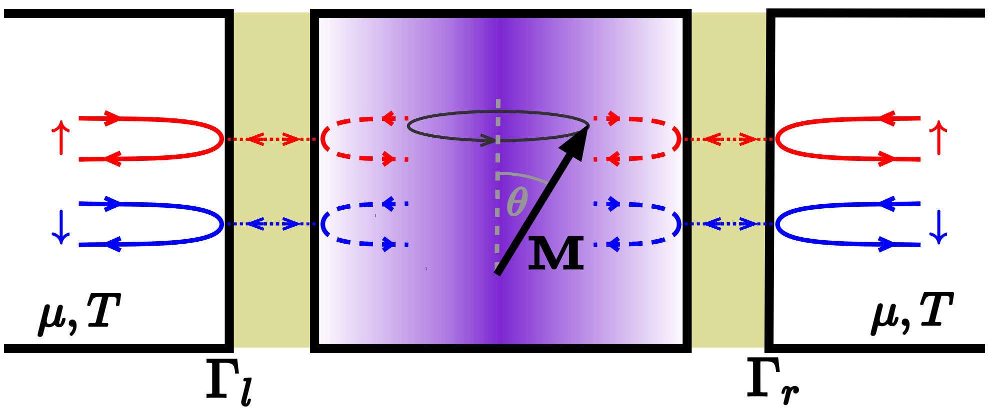
Noise of charge current generated by a driven magnet

Tim Ludwig, Igor S. Burmistrov, Yuval Gefen, Alexander Shnirman

arXiv:1906.02730



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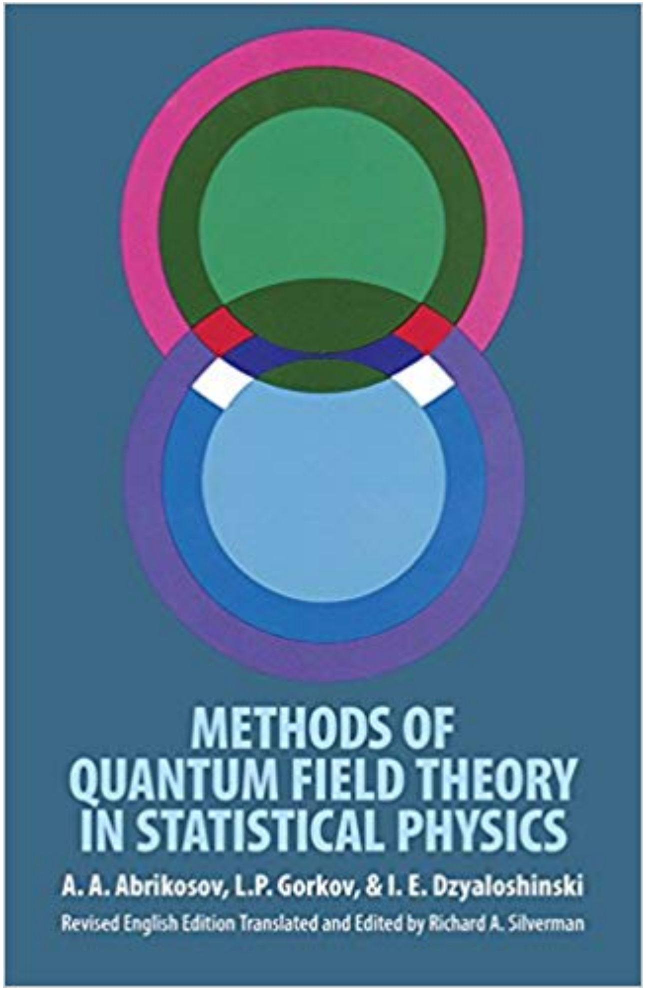
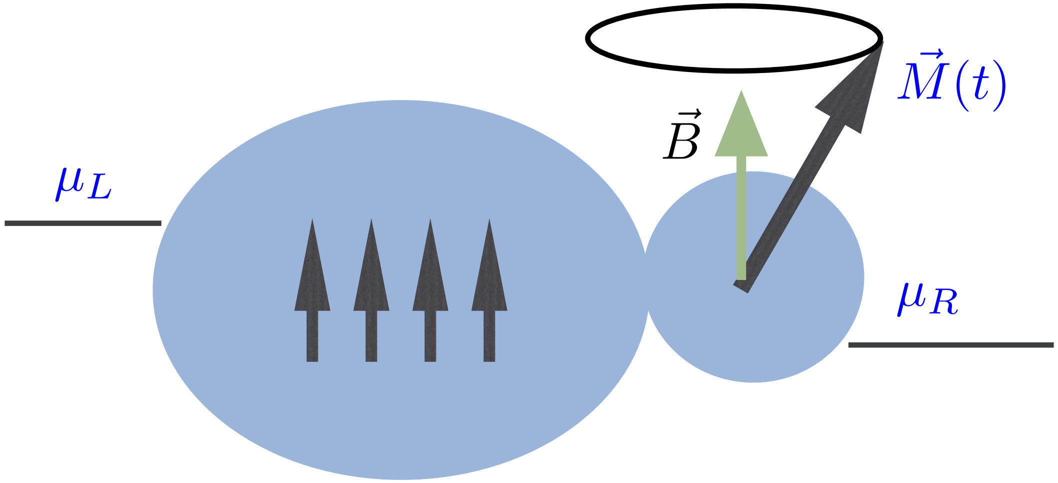

METHODS OF
QUANTUM FIELD THEORY
IN STATISTICAL PHYSICS
A. A. Abrikosov, L.P. Gorkov, & I. E. Dzyaloshinski
Revised English Edition Translated and Edited by Richard A. Silverman

Two main (dual) effects: spin transfer torque



$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = -\mathbf{B}\times\mathbf{M} - \alpha(\theta)\frac{\mathbf{M}}{M_0}\times\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} + \mathbf{M}\times\left(\frac{\mathbf{I}_s}{S}\times\frac{\mathbf{M}}{M_0}\right)$$

L. Berger, Phys. Rev. B 54, 9353 (1996)

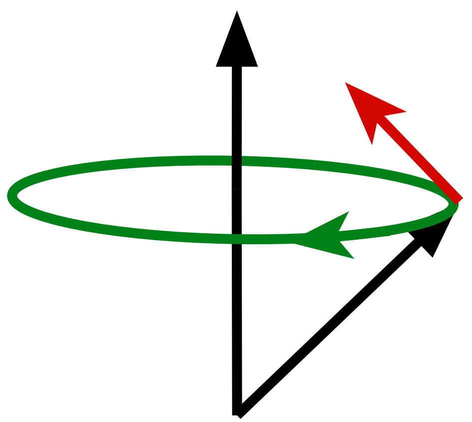
J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1 (1996)

Landau & Lifshitz, Phys. Z. Sowietunion 8, 153 (1935)

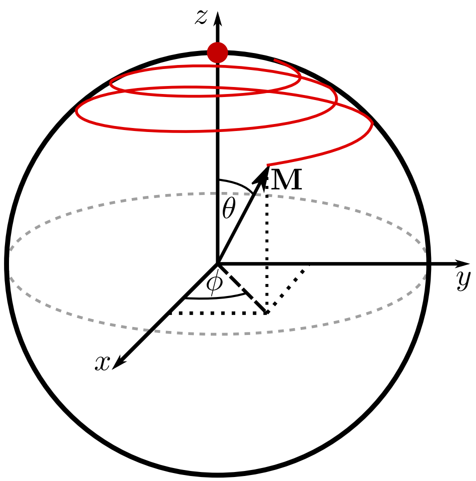
T.L. Gilbert (1955, 2004)

Landau-Lifshitz-Gilbert equation

$$\dot{\mathbf{m}} = \mathbf{m} \times \mathbf{B} - \alpha\, \mathbf{m} \times \dot{\mathbf{m}}$$



$$\mathbf{B} = \begin{pmatrix} 0 \\ 0 \\ B \end{pmatrix}$$



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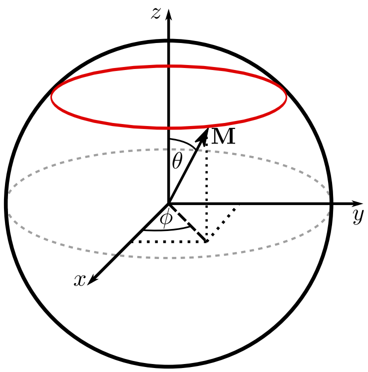
Landau-Lifshitz-Gilbert equation: FMR

