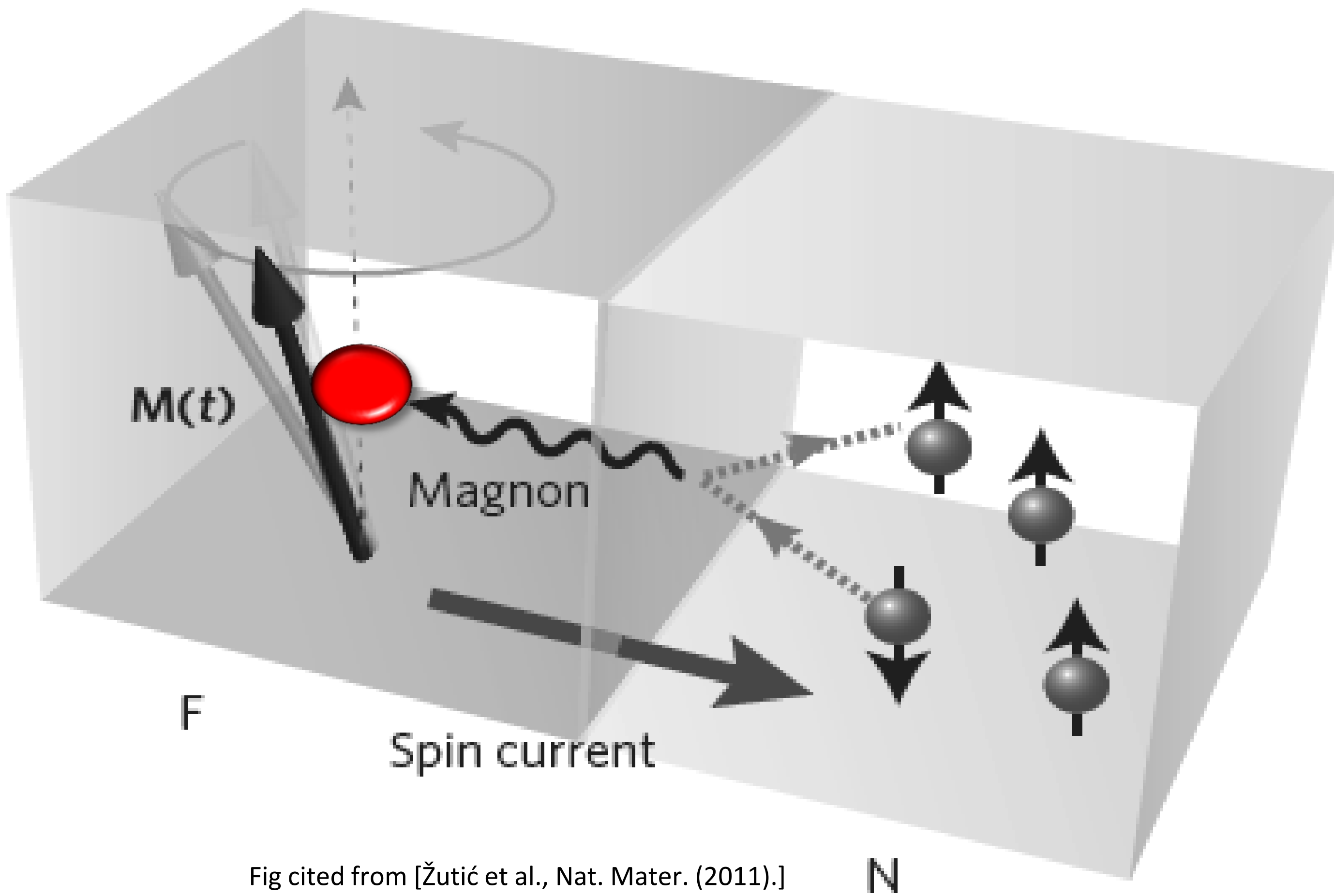
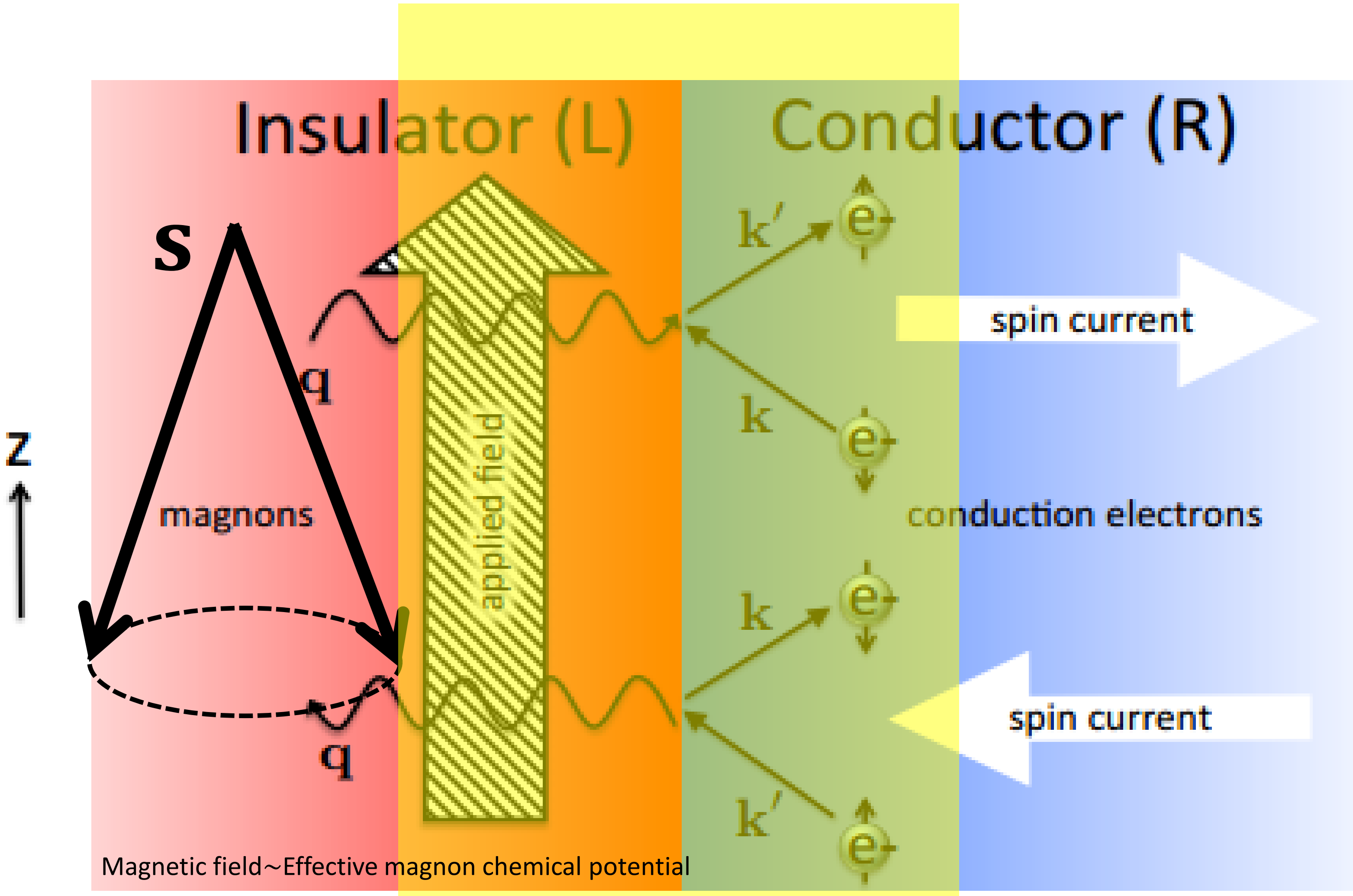


