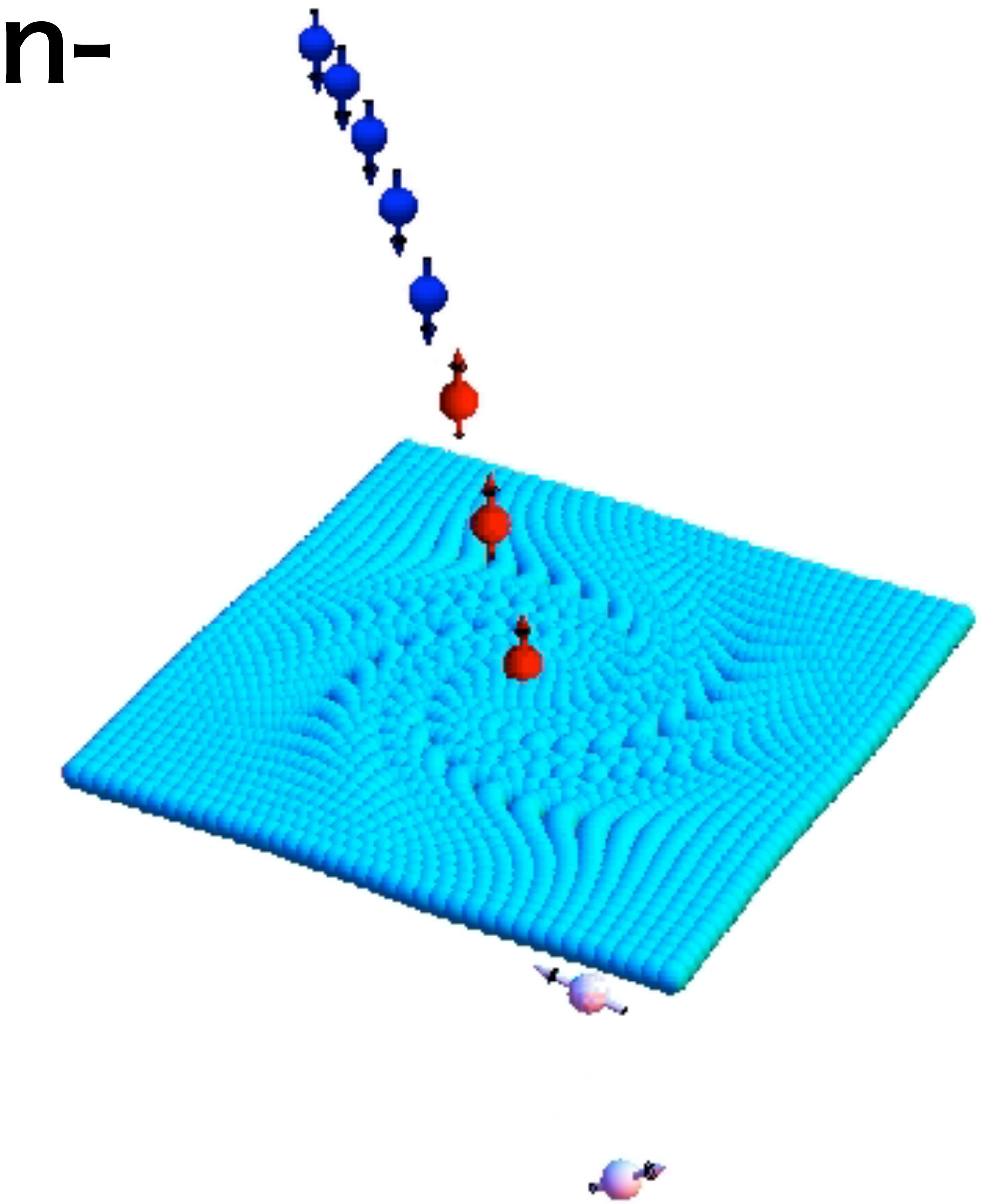
Spin transport driven by spin-vorticity coupling



Mamoru Matsuo
(Kavli Institute for Theoretical Sciences, UCAS)

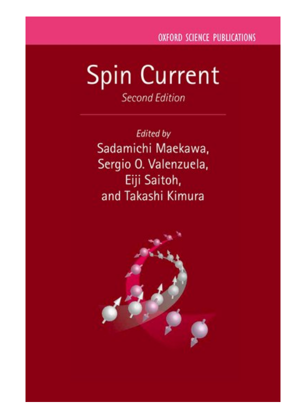
in collaboration with：

(Theory)
Y. Ohnuma, J. Ieda, S. Maekawa

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

Ref.
MM et al., “Spin-mechatronics” Chap. 25 in Spin current 2nd ed.(Oxford, 2017)
R.Takahashi et al., Nat. Phys.12, 52 (2016)
D.Kobayashi et al., Phys. Rev. Lett. 119, 077202 (2017)
G.Okano et al., Phys. Rev. Lett. 122, 217701 (2019)

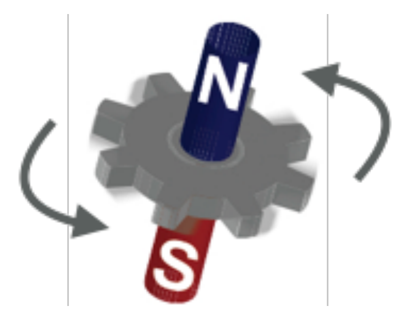
See also.
K.Hattori, M.Hongo, X.-G.Huang, MM, H.Taya, Phys. Lett. B 795, 100 (2019)



Who am I

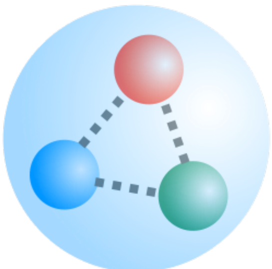
Mamoru Matsuo
2018.4~ Associate Professor at Kavli Institute for Theoretical Sciences,
Univ. of Chinese Academy of Sciences

2009.10~
Working on spin-electronics (spintronics)



Nanosocales
10^{-9} m

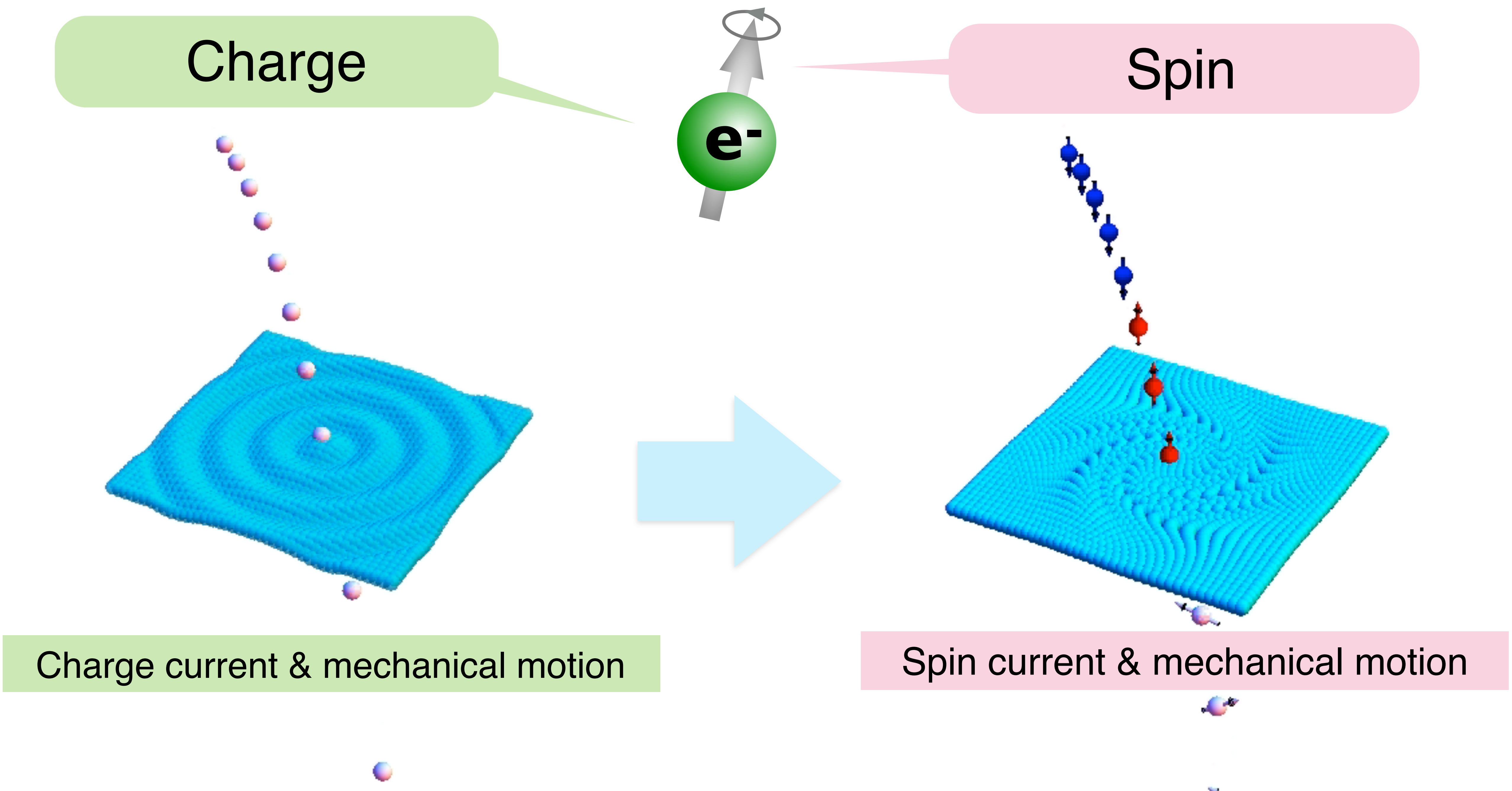
2008.3
Ph.D on quark-gluon physics, Univ. of Tokyo



Femtosocales
10^{-15} m

Target: Spin transport at femto/nano/micro/kilo meter scales

"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)

What is electron?

Electronics

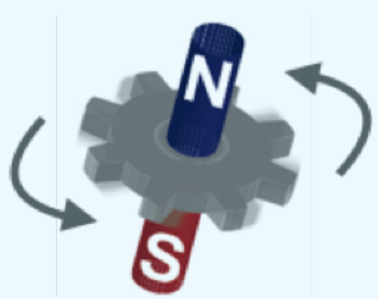
Charge
[electricity]

Spin
[magnetism]

Spintronics

Charge current = flow of charged spheres

robust ⇒ easy to control

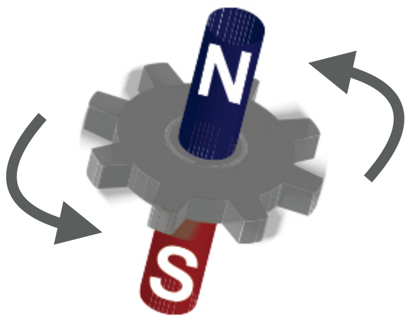


Spin current = flow of spinning gears

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

How to control spins?

Conventional spintronics:
spin as a tiny magnet



Spin mechatronics:
spin as a spinning gear

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

$$H_{\text{Spin-Orbit}} = -S \cdot (\lambda p \times E)$$

$$H_{\text{Spin-vorticity}} = -S \cdot \frac{\omega}{2}$$

$$\text{vorticity}: \ \omega = \nabla \times v$$

Electron in inertial frames
(Non-relativistic limit of
Special relativistic Dirac equation)

Electron in non-inertial frames
(Non-relativistic limit of
General relativistic Dirac equation)

w/ Magnets,
w/ strong spin-orbit materials
(Pt, W, …)

w/o magnets,
w/o spin-orbit coupling!
(Cu, Al, …)

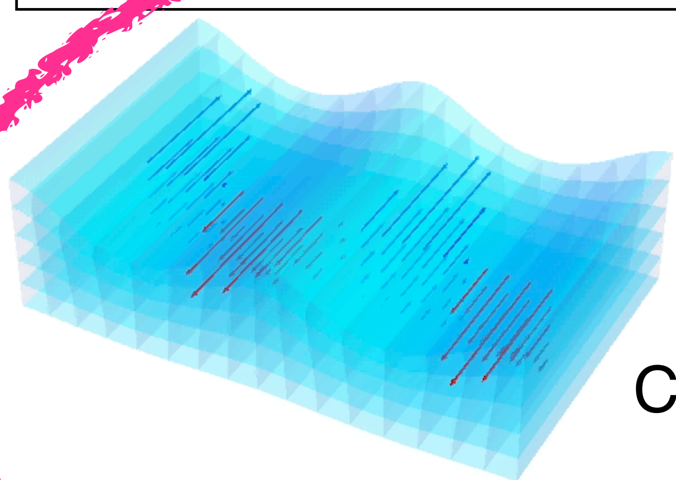
Mechanical generation of spin current

Dirac eq. in non-inertial frame [spin connection]
(Electron in moving materials)

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

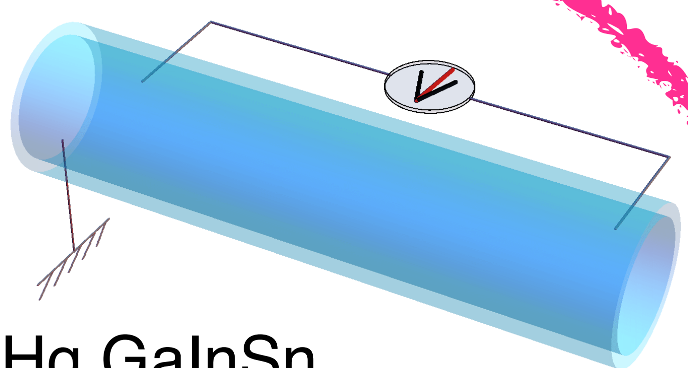
$$H = \frac{(p+eA)^2}{2m} + e\phi - S \cdot \gamma B - S \cdot \omega/2 - \frac{e\lambda}{\hbar} S \cdot p \times \left(E + (\omega \times r) \times B\right)$$