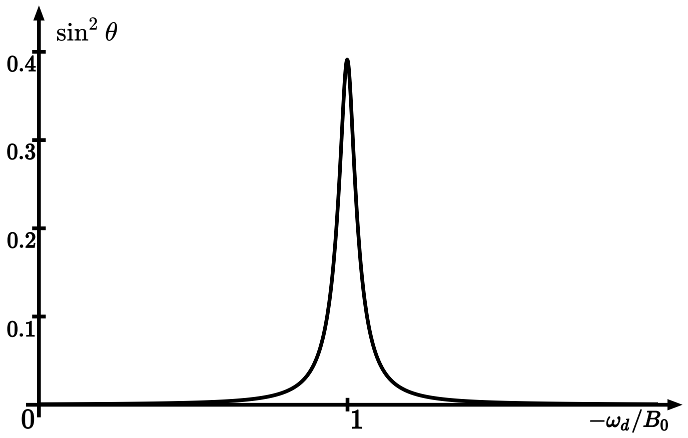
$$\dot{\mathbf{m}} = \mathbf{m} \times \mathbf{B} - \alpha\, \mathbf{m} \times \dot{\mathbf{m}}$$

$$\mathbf{B} = \begin{pmatrix} \Omega \cos \omega_d t \\ \Omega \sin \omega_d t \\ B_0 \end{pmatrix}$$

FMR-driven
steady state precessions



stationary values of the polar angle θ



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Two main (dual) effects: spin/charge pumping

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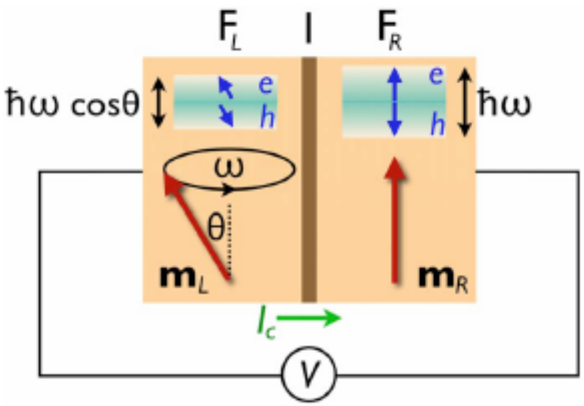

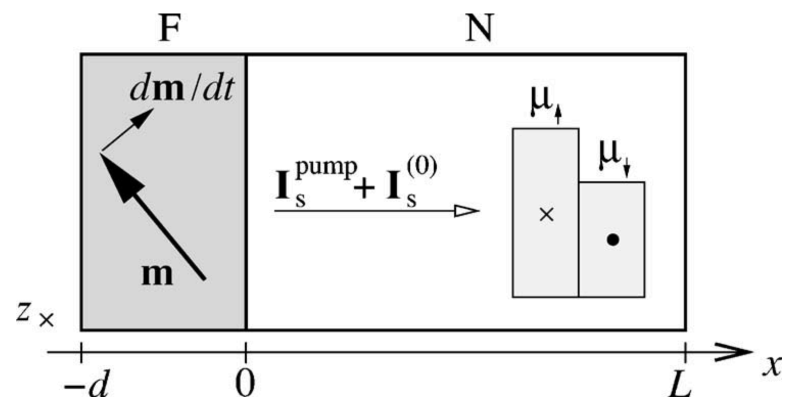

L. Berger, Phys. Rev. B **59**, 11465 (1998)

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

Y. Tserkovnyak et al., Phys. Rev. B **78**, 020401(R) (2008)

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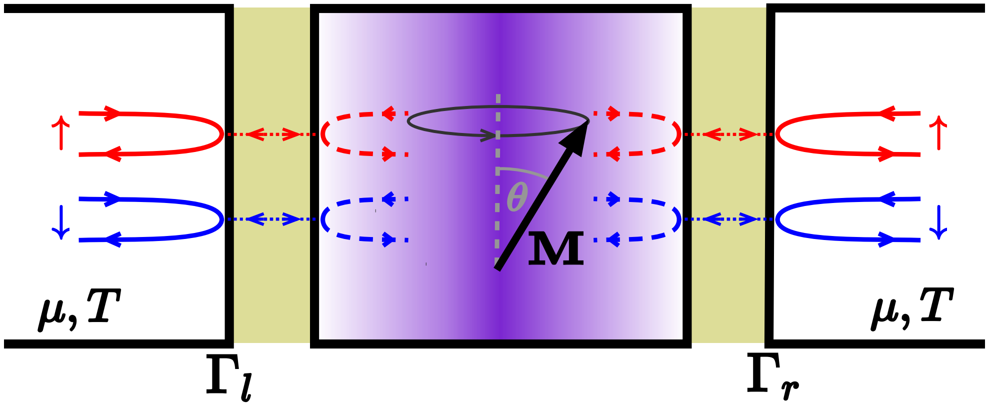
Result: Noise without average current



total conductance

$$g_t = 2(\rho_d^{\uparrow} + \rho_d^{\downarrow}) \frac{\Gamma_l \Gamma_r}{\Gamma_l + \Gamma_r}$$

The average charge current vanishes …

$$I = 0$$

… but its zero-frequency noise remains even at low T

$$S = 2 g_t T + g_t \sin^2\theta \left(\dot{\phi} \coth \frac{\dot{\phi}}{2T} - 2T \right) / 2$$

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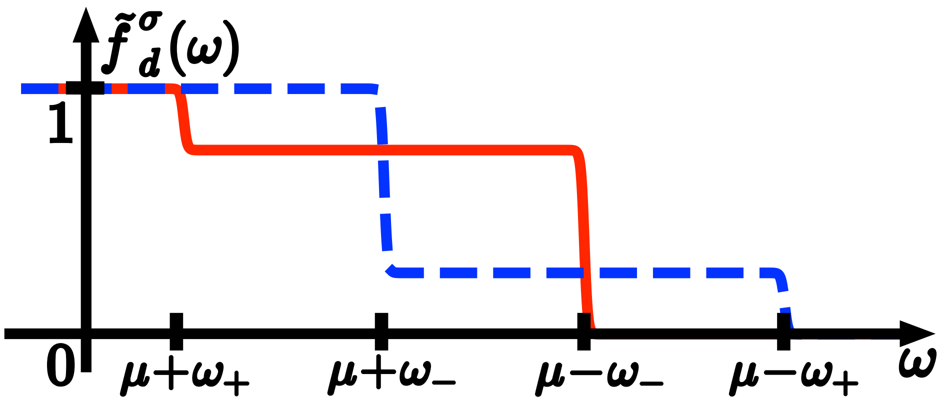
Result: Stationary distribution function



$$\omega_\pm = \dot{\phi}\frac{1 \pm \cos\theta}{2}$$

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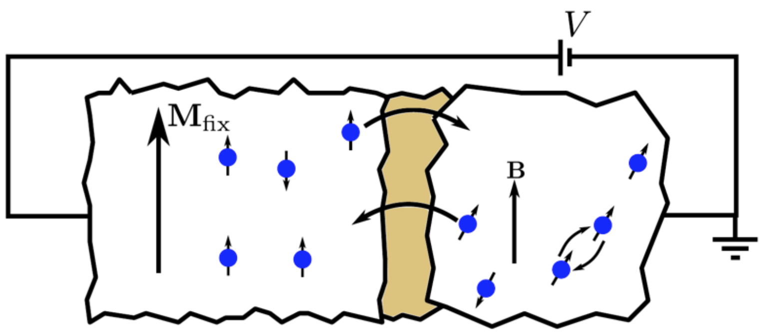
Derivation of Landau-Lifshitz-Gilbert equation

AS, Y. Gefen, A. Saha, I. S. Burmistrov, M. N. Kiselev, A. Altland,
Phys. Rev. Lett. 114, 176806 (2015)



- no anisotropy
- no internal relaxation mechanism
- Stoner ferromagnet:

$$\rho_d J > 1 \qquad |\mathbf{M}| \approx M_0$$

The Hamiltonian:

I. L. Kurland, I. L. Aleiner, and B. L. Altshuler, Phys. Rev. B 62, 14886 (2000)

$$H_{\rm dot} = \sum_{\alpha\sigma} \epsilon_\alpha \, a^\dagger_{\alpha\sigma} a_{\alpha\sigma} - \mathbf{BS} - J\mathbf{S}^2$$

$$H_{\rm lead} = \sum_{\gamma\sigma} \left(\epsilon_\gamma - \sigma \frac{M_{\bf fix}}{2} + V \right) c^\dagger_{\gamma\sigma} c_{\gamma\sigma}$$

$$H_{\rm tun.} = \sum_{\alpha\gamma\sigma} t_{\alpha\gamma} \, a^\dagger_{\alpha\sigma} c_{\gamma\sigma} + h.c.$$

total spin:

$$\mathbf{S} = \frac{1}{2} \sum_{\alpha\sigma\sigma'} a^\dagger_{\alpha\sigma} \vec{\sigma}_{\sigma\sigma'} a_{\alpha\sigma'}$$

The electron distribution:

$$n_d(\epsilon) = \frac{1}{e^{\beta(\epsilon-\mu)} + 1}$$

$$n_l(\epsilon) = \frac{1}{e^{\beta(\epsilon-(\mu+V))} + 1}$$

Derivation of Landau-Lifshitz-Gilbert equation

driving ⟶ **non-equilibrium** ⟶ **Keldysh formalism**

$$i\mathcal{S}[\bar{\Psi},\Psi] = i\oint_K dt\,\left[\bar{\Psi}(i\partial_t)\Psi - H(\bar{\Psi},\Psi)\right]$$

decoupling of exchange interaction

$$\mathrm{e}^{iJ\mathbf{S}^2} = \int d^3\mathbf{\Phi}\; e^{-i\mathbf{\Phi}\cdot\mathbf{S}}\; \mathrm{e}^{-i\frac{|\mathbf{\Phi}|^2}{4J}}$$