Fig cited from [Žutić et al., Nat. Mater. (2011).]

SYSTEM: Metal/Ferromagnetic Insulator



Pic. in Phys. Rev. Lett. **108** (2012) 246601

MAIN PURPOSE

Spin current generated in the metal/FI junction

➢ Classical *but* non-perturbative theory

→ ***Scattering matrix formalism***

Y. Tserkovnyak et al.

- Rev. Mod. Phys. **77**, 1375 (2005).
- Phys. Rev. Lett. **88**, 117601 (2002).
- Phys. Rev. B, **66** (2002) 060404 (R).

$g^{\uparrow\downarrow}$ Spin-mixing conductance (constant)

➢ Quantum *but* perturbative theory

arXiv:1409.7128,
Scott A. Bender and Yaroslav Tserkovnyak

→ ***Kubo formula (Linear response theory):***
Microscopic approach (Spin Hamiltonian)

$$\hat{\mathcal{H}} = -J \int d^2\mathbf{r}\, \hat{\boldsymbol{\rho}}\left(\mathbf{r}\right) \cdot \hat{\mathbf{s}}\left(\mathbf{r}\right)$$

MAIN PURPOSE

Spin current generated in the metal/FI junction

➢ Classical *but* non-perturbative theory

→ ***Scattering matrix formalism***

Y. Tserkovnyak et al.

- Rev. Mod. Phys. **77**, 1375 (2005).
- Phys. Rev. Lett. **88**, 117601 (2002).
- Phys. Rev. B, **66** (2002) 060404 (R).

$g^{\uparrow\downarrow}$ Spin-mixing conductance (constant)

Correspondence ??

$$g^{\uparrow\downarrow} \rightleftarrows \hat{\mathcal{H}} = -J \int d^2\mathbf{r}\, \hat{\boldsymbol{\rho}}(\mathbf{r}) \cdot \hat{\mathbf{s}}(\mathbf{r})$$

→ *To find quantum-mechanical effects arising from spin-flip processes*

➢ Quantum *but* perturbative theory

arXiv:1409.7128,
Scott A. Bender and Yaroslav Tserkovnyak

→ ***Kubo formula (Linear response theory):***
Microscopic approach (Spin Hamiltonian)

$$\hat{\mathcal{H}} = -J \int d^2\mathbf{r}\, \hat{\boldsymbol{\rho}}(\mathbf{r}) \cdot \hat{\mathbf{s}}(\mathbf{r})$$

MAIN PURPOSE

Spin current generated in the metal/FI junction

➢ Classical *but* non-perturbative theory

→ ***Scattering matrix formalism***

Y. Tserkovnyak et al.

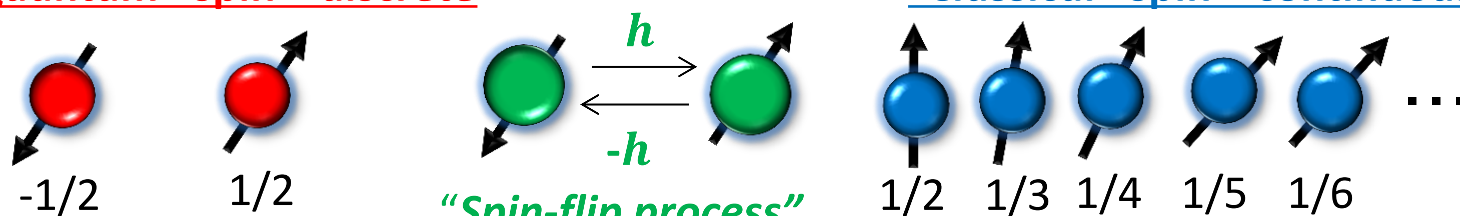
- Rev. Mod. Phys. **77**, 1375 (2005).
- Phys. Rev. Lett. **88**, 117601 (2002).
- Phys. Rev. B, **66** (2002) 060404 (R).

$g^{\uparrow\downarrow}$ Spin-mixing conductance (constant)

KEY POINT

✓ ***"Quantum" spin = discrete***

✓ ***"Classical" spin = continuous***



"Spin-flip process"

→ Essentially the ***quantum-mechanical effect***: $\sigma^{\pm}|\mp> = |\pm>$

➢ Quantum *but* perturbative theory

arXiv:1409.7128,
Scott A. Bender and Yaroslav Tserkovnyak

→ ***Kubo formula (Linear response theory):***
Microscopic approach (Spin Hamiltonian)

$$\hat{\mathcal{H}} = -J \int d^2\mathbf{r}\, \hat{\boldsymbol{\rho}}(\mathbf{r}) \cdot \hat{\mathbf{s}}(\mathbf{r})$$