Surface acoustic wave



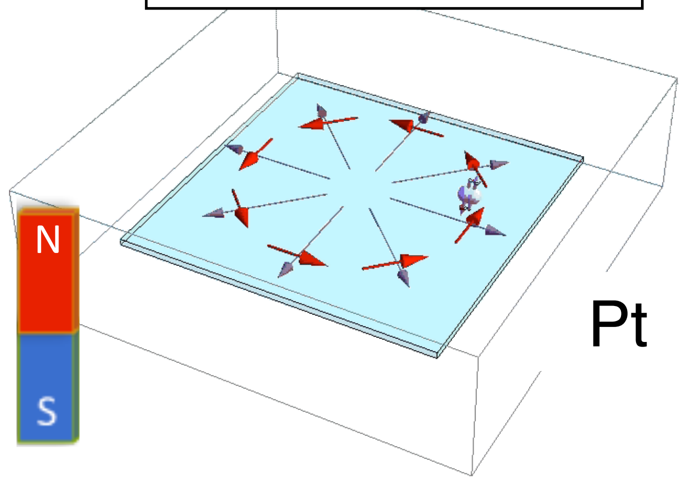
PRB(R)2013
PRL2017

Fluid vorticity



PRB(R)2017
Nat.Phys. 2016

Rigid rotation



PRL2011
Sci.Rept. 2018

Outline

<u>Introduction</u>

- Gyromagnetic effects

<u>Theoretical framework</u>

- Spin-vorticity coupling
- Spin hydrodynamics

<u>Gyro-spintronic effects in moving materials</u>

- Liquid metal flow
- Surface acoustic waves
- Quark gluon plasma

<u>Nonuniform electron dynamics</u>

- Surface-oxidized Cu

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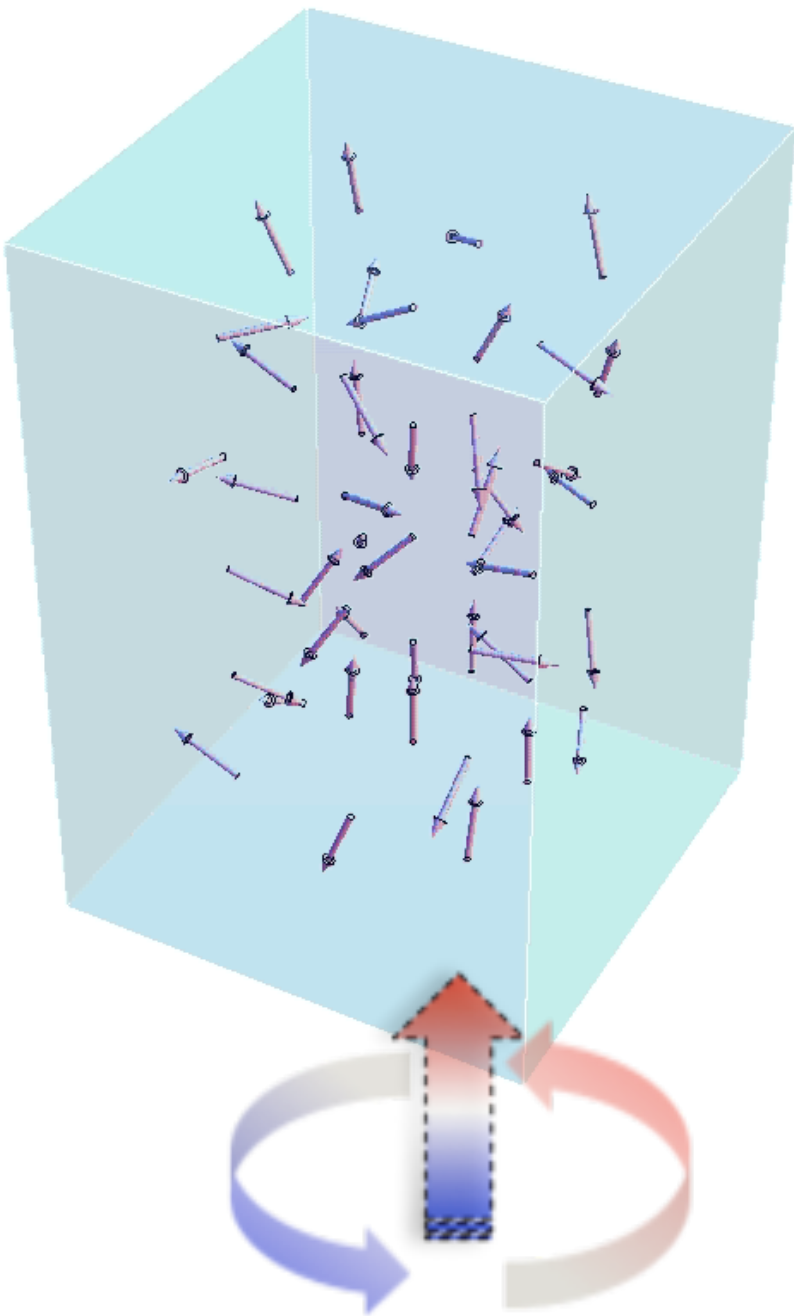
Magnetization by rotation: Barnett effect (1915)

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



$$H_{\text{Cor}} = -L \cdot \Omega$$

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

$$B_{\Omega} = \frac{\Omega}{\gamma} \left[\gamma = \frac{e}{m} \text{:gyromagnetic ratio} \right]$$

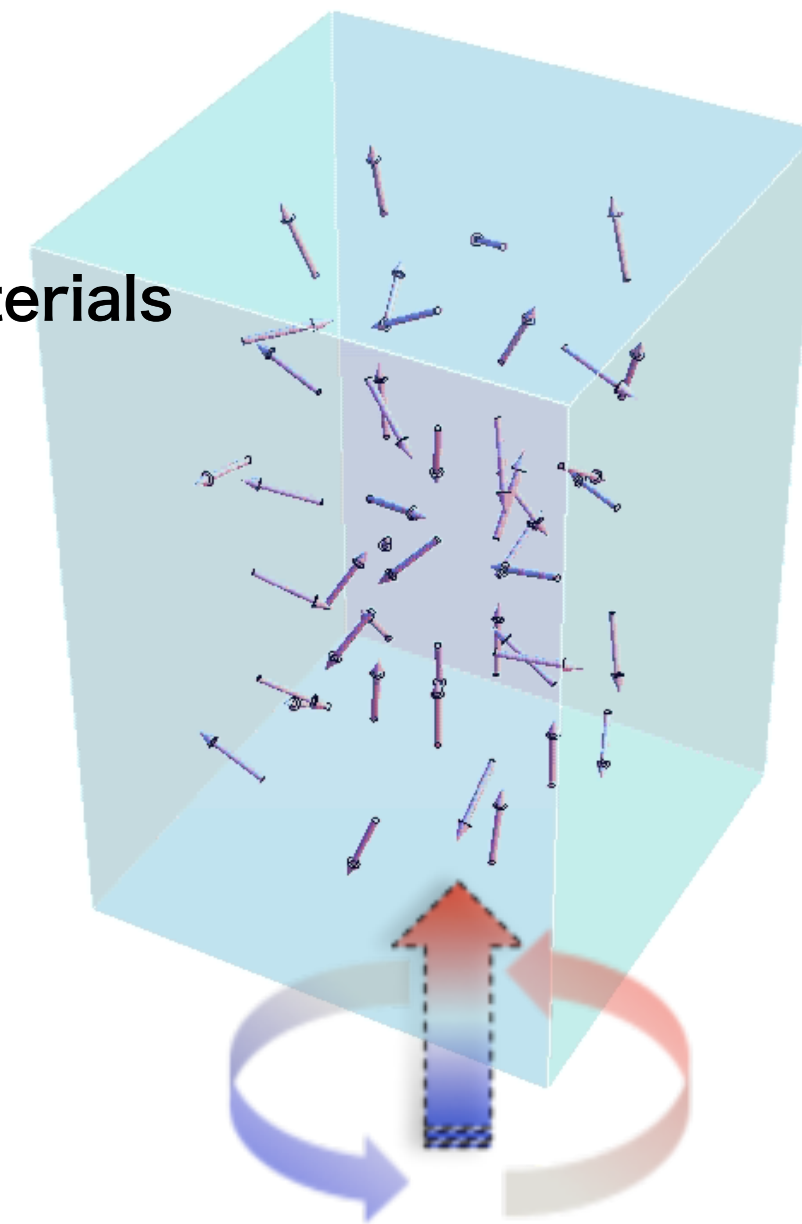
$$H_{\text{Spin-rotation}} = -S \cdot \Omega$$

Observation of spin-vorticity coupling

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

- Theoretical predictions: MM et al., PRL(2011)

$$H_{SV} = -S \cdot \omega / 2$$



Spin-vorticity 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, 2019)
- Nuclear spin:
  Chudo et al., APEX(2014), JPSJ(2015)

Spin-current generation by rotation

- Liquid metal flow: Takahashi et al, Nat.Phys.(2016)
- Surface acoustic wave: Kobayashi et al., PRL(2017)
- Rigid rotation under magnetic field: Hirohata et al., Sci.Rept (2018)

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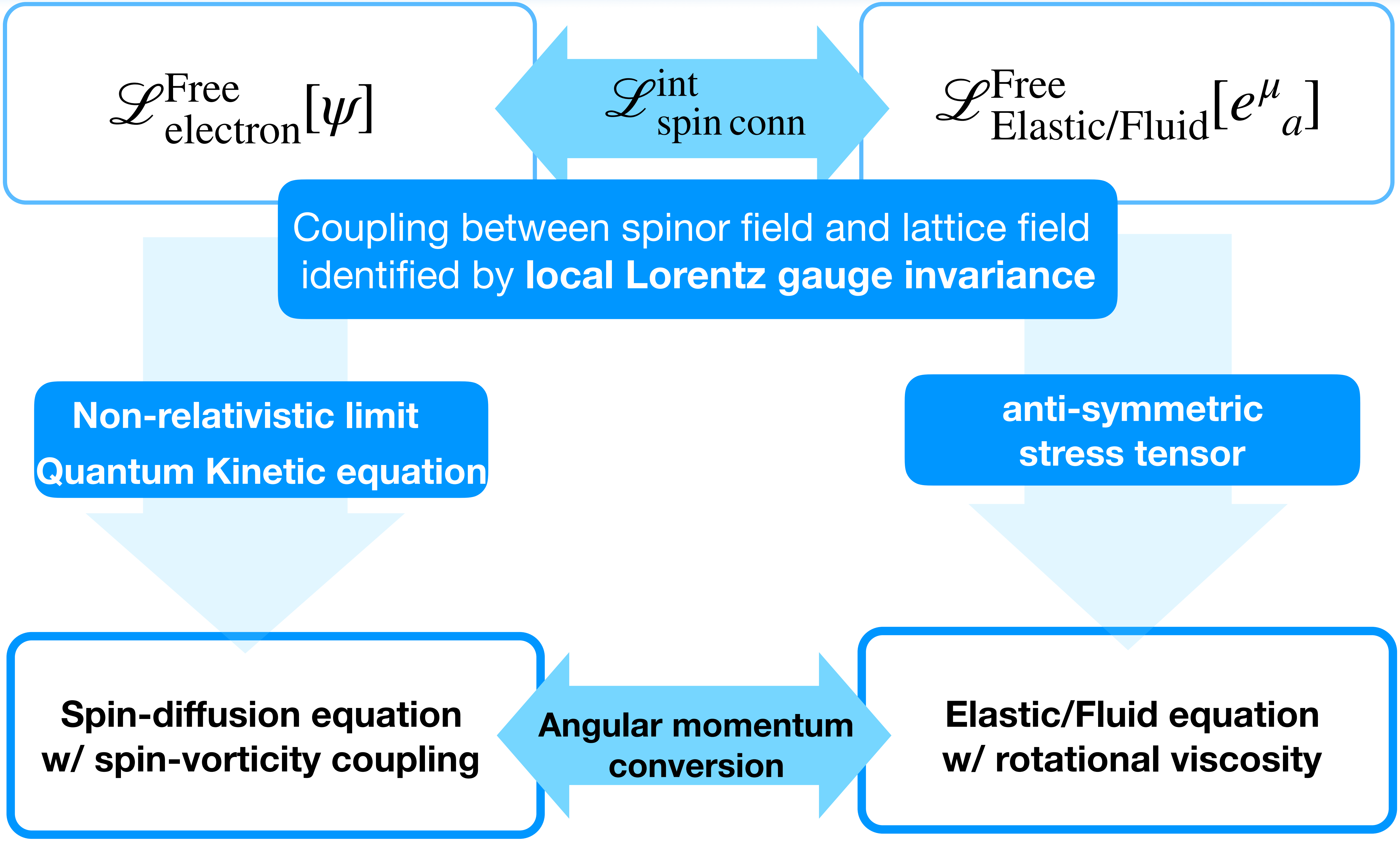
Theoretical framework



MM et al., PRB(R) 2017

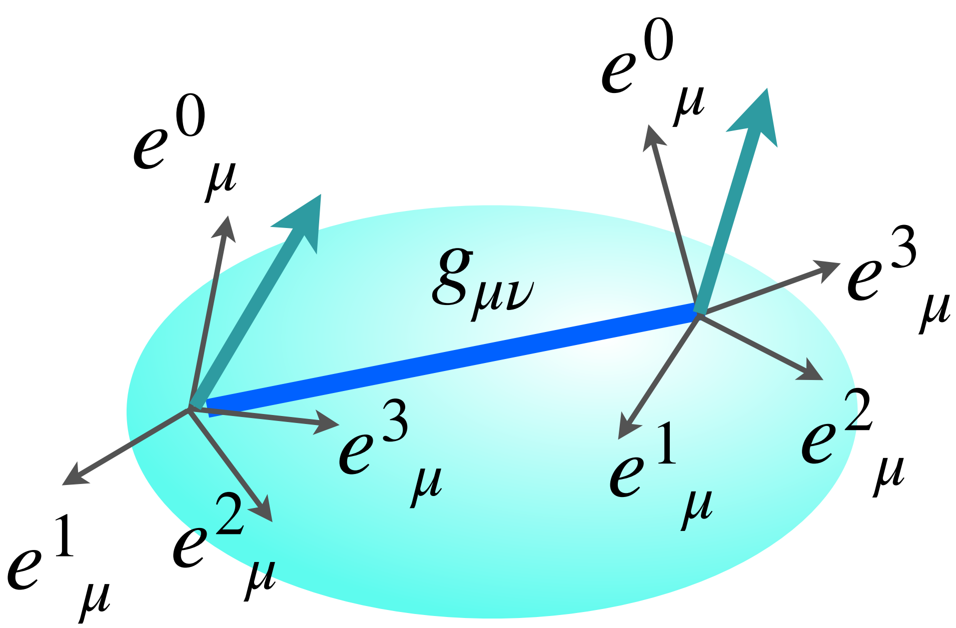
Eringen (1964)

Takahashi, MM et al., NatPhys2016

Tetrad (vierbein) formalism and local Lorentz invariance

Cartan (1922)

Gravity w/ spin & torsion



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

Hehl et al.,(1976)

Dirac algebra in curved spacetime

$$\tilde{\gamma}_\mu(x) := \gamma_a e^a{}_\mu(x) \qquad \{\tilde{\gamma}_\mu(x), \tilde{\gamma}_\nu(x)\} = 2g_{\mu\nu}(x)$$

$$\{\tilde{\gamma}_\mu(x), \tilde{\gamma}_\nu(x)\} = \{\gamma_a, \gamma_b\}e^a{}_\mu e^b{}_\nu$$
$$= 2\eta_{ab}e^a{}_\mu(x)e^b{}_\nu(x) = 2g_{\mu\nu}(x)$$

Local Lorentz inv. Lagrangian

$$\mathscr{L}_{\rm tot} = -\bar{\psi}\left[ie^\mu{}_a\gamma^a(p_\mu - \frac{i}{2}\omega_\mu{}^{ab}\Sigma_{ab}) + m\right]\psi + \mathscr{L}_{\rm gravity}[e^\mu{}_a]$$

Spin connection

$$\psi \to \psi' = \exp[i\theta^{ab}(x)\Sigma_{ab}]\psi \qquad \left(\Sigma_{ab} = \frac{i}{2}[\gamma_a, \gamma_b]\right)$$