Integrating out fermions

Effective action

$$i\mathcal{S}[\mathbf{M}] = \mathrm{tr}\ln\left[-i\left(G_{d,0}^{-1} + \mathbf{M}\frac{\boldsymbol{\sigma}}{2} - \Sigma\right)\right] \overbrace{-i\oint_K dt\,\frac{(\mathbf{M}-\mathbf{B})^2}{4J}}^{-\mathcal{S}_B}$$

$$\mathbf{M} \equiv \mathbf{\Phi} + \mathbf{B}$$

Broadening by the lead

$$\Sigma = t_l\, G_l\, t_l^\dagger$$

Gauge transformation

$$i\mathcal{S} = \mathrm{tr}\ln\left[-i\left(G_{d,0}^{-1} + \mathbf{M}\frac{\boldsymbol{\sigma}}{2} - \Sigma\right)\right] + i\mathcal{S}_B$$

$SU(2)$

$$\mathbf{M}(t) = M(t)\vec{n}(t) \approx M\ \vec{n}(t)$$

$$\vec{n}\cdot\vec{\sigma} = R\sigma_z R^\dagger$$

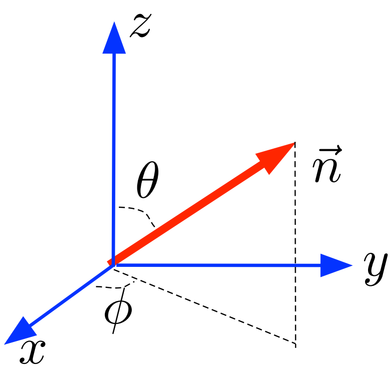
SU(2) gauge transformation

$$Q(t) \equiv R^\dagger(-i\partial_t)R$$

geometric vector potential (connection)

$$i\mathcal{S} = \mathrm{tr}\ln\Big[-i\Big(\underbrace{G_{d,0}^{-1} + \frac{M_0}{2}\sigma_z}_{G_{d,z}^{-1}} - Q - R^\dagger\Sigma R\Big)\Big] + i\mathcal{S}_B$$

SU(2) vector potential



$$\vec{n} \cdot \vec{\mathbf{S}} = R\, S_z\, R^\dagger$$

$$R \in SU(2)/U(1)$$

$$R = \exp\left[-\frac{i\phi}{2}\sigma_z\right] \exp\left[-\frac{i\theta}{2}\sigma_y\right] \exp\left[\frac{i(\phi-\chi)}{2}\sigma_z\right]$$

$$Q \equiv R^\dagger(-i\partial_t)R = Q_\parallel + Q_\perp$$

$$Q_\parallel \equiv \frac{1}{2}\left[\dot{\phi}(1-\cos\theta) - \dot{\chi}\right]\sigma_z$$

Berry's phase, gauge dependent

$$Q_\perp \equiv -\frac{1}{2}\left[\dot{\theta}\,\sigma_y - \dot{\phi}\sin\theta\,\sigma_x\right]\exp\left[i(\phi-\chi)\,\sigma_z\right]$$

Landau-Zener,

neglected: adiabatic approximation

Tunneling expansion, AES

$$i\mathcal{S}_M = \mathrm{tr}\ln\left[-i\left(G_{d,z}^{-1} - Q_q - R^\dagger \Sigma R\right)\right] \overbrace{-i\oint_K dt\,\frac{|\vec{\mathbf{M}}-\vec{\mathbf{B}}|^2}{4J}}^{i\mathcal{S}_B}$$

Expansion

$$\text{first order in } Q_q \longrightarrow i\mathcal{S}_{WZNW} = -\mathrm{tr}\left[G_{d,z} Q_q\right] = iS\oint \dot{\phi}(1-\cos\theta)$$

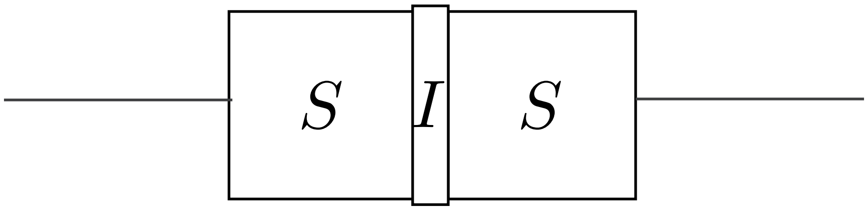
$$\text{first order in } \Sigma \longrightarrow i\mathcal{S}_{AES} = -\mathrm{tr}\left[G_{d,z} R^\dagger\,\Sigma\,R\right]$$

in original U(1) AES

$R^\dagger(t)R(t') \to e^{i\psi(t)}\,e^{-i\psi(t')}$

V. Ambegaokar, U. Eckern, G. Schön
Phys. Rev. Lett. 48, 1745-1748 (1982)

AES action for Josephson contact



$$
i\mathcal{S}_{AES} = i \int dt\, \frac{C\dot{\phi}^2}{2e^2} - \int dt_1 dt_2\, \alpha(t_1,t_2)\, \cos\left[\phi(t_1) - \phi(t_2)\right]
$$

$$
- \int dt_1 dt_2\, \beta(t_1,t_2)\, \cos\left[\phi(t_1) + \phi(t_2)\right]
$$

V. Ambegaokar, U. Eckern, G. Schön
Phys. Rev. Lett. **48**, 1745-1748 (1982)

Explicit form for non-magnetic lead

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$$i\mathcal{S}_M^{AES} = -\int dt_1\, dt_2\, \alpha(t_1 - t_2)\, \mathrm{tr}\left[R(t_1)R^{-1}(t_2)\right]$$

Matsubara

$$\alpha(\tau) = \frac{\pi g}{\sin^2(\pi\tau/\beta)}$$

Tunneling conductance

$$g = \pi\rho_{lead}\rho_{dot}|T|^2$$

$$\mathrm{tr}\left[R(t_1)R^{-1}(t_2)\right] =$$

$$\cos\frac{\theta(t_1)}{2}\cos\frac{\theta(t_2)}{2}\cos\left(\frac{\chi(t_1)-\chi(t_2)}{2}\right)$$

$$+\sin\frac{\theta(t_1)}{2}\sin\frac{\theta(t_2)}{2}\cos\left(\phi(t_1)-\phi(t_2)-\frac{\chi(t_1)-\chi(t_2)}{2}\right)$$

Gauge invariance ???

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Variation of the action ⟶ EOM

$$i\mathcal{S} = i\mathcal{S}_{\rm WZNW} + i\mathcal{S}_B + i\mathcal{S}_{\rm AES}$$

AS, Y. Gefen, A. Saha,
I. S. Burmistrov, M. N. Kiselev, A. Altland
Phys. Rev. Lett. 114, 176806 (2015)

$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = -\mathbf{B}\times\mathbf{M} - \alpha(\theta)\frac{\mathbf{M}}{M_0}\times\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} + \mathbf{M}\times\left(\frac{\mathbf{I}_s}{S}\times\frac{\mathbf{M}}{M_0}\right)$$

Gilbert-damping [1]: $\alpha(\theta) = \frac{\tilde{g}(\theta)}{S}$

Spin-torque current [2]: $I_s = g_s V$

Charge current [3]: $I = 4g(\theta)V - g_s \sin^2\theta\dot{\phi}$

[1] A. L. Chudnovskiy, et al. PRL 101 066601 (2008).

[2] J. C. Slonczewski, JMMM 159, L1 (1996). & L. Berger, Phys. Rev. B 54, 9353 (1996)

[3] L. Berger, Phys. Rev. B 59, 11465 (1998), Y. Tserkovnyak et al., Phys. Rev. B 78, 020401(R) (2008)

Technical details

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$$i\mathcal{S} = \mathrm{tr}\ln\Big[-i\big(\underbrace{G_{d,0}^{-1} + \frac{M_0}{2}\sigma_z}_{G_{d,z}^{-1}} - Q - R^\dagger \Sigma R\big)\Big] + i\mathcal{S}_B$$

$$G_{d,z}(\epsilon) = \begin{pmatrix} -2\pi i\,\delta(\epsilon - \epsilon_\alpha + \frac{M_0}{2}\sigma_z)\,F_d(\epsilon) & \frac{1}{\epsilon-\epsilon_\alpha+\frac{M_0}{2}\sigma_z+i0} \\ \frac{1}{\epsilon-\epsilon_\alpha+\frac{M_0}{2}\sigma_z-i0} & 0 \end{pmatrix}$$

$$\Sigma_\sigma(\epsilon) \approx \begin{pmatrix} 0 & i\Gamma_l^\sigma \\ -i\Gamma_l^\sigma & -2i\Gamma_l^\sigma F_l(\epsilon) \end{pmatrix}$$

$F(\epsilon) \equiv 1 - 2n(\epsilon)$ distribution func.

