Flavors of Magnetic Noise in Quantum Materials

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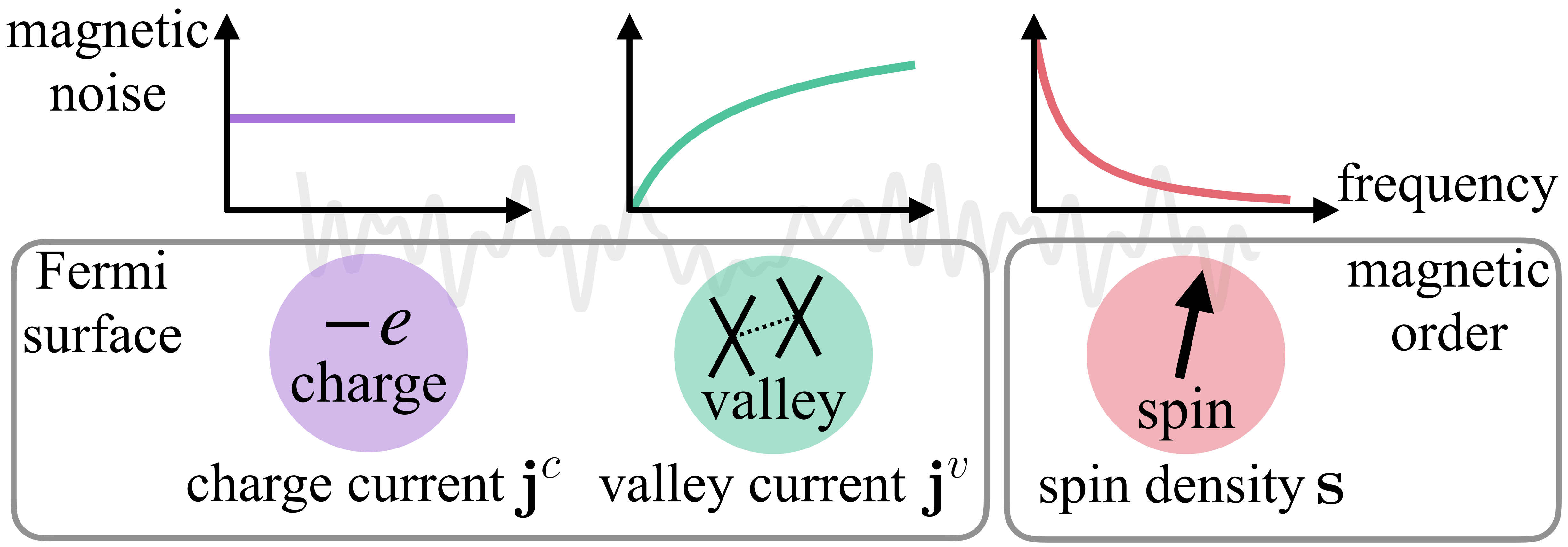
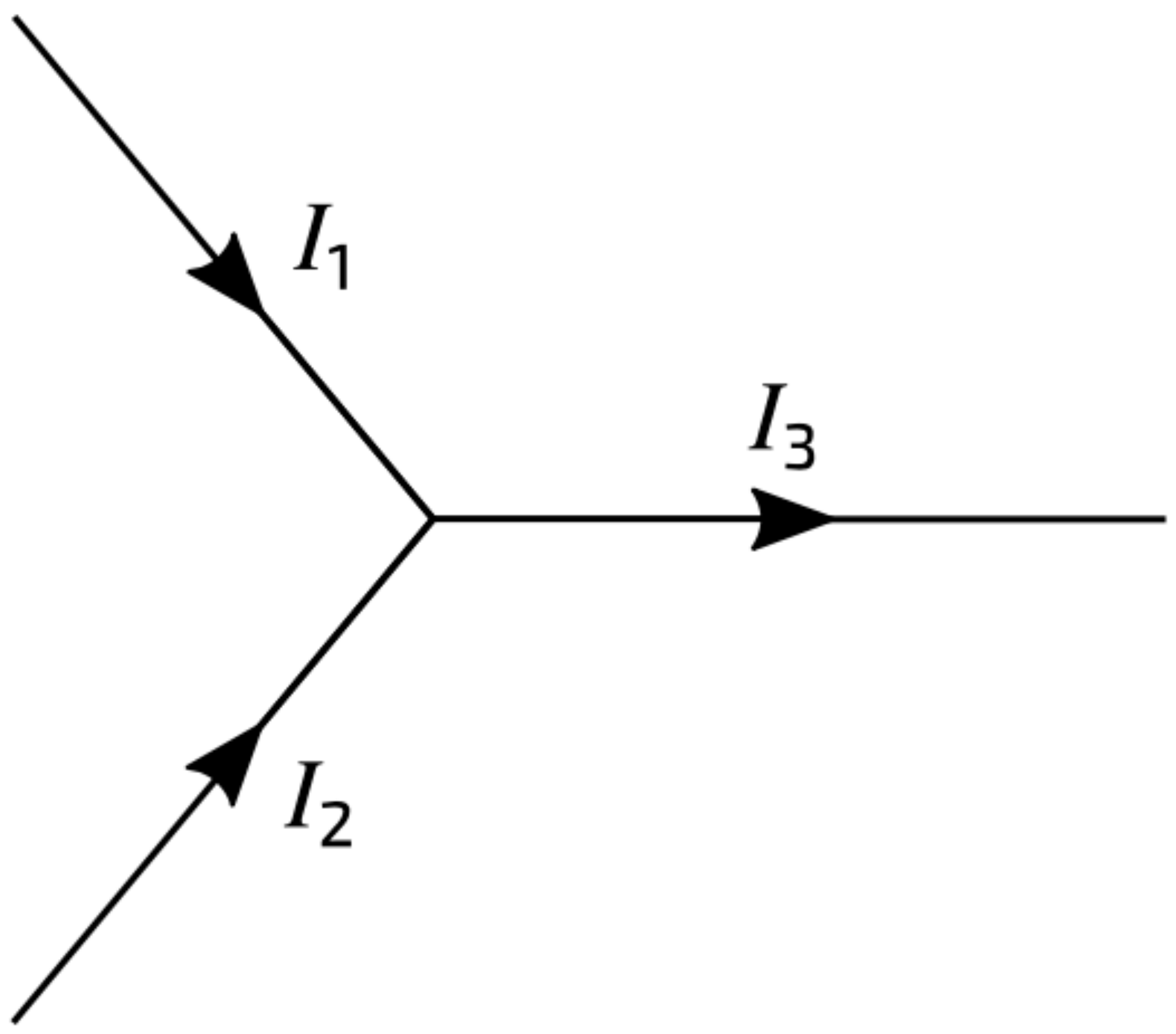
Outline

