非慣性系におけるスピン輸送現象

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in collaboration with：

(Theory)
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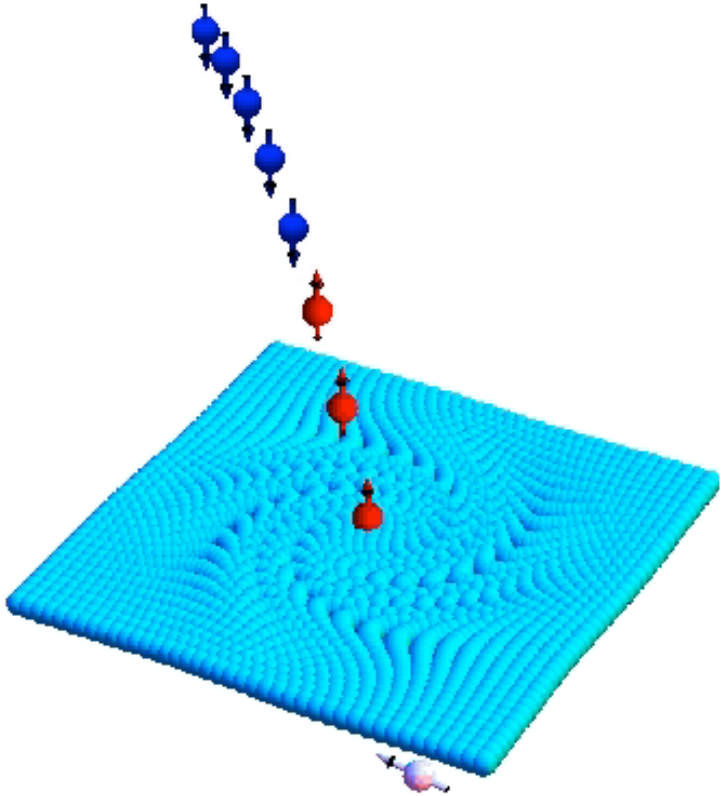
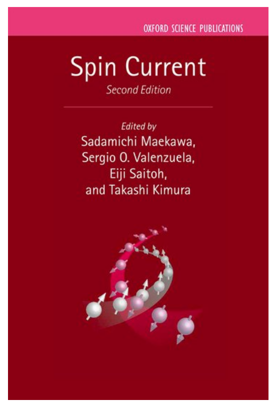
(Experiment)
H. Chudo, R. Takahashi, M. Ono, K. Harii,
Y. Ogata, M. Imai, S. Okayasu, & E. Saitoh (JAEA)
R. Iguchi (NIMS)
D. Kobayashi, Y. Nozaki (Keio Univ.)



Ref.

松尾・齊藤・前川「非慣性系のスピントロニクス」物理学会誌（2017年９月）
MM et al., “Spin-mechatronics”, JPSJ 86, 011011 (2017)
MM et al., “Spin-mechatronics” Chap. 25 in Spin current 2nd ed.(Oxford)



KITS Kavli Institute for Theoretical Sciences
University of Chinese Academy of Sciences (UCAS)

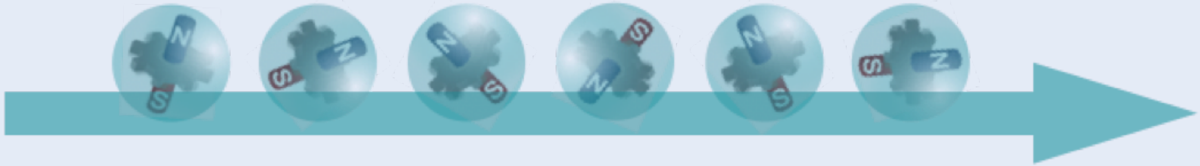
What is electron?

Electronics

Charge
[electricity]

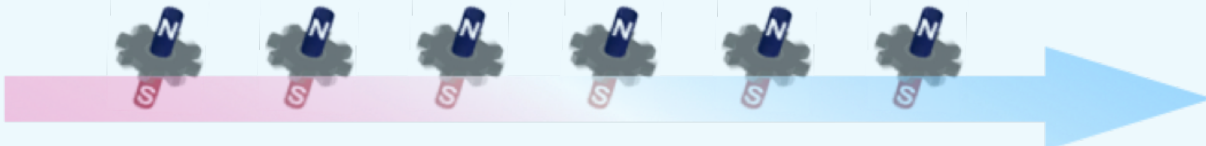
Spin
[magnetism]

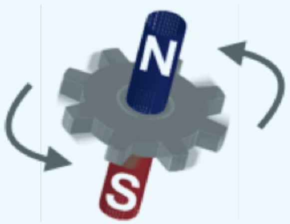
Spintronics



Charge current = flow of charged spheres

robust ⇒ easy to control





Spin current = flow of spinning gears

fragile ⇒ controlled by **nanotechnology**
to utilize **magnetism** and **rotation**

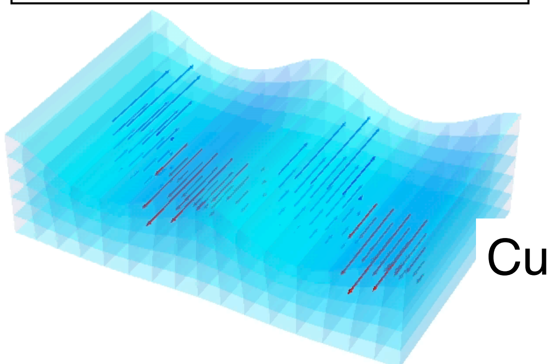
Mechanical generation of spin current

Dirac eq. **in non-inertial frame [spin connection]**

$$H = \beta mc^2 + (c\alpha - v)\cdot(p + eA) + eA_0 - S\cdot\omega$$

$$H = \frac{(p+eA)^2}{2m} + e\phi - S\cdot\gamma B - S\cdot\omega - \frac{e\lambda}{\hbar} S\cdot p\times\left(E + (\omega\times r)\times B\right)$$

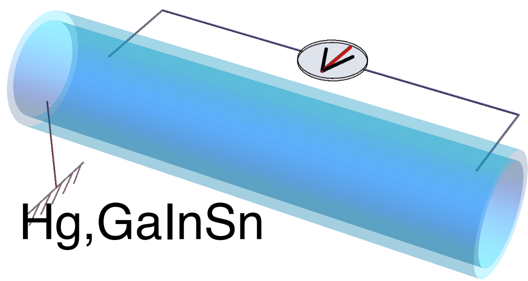
Surface acoustic wave



PRB(R)2013

PRL2017

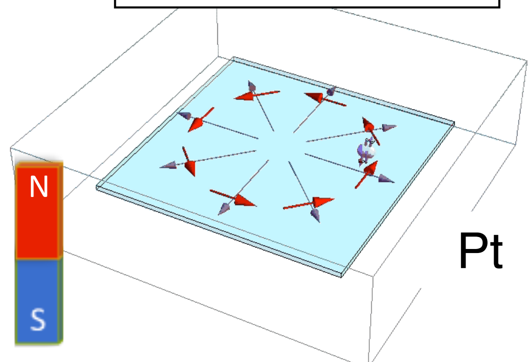
Fluid vorticity



PRB(R)2017

Nat.Phys. 2016

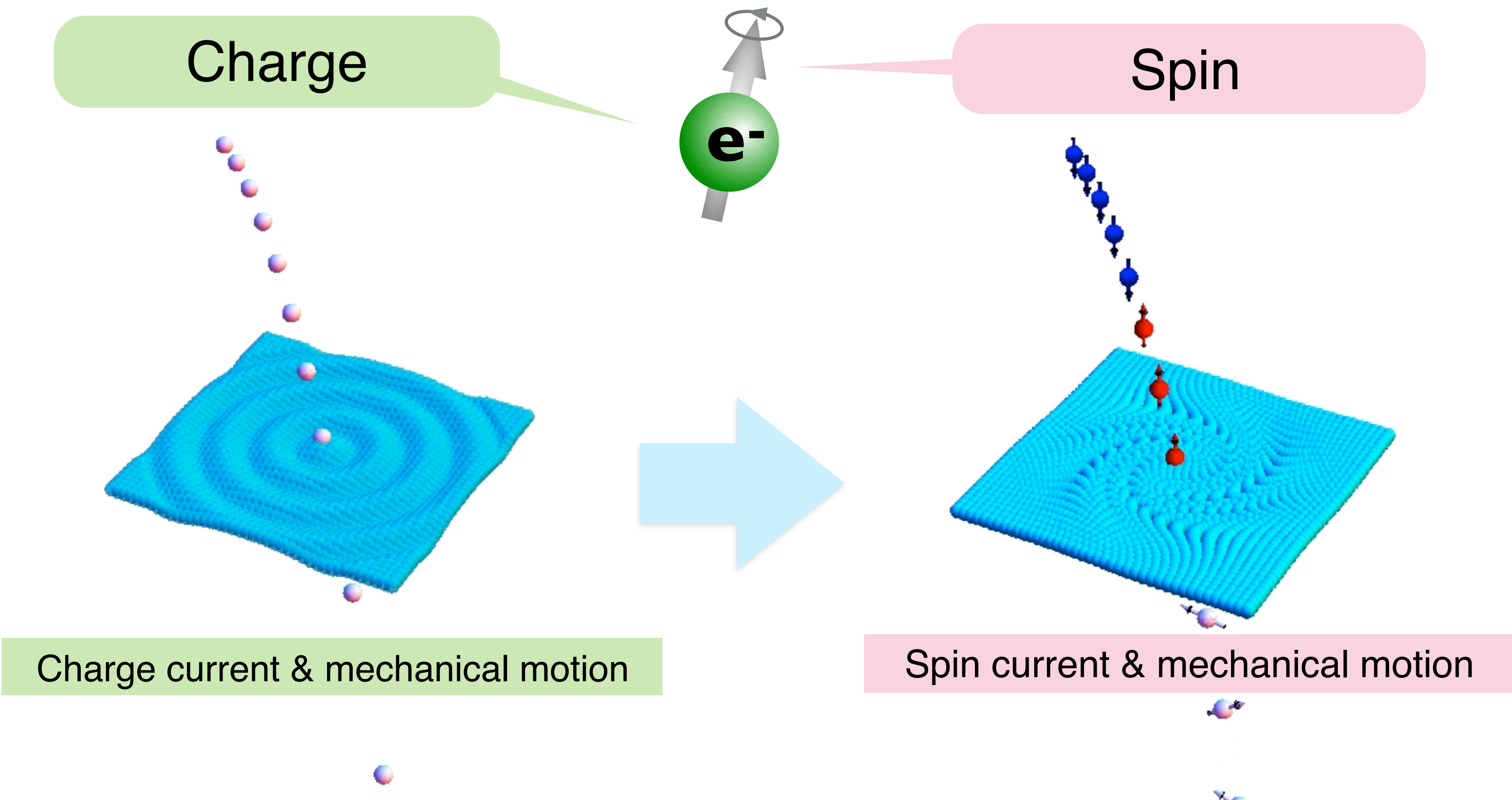
Rigid rotation



PRL2011

Sci.Rept. 2018

“Spin-mechatronics”