Γ_l^σ spin-resolved level width

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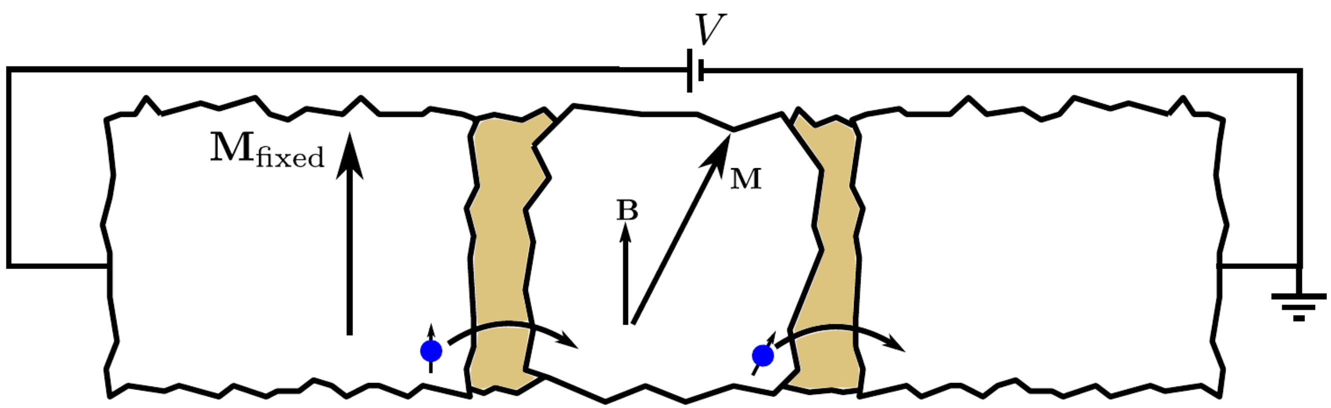
Non-equilibrium taken seriously:

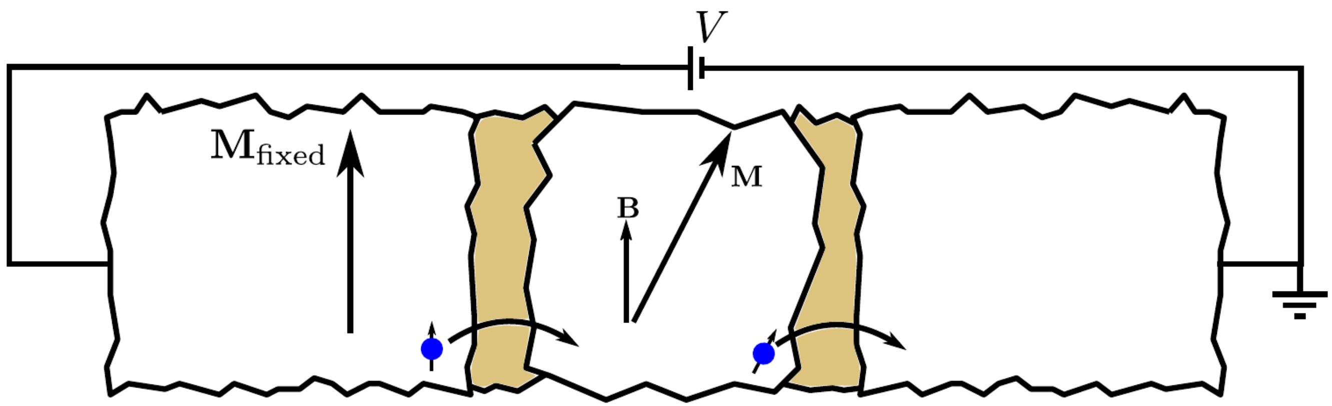
Tim Ludwig, Igor S. Burmistrov, Yuval Gefen, and AS
[Phys. Rev. B 95, 075425 (2017).]

Tim Ludwig, Igor S. Burmistrov, Yuval Gefen, AS
[Phys. Rev. B 99, 045429 (2019).]



The electron distribution on the dot strongly affected by driving!

Results change drastically



$$i\mathcal{S}[\mathbf{M}, V_d] = \mathrm{tr}\ln\left[-i\left(G_{d,0}^{-1} + \mathbf{M}\frac{\boldsymbol{\sigma}}{2} - V_d - \Sigma\right)\right]$$

$$\overbrace{-i\oint_K dt\,\frac{(\mathbf{M}-\mathbf{B})^2}{4J}}^{-\mathcal{S}_B} \overbrace{+i\oint_K dt\left(\frac{CV_d^2}{2} + V_d N_0\right)}^{\mathcal{S}_C}$$

$$\Sigma = \Sigma_l + \Sigma_r = t_l G_l t_l^\dagger + t_r G_r t_r^\dagger$$

AES-strategy:

$SU(2)$ $U(1)$

$$i\mathcal{S} = \mathrm{tr}\ln\left[-i\left(G_{d,0}^{-1} + \mathbf{M}\frac{\boldsymbol{\sigma}}{2} - V_d - \Sigma\right)\right] + i\mathcal{S}_B + i\mathcal{S}_C$$

(1) shift the time dependent fields to the tunneling part (gauge trafo):

$$U = \underbrace{\mathrm{e}^{-i\frac{\phi}{2}\sigma_z}\mathrm{e}^{-i\frac{\theta}{2}\sigma_y}\mathrm{e}^{i\frac{\phi-\chi}{2}\sigma_z}}_{SU(2)}\mathrm{e}^{-i\psi} \qquad \dot{\psi} = V_d$$

(2) expand in the self-energy (tunneling) (and in the Berry-phase):

$$i\mathcal{S} = \mathrm{tr}\ln\left[-i\left(\underbrace{G_{d,0}^{-1} + \frac{M_0}{2}\sigma_z}_{G_{d,z}^{-1}} - Q_q - U^\dagger\Sigma U\right)\right] + i\mathcal{S}_B + i\mathcal{S}_C$$

AES-strategy:

$$i\mathcal{S} = \mathrm{tr}\ln\Big[-i\Big(\underbrace{G_{d,0}^{-1} + \frac{M_0}{2}\sigma_z}_{G_{d,z}^{-1}} - Q_q - U^\dagger \Sigma U\Big)\Big] + i\mathcal{S}_B + i\mathcal{S}_C$$

$$i\mathcal{S}_{\mathrm{AES}} = -\mathrm{tr}\,\left[G_{d,z}U^\dagger \Sigma U\right] \qquad i\mathcal{S}_{\mathrm{WZNW}} = -\mathrm{tr}\,\left[G_{d,z}Q_q\right]$$

We know the self-energy

$$\Sigma_\sigma(\epsilon) \approx \begin{pmatrix} 0 & i(\Gamma_l^\sigma + \Gamma_r) \\ -i(\Gamma_l^\sigma + \Gamma_r) & -2i[\Gamma_l^\sigma F_l(\epsilon) + \Gamma_r F_r(\epsilon)] \end{pmatrix}$$

But what about the GF?

Which distribution should we use for the dot? (kinetic equation)

$$G_{d,z}^{-1}(\epsilon) = \begin{pmatrix} 0 & \epsilon - \epsilon_\alpha + \frac{M_0}{2}\sigma_z - i0 \\ \epsilon - \epsilon_\alpha + \frac{M_0}{2}\sigma_z + i0 & -2i0\, F_?(\epsilon) \end{pmatrix}$$

“improved” AES-like-strategy:

expand around a “classical” trajectory

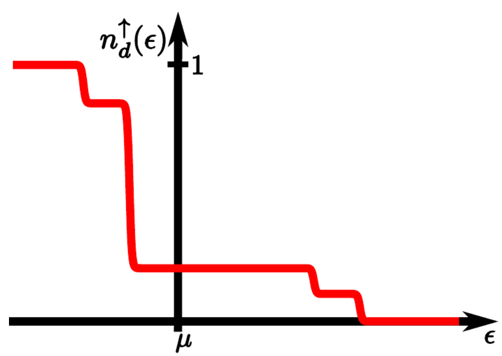
$$i\mathcal{S} = \mathrm{tr}\ln\Big[-i\Big(\underbrace{G_{d,0}^{-1} + \frac{M_0}{2}\sigma_z - U_0^\dagger \Sigma U_0}_{G_d^{-1}} - Q_q - (U^\dagger \Sigma U - U_0^\dagger \Sigma U_0)\Big)\Big] + i\mathcal{S}_B + i\mathcal{S}_C$$