MAIN PURPOSE

Spin current generated in the metal/FI junction

➢ Classical *but* non-perturbative theory

→ ***Scattering matrix formalism***

Y. Tserkovnyak et al.

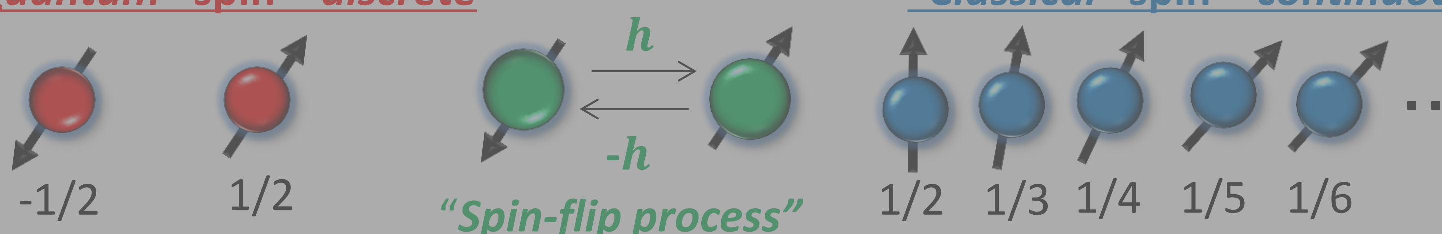
- Rev. Mod. Phys. **77**, 1375 (2005).
- Phys. Rev. Lett. **88**, 117601 (2002).
- Phys. Rev. B, **66** (2002) 060404 (R).

$g^{\uparrow\downarrow}$ Spin-mixing conductance (constant)

KEY POINT

✓ ***"Quantum" spin = discrete***

✓ ***"Classical" spin = continuous***



→ Essentially the ***quantum-mechanical effect***: $\sigma^{\pm}|\mp\rangle = |\pm\rangle$

➢ Quantum *but* perturbative theory

arXiv:1409.7128,
Scott A. Bender and Yaroslav Tserkovnyak

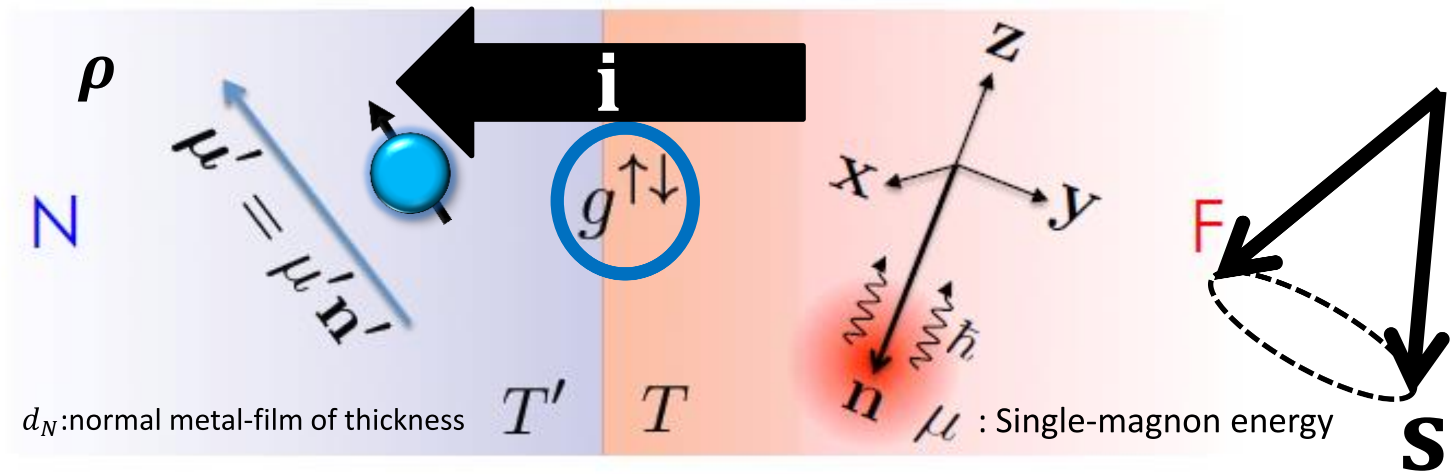
→ ***Kubo formula (Linear response theory):***
Microscopic approach (Spin Hamiltonian)

$$\hat{\mathcal{H}} = -J\int d^2\mathbf{r}\,\hat{\boldsymbol{\rho}}(\mathbf{r})\cdot\hat{\mathbf{s}}(\mathbf{r})$$

Classical *but* non-perturbative theory

Scattering matrix formalism

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



$\boldsymbol{g}^{\uparrow\downarrow} \equiv \boldsymbol{g}^{\uparrow\downarrow}{}_r + i\boldsymbol{g}^{\uparrow\downarrow}{}_i$: T=0 spin-mixing conductance

$$\boldsymbol{\mu}' \equiv \mu'\mathbf{n}' = 2\boldsymbol{\rho}/D$$

$$\mu' \equiv \mu_+ - \mu_-$$

- $\boldsymbol{\rho}$: spin density (spin accumulation)
- D: density of state per spin and unit volume
- μ': Electrochemical potential difference
- **n**: magnetization

$$\text{spin-current density } \mathbf{i} = -\hbar\dot{\boldsymbol{\rho}}d_N$$

$$\mathbf{i} = \frac{1}{4\pi}\left(g_i^{\uparrow\downarrow} + g_r^{\uparrow\downarrow}\mathbf{n}\times\right)\boldsymbol{\mu}' \times \mathbf{n}$$