- Charge-neutral transport degrees of freedom
- Magnetic noise as a noninvasive probe of transport
- Magnetic Weyl semimetal: charge, spin, and valley
- Distinguishable spectral characters of their diffusive transport



Transport degrees of freedom

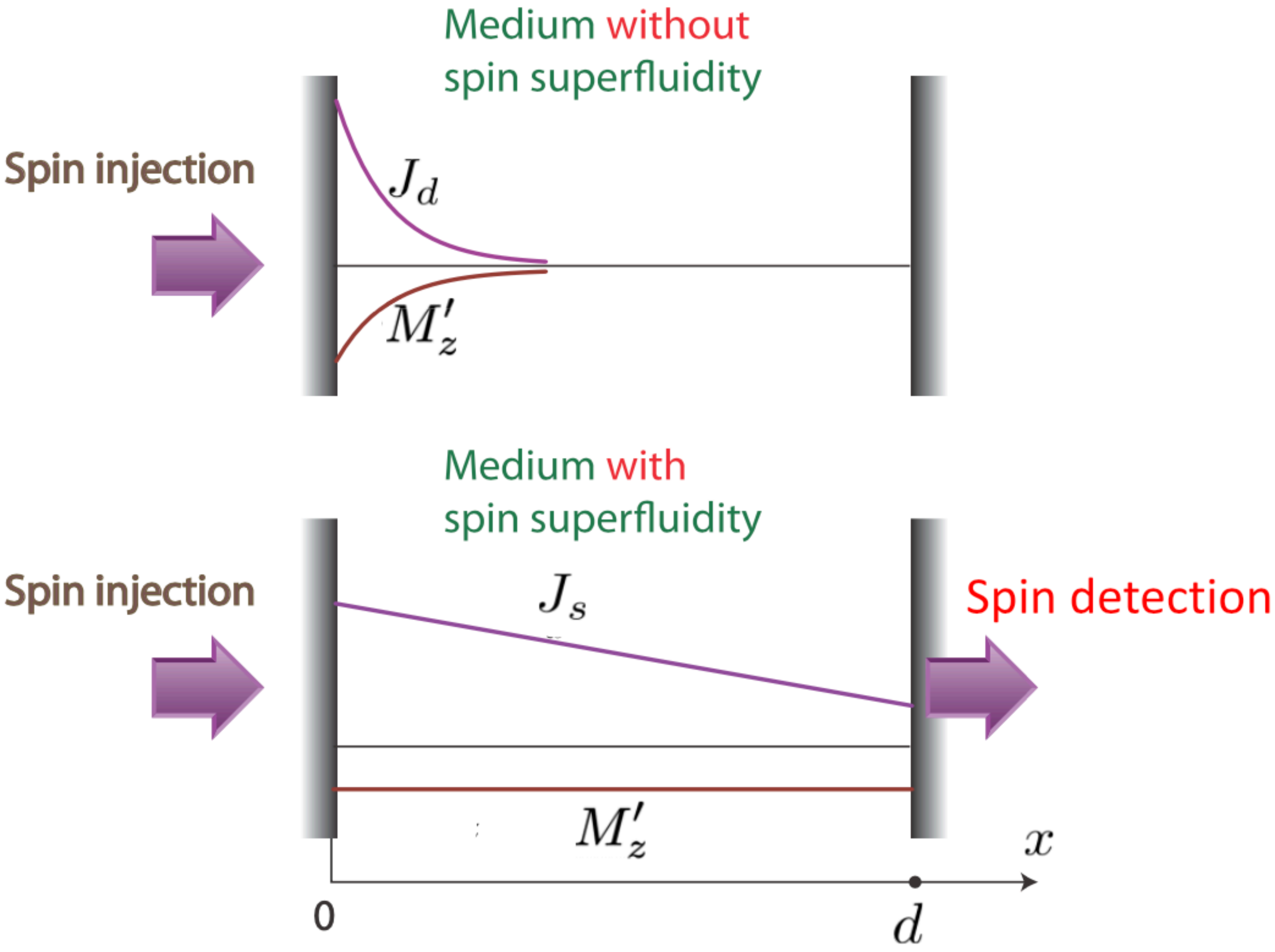
- Charge/electron number