Spin connection absorbs $\partial_\mu\theta^{ab}(x)\Sigma_{ab}$

Spin connection assures **local angular momentum conservation law.**

Spin connection

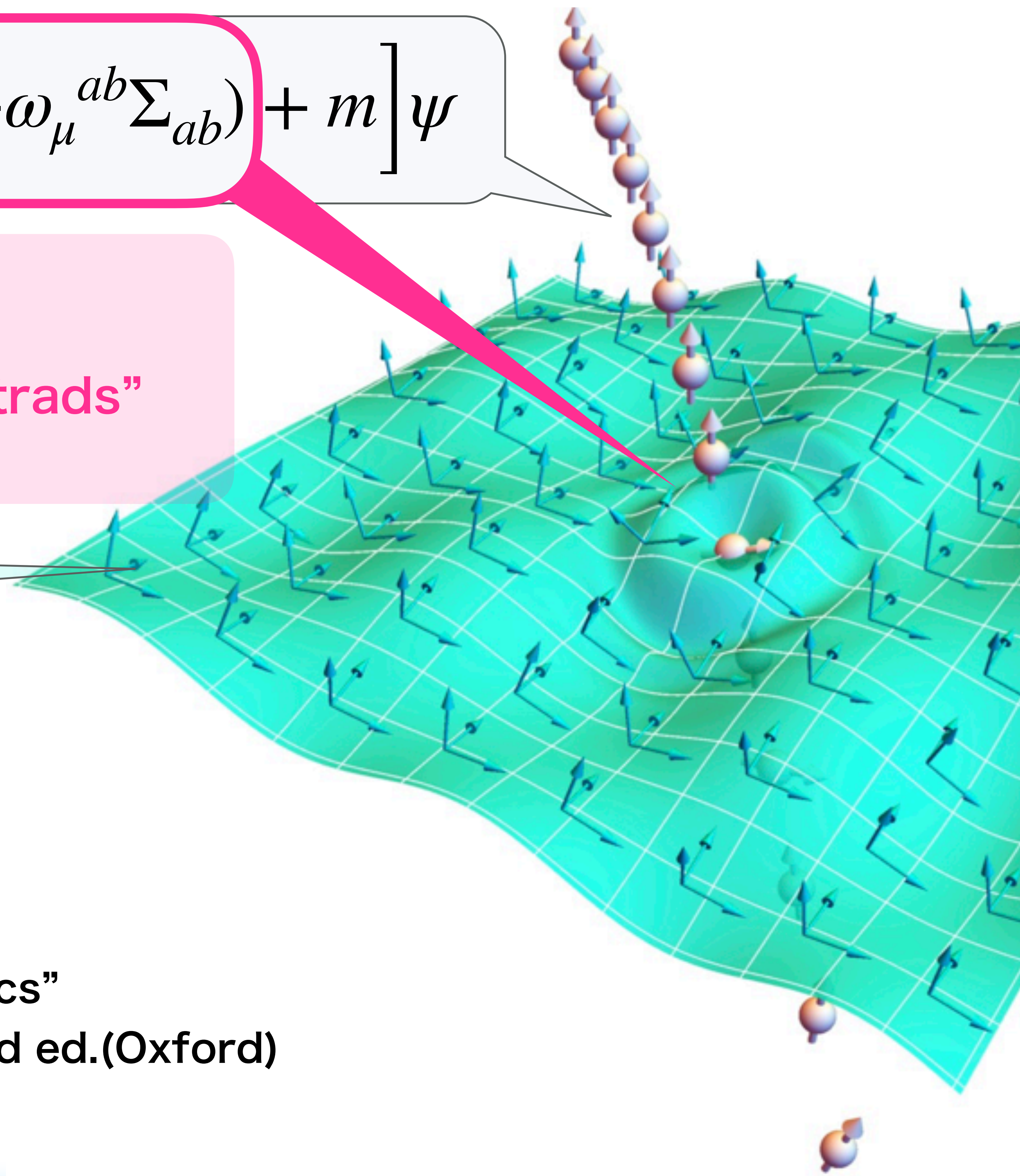
$$\mathcal{L}_{\text{electron}} = -\bar{\psi}\left[ie^{\mu}{}_{a}\gamma^{a}\left(p_{\mu} - \frac{i}{2}\omega_{\mu}{}^{ab}\Sigma_{ab}\right) + m\right]\psi$$

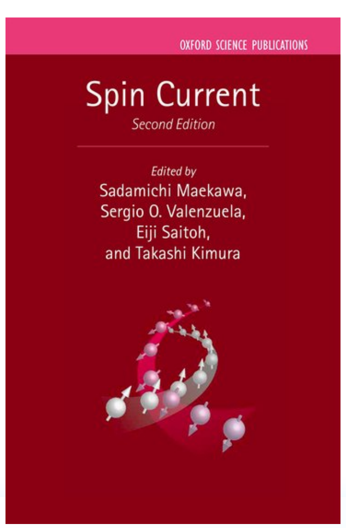
$$\omega^{ab}{}_{\mu}\, dx^{\mu} := e^{a} \cdot de^{b}$$

Spin connection = "Twist of tetrads"

→ spin-vorticity coupling

$$\mathcal{L}_{\text{Elastic/Fluid}} = \mathcal{L}[e^{\mu}{}_{a}]$$





MM et al., "Spin-mechatronics"
Chap. 25 in Spin current 2nd ed.(Oxford)

Hydrodynamics w/ angular momentum

Momentum conservation

$$\rho \frac{Dv}{Dt} = \nabla \cdot T^S + \nabla \times T^A$$

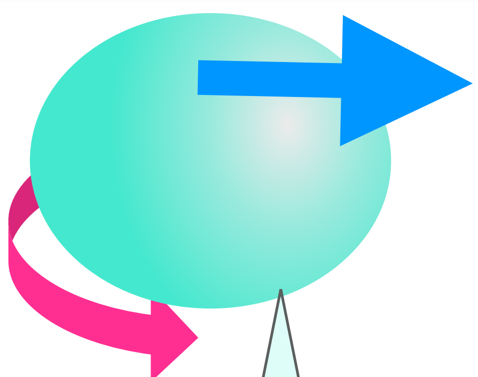
Angular momentum conservation

$$I \frac{D\dot{\theta}}{Dt} = T^A$$

$$T_{ij} = T_{ij}{}^S + T_{ij}{}^A$$

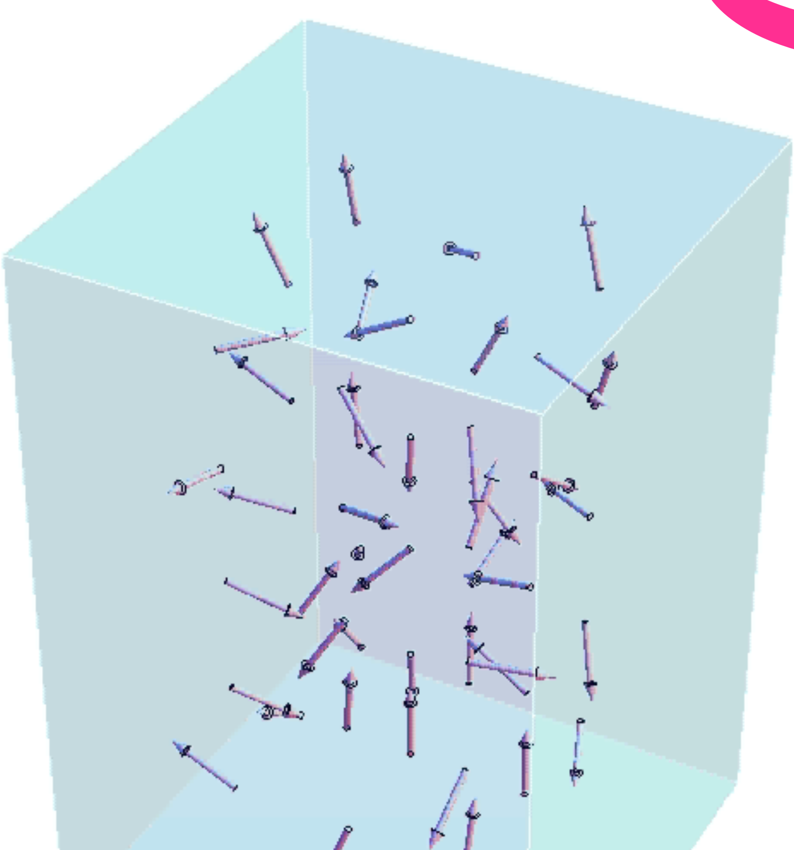
Eringen (1964)

Fluid element



$\rho v(r,t)$ — Momentum

$I\dot{\theta}(r,t)$ — Angular momentum



Angular momentum of fluid
is converted into
spin angular momentum of electrons
via. spin-vorticity coupling

R.Takahashi,MM et al., Nat. Phys (2016)

Anti-symmetric stress tensor

Eringen, Int. J. Engng. Sci. 2, 205 (1964)

Momentum conservation

$$\rho \frac{Dv}{Dt} = \nabla \cdot T^S + \nabla \times T^A$$

Angular momentum conservation

$$I \frac{D\dot{\theta}}{Dt} = T^A$$

$$T_{ij} = T_{ij}^S + T_{ij}^A$$

$$T_{ij}^S = -p\delta_{ij} + \mu\left(\partial_i v_j + \partial_j v_i\right)$$

Viscosity
> momentum relaxation

$$T_{ij}^A = \mu_{rot}\left[\left(\partial_i v_j - \partial_j v_i\right) - 2\varepsilon_{ijk}\dot{\theta}_k\right]$$

vorticity

rotation of fluid element

Rotational viscocity
> angular momentum relaxation
Relative angular velocity between fluid element and vorticity

Momentum conservation

$$\rho \frac{Dv}{Dt} = \nabla \cdot T^S + \nabla \times T^A$$

Angular momentum

$$I \frac{D\dot{\theta}}{Dt} = T^A$$

$$T_{ij}{}^S = -p\delta_{ij} + \mu\left(\partial_i v_j + \partial_j v_i\right)$$

Viscosity

$$T_{ij}{}^A = \mu_{rot}\left[\left(\partial_i v_j - \partial_j v_i\right) - 2\varepsilon_{ijk}\dot{\theta}_k\right]$$

Rotational viscosity

Modified Navier-Stokes equation

Driving force from spin

$$\rho \frac{Dv}{Dt} = -\nabla p + \left(\mu + \mu_{rot}\right)\nabla^2 v - 2\mu_{rot}\nabla \times \dot{\theta}$$

$$\langle S_{\mathrm{el}} \rangle$$

Quantum Kinetic equation of electron w/ spin-vorticity coupling

Non equilibrium Green function

Lessor function (noneq. number density)

$$G^<_{12} \coloneqq (-i)\,\mathrm{Tr}\rho\psi^\dagger_{r_2t_2}\psi_{r_1t_1}$$

Density matrix

$$G^R_{12} \coloneqq (-i)\theta_{12}\left\langle\left[\psi_{r_1t_1},\psi^\dagger_{r_2t_2}\right]\right\rangle$$

$$G^A_{12} \coloneqq (+i)\theta_{21}\left\langle\left[\psi_{r_1t_1},\psi^\dagger_{r_2t_2}\right]\right\rangle$$

Wigner tr.

$$\begin{pmatrix}k\\ \omega\end{pmatrix} \Leftarrow \begin{pmatrix}r_1-r_2\\ t_1-t_2\end{pmatrix},\ \begin{pmatrix}r\\ t\end{pmatrix} = \begin{pmatrix}(r_1+r_2)/2\\ (t_1+t_2)/2\end{pmatrix}$$

$$G^<_{k\omega rt} = 2i\,\mathrm{Im}\,G^R_{k\omega} \times f^{(2)}_{k\omega rt}$$

Number Density | **Spectral Function** | **2 point Dist. Fn**

Spin current

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

Quantum kinetic eq. (Kadanoff-Baym eq.)
w/ spin-vorticity coupling

$$(\partial_t - D\nabla^2 + 1/\tau)\langle S_{\rm el}\rangle = \zeta\omega/\tau$$

τ : spin relaxation time

$$H_{\rm svc} = -\frac{1}{2}S\cdot\omega$$

MM et al., PRB(R)2017

Mechanical analogue of Stern-Gerlach effect

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

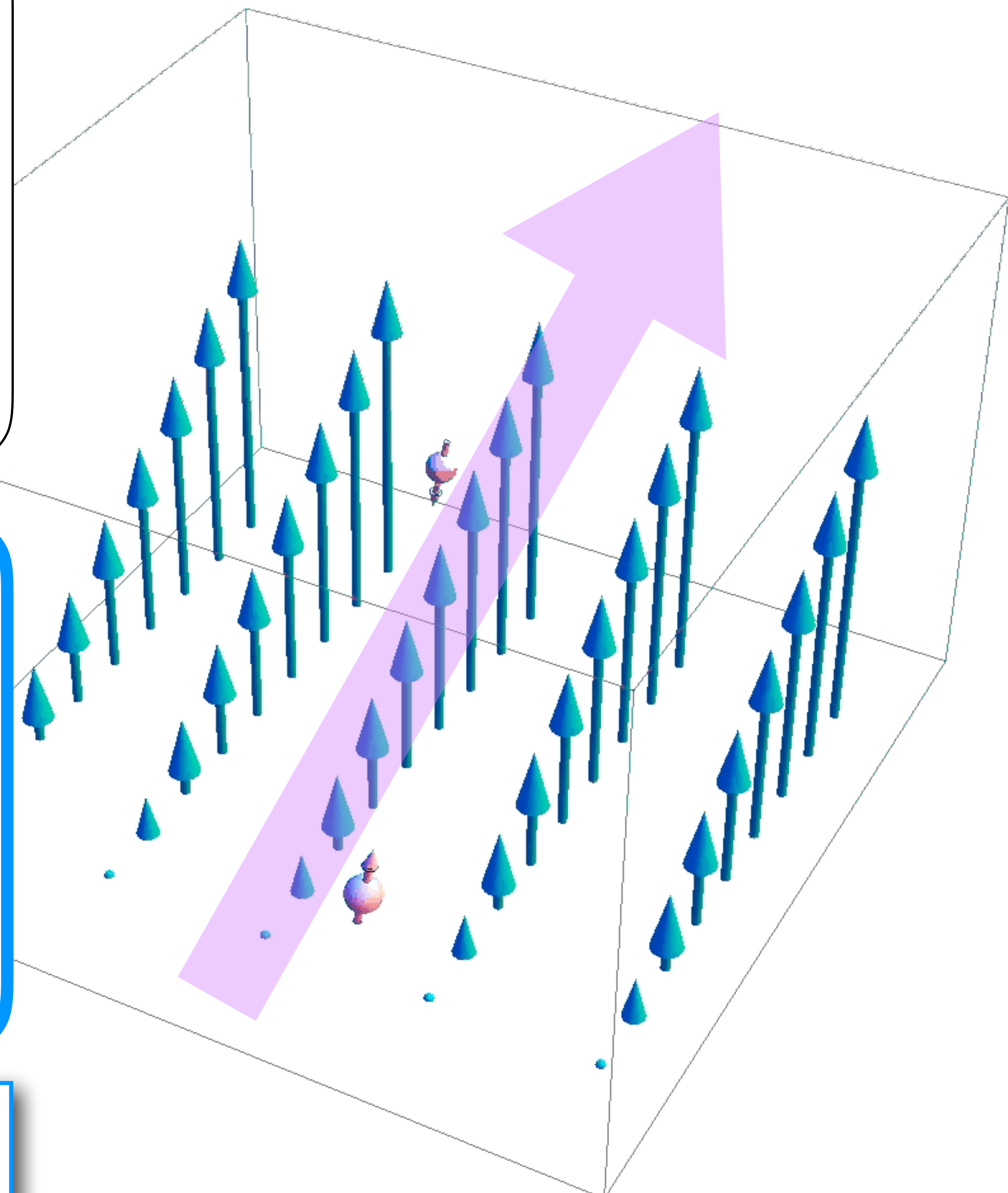
$$\Rightarrow F = -\nabla H_{Zeeman} = S \cdot \nabla(\gamma B)$$

Spin current is generated
along gradient of mag. field.

$$H_{\text{sv}} = -S \cdot \frac{\omega}{2}$$

$$F = -\nabla H_{\text{sv}} = \frac{1}{2} S \cdot \nabla \omega$$

Spin current is generated
along rotation gradient.