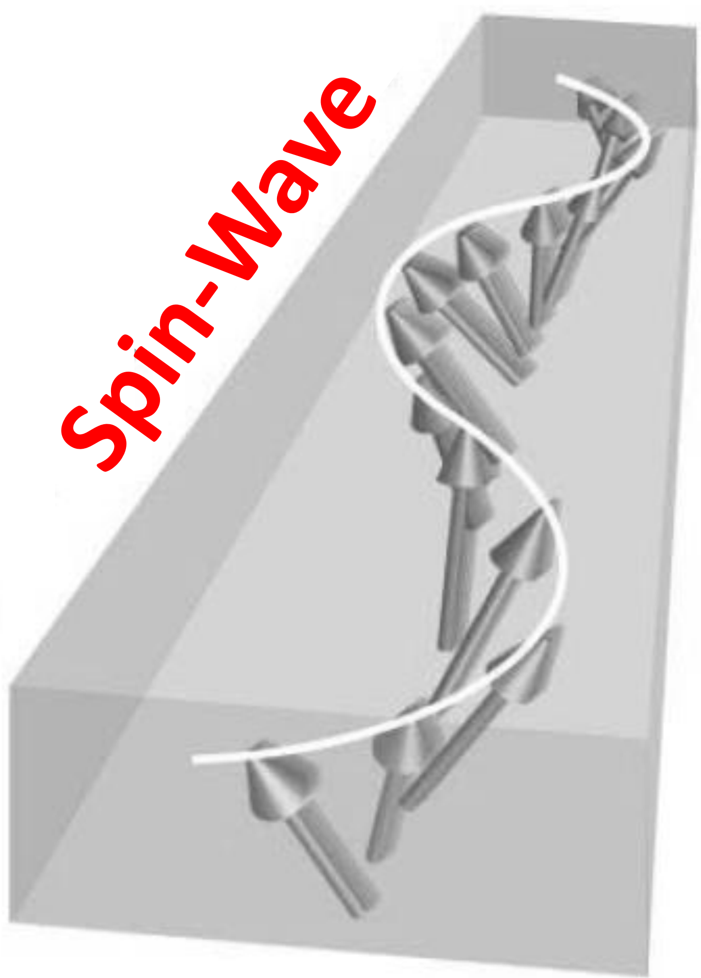
- # Quantum *but* perturbative theory

Kubo formula (Linear response theory)

arXiv:1409.7128,
Scott A. Bender and Yaroslav Tserkovnyak

Magnon ≈ Spin-Wave

✓ **Magnons**; the bosonic quanta of **magnetic excitations** in a magnetically ordered spins

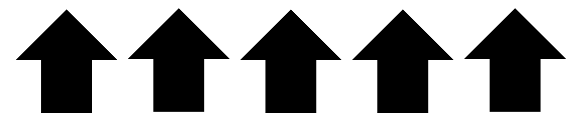


[Y. Kajiwara et al., Nature **464** (2010) 262]

Ferromagnetic Heisenberg model (J > 0)

$$-J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

Ground state; $S_i^z = S$



Magnon ≈ Spin-Wave

✓ **Magnons**; the bosonic quanta of **magnetic excitations** in a magnetically ordered spins

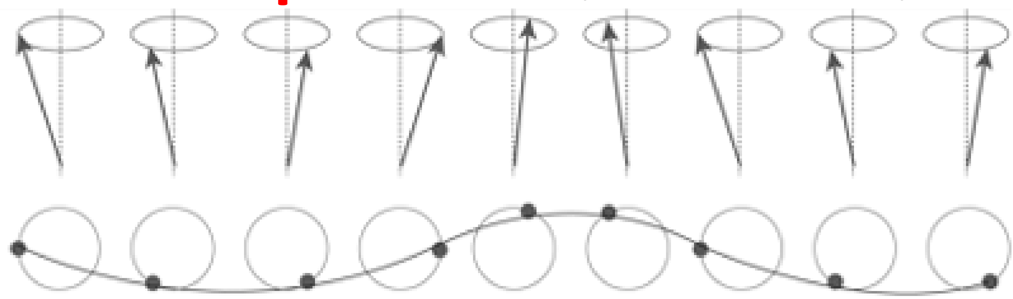
[Y. Kajiwara et al., Nature **464** (2010) 262]

Ferromagnetic Heisenberg model (J > 0)

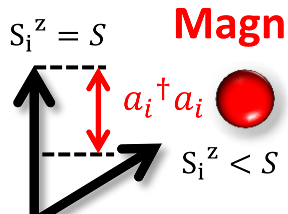
$$-\mathrm{J} \sum_{\langle \mathrm{i,j} \rangle} \mathbf{S}_\mathrm{i} \cdot \mathbf{S}_\mathrm{j}$$

Ground state; $\mathrm{S_i}^\mathrm{z} = S$

Spin-wave (collective mode)



Holstein-Primakoff transformation; magnon



Magnon

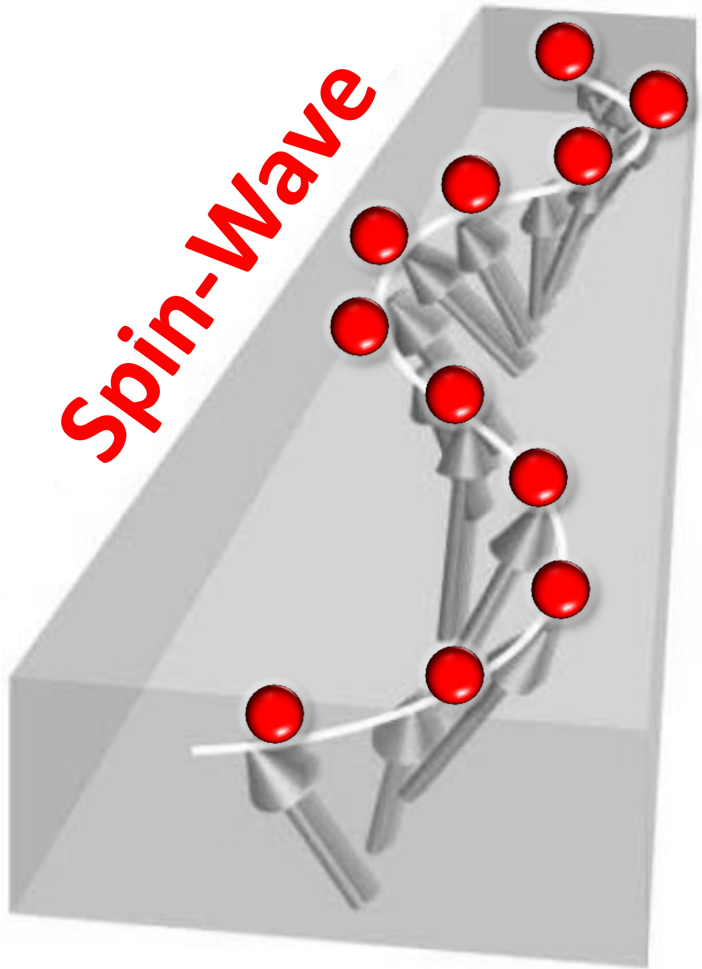
$$\mathrm{S_i}^\mathrm{z} = S - a_i{}^\dagger a_i$$

$$\mathrm{S_i}^+ \simeq \mathrm{S_i}^\mathrm{x} + i\mathrm{S_i}^\mathrm{y} \approx a_i \simeq (\mathrm{S_i}^-)^\dagger$$

with $[a_i, a_j{}^\dagger] = \delta_{ij}$

Magnon ≈ Spin-Wave

- ✓ **Magnons**; the bosonic quanta of **magnetic excitations** in a magnetically ordered spins
- ✓ *Spin-wave spin (i.e. magnon) current* is also measurable by ISHE.
  [Y. Kajiwara et al., Nature **464** (2010) 262]