Observation of spin-current generation by

- Liquid metal motion in Hg (R.Takahashi et al., Nat. Phys. 2016)
- Surface acoustic wave in Cu (D.Kobayashi et al., PRL 2017)
- Rigid rotation in Pt (A.Hirohata et al., Sci.Rept.2018)

How to detect? Rotation at 10kHz

Rotation as gravity

0.4 million G !!
(@ 1 mm from rotation axis)

gravity on white dwarf star
0.1 million G

$$r\Omega^2 = 1\text{mm} \times \left(2\pi \times 10^4 \text{s}^{-1}\right)^2 = 4 \times 10^6 \text{m/s} \sim 0.4 \times 10^6 \text{G}$$

Rotation as magnetic field

Gyromagnetic ratio of electron:
1T~30GHz
10kHz→0.3μT

Geomagnetism in Tokyo
46 ± 0.05 μT

$$B = \Omega / \gamma_e, \quad \gamma_e = \frac{e}{m} = 1.76 \times 10^{11} \text{rad} \cdot \text{s}^{-1} \cdot \text{T}^{-1}$$

Challenge: How to use mechanical rotation to manipulate spins?

Observation of spin-rotation coupling

・Ferromagnets: Barnett's original exp. (1915)

$$H_{\text{Spin-rotation}} = -S \cdot \Omega$$

Theoretical predictions:

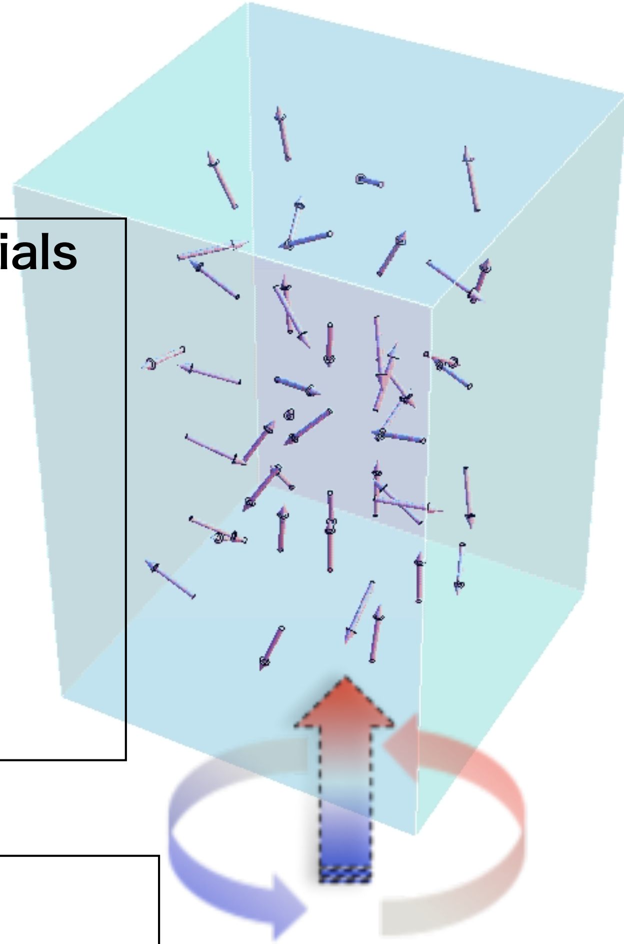
・MM et al., PRL(2011), ···

Spin-rotation coupling arise universally in rotating materials

・Paramagnetic states (Gd, Tb, Dy):
  Ono et el., PRB(2015),
  Ogata et al., APL(2017); JMMM(2017)

・Ferrimagnetic states
  Imai et al., APL(2018)

・Nuclear spin:
  Chudo et al., APEX(2014), JPSJ(2015)



Spin-current generation by SRC

・Liquid metal flow: Takahashi et al, Nat.Phys.(2016)

・Surface acoustic wave: Kobayashi et al., PRL(2017)

Contents

Gyromagnetic effect

Spin current generation by rigid, fluid, elastic motion

Mechanical generation of spin current

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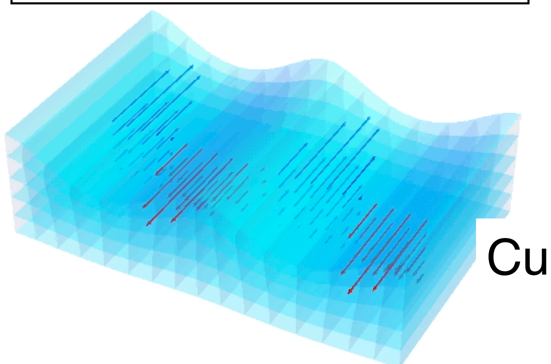
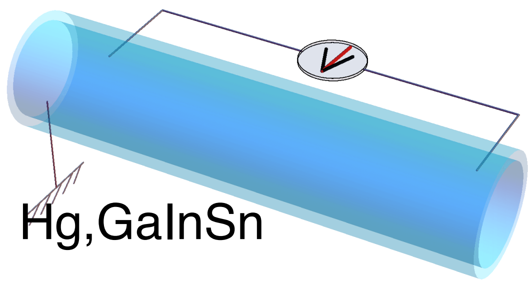
Surface acoustic wave



PRB(R)2013

PRL2017

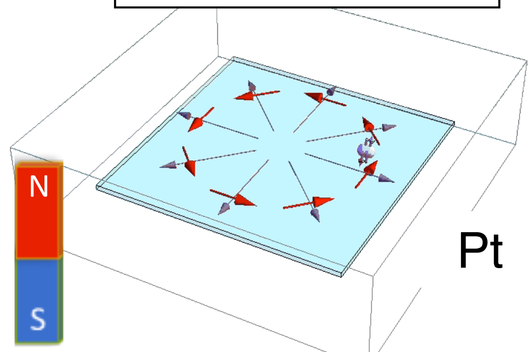
Fluid vorticity



PRB(R)2017

Nat.Phys. 2016

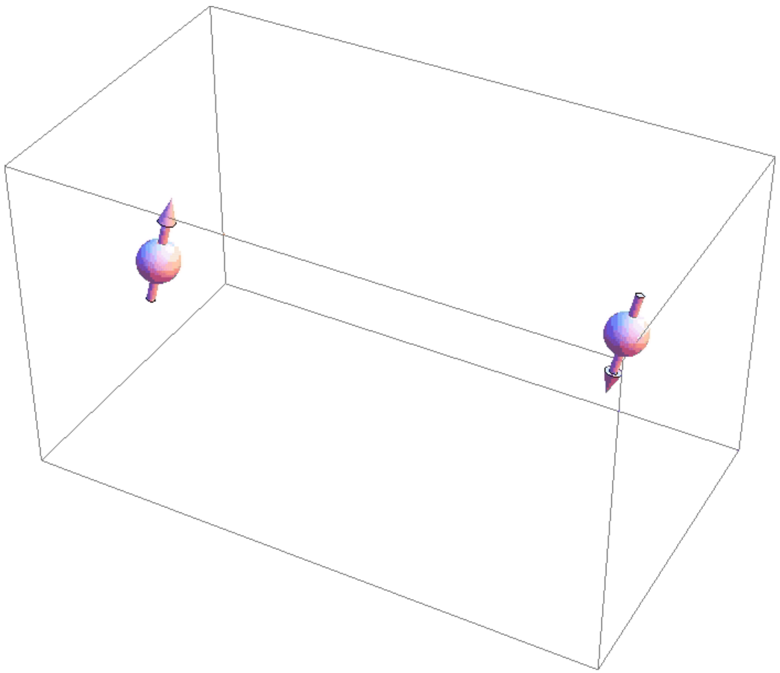
Rigid rotation



PRL2011

Sci.Rept. 2018

Spin current



Spin current

$$J^{z}_{s,x} = J^{\uparrow}_{c,x} - J^{\downarrow}_{c,x}$$

$$J^{\sigma}_{i,s} = \frac{\hbar}{2}\mathrm{Tr}\left[\int_{\omega,k}\{\sigma, v_{k,i}\}G^{<}_{k\omega,\sigma}\right]$$

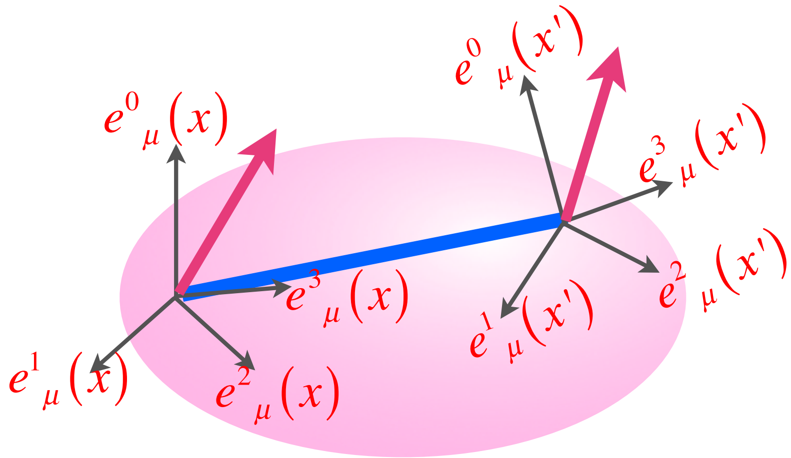
$$G^{<}_{1,2,\sigma} := -i\mathrm{Tr}\rho\psi^{\dagger}_{1}\psi_{2}$$

$$G^{<}_{k\omega,\sigma} = 2i\mathrm{Im}G^{R}_{k\omega}f^{(2)}_{k\omega,\sigma}$$

Spin connection: Spin couples to space-time rotation

Cartan (1922)