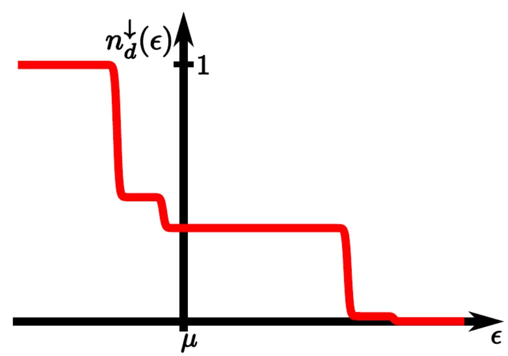
Kinetic equation ⇒ **Distribution function**

$$i\mathcal{S}_{\mathrm{AES}} = -\mathrm{tr}\left[G_d(U^\dagger \Sigma U - U_0^\dagger \Sigma U_0)\right]$$

“improved” AES-like-strategy: multi-step distribution function

$$F_d^\sigma(\epsilon) = \frac{1}{\Gamma_\sigma(\theta_0)}\Big[\cos^2\frac{\theta_0}{2}\Gamma_l^\sigma F(\epsilon - \sigma B_- + V_d^0 - V) + \sin^2\frac{\theta_0}{2}\Gamma_l^{\bar\sigma} F(\epsilon - \bar\sigma B_+ + V_d^0 - V) + \cos^2\frac{\theta_0}{2}\Gamma_r F(\epsilon - \sigma B_- + V_d^0) + \sin^2\frac{\theta_0}{2}\Gamma_r F(\epsilon - \bar\sigma B_+ + V_d^0)\Big]$$





$$B_\pm \equiv B_0(1 \pm \cos\theta_0)/2$$

AES-like-action

Landau-Lifshitz-Gilbert-Slonczewski equation:

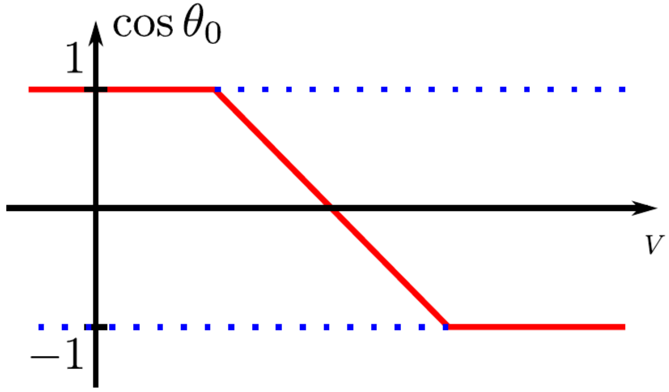
$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = -\mathbf{B}\times\mathbf{M} - \alpha(\theta)\frac{\mathbf{M}}{M_0}\times\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} + \mathbf{M}\times\left(\frac{\mathbf{I}_s}{S}\times\frac{\mathbf{M}}{M_0}\right)$$

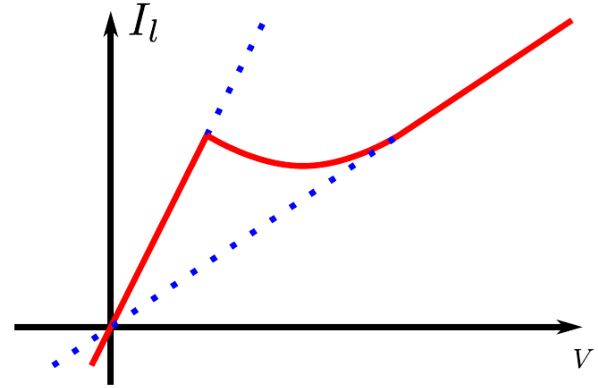
Kirchhoff's law:

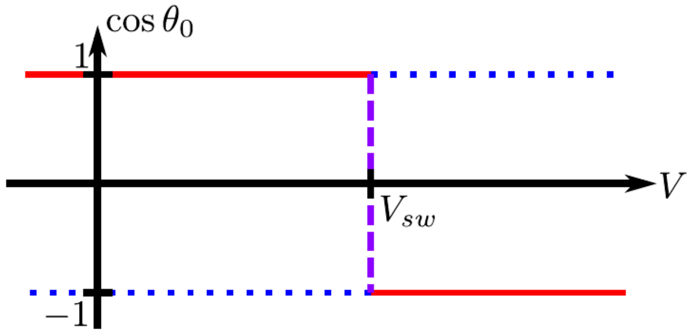
$$C\dot{V}_d = I_l - I_r$$

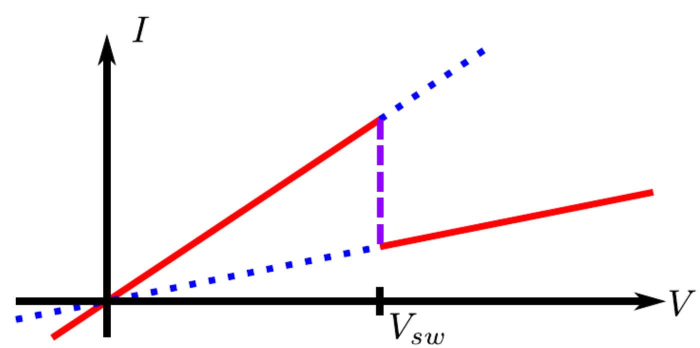
BUT: I_s, I_l, I_r **Modified completely**

I_s, I_l, I_r **Modified completely**

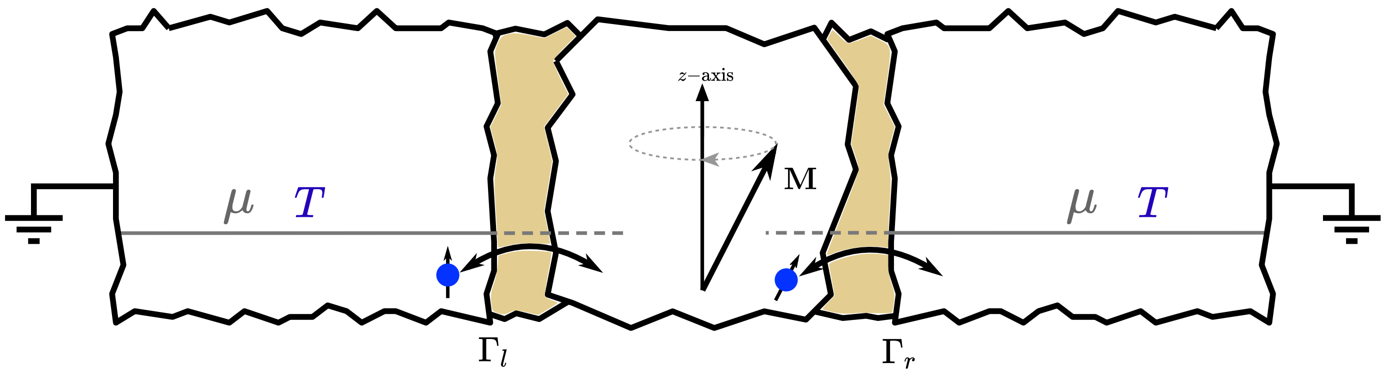








FMR driven micromagnet



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Counting field

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$$i\mathcal{S}(\lambda) = \mathrm{tr}\ln\Big[\underbrace{i\partial_t - h_d - \Sigma(\lambda)}_{G_\lambda^{-1}}\Big] \qquad h_d = \epsilon_\alpha - \mathbf{M}(t)\frac{\boldsymbol{\sigma}}{2}$$

this corresponds to: $t_l \to t_l e^{-i\lambda(t)}$ $\qquad t_l^\dagger \to t_l^\dagger e^{i\lambda(t)}$

$$\langle Q\rangle = i\partial_\lambda \mathcal{Z}(\lambda)\big|_{\lambda=0}$$

$$\langle Q^2\rangle = (i\partial_\lambda)^2 \mathcal{Z}(\lambda)\big|_{\lambda=0}$$

It follows:

$$\langle Q\rangle = -i\,\langle \mathrm{tr}[G_0\Sigma']\rangle_{\mathbf{M}(t)}$$

$$\langle\langle Q^2\rangle\rangle = \big\langle \mathrm{tr}[G_0\Sigma''] + \mathrm{tr}[G_0'\Sigma']\big\rangle_{\mathbf{M}(\mathbf{t})}$$