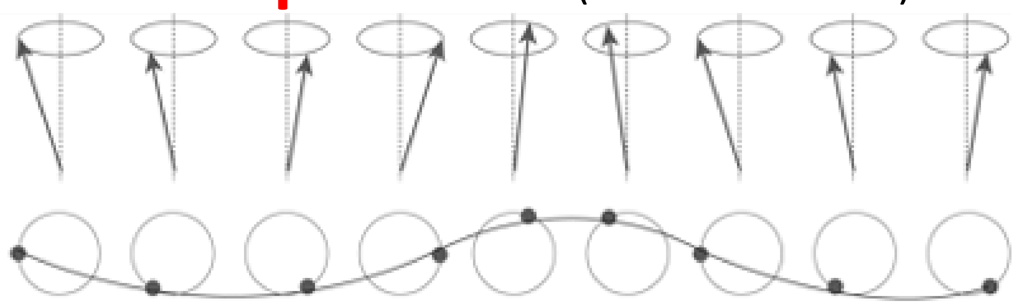
[Y. Kajiwara et al., Nature **464** (2010) 262]

Ferromagnetic Heisenberg model (J > 0)

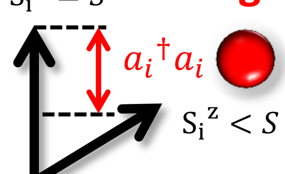
$$-J \sum_{<i,j>} \mathbf{S}_i \cdot \mathbf{S}_j$$

Ground state; $S_i^z = S$

Spin-wave (collective mode)



Holstein-Primakoff transformation; magnon



Magnon

$$S_i^z = S - a_i^\dagger a_i$$

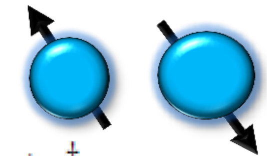
$$S_i^+ \simeq S_i^x + iS_i^y \approx a_i \simeq (S_i^-)^\dagger$$

with $[a_i, a_j^\dagger] = \delta_{ij}$

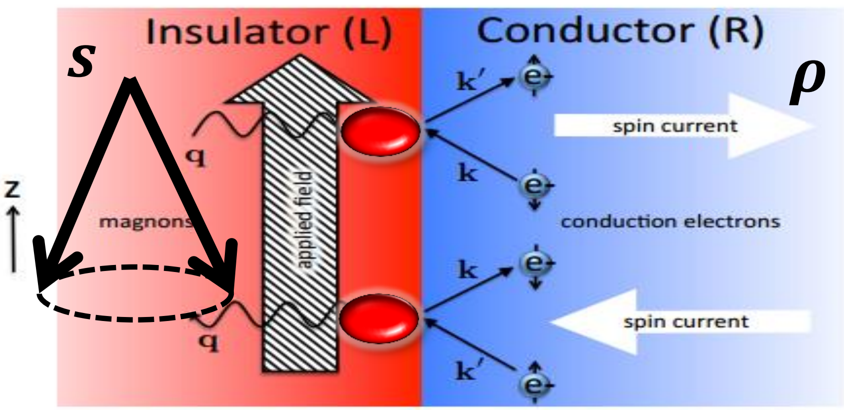
Spin Hamiltonian

$$\hat{\mathcal{H}} = -J \int d^2\mathbf{r}\, \hat{\boldsymbol{\rho}}(\mathbf{r}) \cdot \hat{\mathbf{s}}(\mathbf{r})$$

✓ **Spin density**



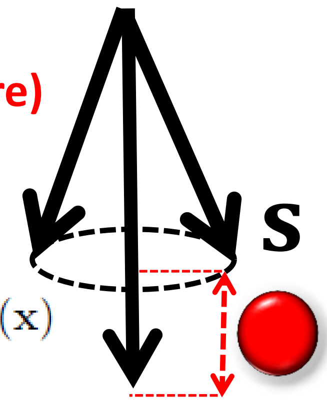
$$\hat{\rho}(\mathbf{x}) = \frac{1}{2} \sum_{\sigma\sigma' k k'} \psi_k^*(\mathbf{x})\psi_{k'}(\mathbf{x})\hat{c}_{k\sigma}^\dagger \boldsymbol{\sigma}_{\sigma\sigma'}\hat{c}_{k'\sigma'}$$



Pic. in Phys. Rev. Lett. **108** (2012) 246601

✓ **Holstein-Primakoff Tr.**
(Spin S →Magnon picture)

$$\begin{cases} \hat{s}_z(\mathbf{x}) = \hat{\phi}^\dagger(\mathbf{x})\hat{\phi}(\mathbf{x}) - s \\ \hat{s}_-(\mathbf{x}) = \sqrt{2s - \hat{\phi}^\dagger(\mathbf{x})\hat{\phi}(\mathbf{x})}\hat{\phi}(\mathbf{x}) \\ [\phi(\mathbf{x}), \phi^\dagger(\mathbf{x}')] = \delta(\mathbf{x} - \mathbf{x}') \end{cases}$$



$$\hat{\mathcal{H}} \approx \sum_{kk'\sigma} U_{kk'\sigma}\hat{c}_{k\sigma}^\dagger \hat{c}_{k'\sigma}(1 - \hat{n}/s) + \left(\sum_{kk'q} V_{kk'q}\hat{c}_{k\uparrow}^\dagger \hat{c}_{k'\downarrow}\hat{a}_q + \mathrm{H.c.}\right)$$