Curved spacetime w/ spin & torsion



$$g_{\mu\nu}(x) = \eta_{ab} e^{a}{}_{\mu}(x) e^{b}{}_{\nu}(x)$$

$$\left[e_{\mu}(x) \sim \sqrt{g_{\mu\nu}(x)} \right]$$

Cartan theory (1922)

Gravity w/ spin & torsion

$$\mathcal{L} = \bar{\psi}\left[i e^{\mu}{}_{a} \gamma^{a} \left(p_{\mu} - \omega_{\mu}{}^{ab} \Sigma_{ab} \right) - m \right] \psi$$

spin connection:

$$\omega_{\mu}{}^{ab} dx^{\mu} = \mathbf{e}^{a} \cdot d\mathbf{e}^{b}$$

$$\Sigma_{ab} = \frac{\hbar}{2} \varepsilon_{abc} \begin{pmatrix} \sigma_c & O \\ O & \sigma_c \end{pmatrix}$$

Spin connection gives rise to “spin gauge field”

⇒ mechanical control of spin & spin current

Pauli-Schrödinger eq. in rotating frame

Low energy limit of Dirac eq. in rotating frame

$$H = \frac{1}{2m}(\mathbf{p} + e\mathbf{A})^2 + e\phi \quad - \mathbf{L}\cdot\boldsymbol{\Omega}$$

Coulomb & Lorentz | Coriolis

electric/magnetic field + rotation → charge

$$-\mu_B \boldsymbol{\sigma}\cdot\left(\mathbf{B} + (m/e)\boldsymbol{\Omega}\right)$$

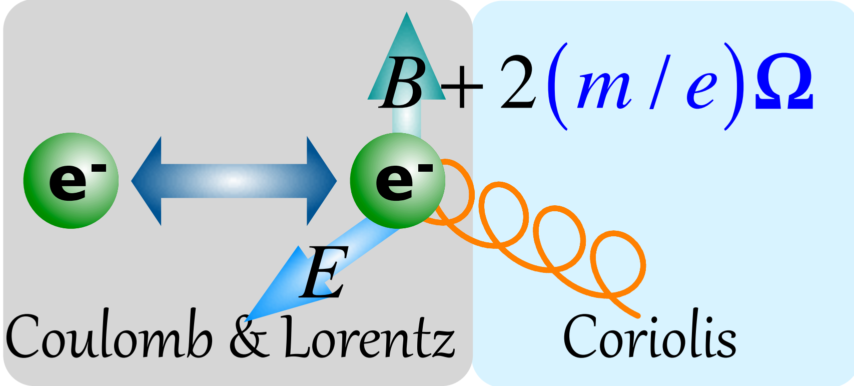
Zeeman | Spin-rotation

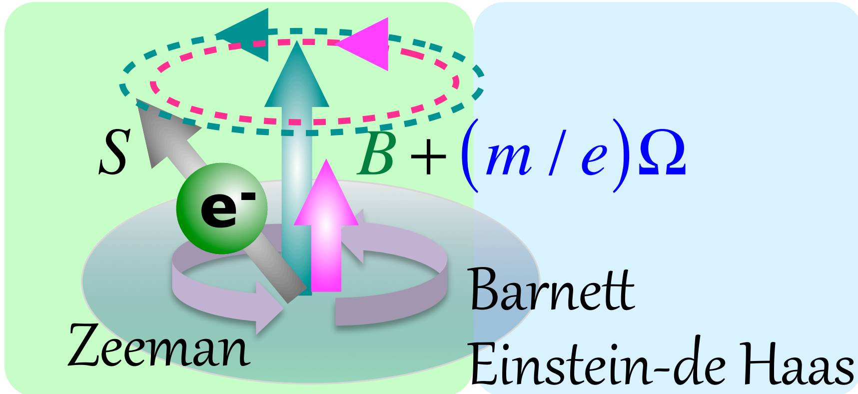
magnetic field+ rotation → spin

$$+\frac{\lambda}{\hbar}\boldsymbol{\sigma}\cdot\left[(\mathbf{p}+e\mathbf{A})\times(-e)\left(\mathbf{E} + (\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)\right]$$

Spin Orbit Int. | NEW!

electric field / magnetic field x rotation → spin current





?

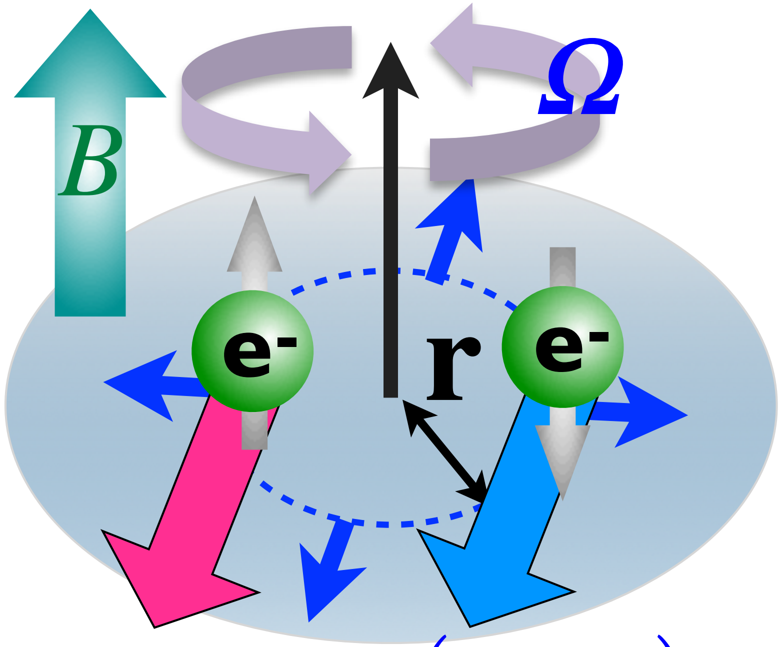
Mechanical Spin Hall Effect due to rotation

Mechanical Spin-Orbit Int.

$$\frac{\bar{\lambda}}{\hbar}\boldsymbol{\sigma}\cdot\left[(\mathbf{p}+e\mathbf{A})\times(-e)\left(\mathbf{E}+(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)\right]$$

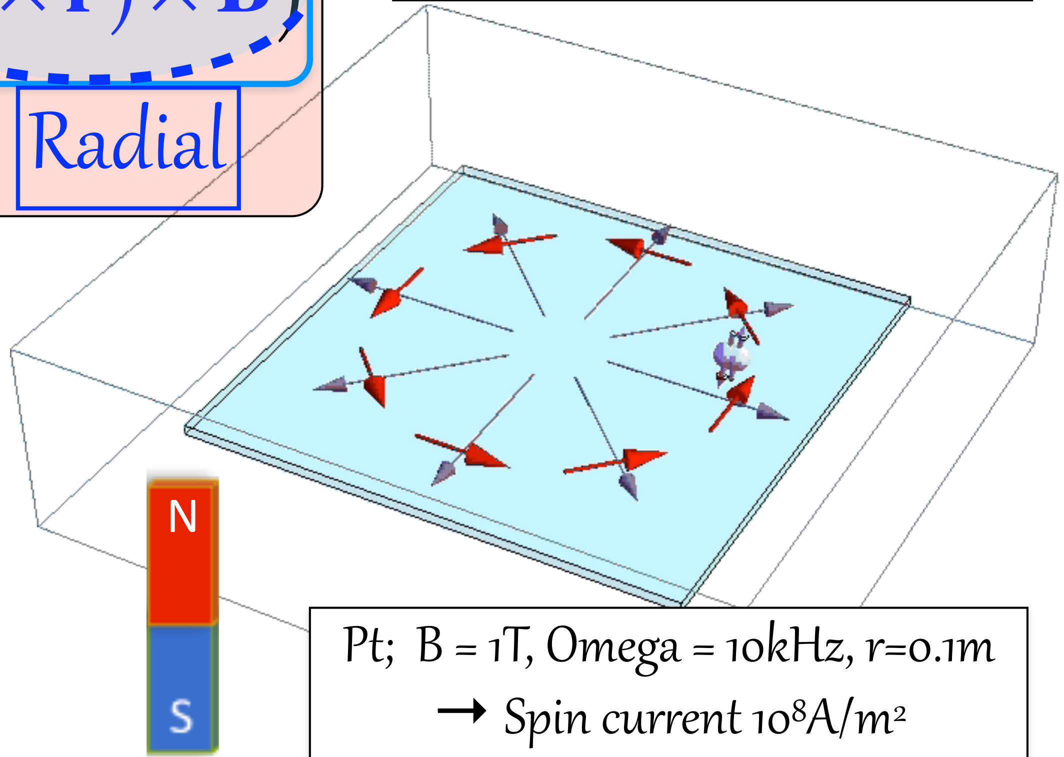
$$\frac{d}{dt}\mathbf{r}=\mathbf{v}-\frac{e\bar{\lambda}}{\hbar}\boldsymbol{\sigma}\times\left(\mathbf{E}+(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)$$

±Azimuthal | $\pm z$ | $\mathbf{E}_{rot}$ | Radial



$$\mathbf{E}_{rot}=(\Omega\cdot B)\mathbf{r}$$

Spin current generated in azimuthal direction



Pt; B = 1T, Omega = 10kHz, r=0.1m
→ Spin current $10^8 A/m^2$

MM et al., PRL 106, 076601(2011)

Hirohata et al., Sci.Rept. 2018

Mechanical generation of spin current

Dirac eq. **in non-inertial frame [spin connection]**

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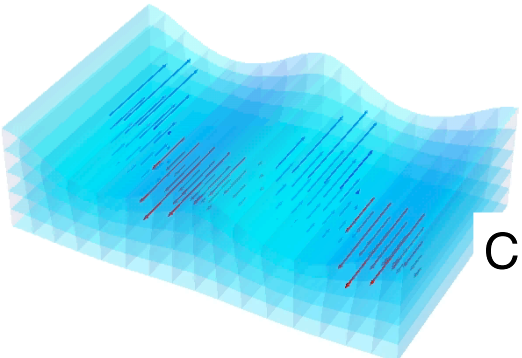
$$H = \frac{(p + eA)^2}{2m} + e\phi - S \cdot \gamma B - S \cdot \omega - \frac{e\lambda}{\hbar} S \cdot p \times \left(E + (\omega \times r) \times B\right)$$