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

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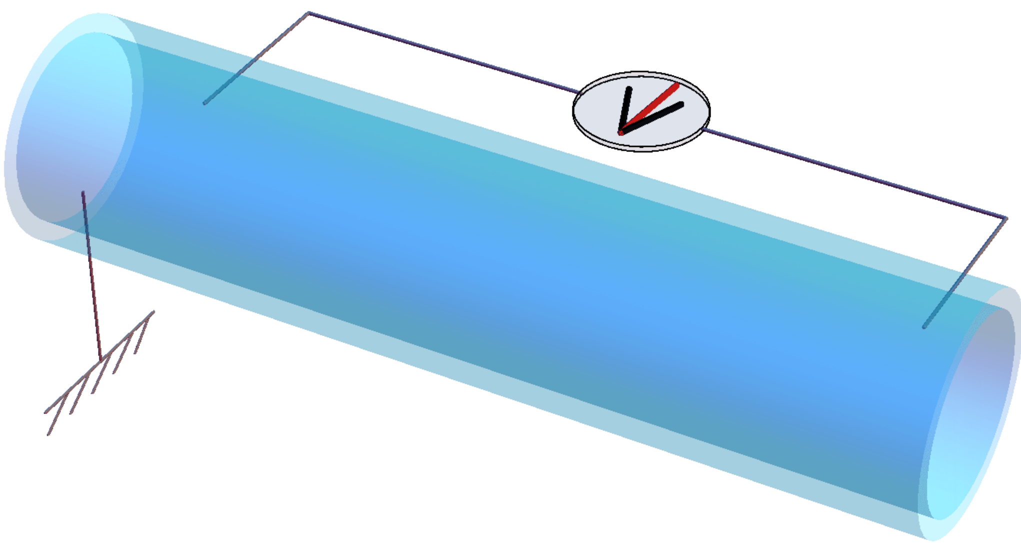
Spin current by vorticity gradient

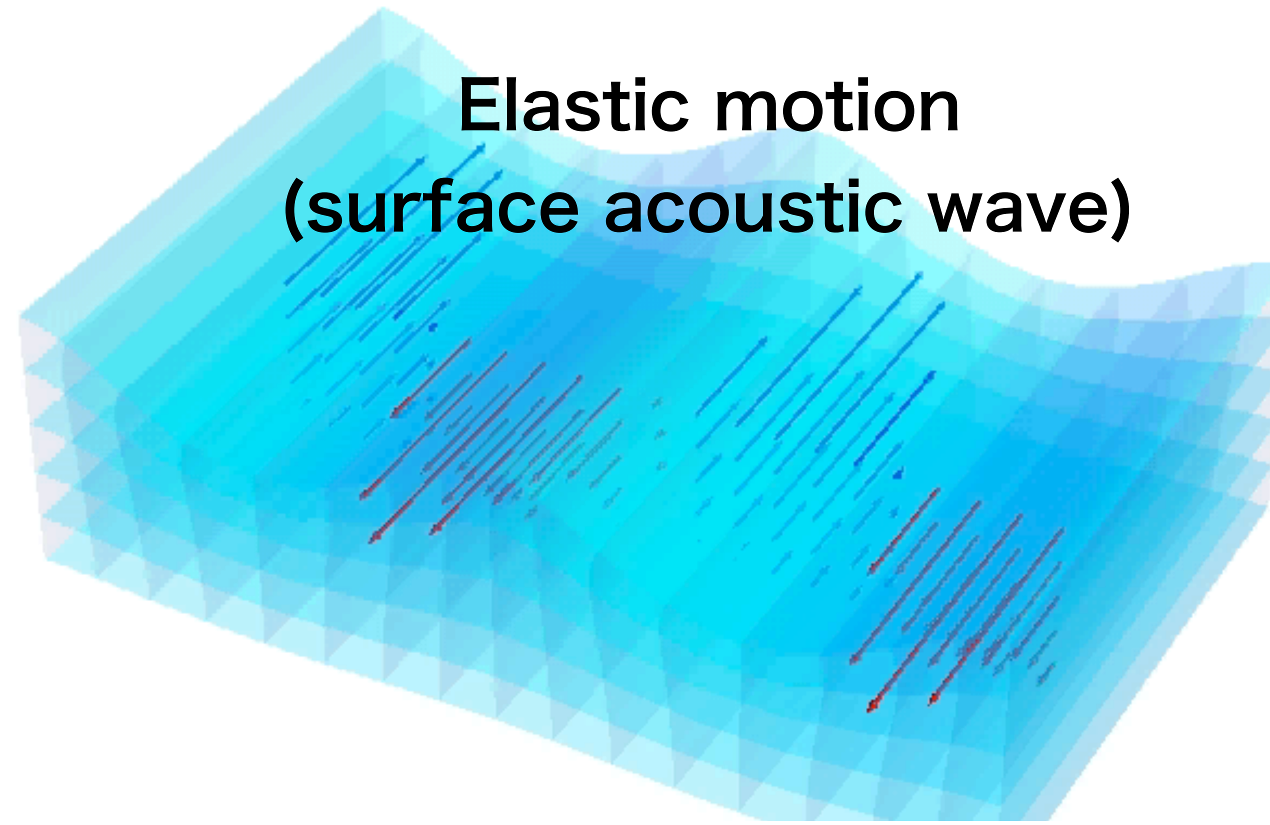
Fluid motion

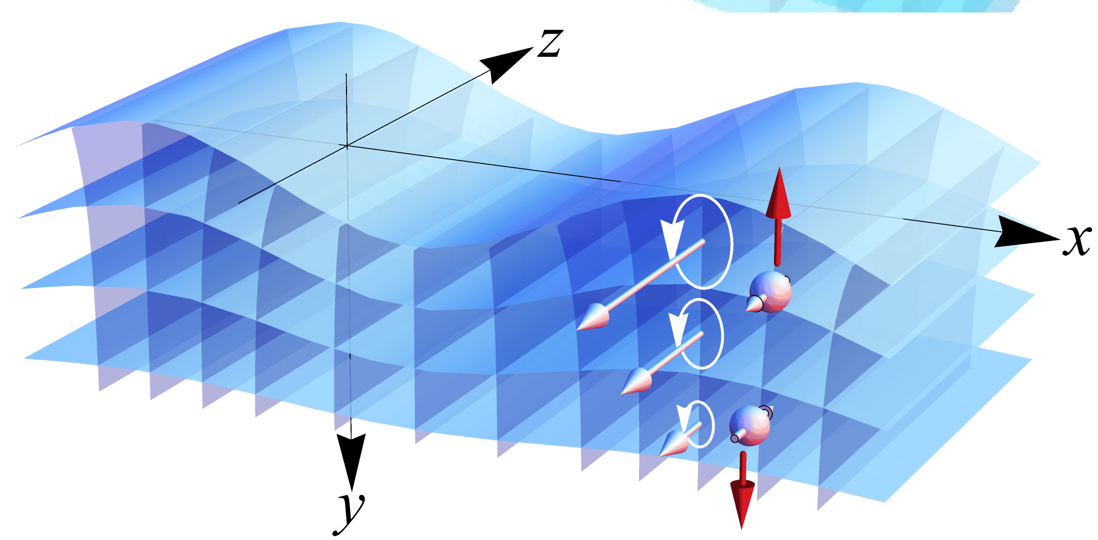


R. Takahashi, MM. et al.,
Nature Physics 2016
MM et al., PRB(R)2017

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

Elastic motion
(surface acoustic wave)

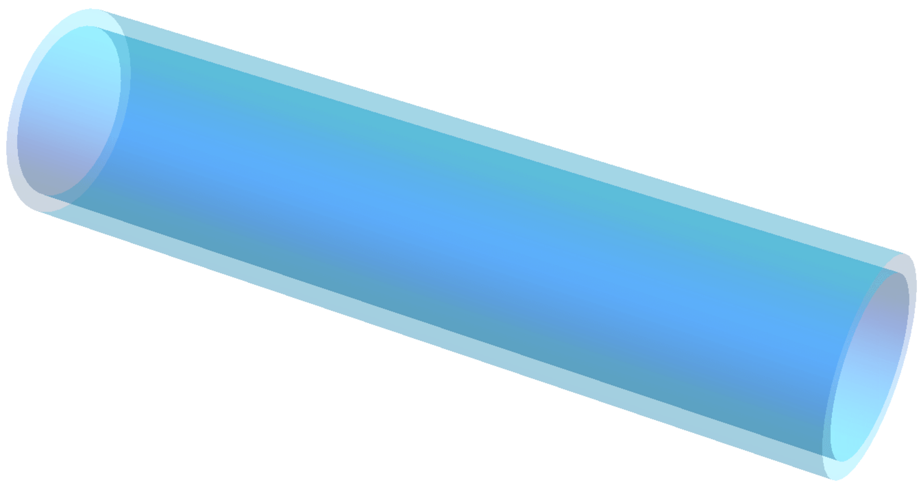




MM et al., PRB(R)2013

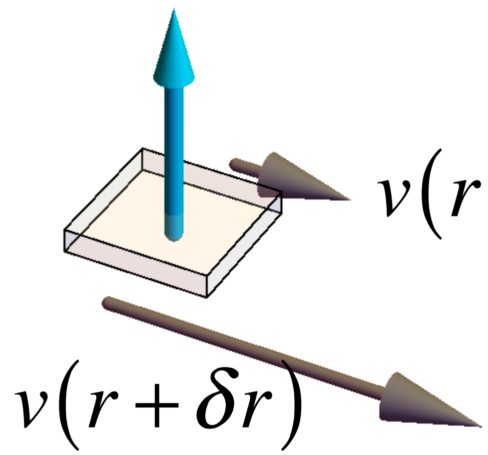
Kobayashi, Nozaki, MM et al.,
PRL2017 (Editors' Suggestion)

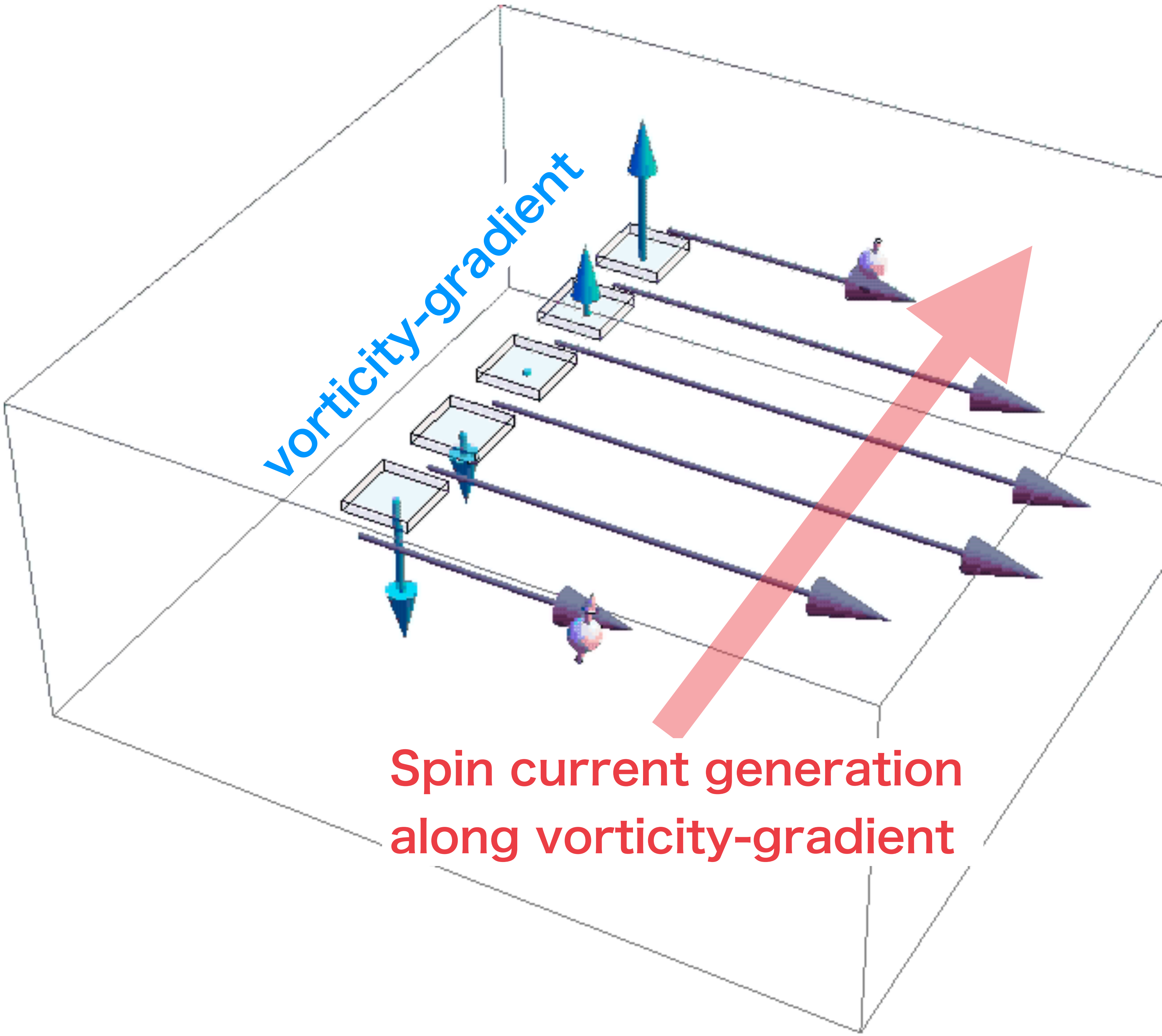
Rotation (vorticity) -gradient in a pipe flow of liquid metal