Kirchhoff’s law

Transport degrees of freedom

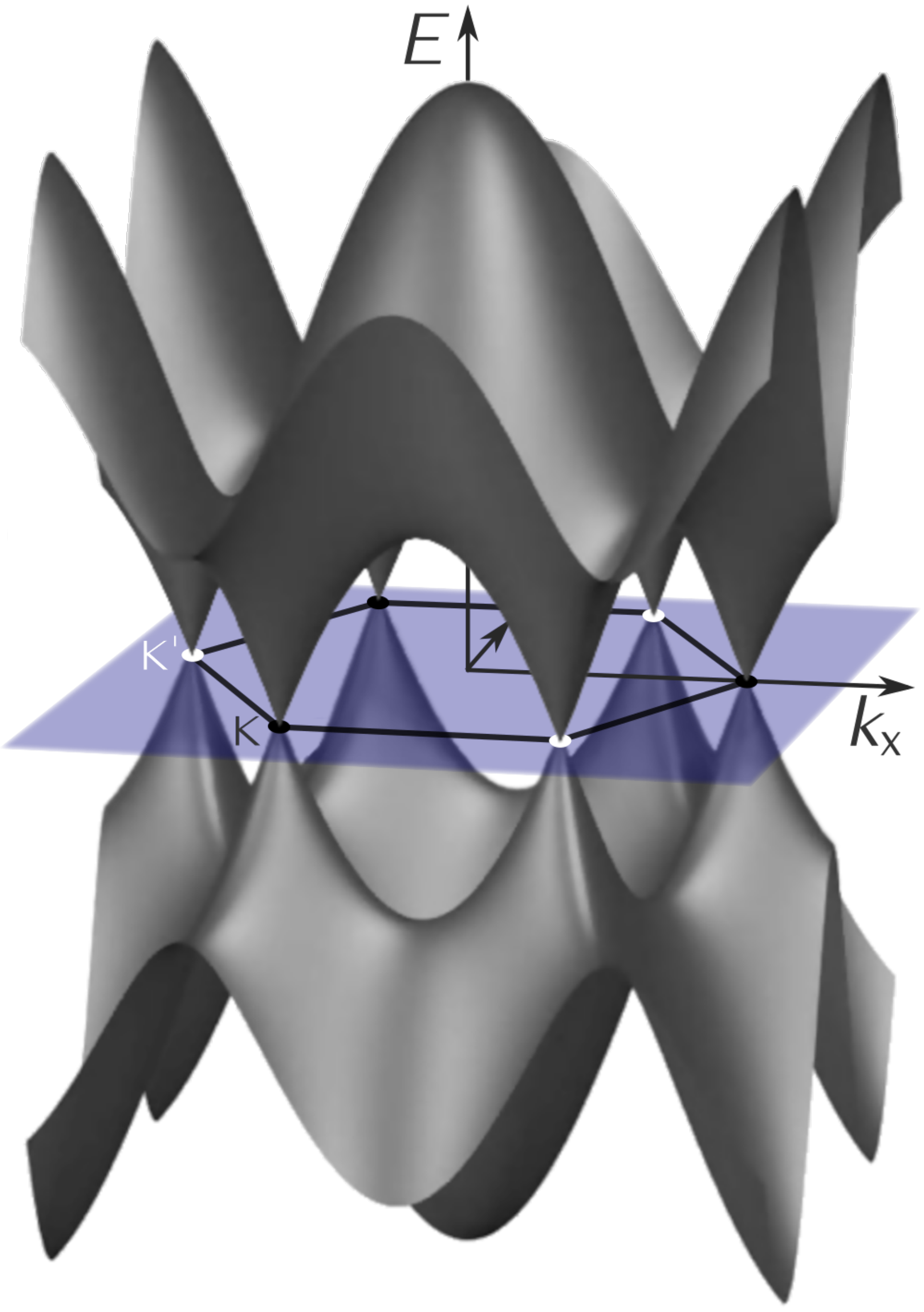
- Charge/electron number
- Spin (rotational symmetry)



E. B. Sonin

Transport degrees of freedom

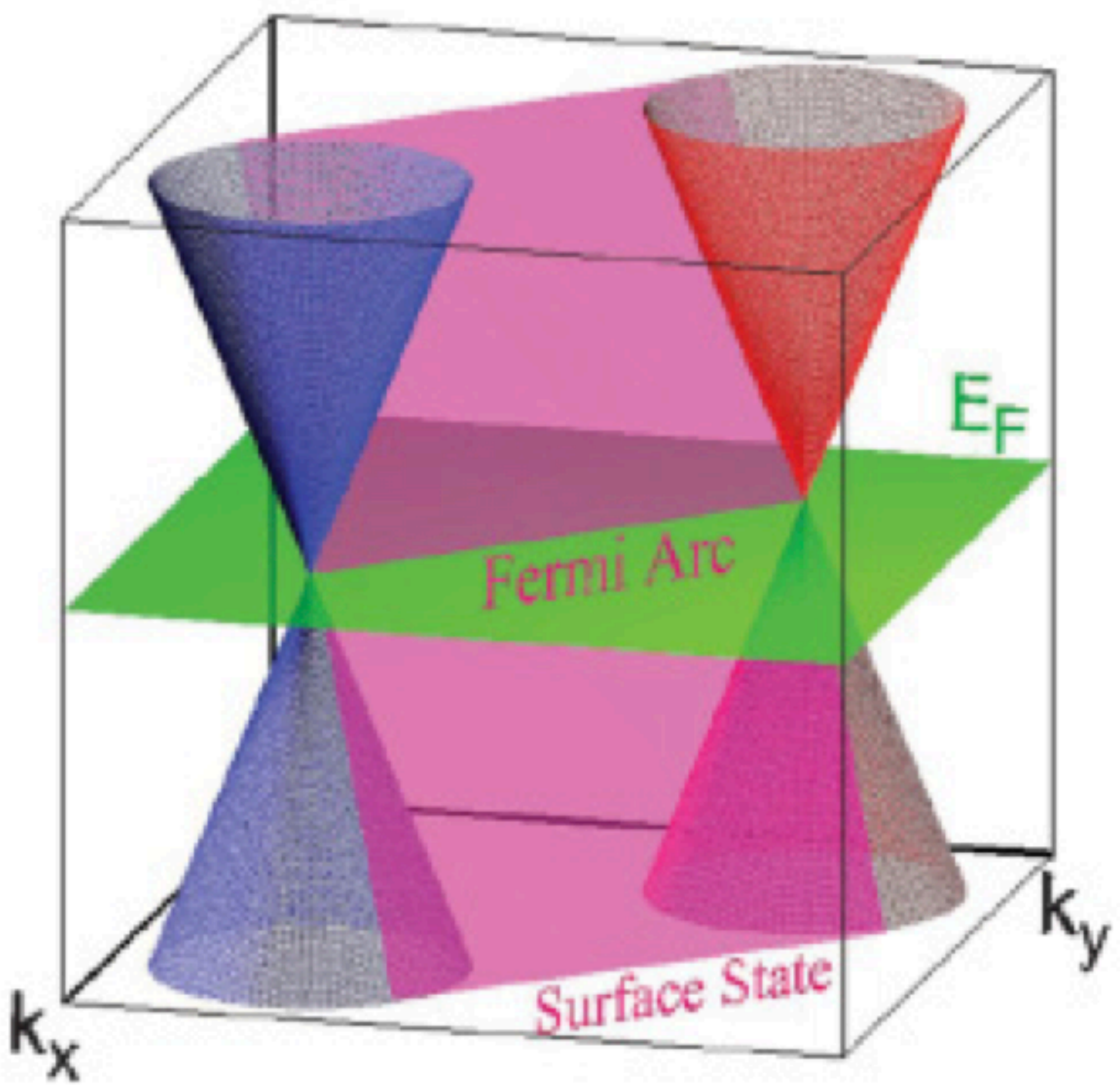
- Charge/electron number
- Spin
- Valley (a pseudospin dof protected by band topology)