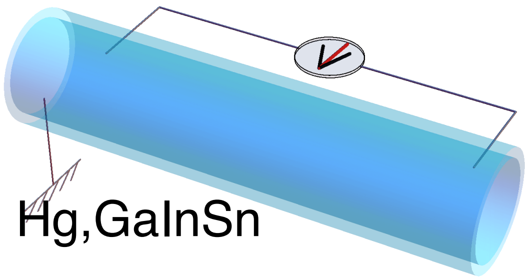
Surface acoustic wave



PRB(R)2013

PRL2017

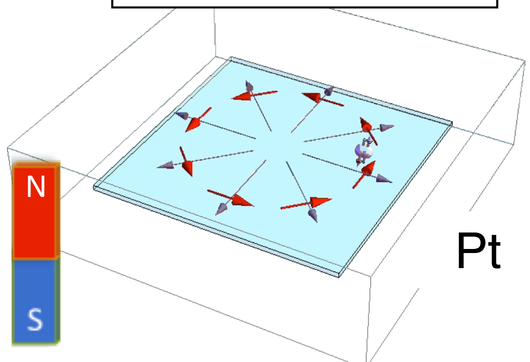
Fluid vorticity



PRB(R)2017

Nat.Phys. 2016

Rigid rotation



PRL2011

Sci.Rept. 2018

Mechanical analogue of Stern-Gerlach effect

$$H_{\text{Zeeman}} = -S \cdot \gamma B$$

$$\Rightarrow F = -\nabla H_{Zeeman} = S \cdot \nabla(\gamma B)$$

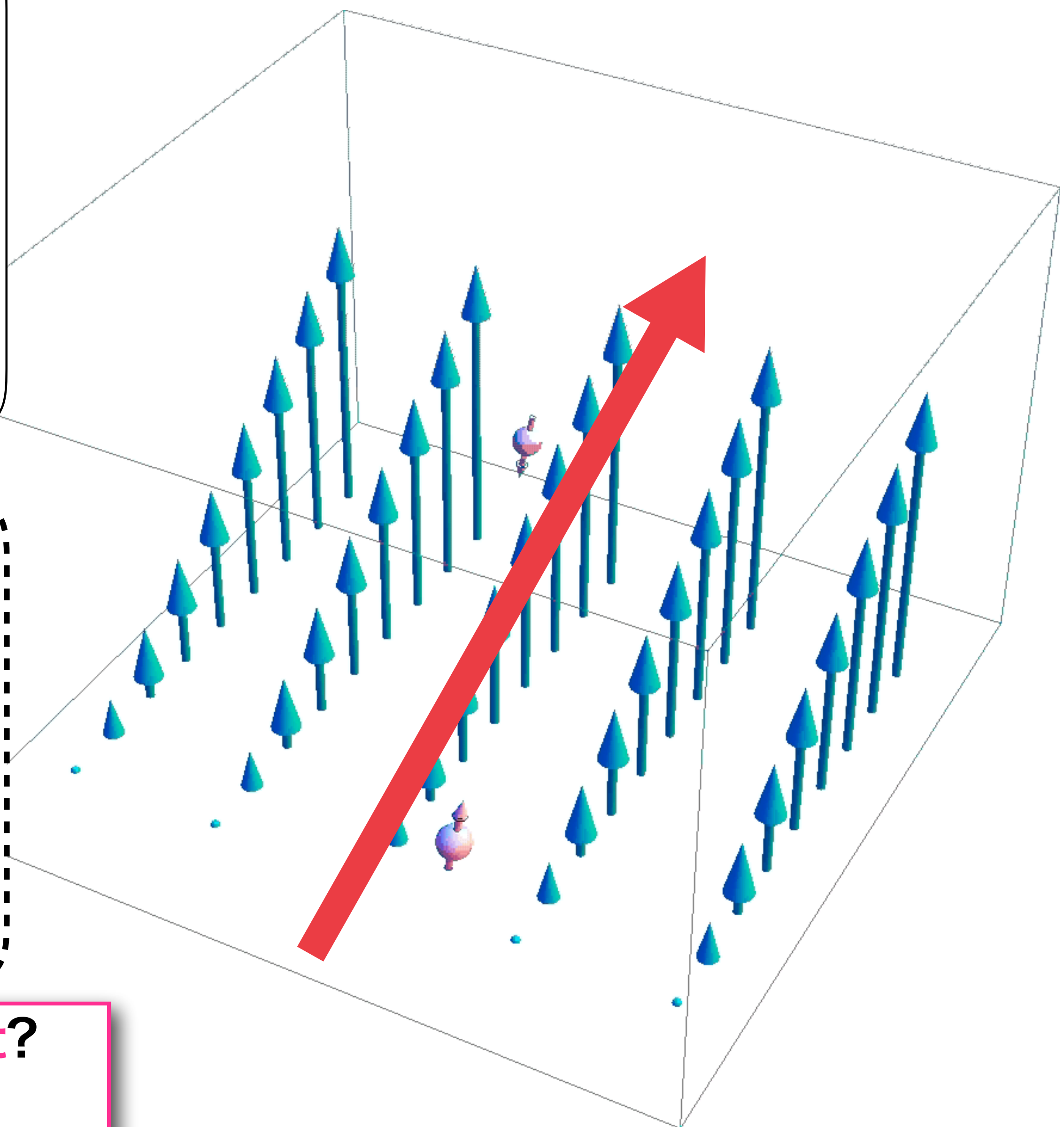
Spin current is generated
along gradient of mag. field.

$$H_{Spin-rotation} = -S \cdot \Omega$$

$$\Rightarrow F = -\nabla H_{Spin-rotation} = S \cdot \nabla \Omega$$

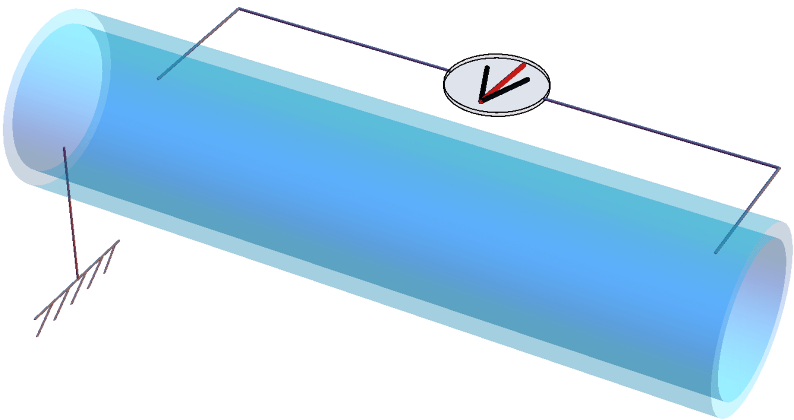
Spin current is generated
along rotation-gradient.

How to create rotation-gradient?
→ 1. Surface acoustic wave,
2. Fluid motion of liquid metal !!



Spin current by vorticity gradient

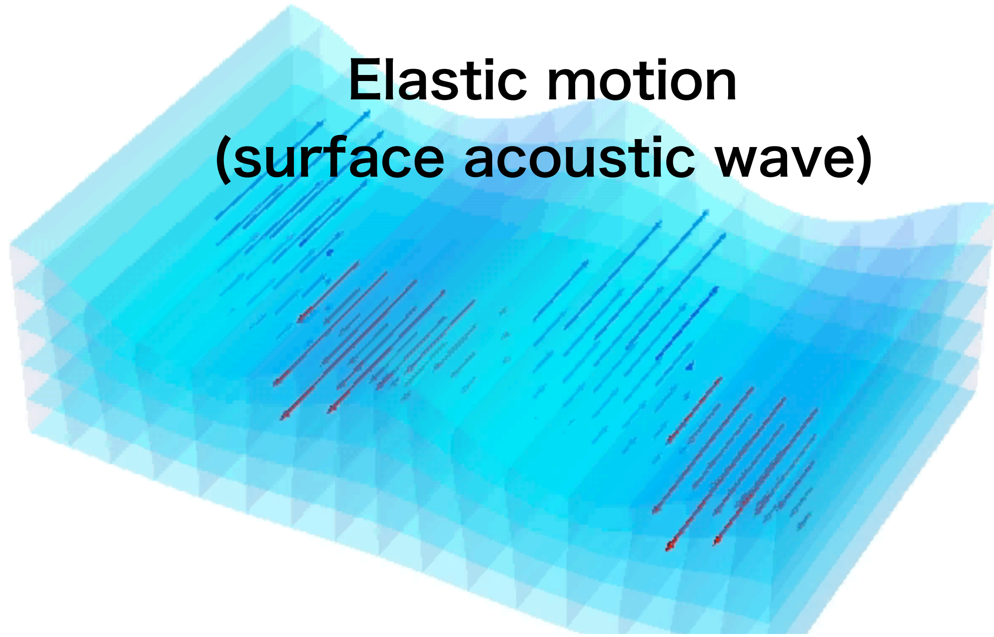
Fluid motion

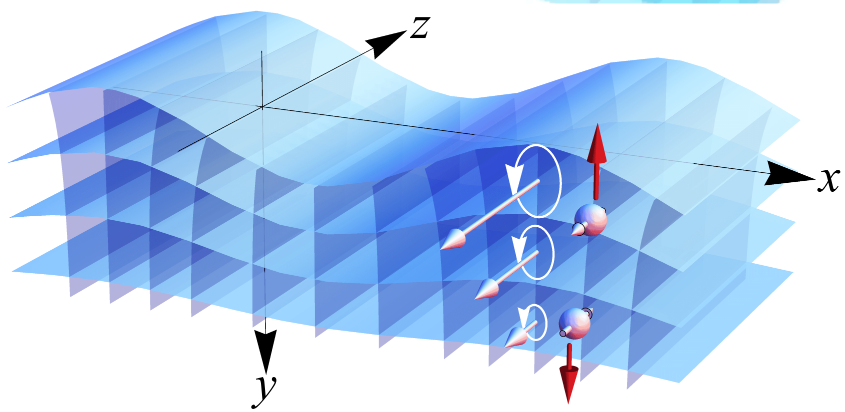


R. Takahashi, MM. et al.,
Nature Physics 2016
MM et al., PRB(R)2017

Science, Editor's choice
Nature Physics, N&V
Nature Materials, N&V

Elastic motion
(surface acoustic wave)