Solution: Rotation in spin-space

$$i\mathcal{S}(\lambda) = \mathrm{tr}\ln\Big[\underbrace{i\partial_t - \tilde{h}_d - \tilde{\Sigma}(\lambda)}_{\tilde{G}_\lambda^{-1}}\Big]$$

$$h_d = \epsilon_\alpha - \mathbf{M}(t)\frac{\boldsymbol{\sigma}}{2}$$

rotates the Hamiltonian …

$$R^\dagger \mathbf{M}\boldsymbol{\sigma} R = M\sigma_z$$

$$\tilde{h}_d = \epsilon_\alpha - M\frac{\sigma_z}{2} - iR^\dagger \dot{R}$$

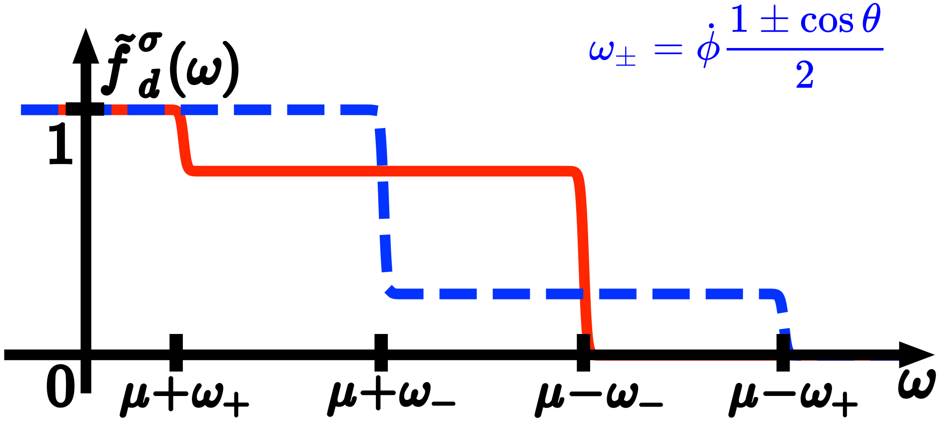
… and the self-energy $\tilde{\Sigma} = R^\dagger \Sigma R$

distribution function

$$F^\sigma_{l/r}(\omega) = \cos^2\frac{\theta}{2} F_{l/r}(\omega + \sigma\omega_-) + \sin^2\frac{\theta}{2} F_{l/r}(\omega + \bar{\sigma}\omega_+)$$

$$\tilde{F}^\sigma_d(\omega) = [\Gamma_l \tilde{F}^\sigma_l(\omega) + \Gamma_r \tilde{F}^\sigma_r(\omega)]/\Gamma_\Sigma$$

$$\omega_\pm = \dot{\phi}\frac{1 \pm \cos\theta}{2}$$



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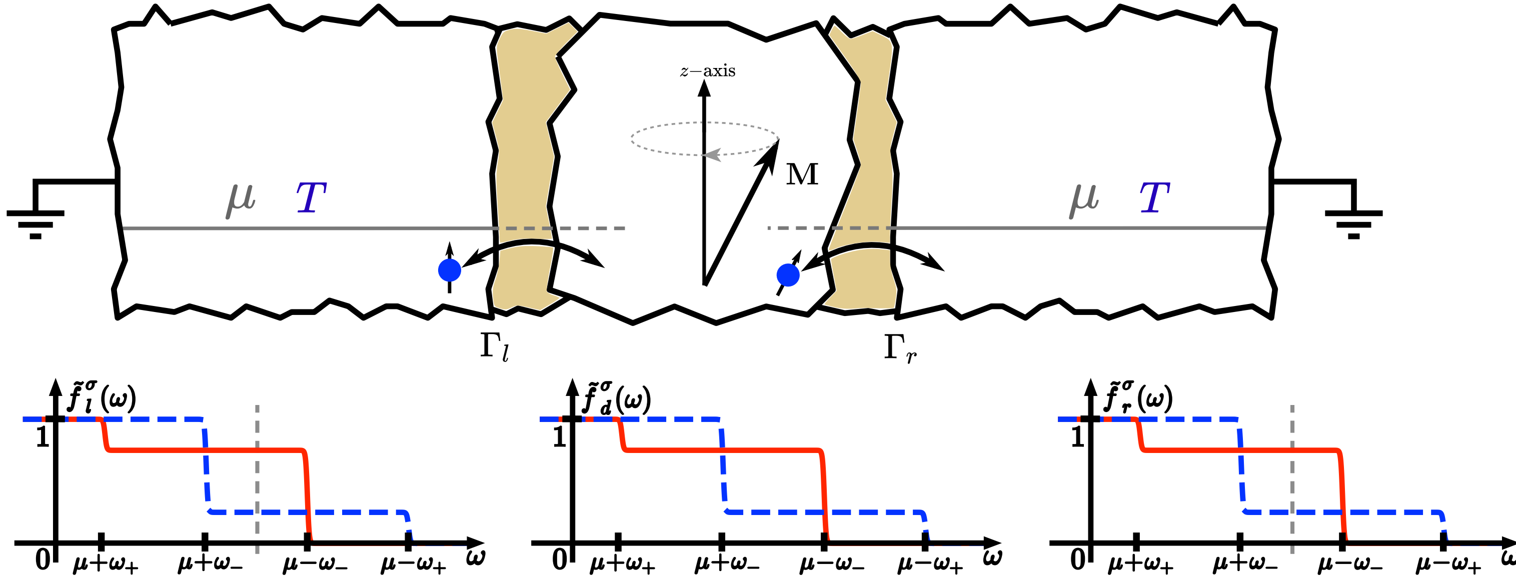

$$\langle Q \rangle = -i\, \mathrm{tr}[\tilde{G}_0 \tilde{\Sigma}']$$

$\Rightarrow$ Landauer-formula in rotating-frame

$$I_l = \sum_\sigma \rho_d^\sigma \Gamma_l \int d\omega \left[\tilde{F}_l^\sigma(\omega) - \tilde{F}_d^\sigma(\omega)\right] = 0$$

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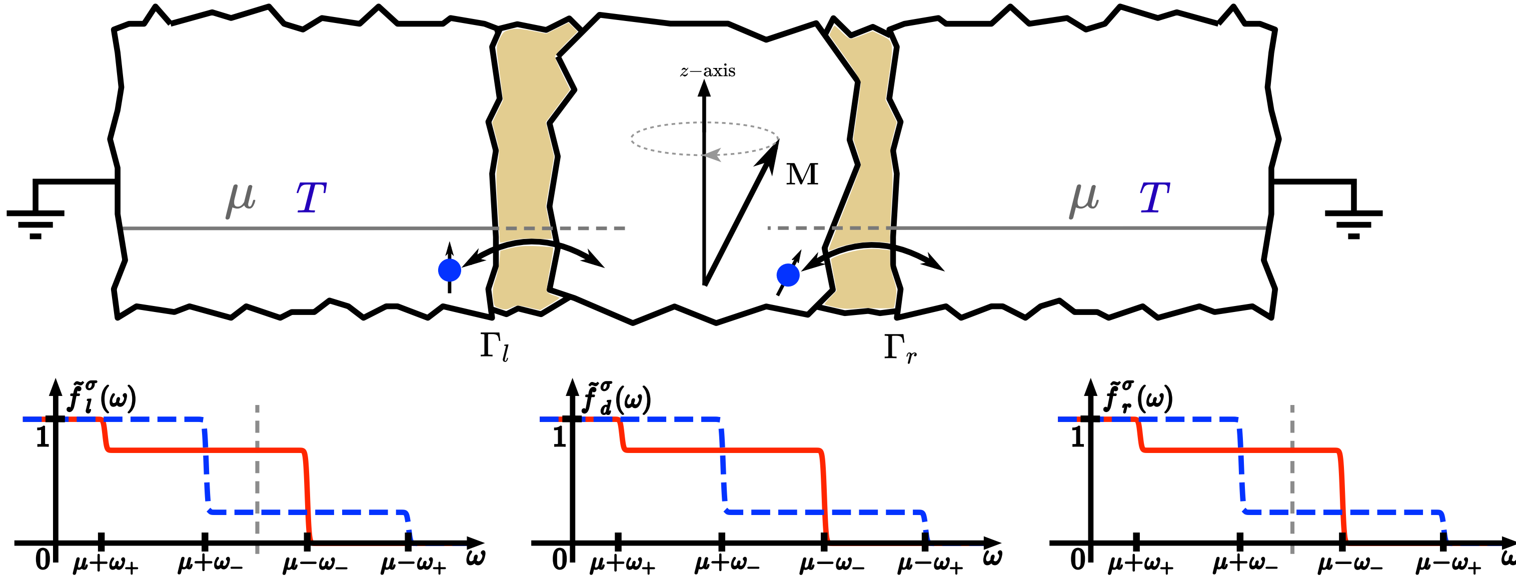

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$$\langle\langle Q^2 \rangle\rangle = \mathrm{tr}[\tilde{G}_0 \tilde{\Sigma}''] + \mathrm{tr}[\tilde{G}_0' \tilde{\Sigma}']$$

$\Rightarrow$ **zero-frequency noise** $g_\sigma = 2\rho_d^\sigma \Gamma_l \Gamma_r / (\Gamma_l + \Gamma_r)$

$$S_l = \sum_\sigma g_\sigma \int d\omega \left\{ \left[1 - \tilde{F}_s^\sigma(\omega) \tilde{F}_l^\sigma(\omega)\right] + \frac{\Gamma_l}{\Gamma_r} \tilde{F}_s^\sigma(\omega) \left[\tilde{F}_l^\sigma(\omega) - \tilde{F}_s^\sigma(\omega)\right] \right\}$$

$$S_l = 2 g_t T + g_t \sin^2\theta \left(\dot{\phi} \coth \frac{\dot{\phi}}{2T} - 2T \right) / 2$$