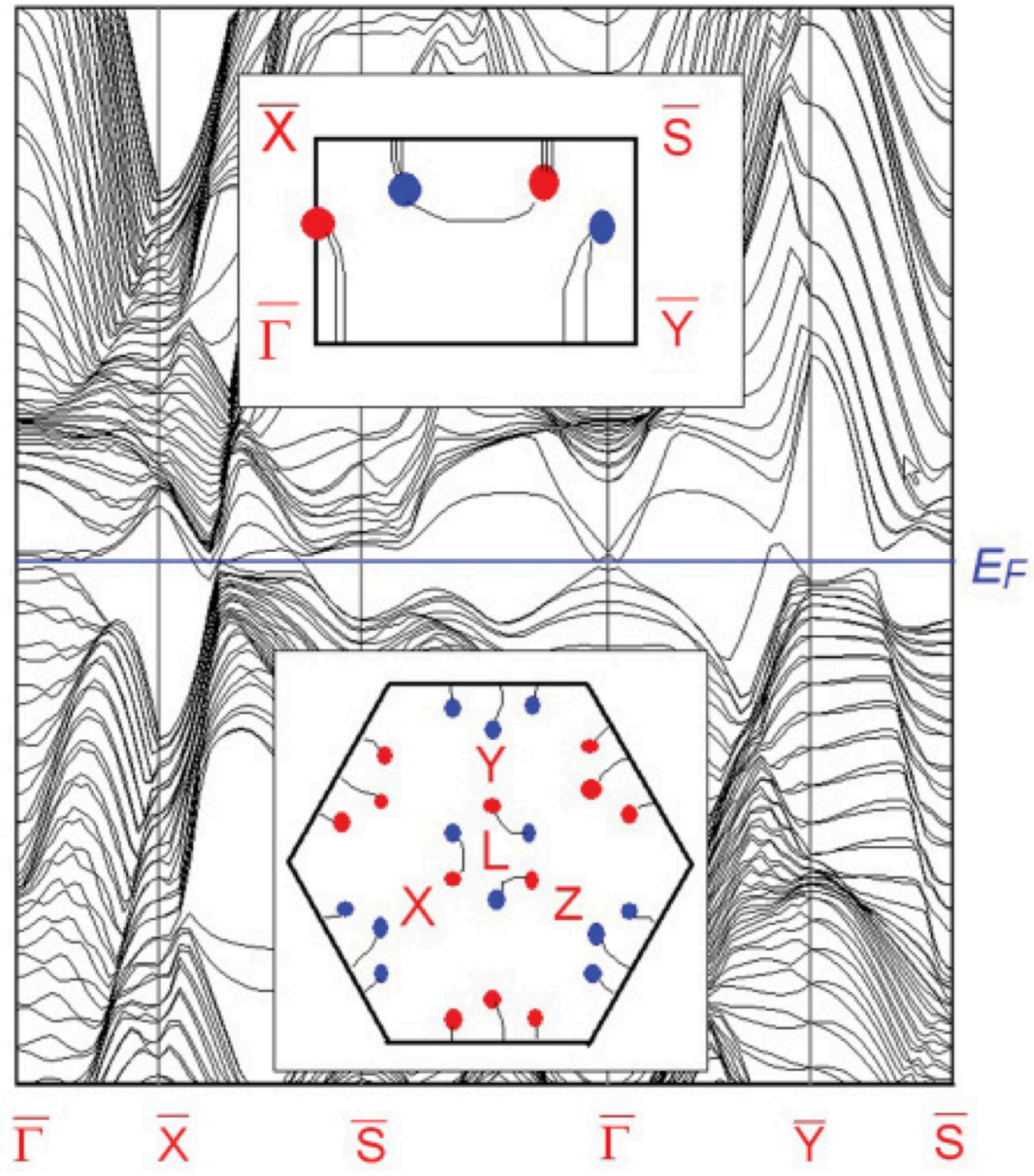
Graphene
Wikipedia

Transport degrees of freedom

- Charge/electron number
- Spin
- Valley



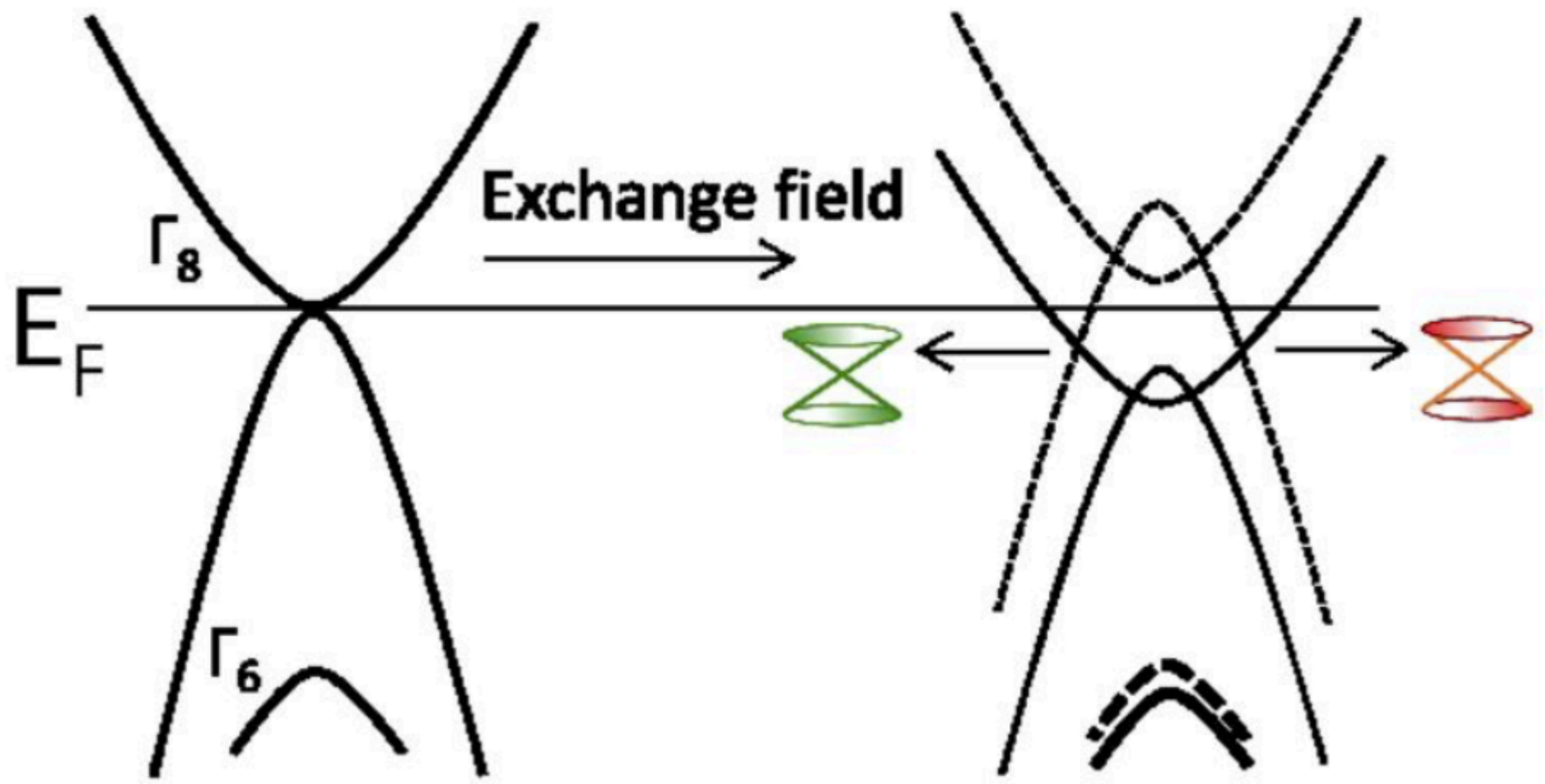
Weyl semimetal