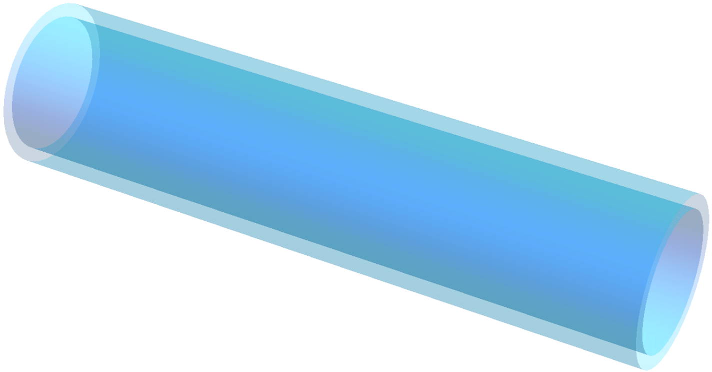




MM et al., PRB(R)2013

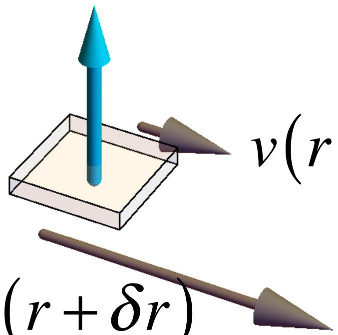
Kobayashi, MM et al.,
PRL2017 (Editors' Suggestion)

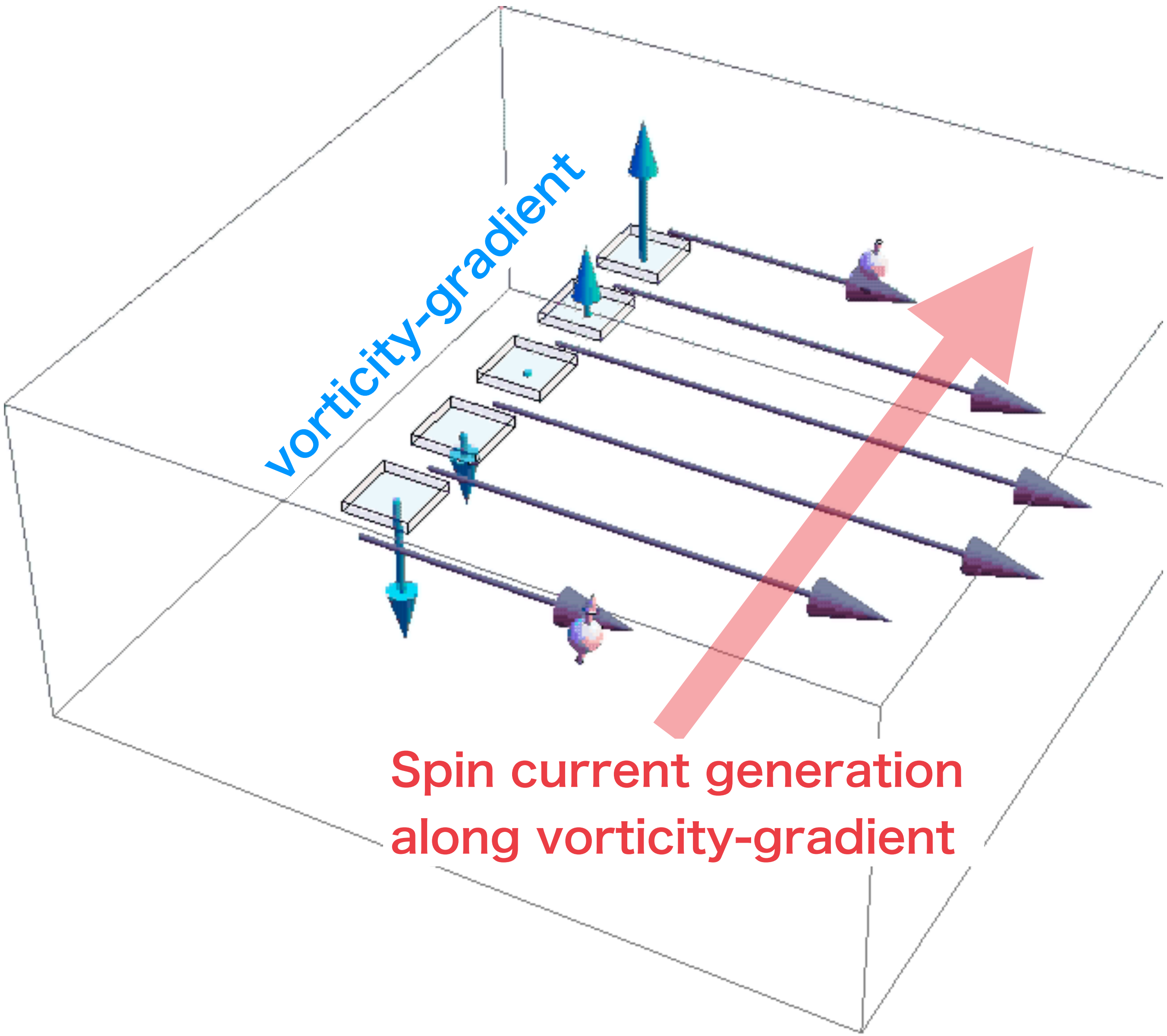
Rotation (vorticity) -gradient in a pipe flow of liquid metal