(n~magnetization)

$$U_{kk'\uparrow} \equiv J\frac{s}{2}\int d^2\mathbf{r}\,\psi_k^*(\mathbf{r})\,\psi_{k'}(\mathbf{r}) = -U_{kk'\downarrow} \qquad V_{kk'q} \equiv -J\sqrt{\frac{s}{2}}\int d^2\mathbf{r}\,\psi_{\mathbf{k}}^*(\mathbf{r})\,\psi_{\mathbf{k}'}(\mathbf{r})\,\phi_{\mathbf{q}}(\mathbf{r})$$

Spin-flip Mediated by Magnons

$$\hat{\mathcal{H}} \approx \sum_{kk'\sigma} U_{kk'\sigma} \hat{c}^{\dagger}_{k\sigma} \hat{c}_{k'\sigma} (1 - \hat{n}/s) + \left(\sum_{kk'q} V_{kk'q} \hat{c}^{\dagger}_{k\uparrow} \hat{c}_{k'\downarrow} \hat{a}_q + \text{H.c.} \right)$$

Elastic scattering

$$\sum_{kk'\sigma} U_{kk'\sigma} \hat{c}^{\dagger}_{k\sigma} \hat{c}_{k'\sigma} (1 - \hat{n}/s)$$

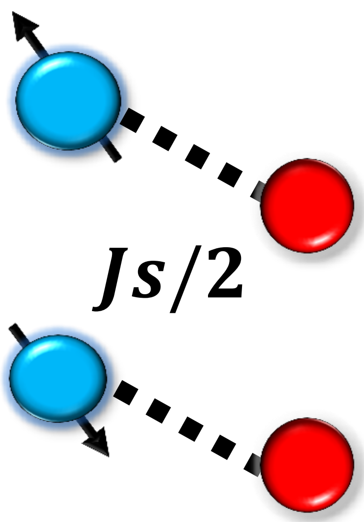
Inelastic scattering

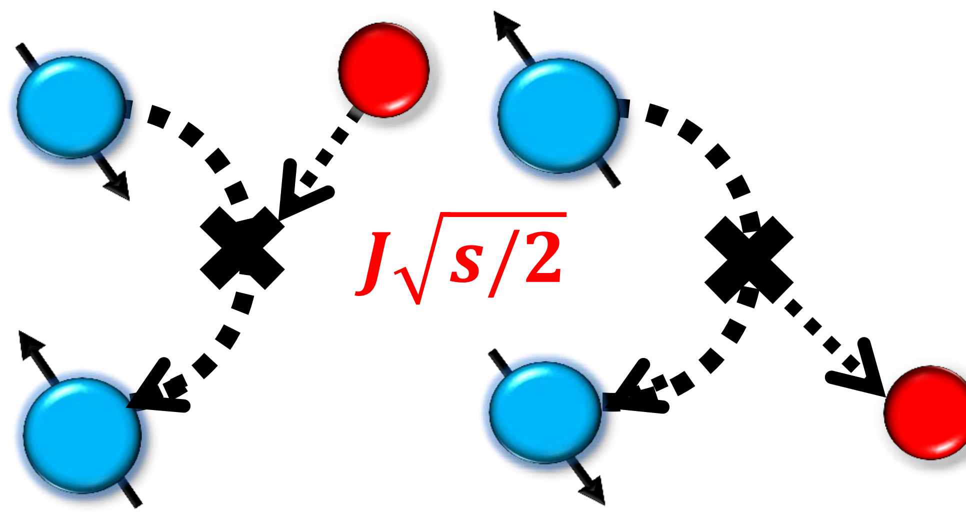
$$\left(\sum_{kk'q} V_{kk'q} \hat{c}^{\dagger}_{k\uparrow} \hat{c}_{k'\downarrow} \hat{a}_q + \text{H.c.} \right)$$

$$U_{kk'\uparrow} \equiv J \frac{s}{2} \int d^2\mathbf{r}\, \psi^*_k(\mathbf{r})\, \psi_{k'}(\mathbf{r}) = -U_{kk'\downarrow}$$

$$V_{kk'q} \equiv -J \sqrt{\frac{s}{2}} \int d^2\mathbf{r}\, \psi^*_{\mathbf{k}}(\mathbf{r})\, \psi_{\mathbf{k}'}(\mathbf{r})\, \phi_{\mathbf{q}}(\mathbf{r})$$

→ **Spin-flip** ***mediated by*** **magnon**





MAIN PURPOSE

Spin current generated in the metal/FI junction

- **Classical *but* non-perturbative theory**

→ ***Scattering matrix formalism***

Y. Tserkovnyak et al.

- Rev. Mod. Phys. **77**, 1375 (2005).
- Phys. Rev. Lett. **88**, 117601 (2002).
- Phys. Rev. B, **66** (2002) 060404 (R).

$g^{\uparrow\downarrow}$ Spin-mixing conductance (constant)

Correspondence ??

$$g^{\uparrow\downarrow} \rightleftarrows \hat{\mathcal{H}} = -J \int d^2\mathbf{r}\, \hat{\boldsymbol{\rho}}(\mathbf{r}) \cdot \hat{\mathbf{s}}(\mathbf{r})$$

→ *To find quantum-mechanical effects arising from spin-flip processes*

- **Quantum *but* perturbative theory**

arXiv:1409.7128,
Scott A. Bender and Yaroslav Tserkovnyak

→ ***Kubo formula (Linear response theory):***
Microscopic approach (Spin Hamiltonian)

$$\hat{\mathcal{H}} = -J \int d^2\mathbf{r}\, \hat{\boldsymbol{\rho}}(\mathbf{r}) \cdot \hat{\mathbf{s}}(\mathbf{r})$$

- **Correspondences**

Correspondence I

Classical *but* non-perturbative theory

Spin current density

$$\mathbf{i} = \frac{1}{4\pi}\left(g_i^{\uparrow\downarrow} + g_r^{\uparrow\downarrow}\mathbf{n}\times\right)\boldsymbol{\mu}' \times \mathbf{n}$$

$g_i^{\uparrow\downarrow}$ $g_r^{\uparrow\downarrow}$ Spin-mixing conductance at zero-temperature (constant)