Wan, Turner, Vishwanath, and Savrasov, 2015

Magnetic Weyl semimetal

Shekhar, …, Felser, 2018
Soh, …, Boothroyd, 2019



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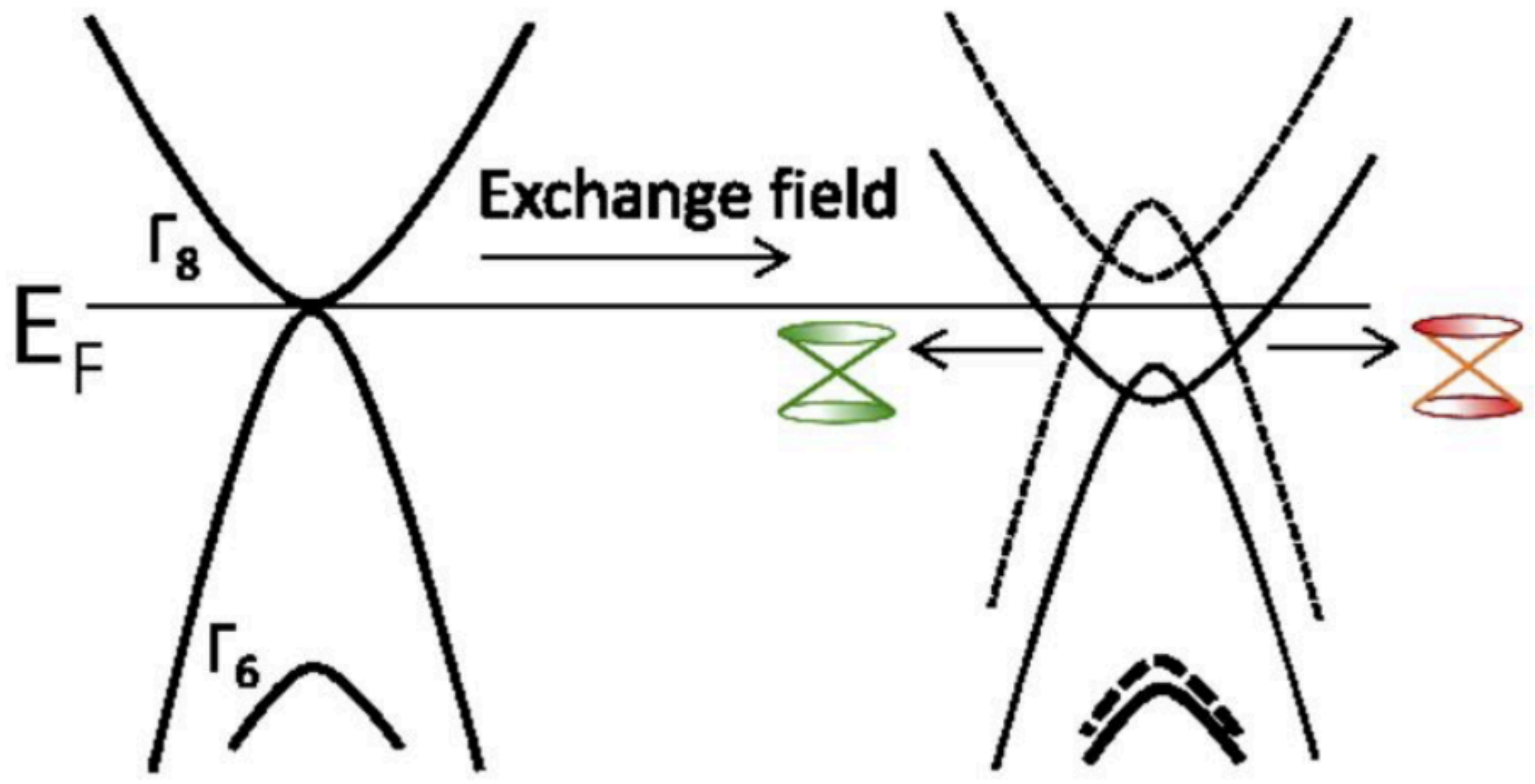