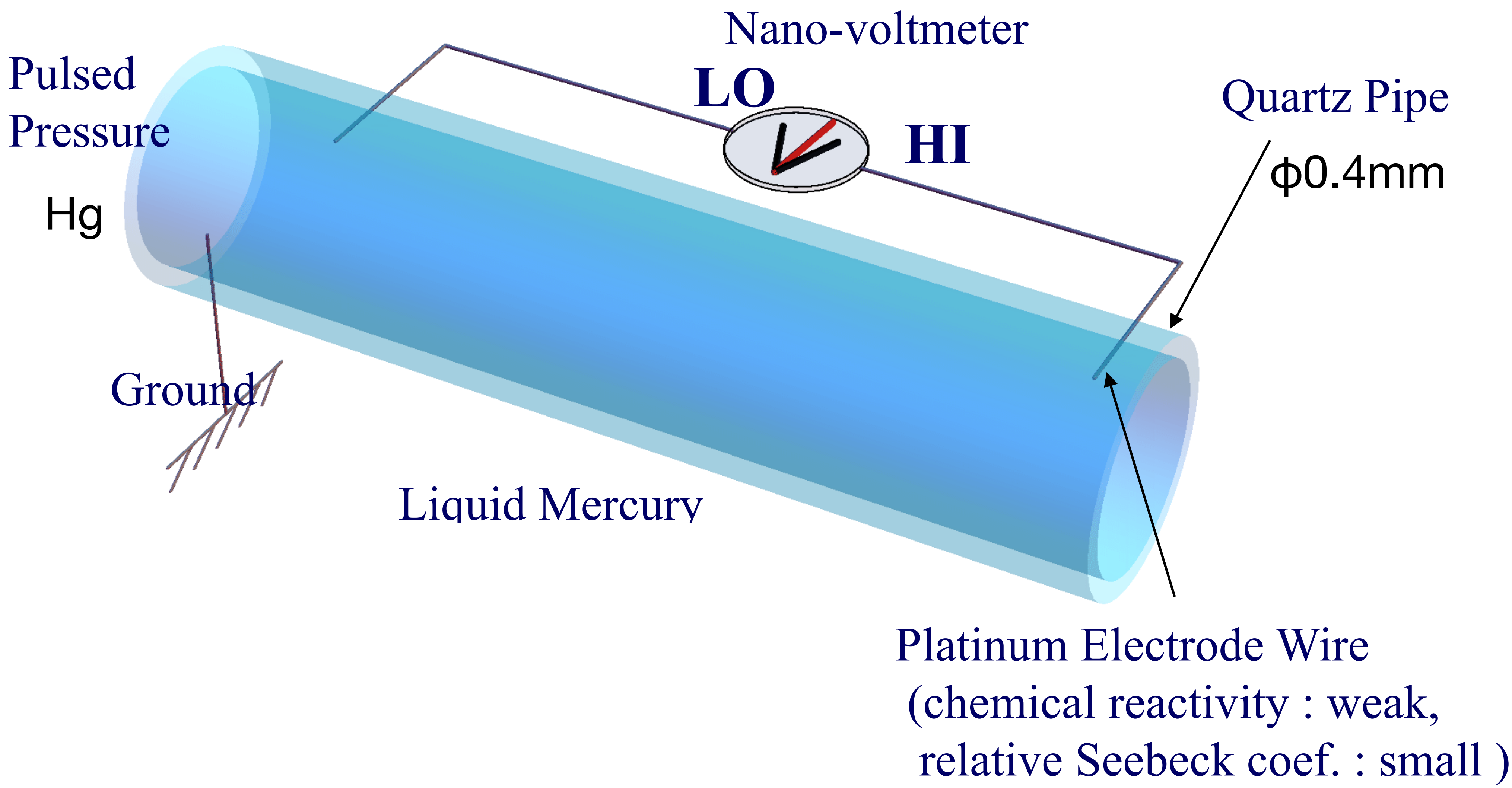
Vorticity:
local rotation of fluid

$$\nabla \times v$$



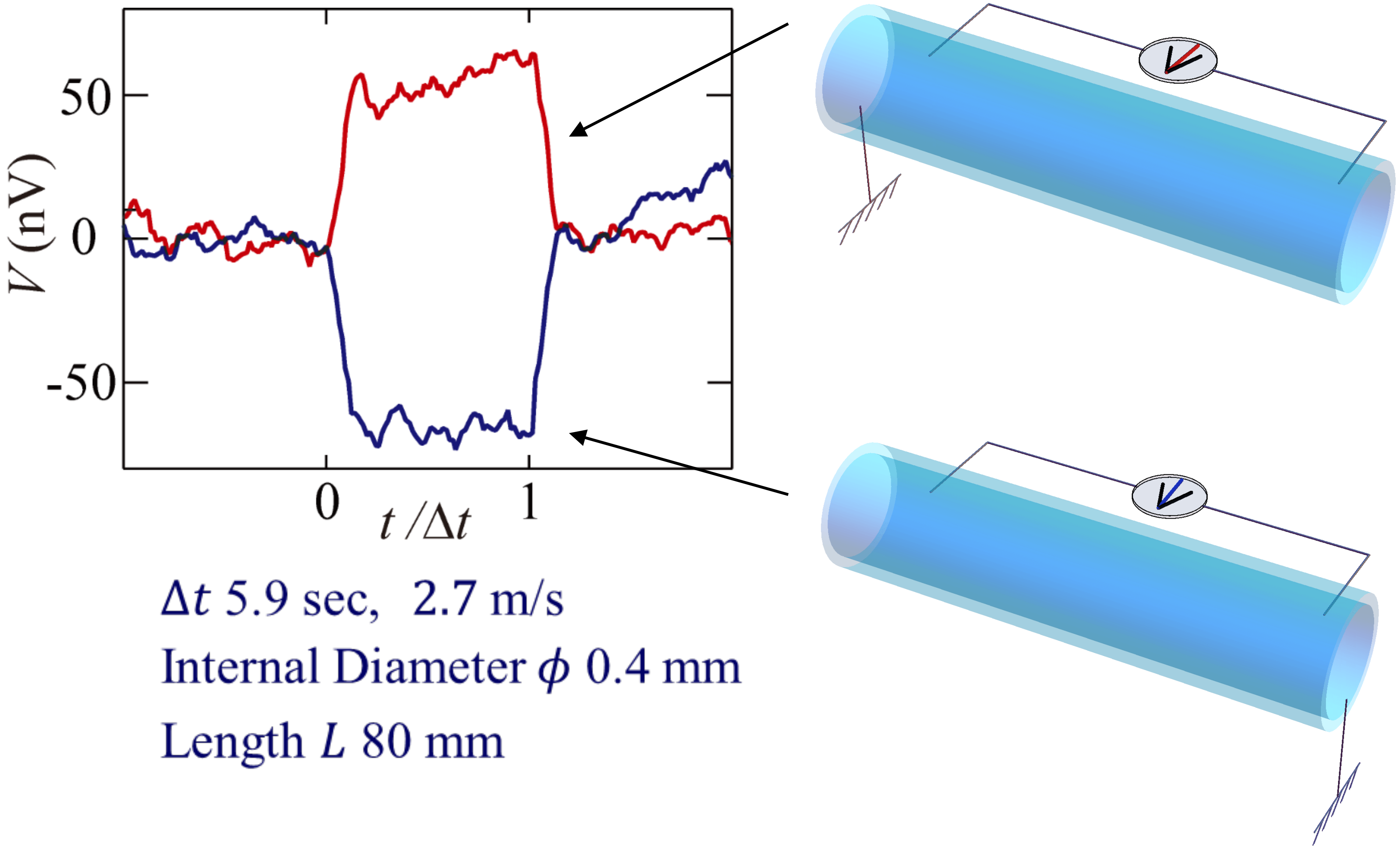


Experimental setup for spin hydrodynamic generation



R. Takahashi, MM et al., Nat. Phys. **12**, 52-56 (2016)

Result - Spin-hydrodynamic signal measurement



Δt 5.9 sec, 2.7 m/s

Internal Diameter ϕ 0.4 mm

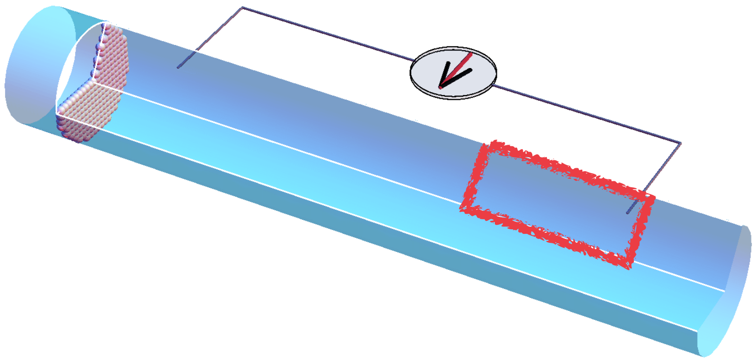
Length L 80 mm

R. Takahashi, MM et al., Nat. Phys. **12**, 52-56 (2016)

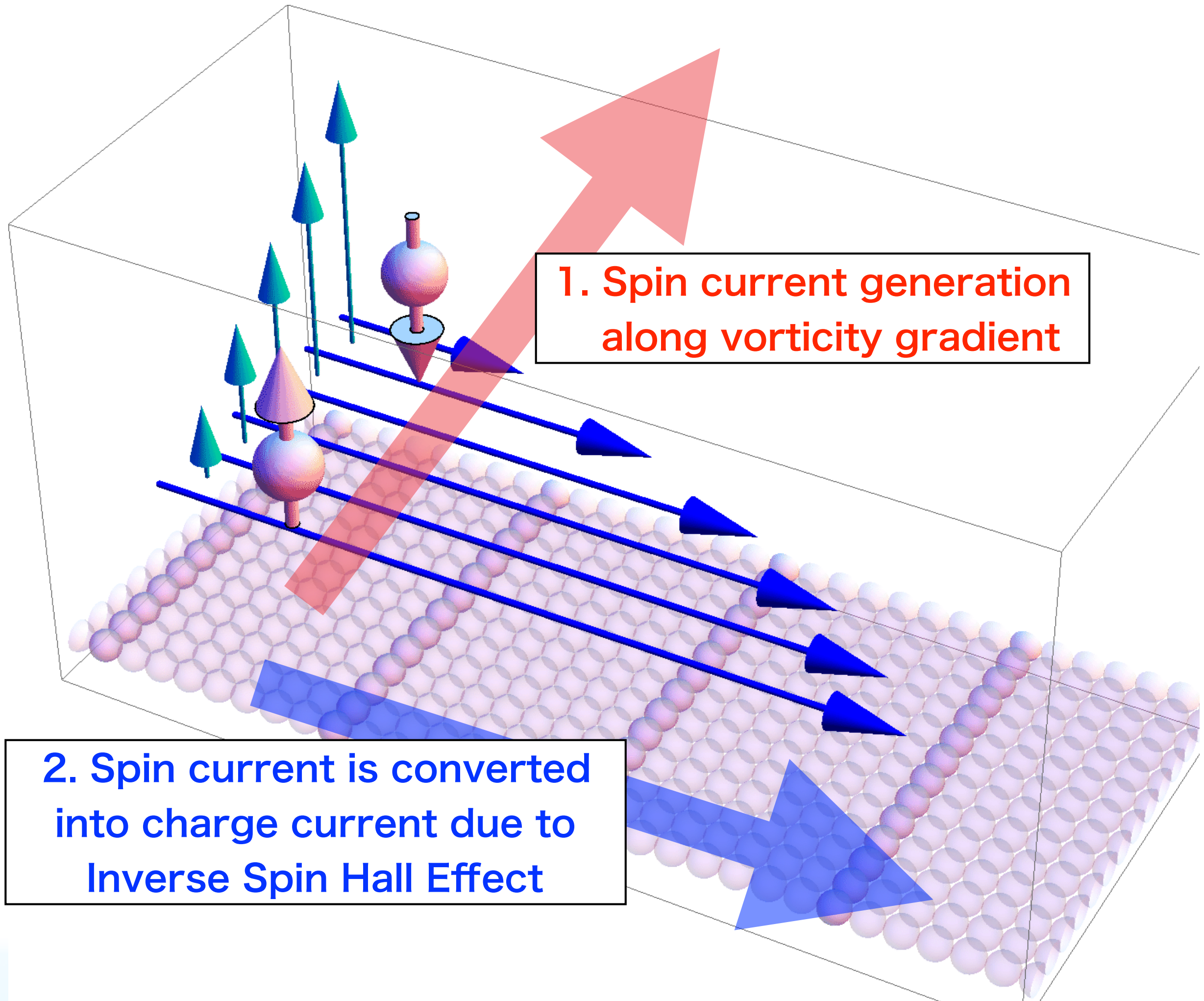
Mechanism of Spin-hydrodynamic voltage generation

"Spin-hydrodynamic generation"

1. Spin current generation along vorticity gradient + **2. Spin current is converted into charge current by ISHE**



flow of liquid metal: Hg



SHD bridges spintronics and hydrodynamics

Navier-Stokes-like eq.

Spin diffusion with spin-vorticity

Solution of “Navier-Stoke” equation:

Turbulent flow in a pipe MM et al.,PRB(R) (2017)

SHD signal

$$\frac{r_0}{L} V_{SHD} = \frac{4e}{\hbar} \times \frac{\theta_{SHE} \lambda_{sf}^{\ 2}}{\sigma_0} \times \xi \times \frac{v_*^{\ 2}}{\kappa}$$

size | Electron | **Fluid⇔ electron** | fluid

$$\left[\lambda_{sf} \ll r_0 \right]$$

L :pipe length

r_0 : pipe radius

η : viscosity

ρ :mass density

κ : Karman constant =0.41

σ_0 : conductivity

θ_{SH} : Spin Hall Angle

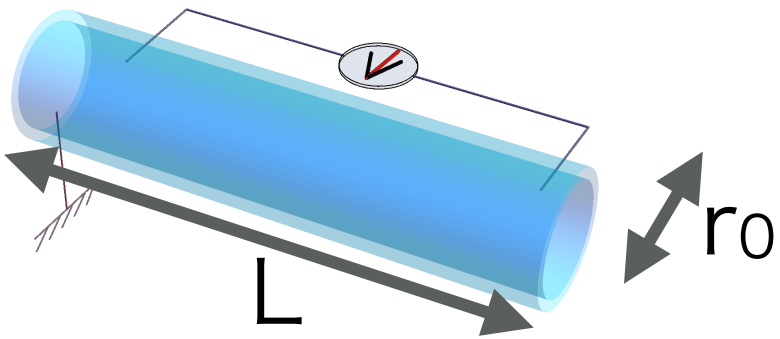
λ_{sf} : Spin diffusion length

χ_0^{zz} : susceptibility

γ : gyromagnetic ratio

$$\lambda_{sf} = 10nm$$

$$\theta_{SHE} = 0.01$$



v_* :average velocity of turbulernt flow

R. Takahashi, MM et al., Nat. Phys. **12**, 52-56 (2016)

Observation of spin-rotation coupling in quark-gluon plasma (Nature 2017)