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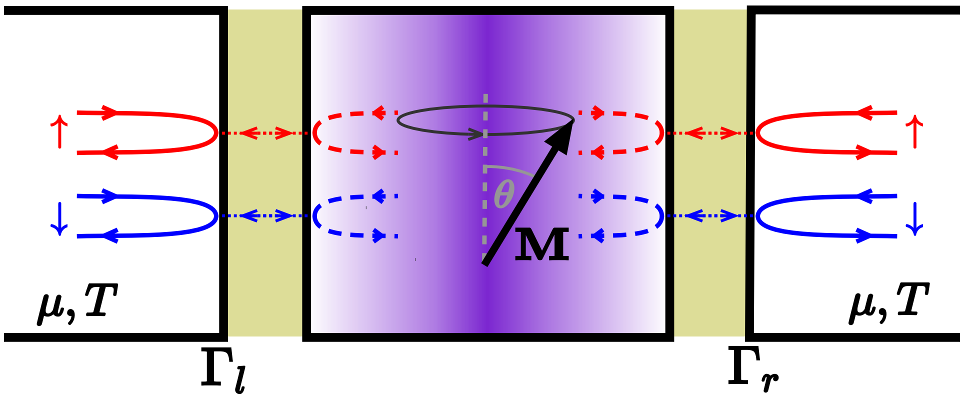
Noise of charge current: even without average charge current

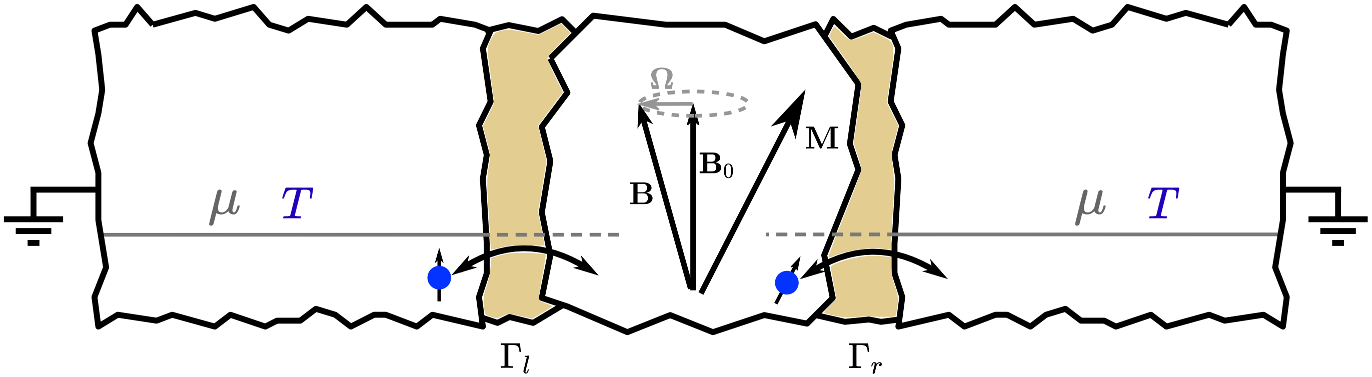


$$I = 0$$

$$S = 2g_t T + g_t \sin^2\theta \left(\dot{\phi} \coth \frac{\dot{\phi}}{2T} - 2T\right)/2$$

high T ↓ $S = 2g_t T$

low T ↓ $S = g_t \sin^2\theta \, |\dot{\phi}|/2$

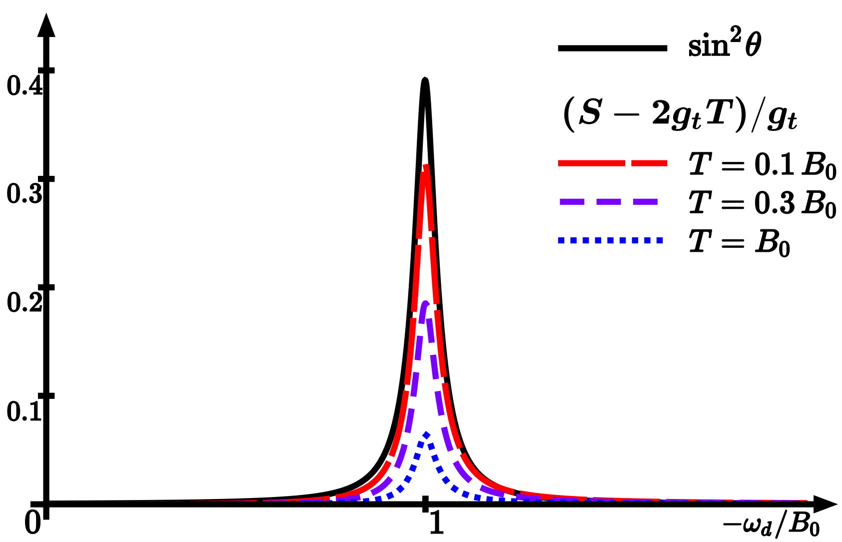


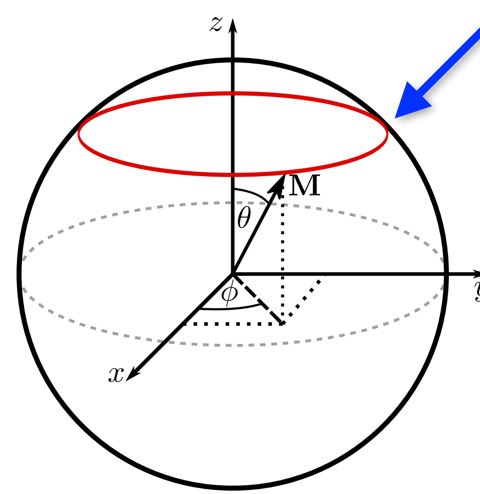
$$\mathbf{B} = \begin{pmatrix} \Omega \cos \omega_d t \\ \Omega \sin \omega_d t \\ B_0 \end{pmatrix}$$

Noise of charge current

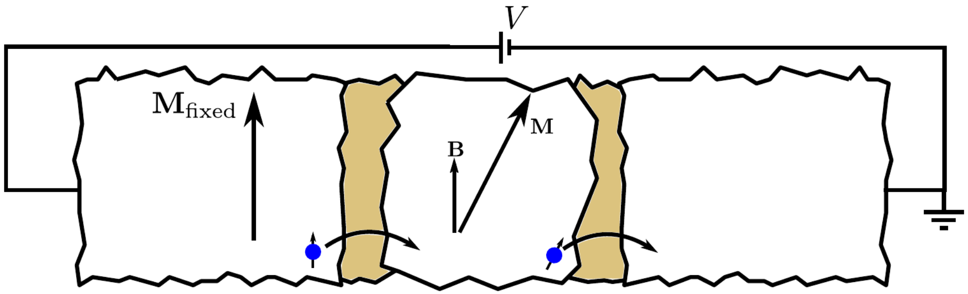
$$S = 2 g_t T + g_t \sin^2 \theta \left(\dot{\phi} \coth \frac{\dot{\phi}}{2T} - 2T \right) / 2$$