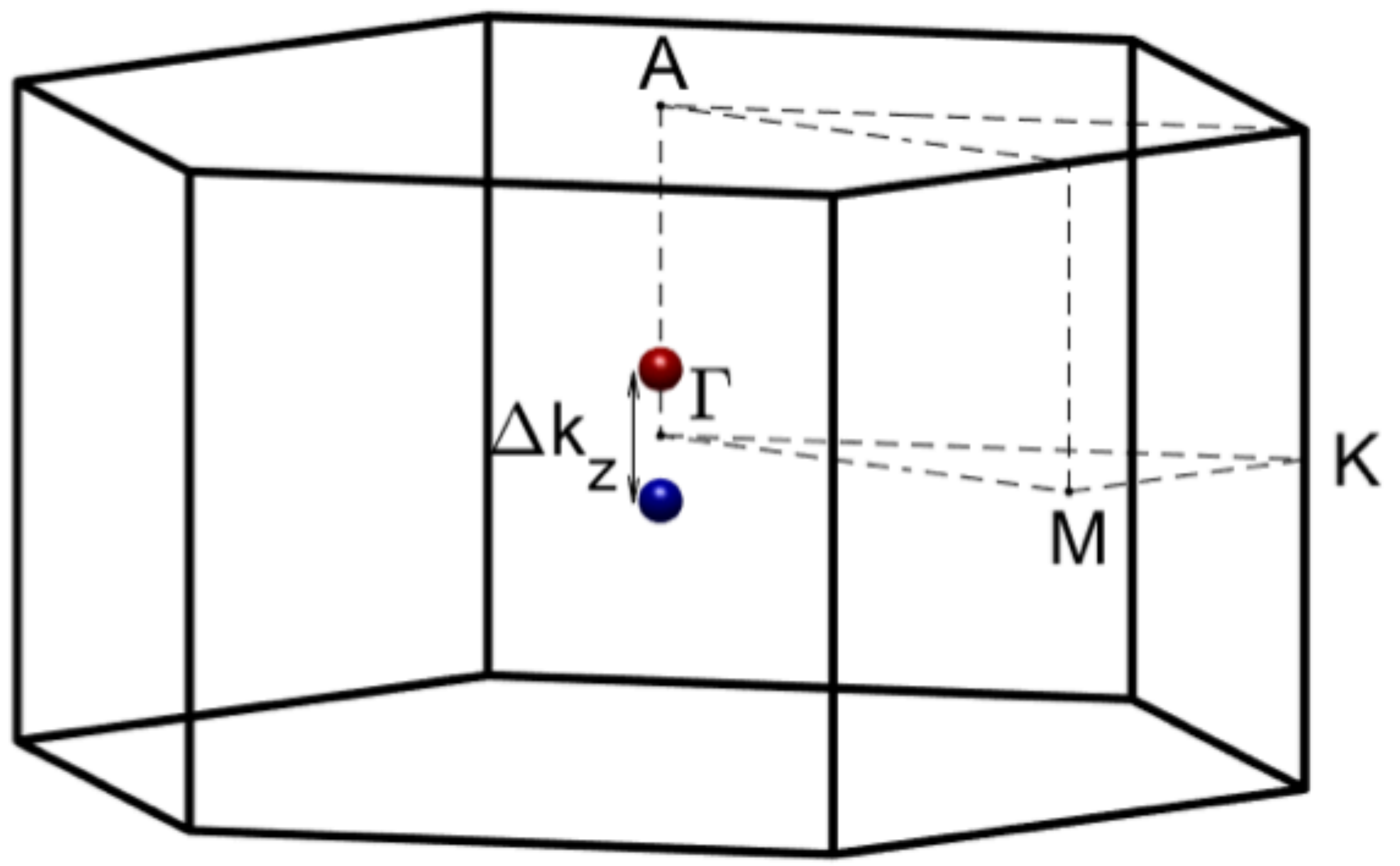

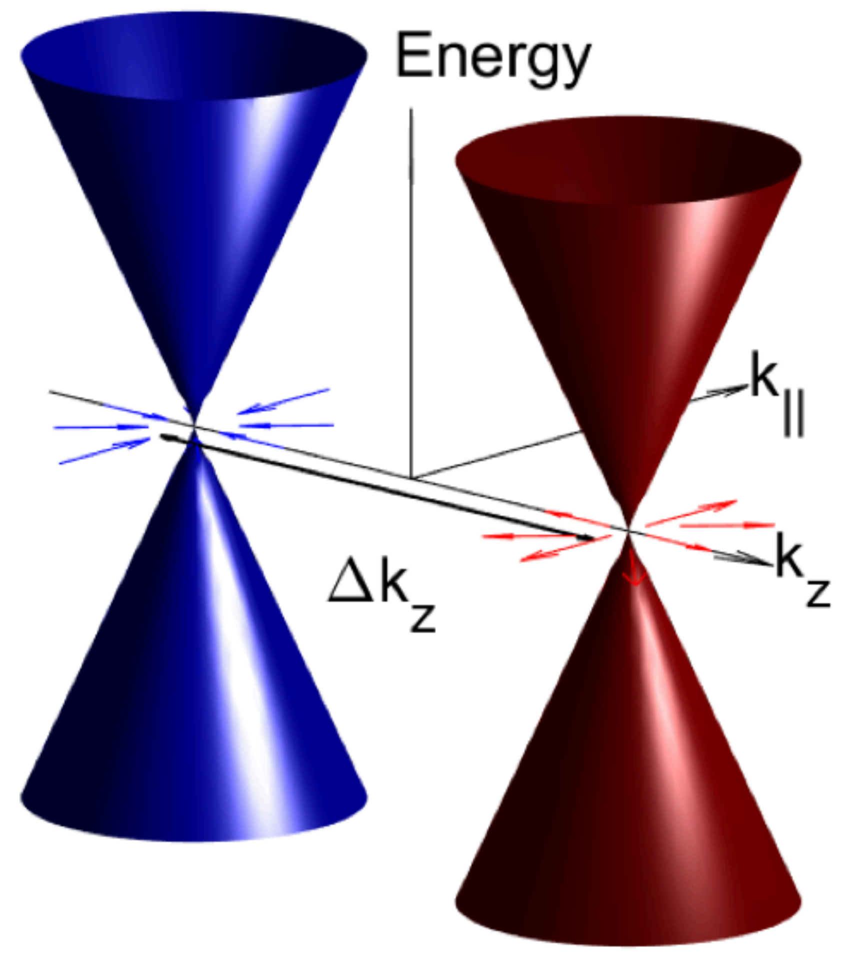

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