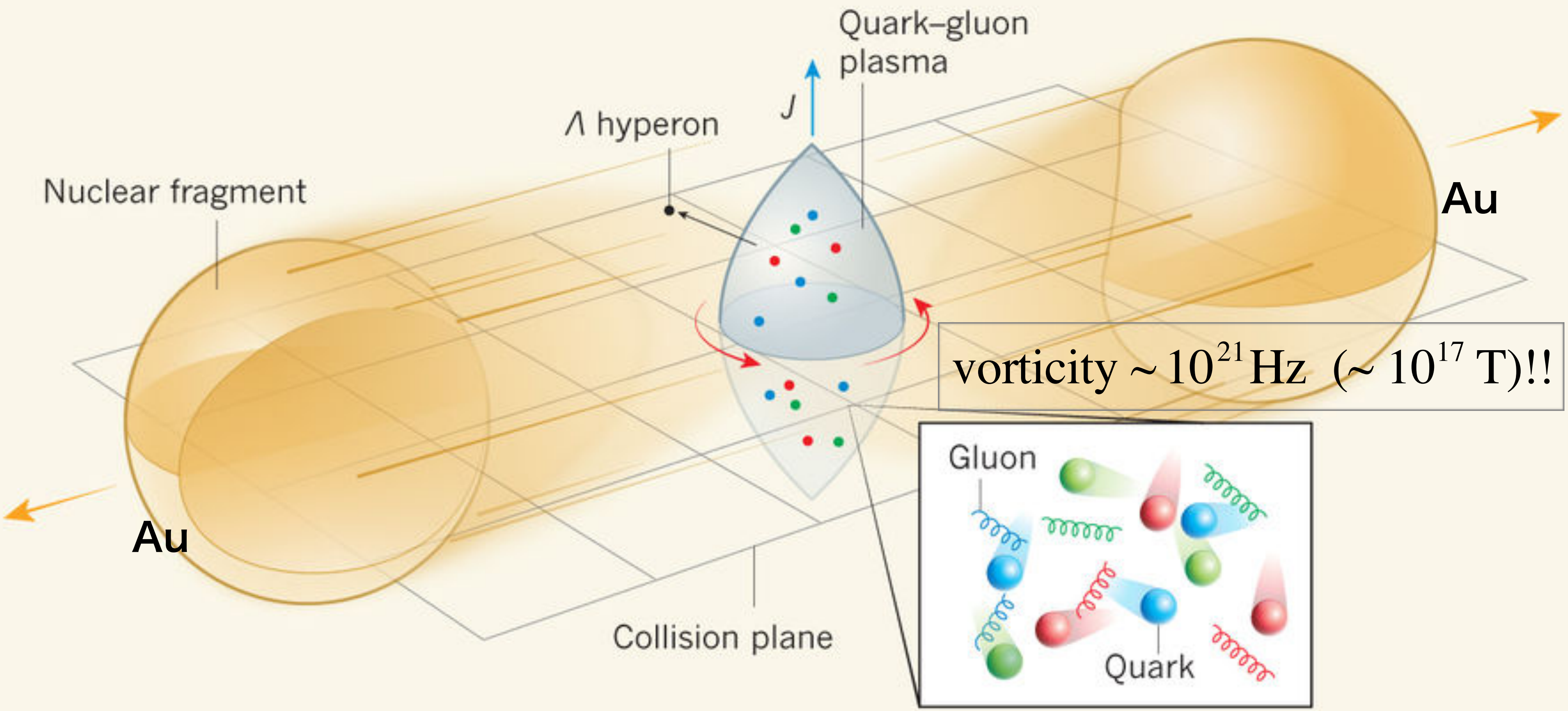
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*

Au+Au, non-central collision in Relativistic Heavy Ion Collider (RHIC)



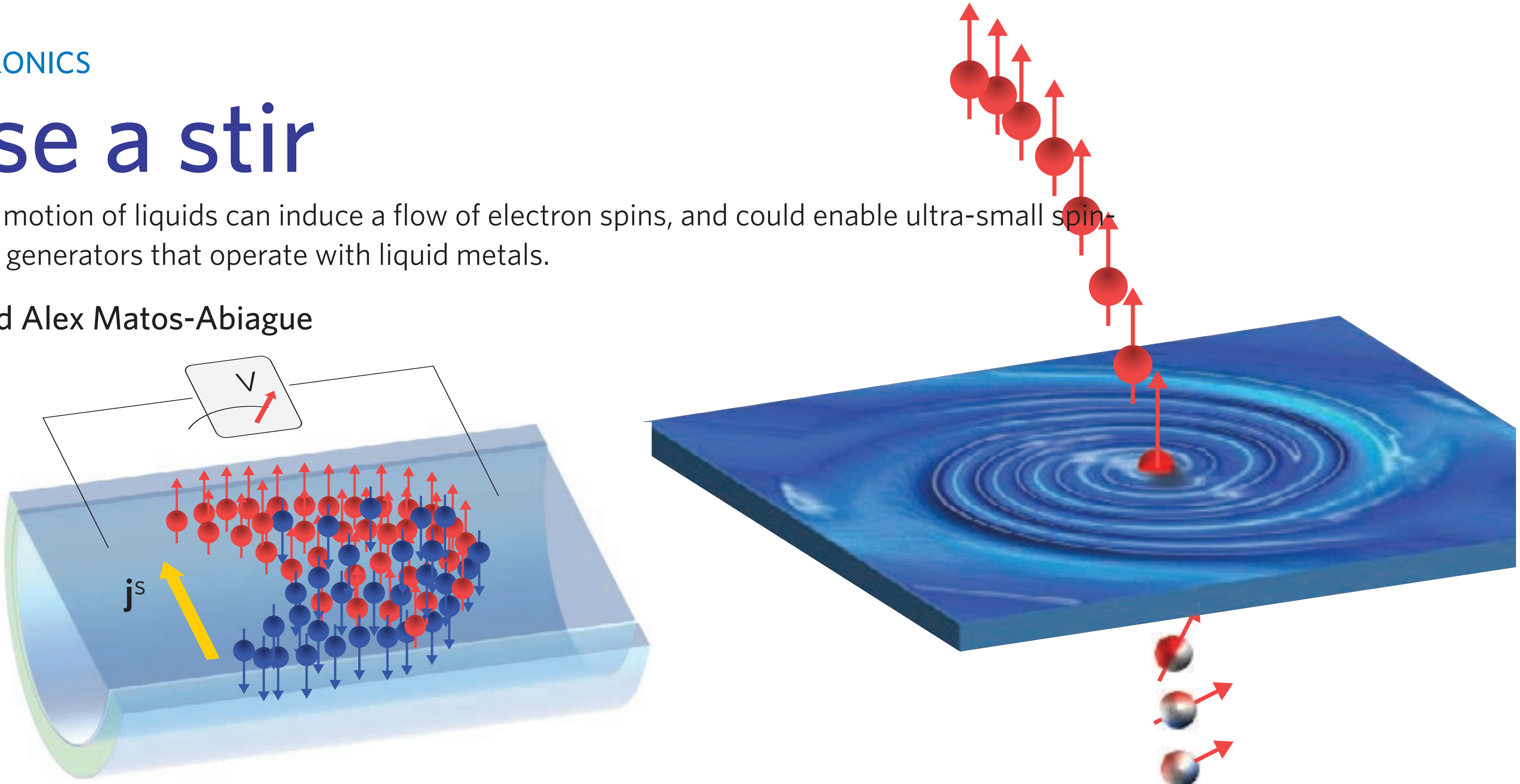
Recently, Takahashi *et al.*[14] reported the first observation of a coupling between the vorticity of a fluid and the internal quantum spin of the electron, opening the door to a new field of fluid spintronics. In their study, the vorticity ω—a measure of the 'swirl' of the velocity flow field around any point (non-relativistically, $\boldsymbol{\omega} = \frac{1}{2}\nabla \times \boldsymbol{v}$)—is generated through shear viscous effects as liquid mercury flows next to a rigid wall. Ref.14: R.Takahashi et al., Nature Physics 12, 52 (2016)

FLUID SPINTRONICS

Cause a stir

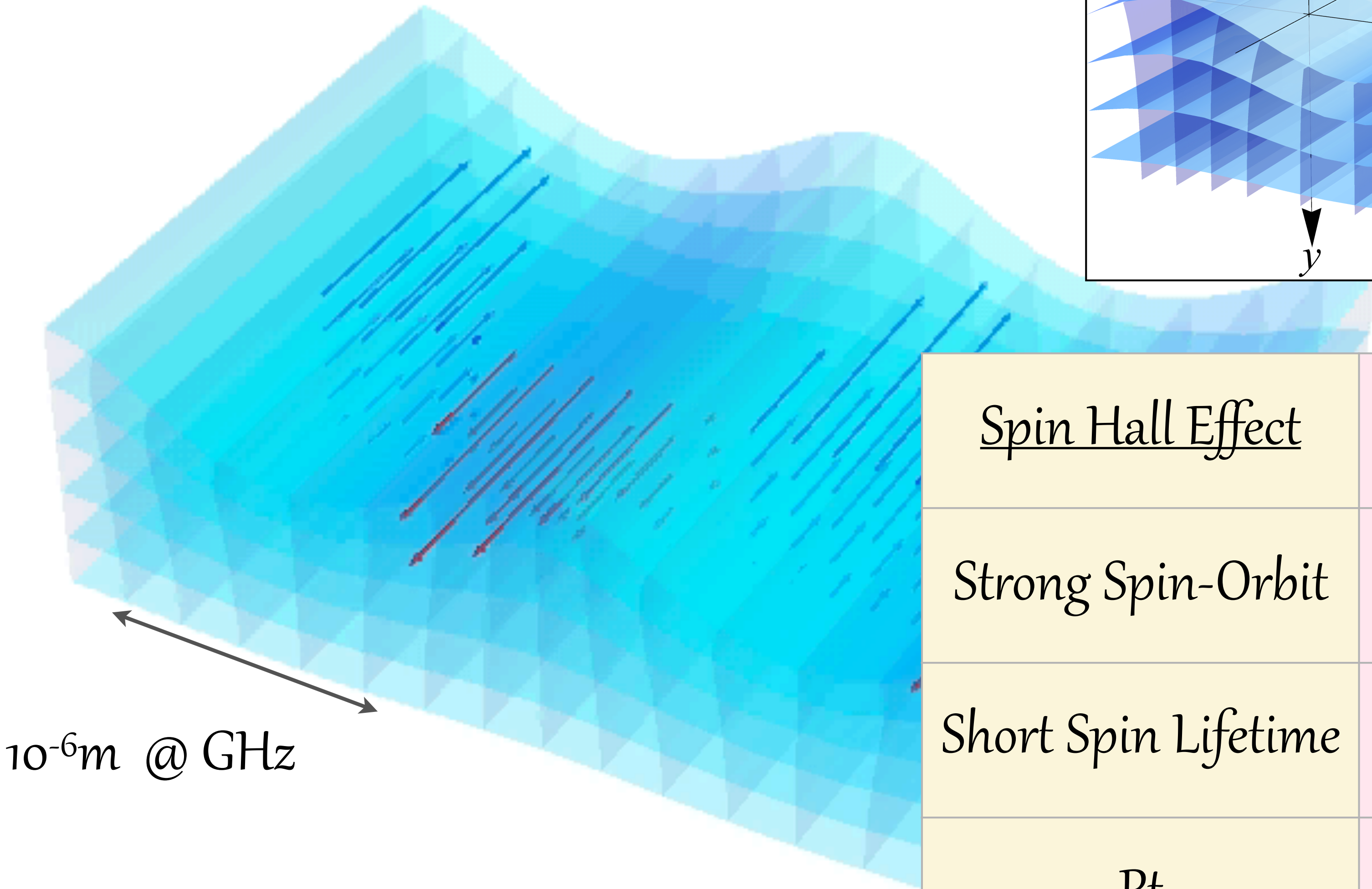
The rotational motion of liquids can induce a flow of electron spins, and could enable ultra-small spin-hydrodynamic generators that operate with liquid metals.