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

Quantum *but* perturbative theory

Spin current density

$$\mathbf{i} = \frac{1}{4\pi}\left(\tilde{g}_i^{\uparrow\downarrow} + \tilde{g}_r^{\uparrow\downarrow}\mathbf{n}\times\right)\boldsymbol{\mu}' \times \mathbf{n}$$

$$\begin{cases} \tilde{g}_i^{\uparrow\downarrow} = (1 - n/s)\, g_i^{\uparrow\downarrow} \\ \tilde{g}_r^{\uparrow\downarrow} = (1 - 2n/s)\, g_r^{\uparrow\downarrow} \end{cases}$$

(n~ magnetization of FI)

Correspondence I

Classical *but* non-perturbative theory

Spin current density $\mathbf{i} = \frac{1}{4\pi}\left(g_i^{\uparrow\downarrow} + g_r^{\uparrow\downarrow}\mathbf{n}\times\right)\boldsymbol{\mu}' \times \mathbf{n}$

$g_i^{\uparrow\downarrow}$ $g_r^{\uparrow\downarrow}$ Spin-mixing conductance at zero-temperature (constant)

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

Quantum *but* perturbative theory

Spin current density $\mathbf{i} = \frac{1}{4\pi}\left(\tilde{g}_i^{\uparrow\downarrow} + \tilde{g}_r^{\uparrow\downarrow}\mathbf{n}\times\right)\boldsymbol{\mu}' \times \mathbf{n}$

$$\tilde{g}_i^{\uparrow\downarrow} = (1 - n/s) g_i^{\uparrow\downarrow} \rightarrow g_i^{\uparrow\downarrow} = DU \qquad U \equiv \frac{2\pi}{AD}\sum_k \delta(\epsilon_F - \epsilon_k)(U_{kk\uparrow} - U_{kk\downarrow})$$

$$\tilde{g}_r^{\uparrow\downarrow} = (1 - 2n/s) g_r^{\uparrow\downarrow} \rightarrow g_r^{\uparrow\downarrow} = D^2 \left|U'\right|^2 \qquad |U'|^2 \equiv \frac{\pi^2}{2AD^2}\sum_{kk'} \delta(\epsilon_F - \epsilon_k)\delta(\epsilon_F - \epsilon_{k'})$$

$$\times \left[|U_{kk'\uparrow}|^2 + |U_{kk'\downarrow}|^2 - 2\mathrm{Re}\left(U_{kk'\uparrow}U^*_{kk'\downarrow}\right)\right]$$

(n~ magnetization of FI)

✓ ***Elastic scattering***

Correspondence II

Classical *but* non-perturbative theory

Spin current density $\mathbf{i} = \frac{1}{4\pi}\left(g_i^{\uparrow\downarrow} + g_r^{\uparrow\downarrow}\mathbf{n}\times\right)\boldsymbol{\mu}' \times \mathbf{n}$

$g_i^{\uparrow\downarrow}$ $g_r^{\uparrow\downarrow}$ Spin-mixing conductance at zero-temperature (constant)

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

Quantum *but* perturbative theory

$\tilde{\boldsymbol{\imath}} = \sum_q \tilde{\boldsymbol{\imath}}_q$

Spin current density $\mathbf{i} = \frac{1}{4\pi}\left(\tilde{g}_i^{\uparrow\downarrow} + \tilde{g}_r^{\uparrow\downarrow}\mathbf{n}\times\right)\boldsymbol{\mu}' \times \mathbf{n} + \tilde{\mathbf{i}}$

$$\tilde{g}_i^{\uparrow\downarrow} = (1 - n/s)g_i^{\uparrow\downarrow} \rightarrow g_i^{\uparrow\downarrow} = DU \qquad U \equiv \frac{2\pi}{AD}\sum_k \delta(\epsilon_F - \epsilon_k)(U_{kk\uparrow} - U_{kk\downarrow})$$

$$\tilde{g}_r^{\uparrow\downarrow} = (1 - 2n/s)g_r^{\uparrow\downarrow} \rightarrow g_r^{\uparrow\downarrow} = D^2\left|U'\right|^2 \qquad |U'|^2 \equiv \frac{\pi^2}{2AD^2}\sum_{kk'}\delta(\epsilon_F - \epsilon_k)\delta(\epsilon_F - \epsilon_{k'})$$

$$\times\left[|U_{kk'\uparrow}|^2 + |U_{kk'\downarrow}|^2 - 2\mathrm{Re}\left(U_{kk'\uparrow}U^*_{kk'\downarrow}\right)\right]$$

(n~ magnetization of FI)

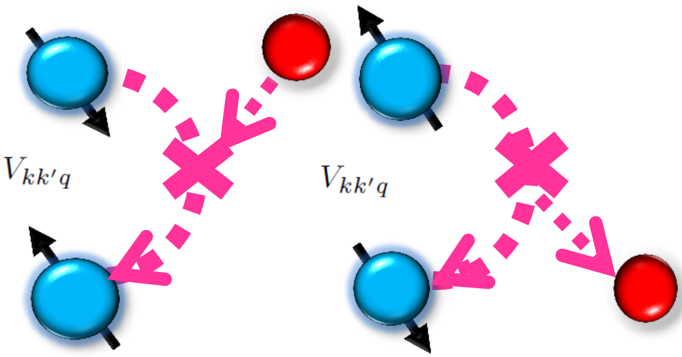
✓ ***Elastic scattering***

Correspondence II

($\hbar\Omega$: magnon gap)

✓ *Inelastic scattering*

$$\tilde{\mathbf{i}}_q = n_q \left|V_q\right|^2 D^2 \left[\mathbf{n}\times\boldsymbol{\mu}'\times\mathbf{n} + 2\mathbf{n}(\mathbf{n}\cdot\boldsymbol{\mu}' + \hbar\Omega)\right]$$



$$\left|V_q\right|^2 \equiv \frac{\pi d_F}{D^2}\sum_{kk'}\left|V_{kk'q}\right|^2 \delta\left(\epsilon_F - \epsilon_k\right)\delta\left(\epsilon_F - \epsilon_{k'}\right)$$

$$V_{kk'q} \equiv -J\sqrt{\frac{s}{2}}\int d^2\mathbf{r}\, \psi^*_{\mathbf{k}}(\mathbf{r})\, \psi_{\mathbf{k}'}(\mathbf{r})\, \phi_{\mathbf{q}}(\mathbf{r})$$