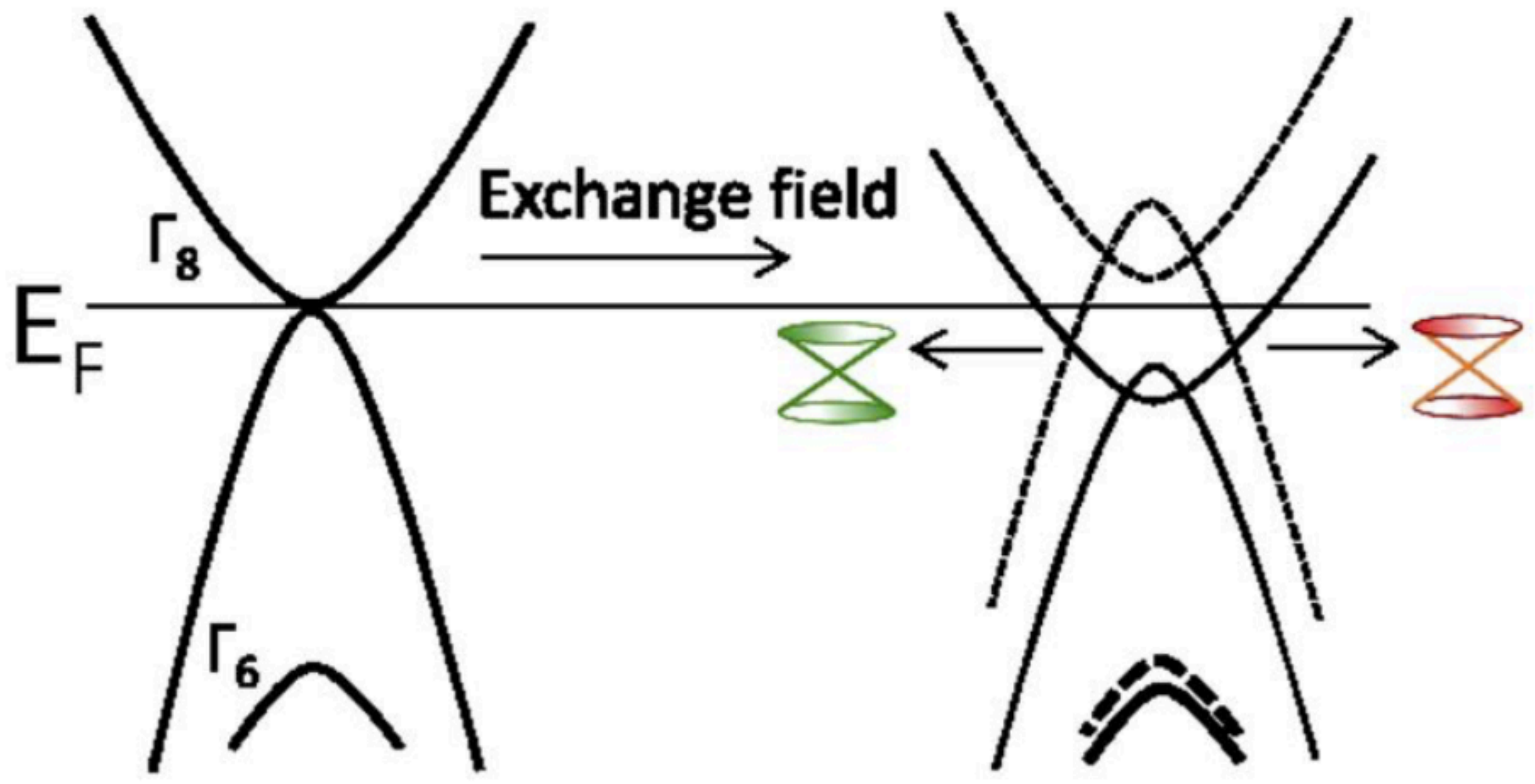
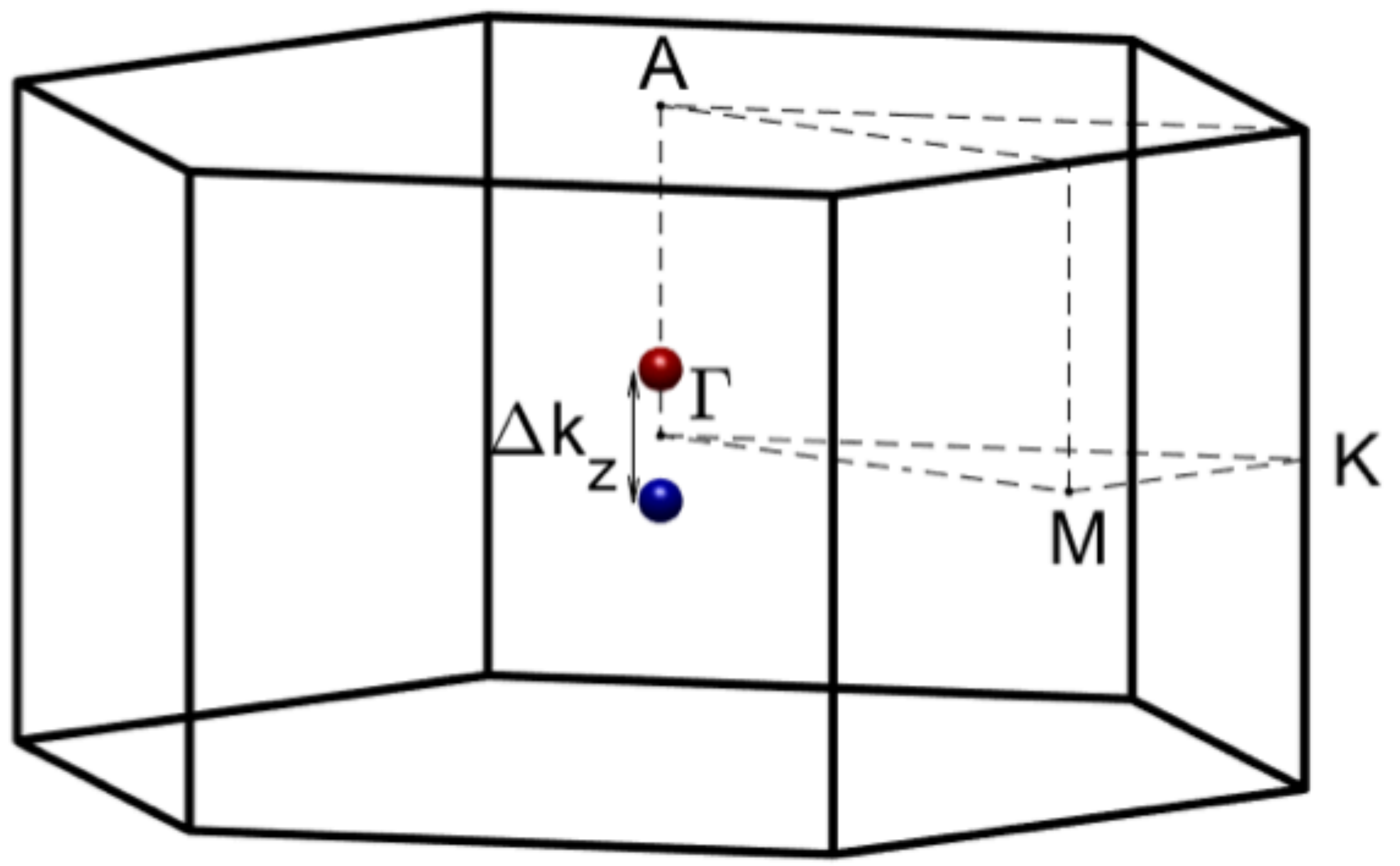
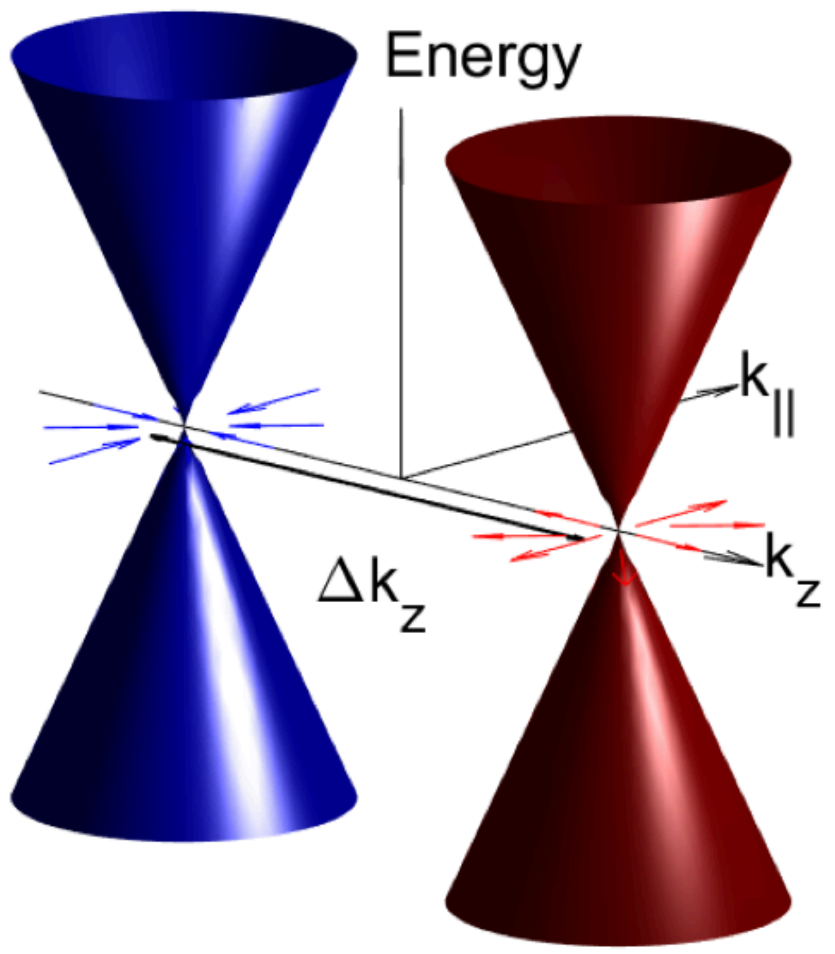