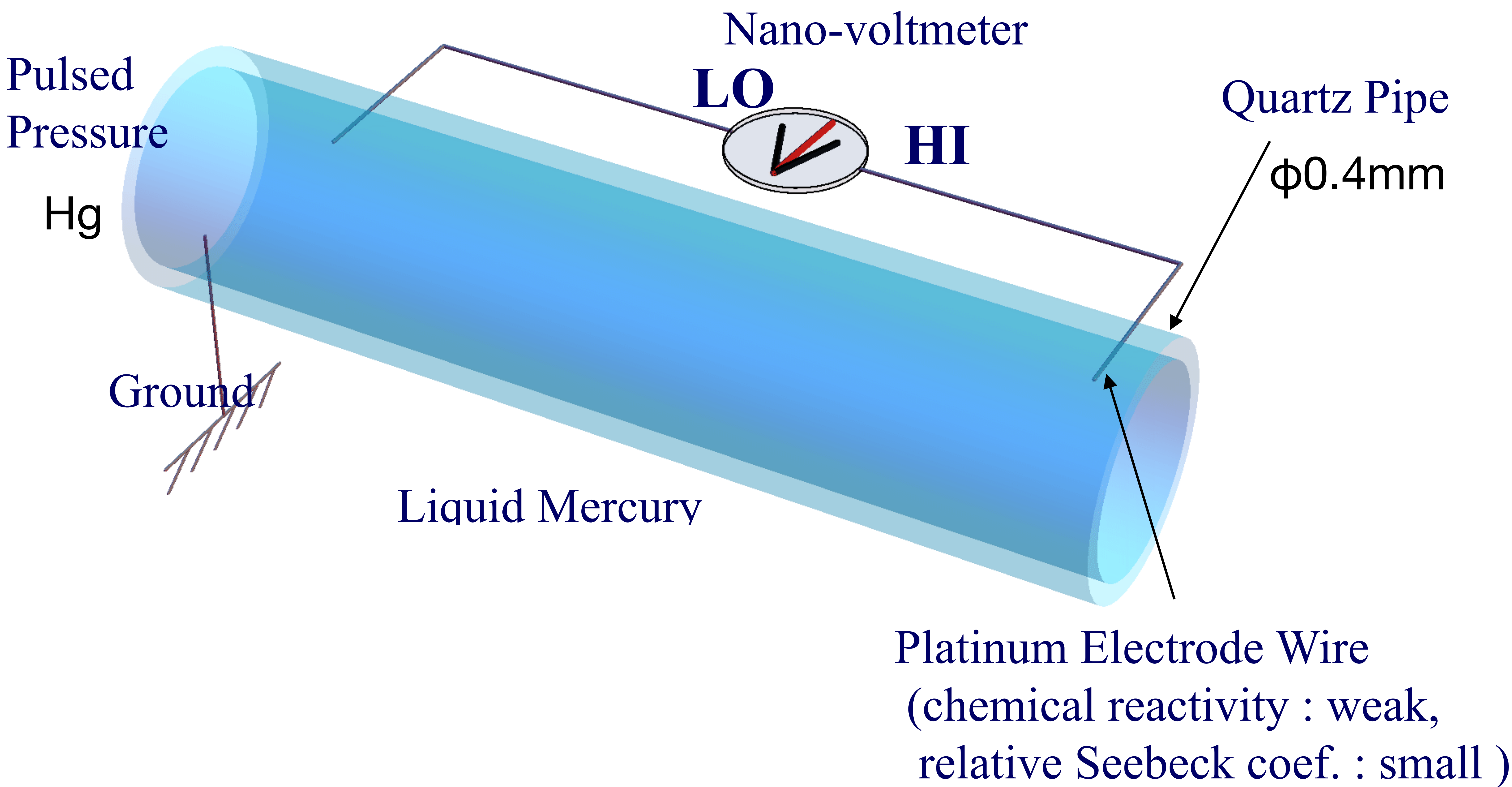
Vorticity:
local rotation of fluid

$\nabla \times v$



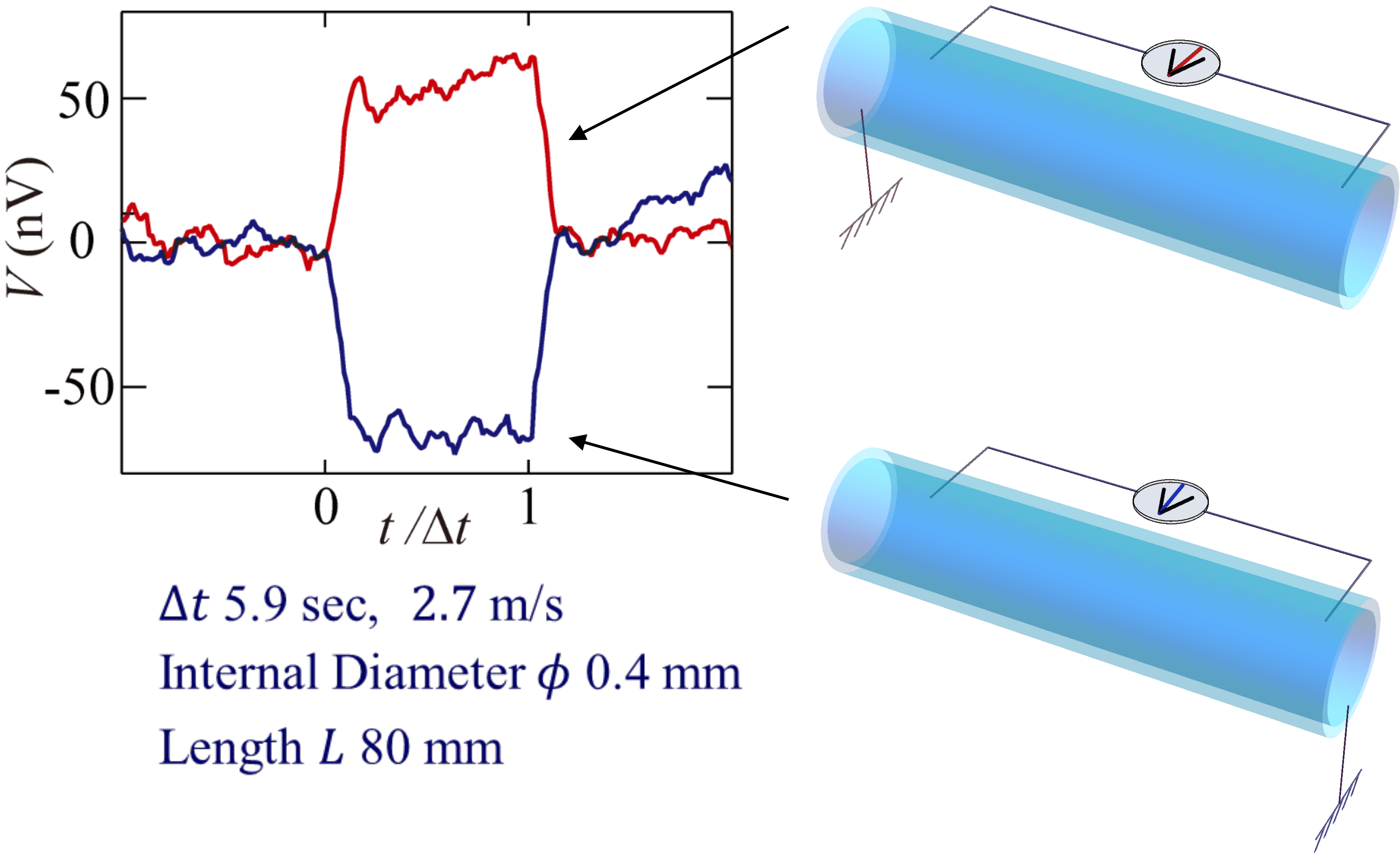


Experimental setup for spin hydrodynamic generation



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

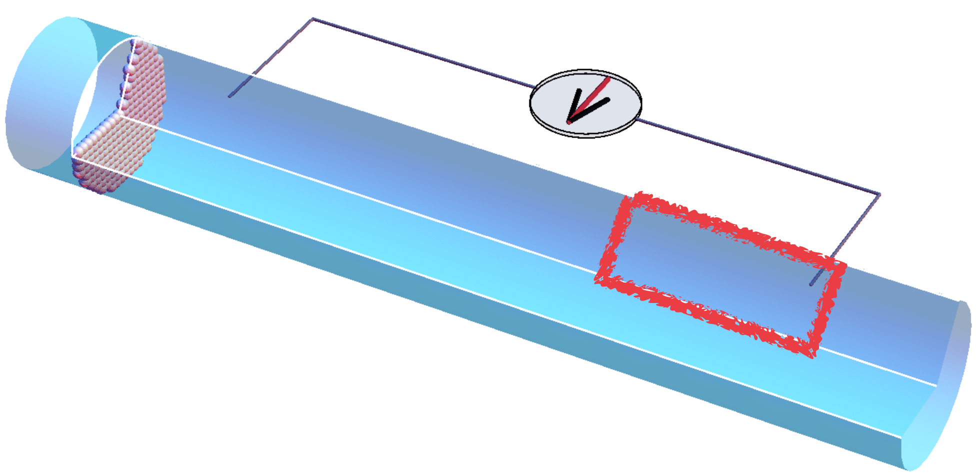
Length L 80 mm

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

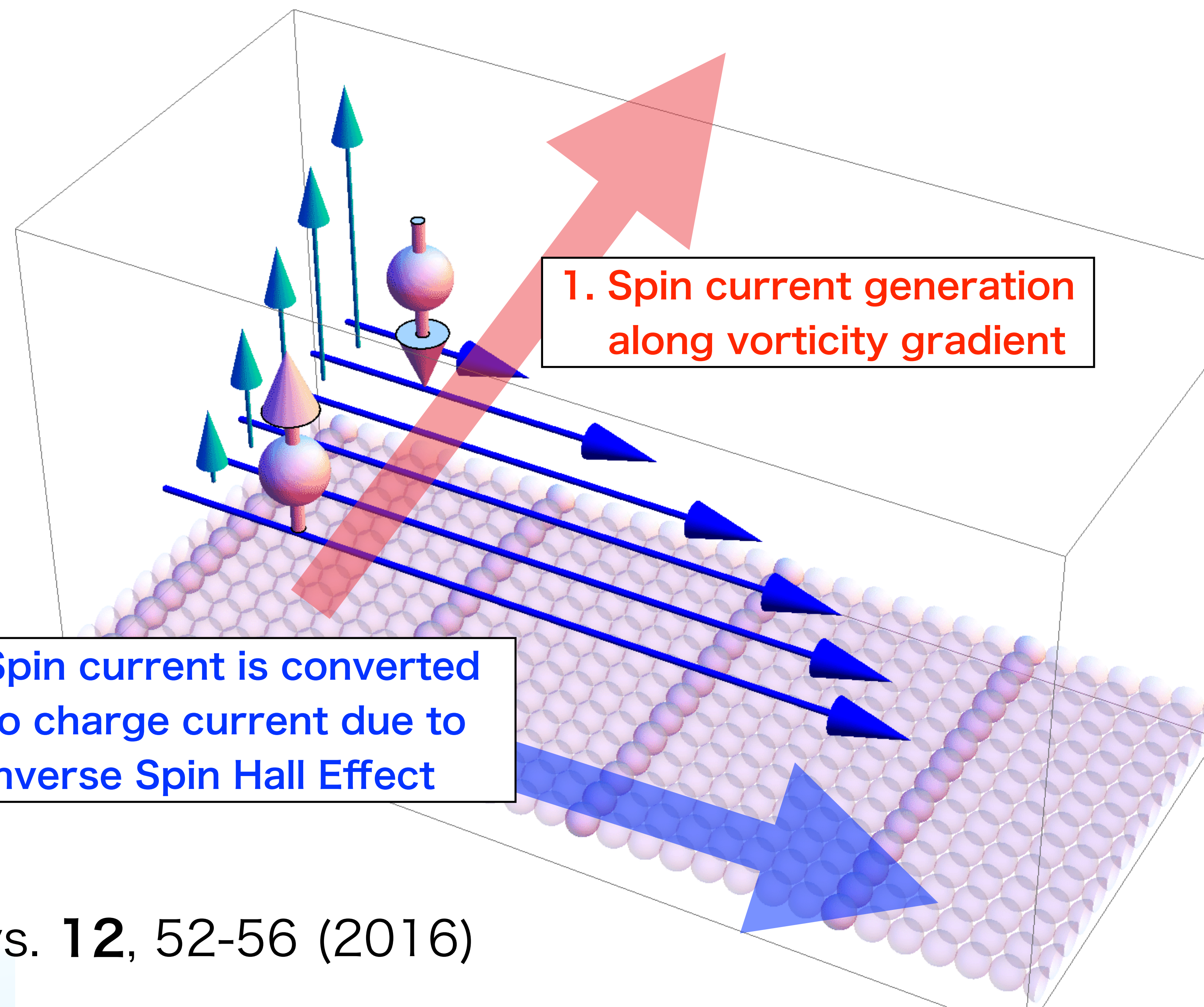
Mechanism of Spin-hydrodynamic voltage generation