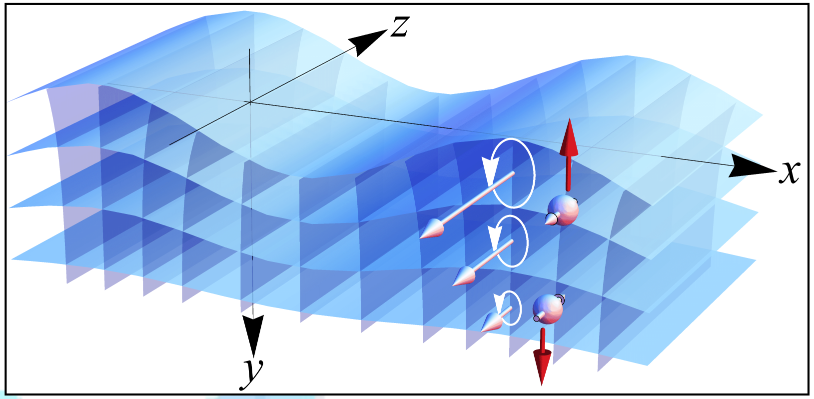
Igor Žutić and Alex Matos-Abiague



Spin current from Surface Acoustic Wave

Spin current ∝ Gradient of rotation



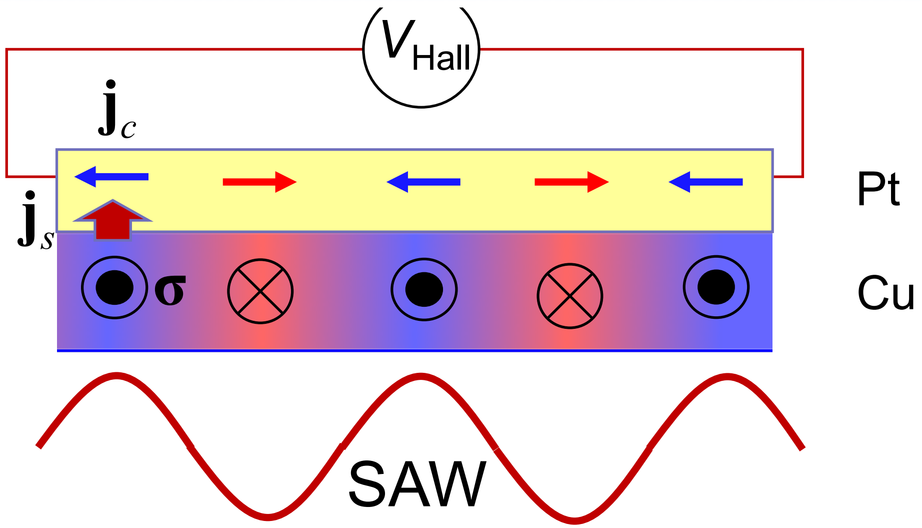


Spin Hall Effect	Spin-rotation
Strong Spin-Orbit	w/o Spin-Orbit
Short Spin Lifetime	Long Spin Lifetime
Pt	Cu

MM et al., Phys. Rev. B87, 180402(R) (2013)

Cu can be utilized for spin-current source! → Rare metal free spintronics

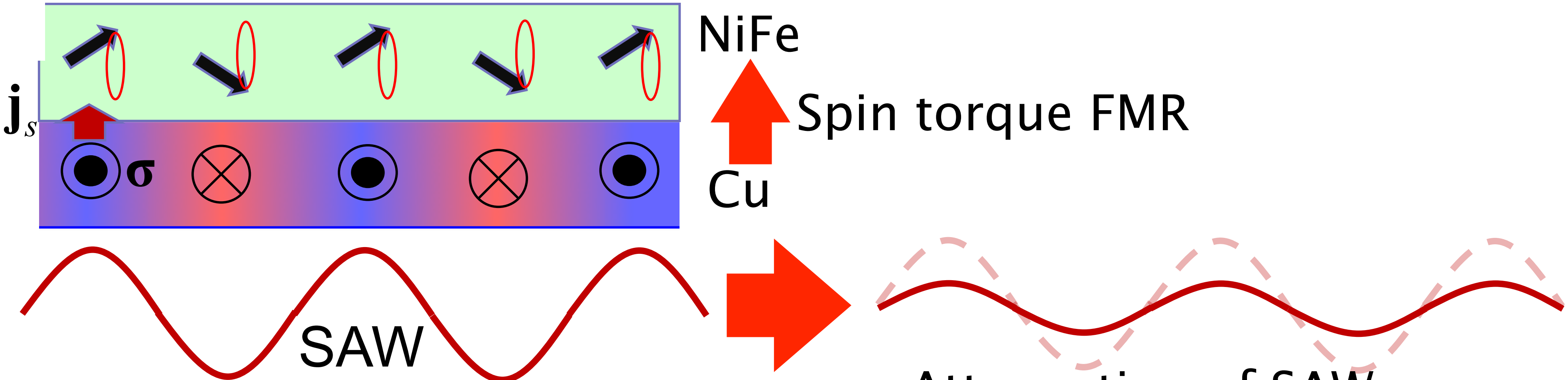
How to detect AC spin current by SAW?



Inverse SHE:
Hall voltage caused by
Non-uniform spin current
is compensated…

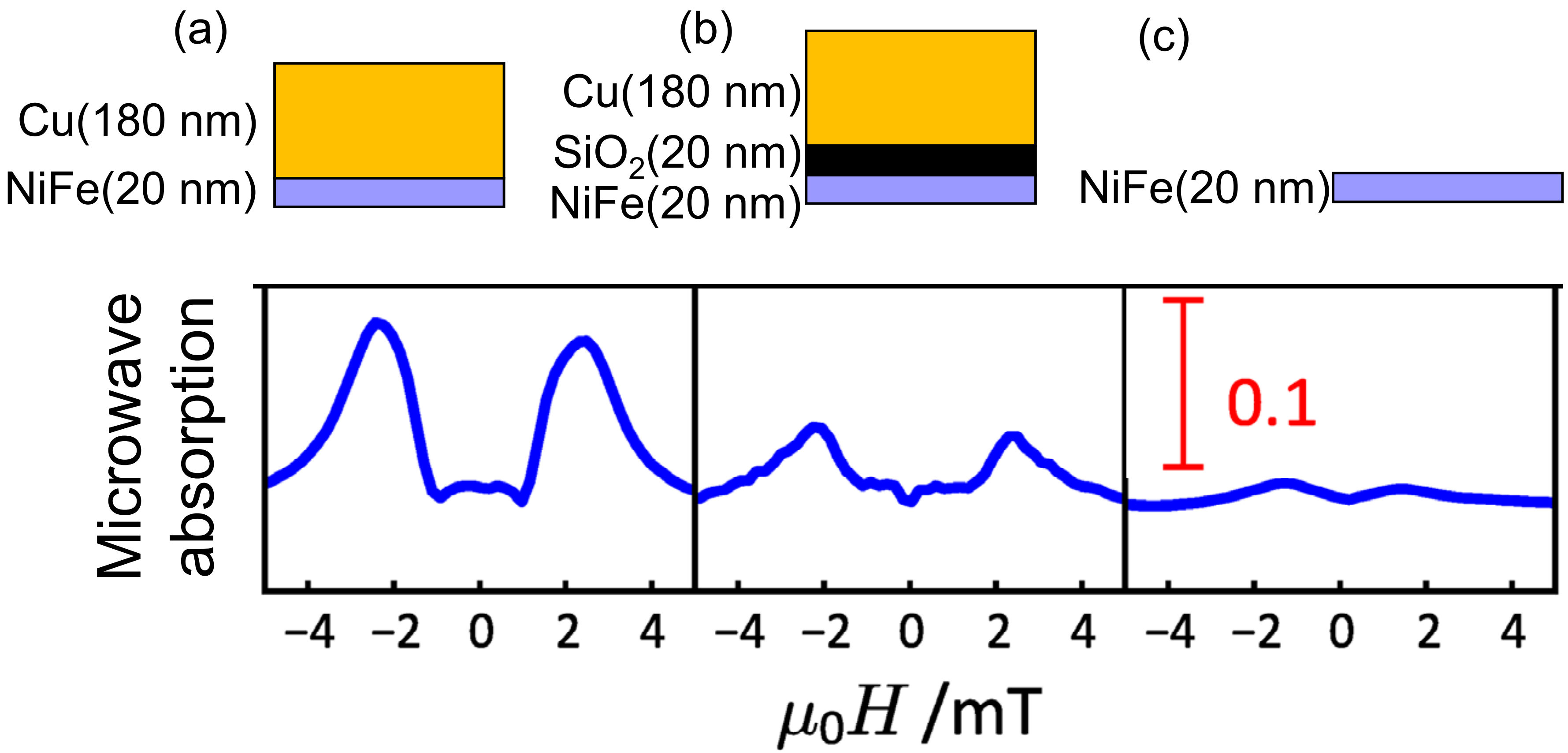
Prof. Nozaki's beautiful idea!

Kobayashi, Nozaki, MM et al., PRL2017



Attenuation of SAW
Due to magnetic damping!

First observation of spin-current generation in Cu by spin-rotation coupling



Direct excitation of FMR due to microwave is small.

⇒ Cu/NiFe interface!!

Kobayashi, Nozaki, MM et al., PRL2017