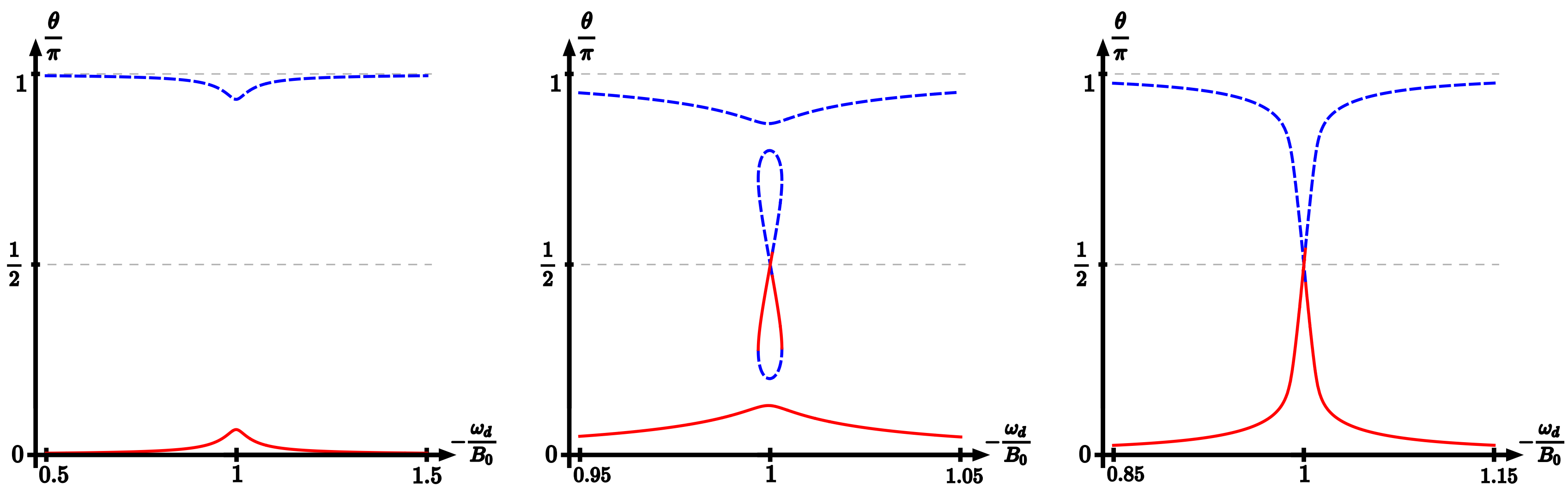
FMR-driven steady state precessions





FMR driven micromagnet with a magnetic lead





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Summary

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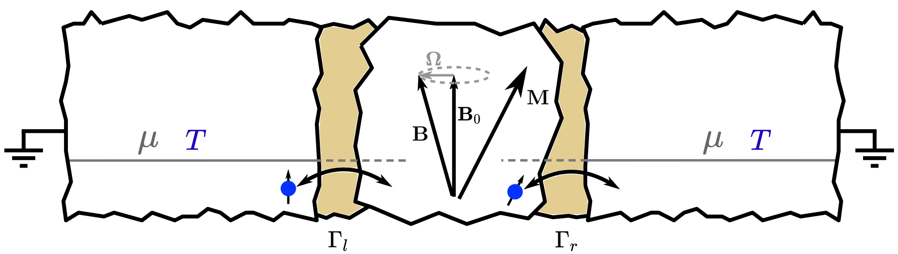
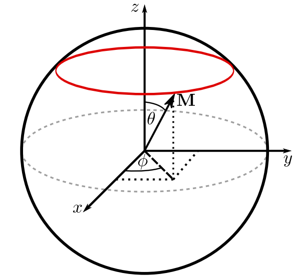
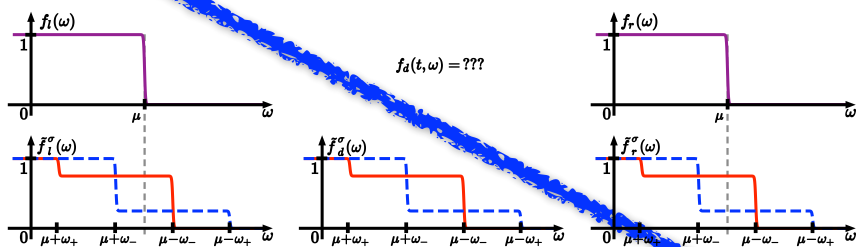
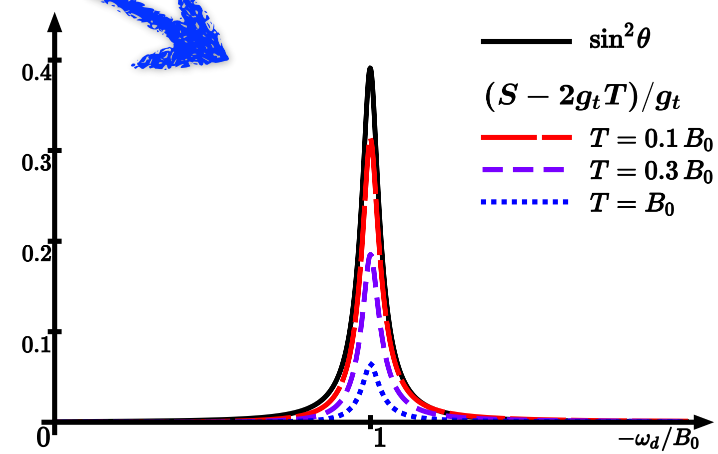


FMR-driven
steady state precessions







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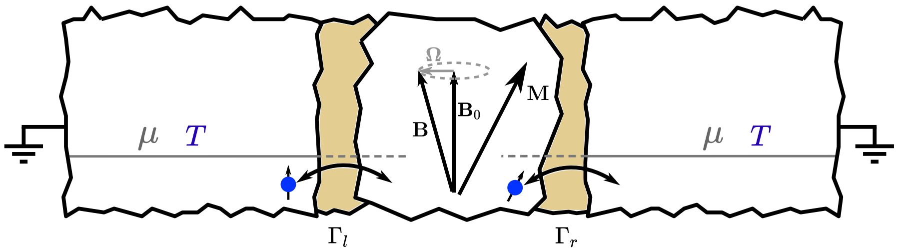
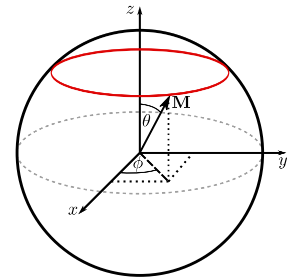
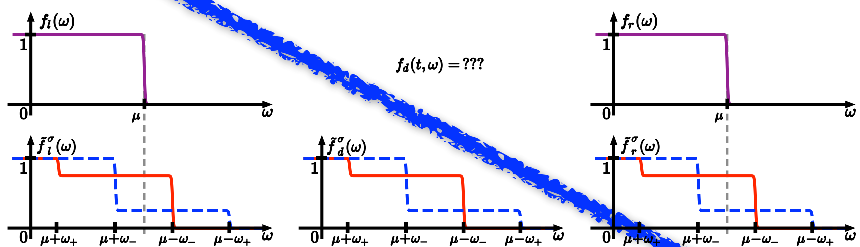
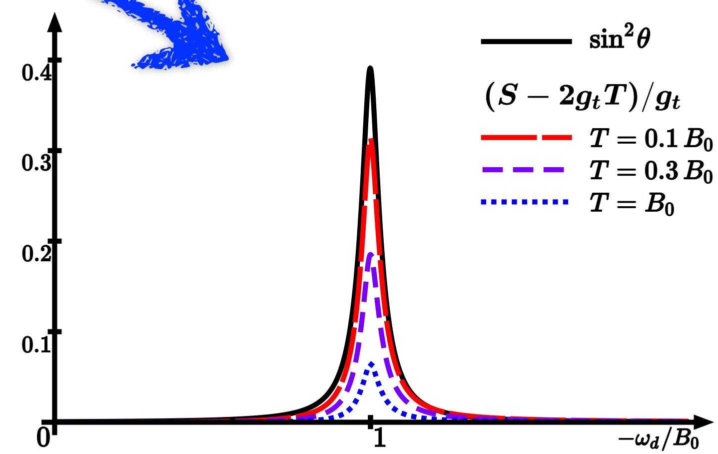


FMR-driven
steady state precessions







Thank you
for your attention!

Equation of Motion - LLG+Slonczewski

$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = -\mathbf{B}\times\mathbf{M} - \alpha(\theta)\frac{\mathbf{M}}{M_0}\times\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} + \mathbf{M}\times\left(\frac{\mathbf{I}_s}{S}\times\frac{\mathbf{M}}{M_0}\right)$$

Gilbert-damping $\alpha(\theta) = \frac{\tilde{g}(\theta)}{S}$

Spin-torque current $I_s = g_s V$

Charge current $I = 4g(\theta)V - g_s\sin^2\theta\dot{\phi}$

Conductances

$$\tilde{g}(\theta) = \frac{\sin^2(\frac{\theta}{2})}{4}(g_{\uparrow\uparrow} + g_{\downarrow\downarrow}) + \frac{\cos^2(\frac{\theta}{2})}{4}(g_{\uparrow\downarrow} + g_{\downarrow\uparrow})$$

$$g_s = \frac{1}{4}(g_{\uparrow\uparrow} - g_{\downarrow\downarrow} - g_{\uparrow\downarrow} + g_{\downarrow\uparrow}) \qquad g_{\sigma\sigma'} = 2\pi|t_l|^2\rho^{\sigma}_{dot}\rho^{\sigma'}_{lead}$$

$$g(\theta) = \frac{\cos^2(\frac{\theta}{2})}{4}(g_{\uparrow\uparrow} + g_{\downarrow\downarrow}) + \frac{\sin^2(\frac{\theta}{2})}{4}(g_{\uparrow\downarrow} + g_{\downarrow\uparrow})$$

A. L. Chudnovskiy, J. Swiebodzinski, and A. Kamenev, Phys. Rev. Lett. 101, 066601 (2008)

Gauge fixing

$$Q_{\|} = 0 \quad \Rightarrow \quad \dot{\chi} = \dot{\phi}(1 - \cos\theta)$$

Would be nice, but impossible

Berry phase different on two contours

$$\dot{\chi}_c(t) = \dot{\phi}_c(t)\,(1 - \cos\theta_c(t)) \quad \Rightarrow \quad Q_{\|,c} = 0$$

$$\chi_q(t) = \phi_q(t)\,(1 - \cos\theta_c(t))$$

$$\Rightarrow \quad Q_{\|,q} = \frac{1}{2}\,\sigma_z\,\sin\theta_c\,\left[\dot{\phi}_c\theta_q - \dot{\theta}_c\phi_q\right]$$

$$i\mathcal{S}_{WZNW} = iS\int dt\,\sin\theta_c\,\left[\dot{\phi}_c\theta_q - \dot{\theta}_c\phi_q\right]$$

Keldysh Berry phase action