"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

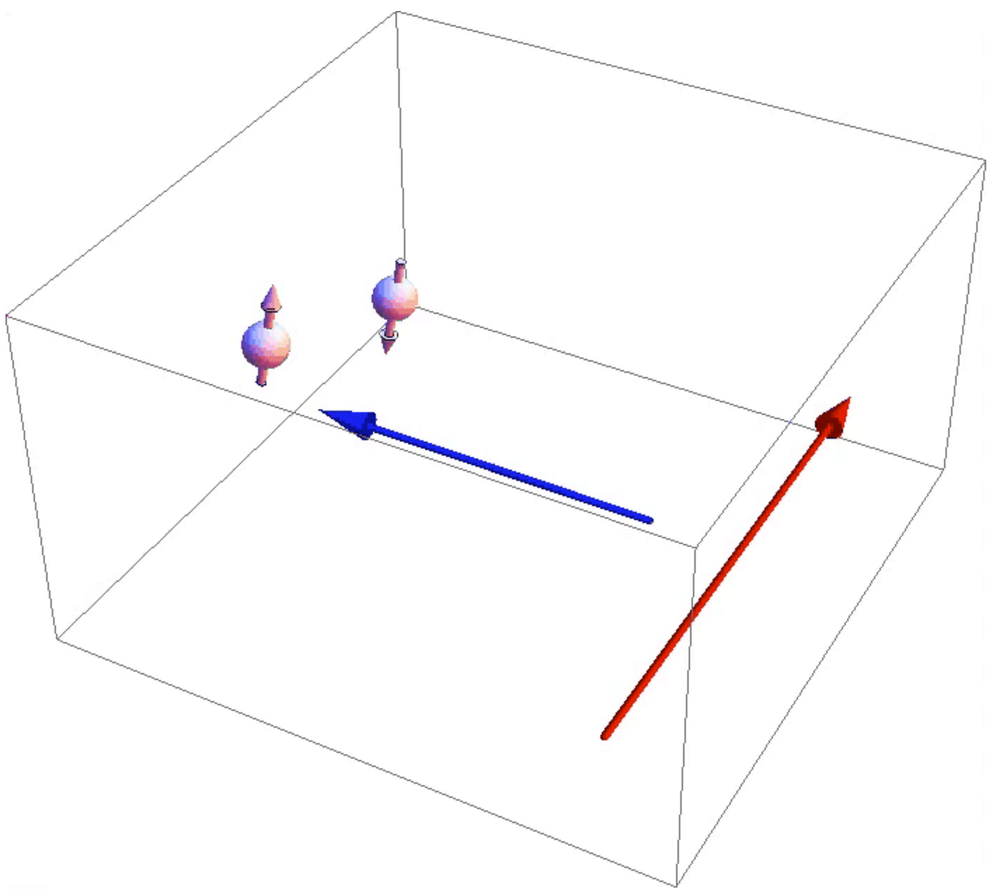


R. Takahashi, MM et al., Nat. Phys. **12**, 52-56 (2016)

Charge to spin/spin to charge conversion

Spin Hall Effect

charge current
→spin current



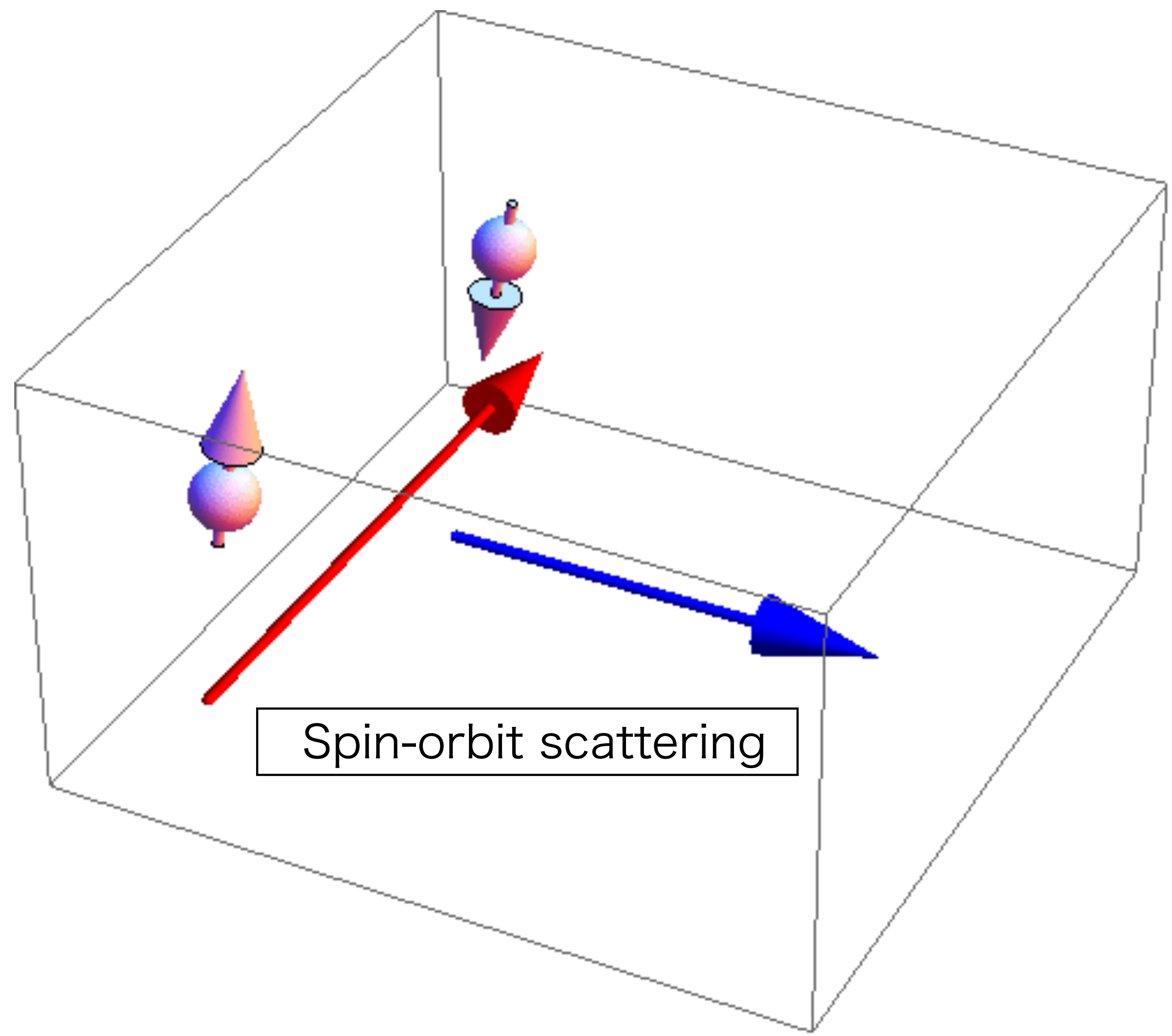
Spin-Orbit Coupling

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

$$v_{\sigma} = \frac{1}{i\hbar}\left[r, H_{SOI} \right] = \frac{(-e)\bar{\lambda}}{\hbar} \boldsymbol{\sigma} \times \mathbf{E}$$

Inverse Spin Hall Effect

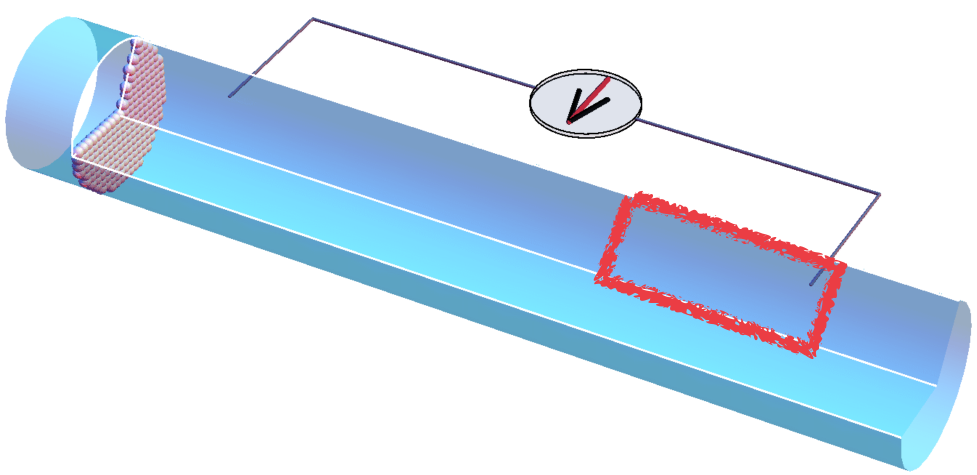
spin current
→charge current



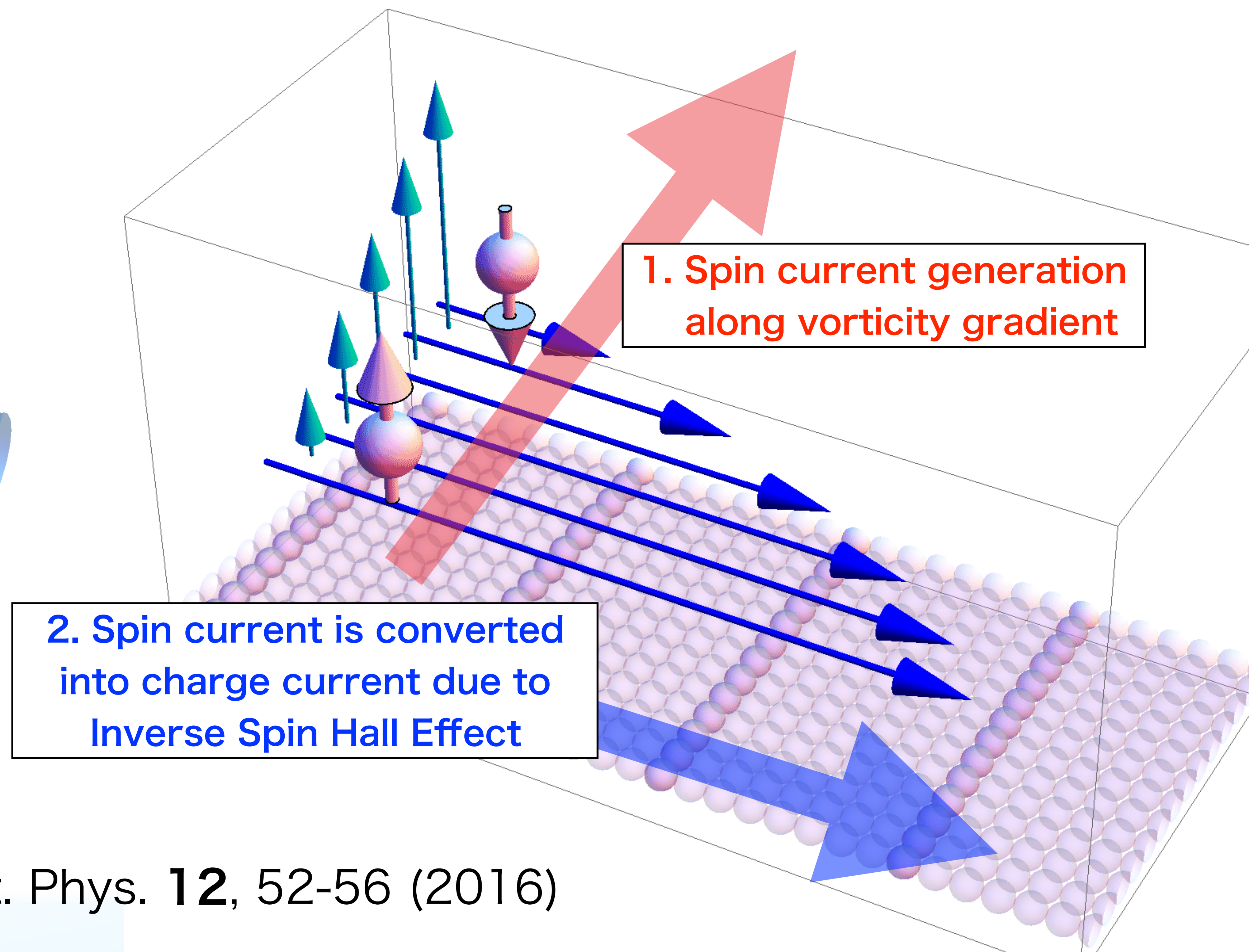
Mechanism of Spin-hydrodynamic voltage generation