Quantum *but* perturbative theory

$\tilde{\boldsymbol{i}} = \sum_q \tilde{\boldsymbol{i}}_q$

Spin current density

$$\mathbf{i} = \frac{1}{4\pi}\left(\tilde{g}_i^{\uparrow\downarrow} + \tilde{g}_r^{\uparrow\downarrow}\mathbf{n}\times\right)\boldsymbol{\mu}'\times\mathbf{n} + \tilde{\mathbf{i}}$$

$$\tilde{g}_i^{\uparrow\downarrow} = (1 - n/s)\, g_i^{\uparrow\downarrow} \rightarrow g_i^{\uparrow\downarrow} = DU \qquad U \equiv \frac{2\pi}{AD}\sum_k \delta(\epsilon_F - \epsilon_k)(U_{kk\uparrow} - U_{kk\downarrow})$$

$$\tilde{g}_r^{\uparrow\downarrow} = (1 - 2n/s)\, g_r^{\uparrow\downarrow} \rightarrow g_r^{\uparrow\downarrow} = D^2\left|U'\right|^2 \qquad \left|U'\right|^2 \equiv \frac{\pi^2}{2AD^2}\sum_{kk'}\delta(\epsilon_F - \epsilon_k)\delta(\epsilon_F - \epsilon_{k'}) \times \left[\left|U_{kk'\uparrow}\right|^2 + \left|U_{kk'\downarrow}\right|^2 - 2\mathrm{Re}\left(U_{kk'\uparrow}U^*_{kk'\downarrow}\right)\right]$$

(n~ magnetization of FI)

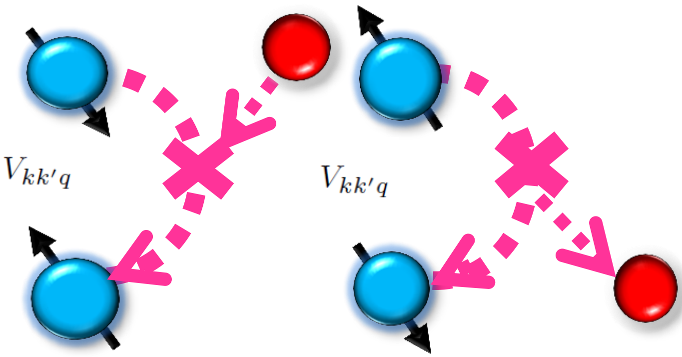
✓ *Elastic scattering*

Correspondence II

($\hbar\Omega$: magnon gap)

✓ *Inelastic scattering*

$$\tilde{\mathbf{i}}_q = n_q \left|V_q\right|^2 D^2 \left[\mathbf{n}\times\boldsymbol{\mu}'\times\mathbf{n} + 2\mathbf{n}(\mathbf{n}\cdot\boldsymbol{\mu}' + \hbar\Omega)\right]$$



$\tilde{\boldsymbol{\imath}} = \sum_q \tilde{\boldsymbol{\imath}}_q \rightarrow$

$$\tilde{\mathbf{i}} = \sum_{a,b=\pm} M_{ab}[(1-a\mathbf{n}\cdot\mathbf{n}')(1+b\mathbf{n}\cdot\mathbf{n}')\mathbf{n} + (a/2-b/2+ab\mathbf{n}\cdot\mathbf{n}')\mathbf{n}\times\mathbf{n}'\times\mathbf{n}]$$

"Temperature"

Thermally-activated magnons

$$M_{ab} = |V_0|^2 D^2 \int_0^\infty d\epsilon\, g(\epsilon)\,(\epsilon+\hbar\Omega-\mu_{ab}) \times \{n\left[\beta(\epsilon-\mu^*)\right] - n\left[\beta'(\epsilon+\hbar\Omega-\mu_{ab})\right]\}$$

$$\langle \hat{a}^\dagger_{q'}\hat{a}_q\rangle = n[\beta(\epsilon_q-\mu)]\delta_{qq'}$$

Quantum *but* perturbative theory

$\tilde{\boldsymbol{\imath}} = \sum_q \tilde{\boldsymbol{\imath}}_q$

Spin current density

$$\mathbf{i} = \frac{1}{4\pi}\left(\tilde{g}_i^{\uparrow\downarrow} + \tilde{g}_r^{\uparrow\downarrow}\mathbf{n}\times\right)\boldsymbol{\mu}'\times\mathbf{n} + \tilde{\mathbf{i}}$$

$$\tilde{g}_i^{\uparrow\downarrow} = (1-n/s)g_i^{\uparrow\downarrow} \rightarrow g_i^{\uparrow\downarrow} = DU$$

$$U \equiv \frac{2\pi}{AD}\sum_k \delta(\epsilon_F-\epsilon_k)(U_{kk\uparrow}-U_{kk\downarrow})$$

$$\tilde{g}_r^{\uparrow\downarrow} = (1-2n/s)g_r^{\uparrow\downarrow} \rightarrow g_r^{\uparrow\downarrow} = D^2\left|U'\right|^2$$

$$|U'|^2 \equiv \frac{\pi^2}{2AD^2}\sum_{kk'}\delta(\epsilon_F-\epsilon_k)\delta(\epsilon_F-\epsilon_{k'}) \times \left[|U_{kk'\uparrow}|^2 + |U_{kk'\downarrow}|^2 - 2\mathrm{Re}\left(U_{kk'\uparrow}U^*_{kk'\downarrow}\right)\right]$$

(n~ magnetization of FI)

✓ *Elastic scattering*

CONCLUSIONS

"Interfacial Spin Transfer between Metals/Magnetic Insulators"

arXiv:1409.7128

Scott A. Bender and Yaroslav Tserkovnyak

✓ The correspondence between the ***"classical non-perturbative theory"*** and the ***"quantum-mechanical perturbative one"*** on the interfacial spin transport between a metal/FI junction has been clarified.

✓ The spin-mixing conductance $g^{\uparrow\downarrow}$ governs interfacial spin transport.

→ The classical non-perturbative theory based on scattering matrix formalism is *valid*.

✓ ***Inelastic scattering***, which describes the ***spin-flip processes mediated by magnons***, characterizes the temperature dependence of spin currents and gives the *quantum-mechanical contribution*.

-RELATED THEIR WORK-

"Electronic Pumping of Quasiequilibrium Bose-Einstein Condensed Magnons"

[Phys. Rev. Lett. **108** (2012) 246601] Scott A. Bender, Rembert A. Duine, Yaroslav Tserkovnyak