"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

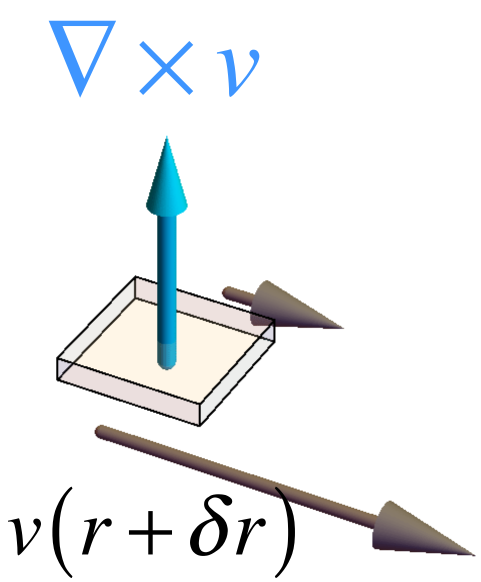


R. Takahashi, MM et al., Nat. Phys. **12**, 52-56 (2016)

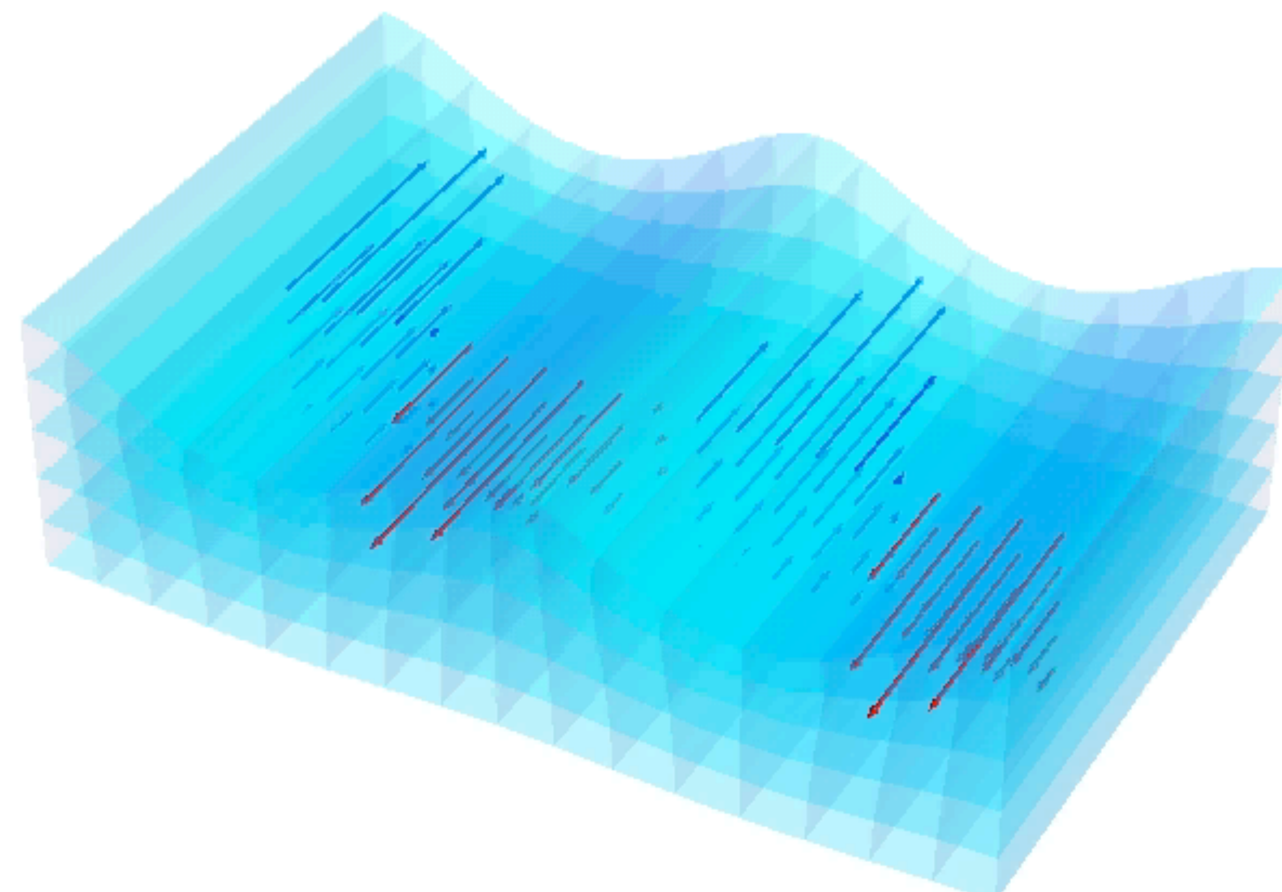
Outline

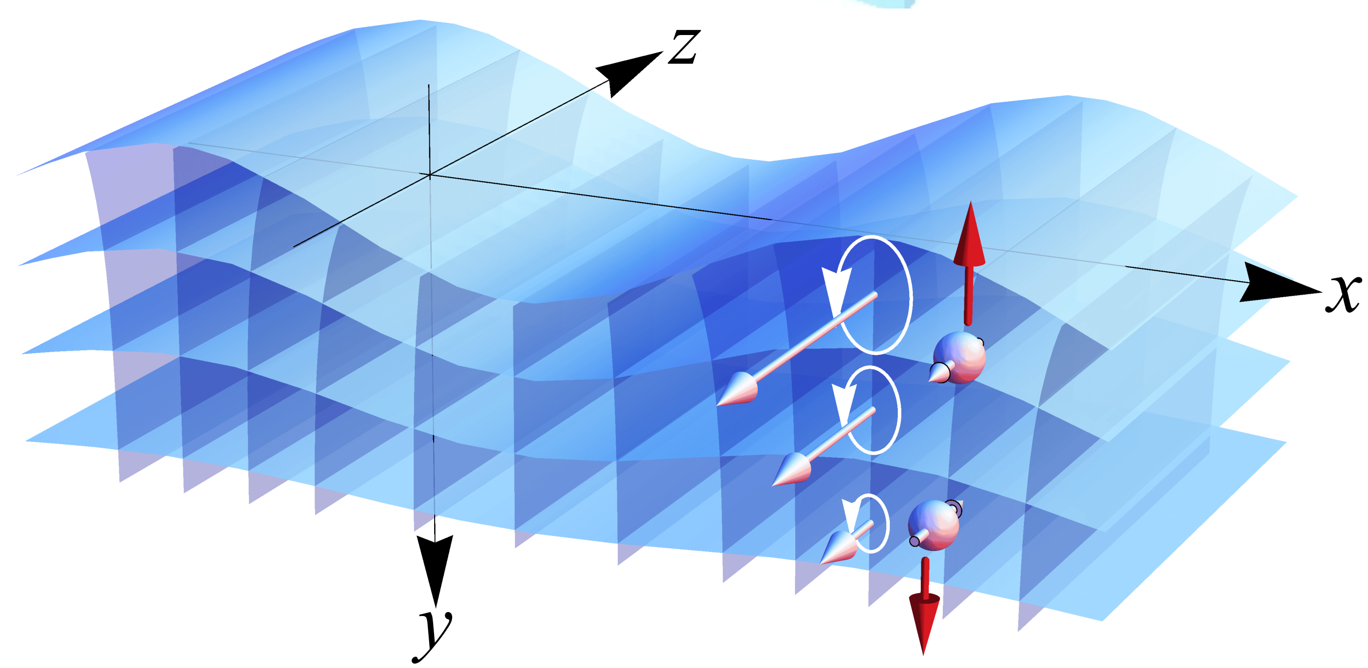
Spin current generation by surface acoustic wave

Vorticity:
local rotation of lattice



Spin current is generated along vorticity gradient!





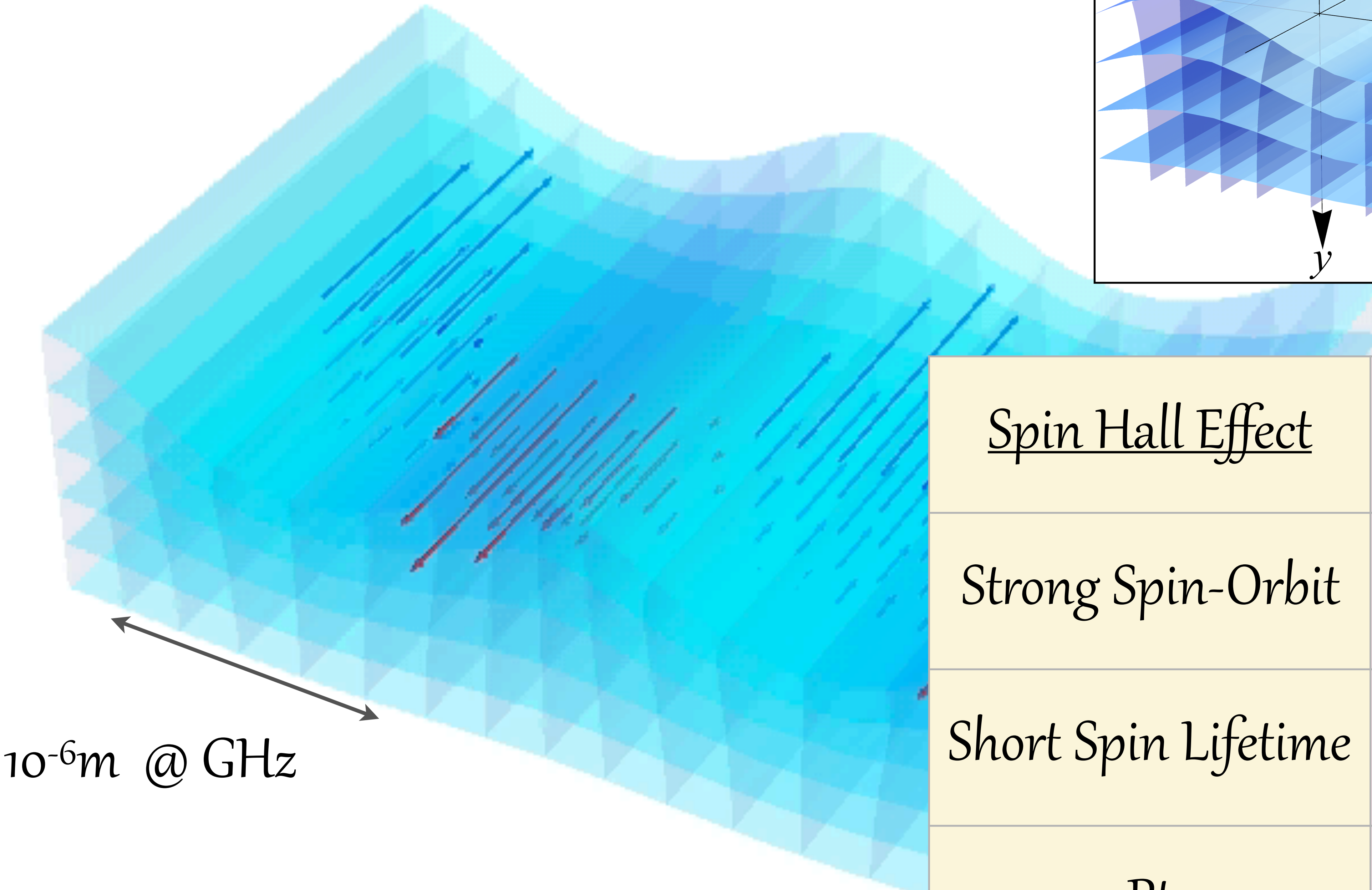
Spin-vorticity vs. Zeeman

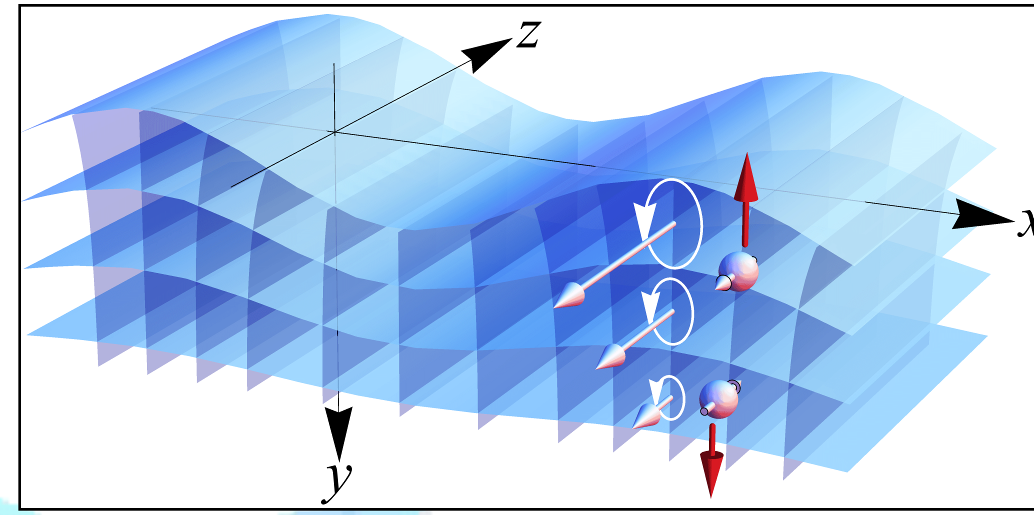
Mechanical	Electromagnetic
$H_{\text{Spin-vorticity}} = -S \cdot \frac{\omega}{2}$	$H_{\text{Zeeman}} = -S \cdot \frac{eB}{m}$
$\omega = \nabla \times v$	$B = \nabla \times A$
v : velocity field	A : vector potential

For theoretical details: MM et al., “Spin-mechatronics”, JPSJ 86, 011011 (2017).

Spin current from Surface Acoustic Wave

Spin current ∝ Gradient of rotation



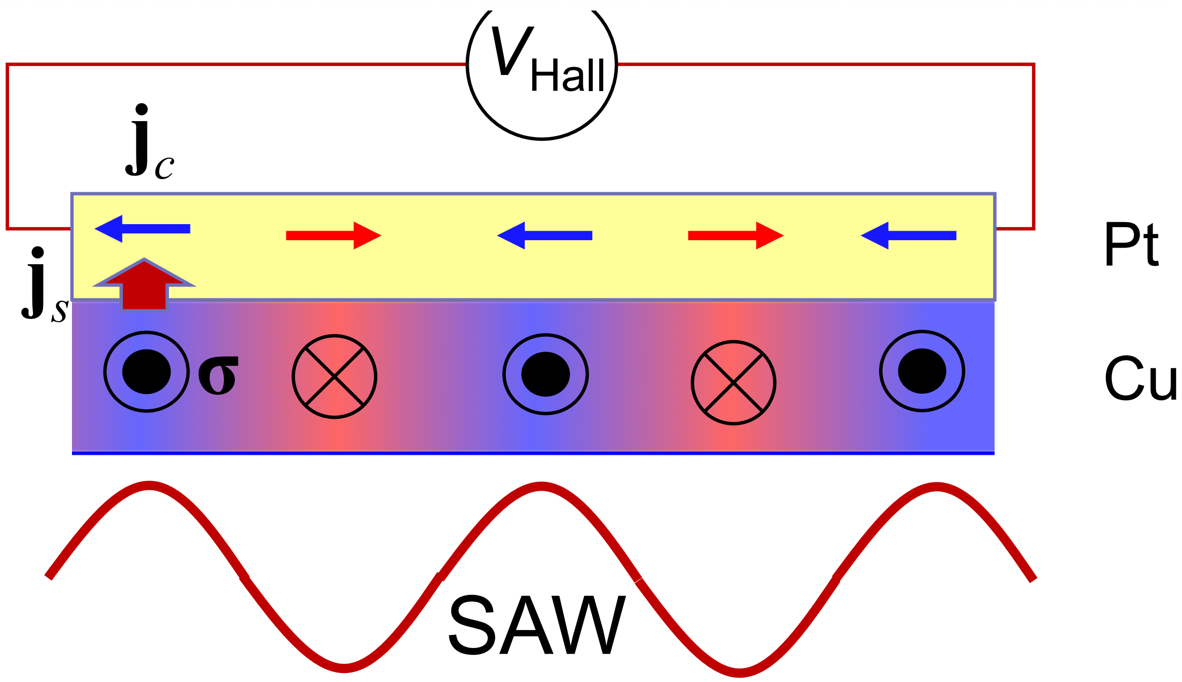


MM et al., Phys. Rev. B87, 180402(R) (2013)

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

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

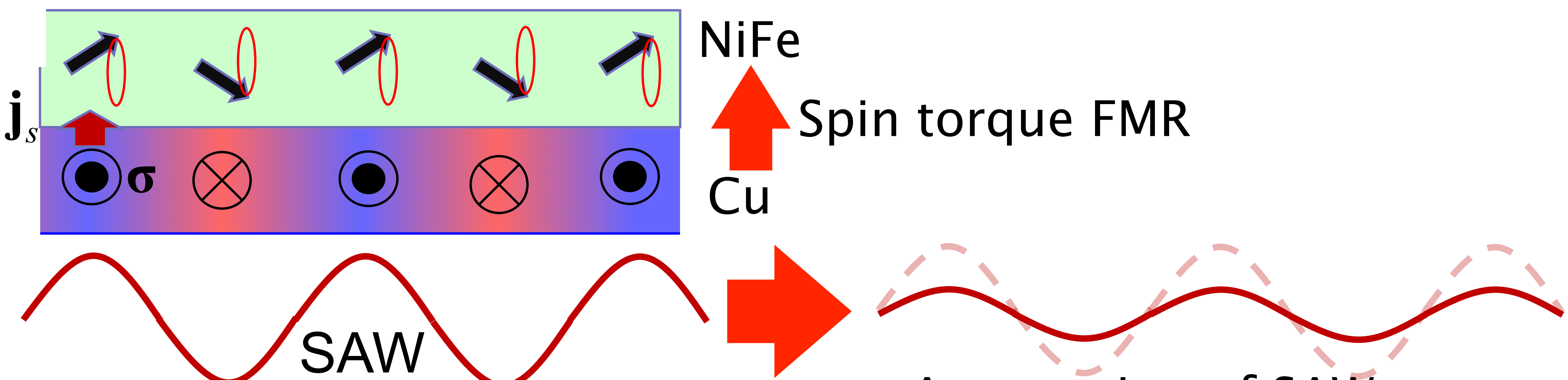
How to detect AC spin current by SAW?



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

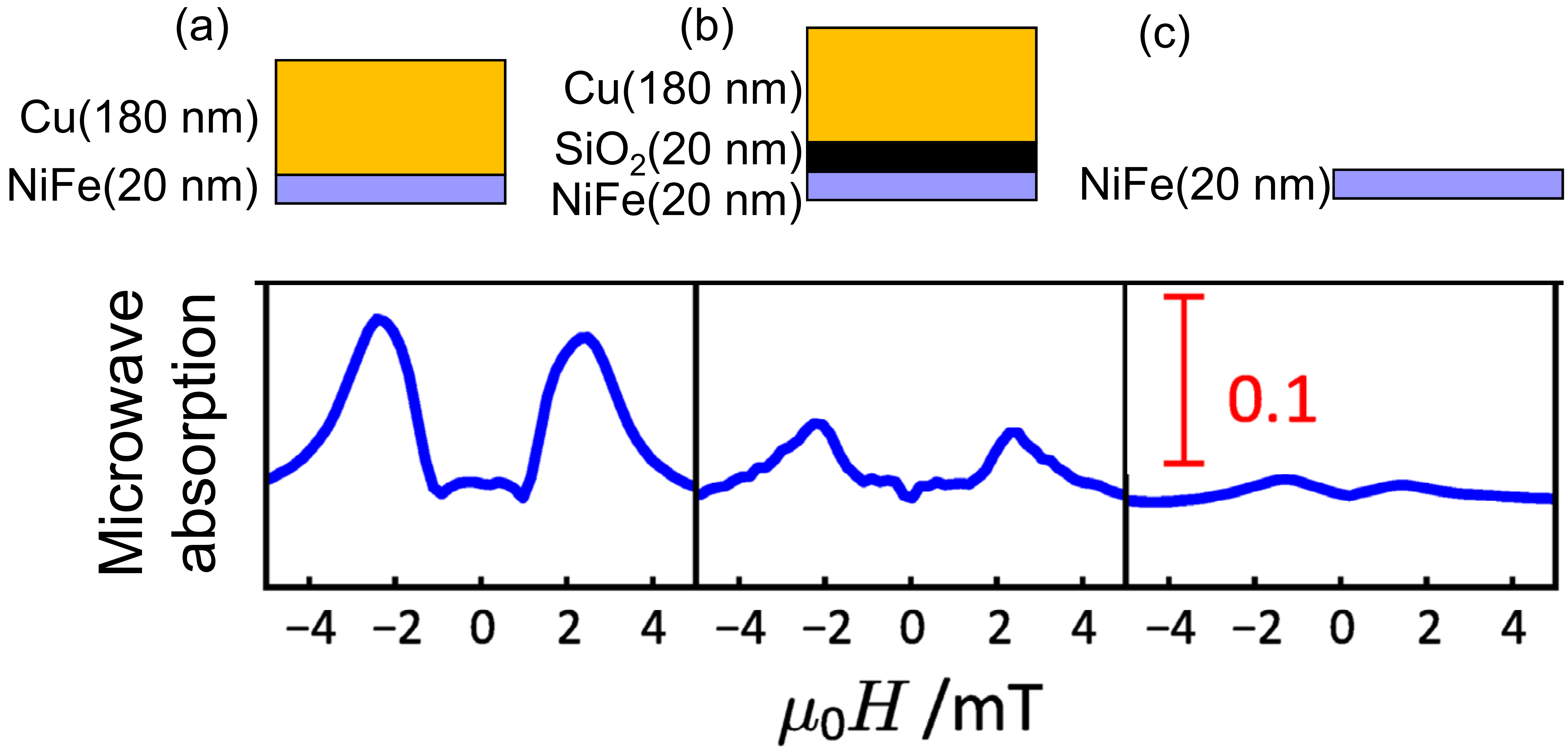
Prof. Nozaki's beautiful idea!

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

Outline

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- Gyromagnetic effects

Theoretical framework

- Spin-vorticity coupling
- Spin hydrodynamics

Gyro-spintronic effects in moving materials

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- Quark gluon plasma

Nonuniform electron dynamics

- Surface-oxidized Cu

Vorticity ⇒ quark/gluon in quark-gluon plasma (Nature 2017)

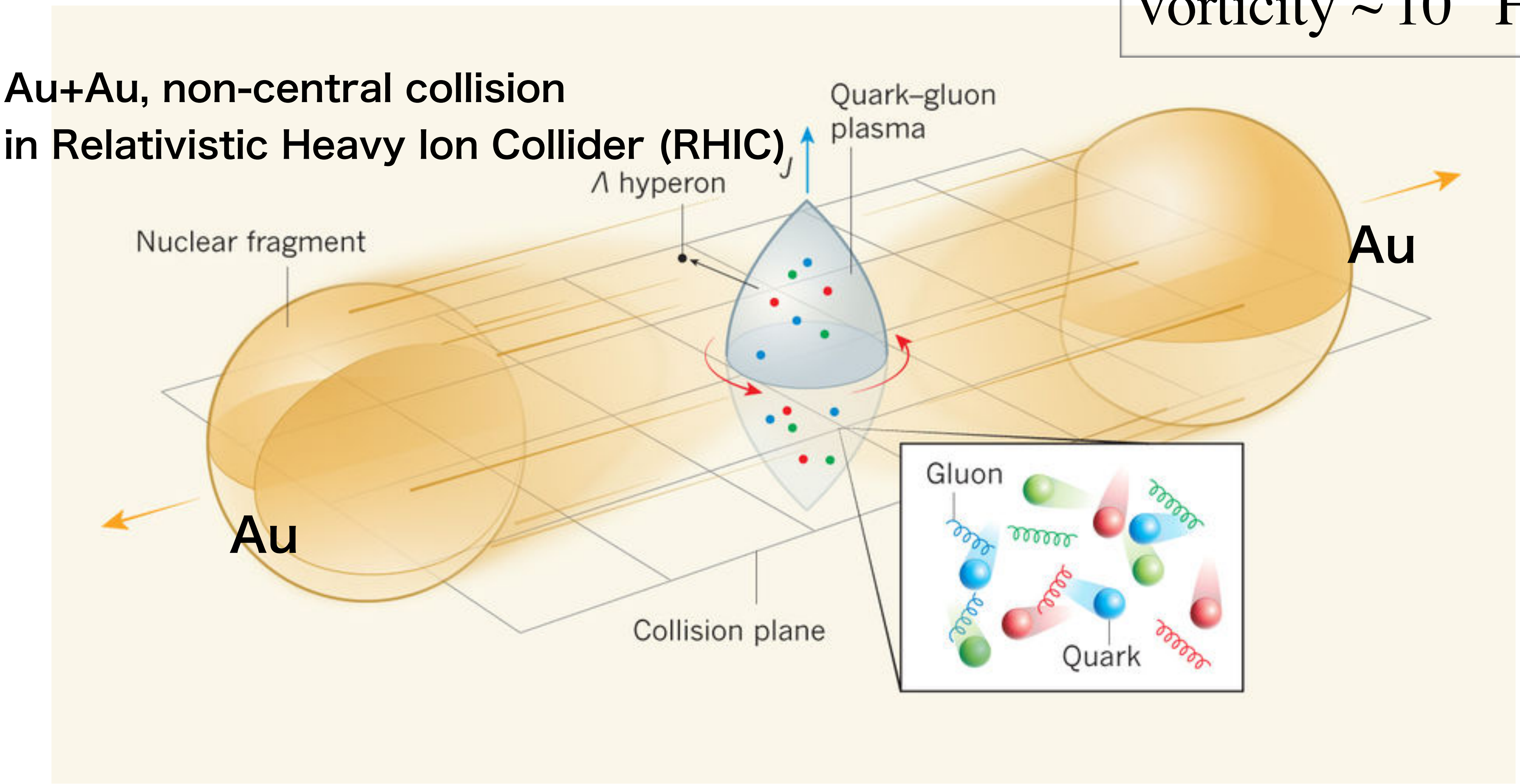
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*

vorticity $\sim 10^{21}$ Hz (~ 10^{17} T)!!



Theory of relativistic spin hydrodynamics
K.Hattori, M.Hongo, X.-G.Huang, M.Matsuo, and H.Taya, Physics Letters B (2019)

Vortical effects on early universe?

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, $\omega = \frac{1}{2}\nabla \times v$)—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)

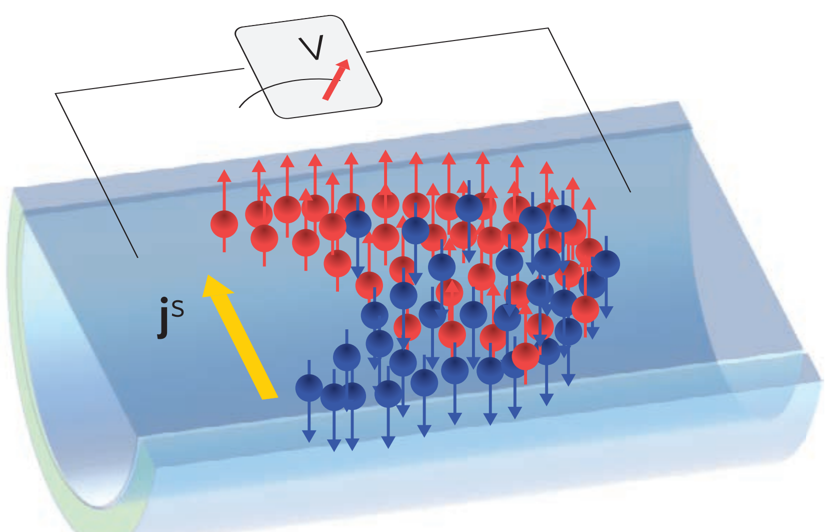
news & views

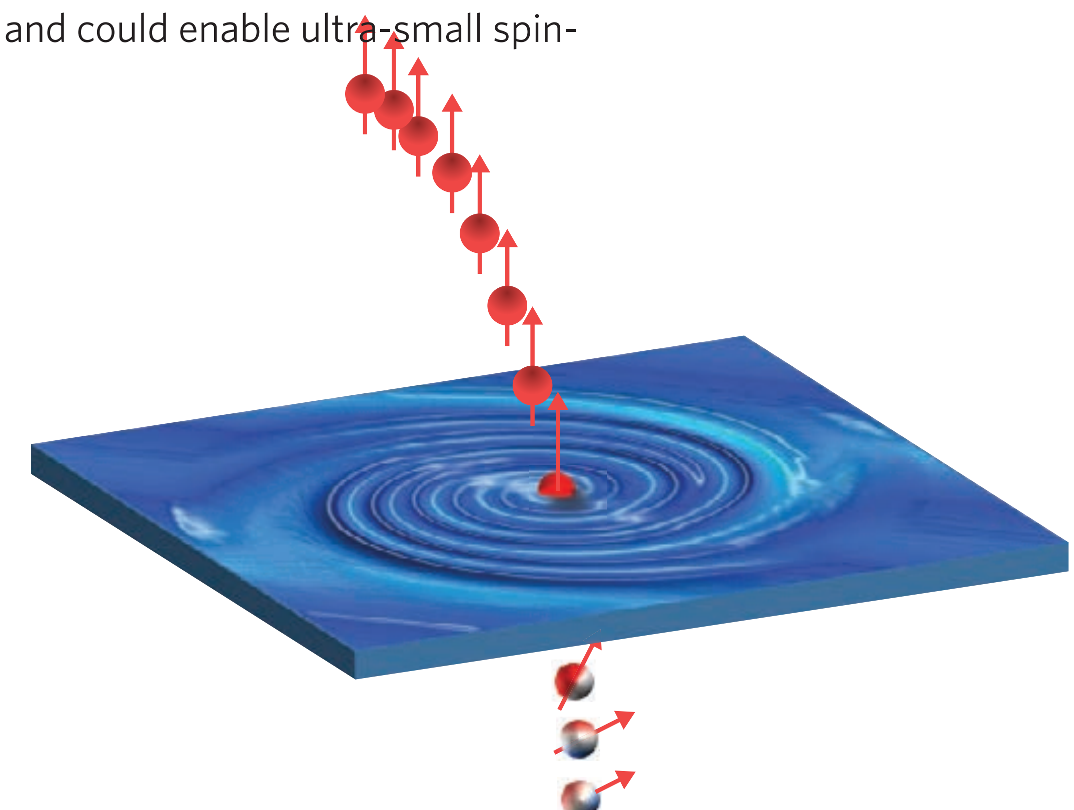
FLUID SPINTRONICS

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





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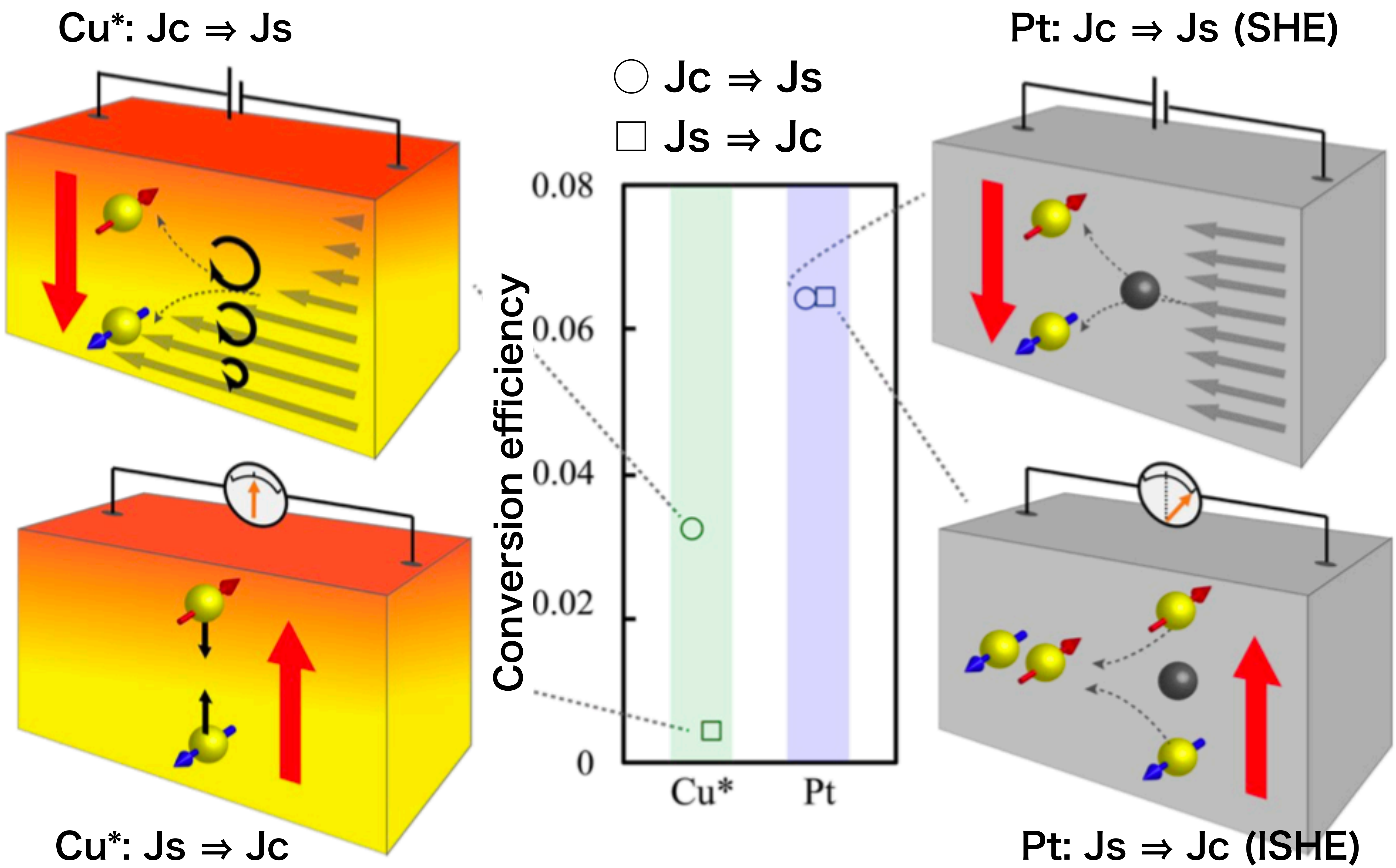
Nonreciprocal spin current generation in surface oxidized Cu



Okano, MM, Ohnuma, Maekawa, Nozaki, PRL 2019
(Theoretical details: Suppl. Mat.)

Summary

Spin hydrodynamics in condensed matter systems

Spin-diffusion equation w/ spin-vorticity coupling ⟷ **Angular momentum conversion** ⟷ **Elastic/Fluid equation w/ rotational viscosity**

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