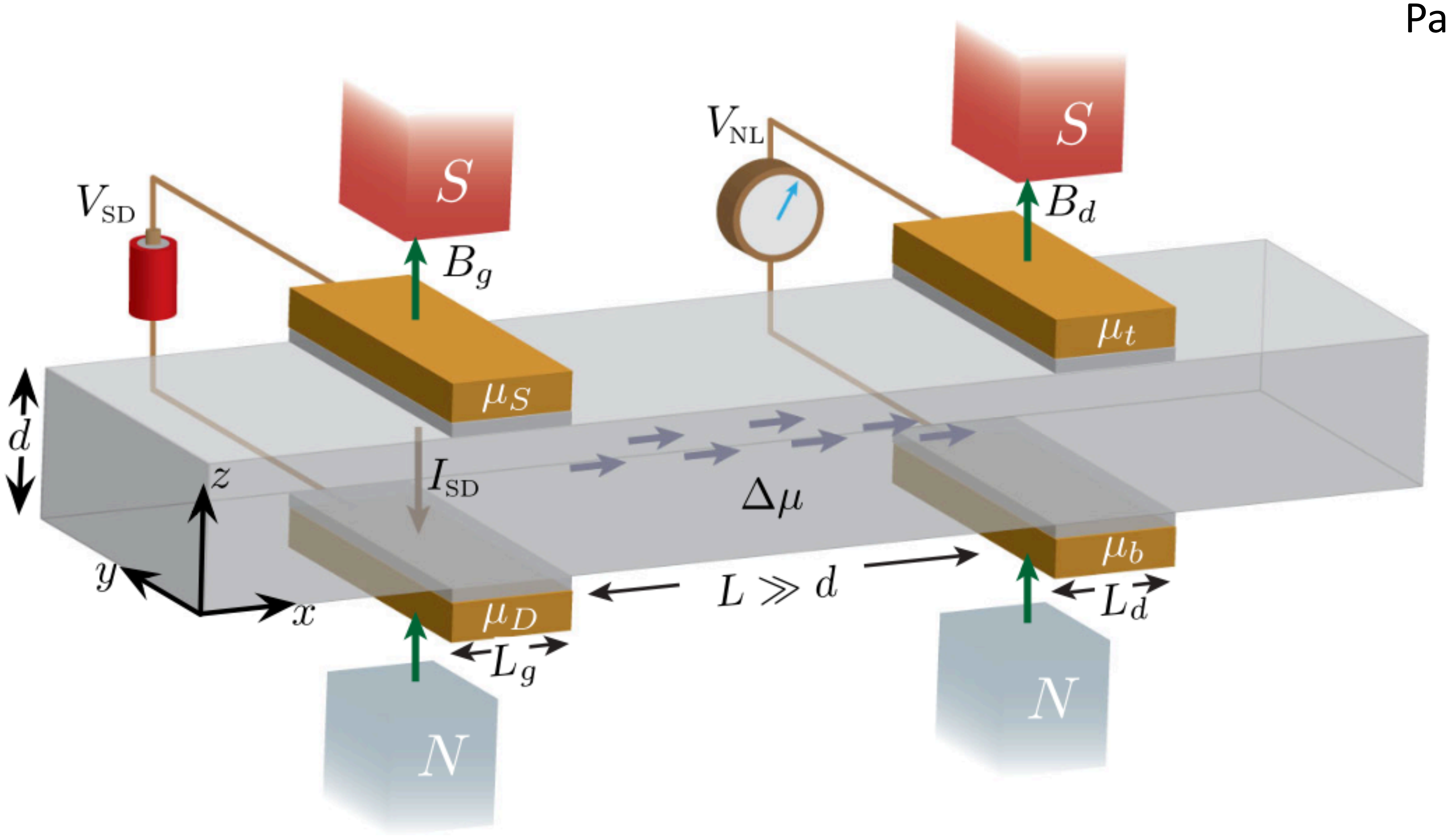


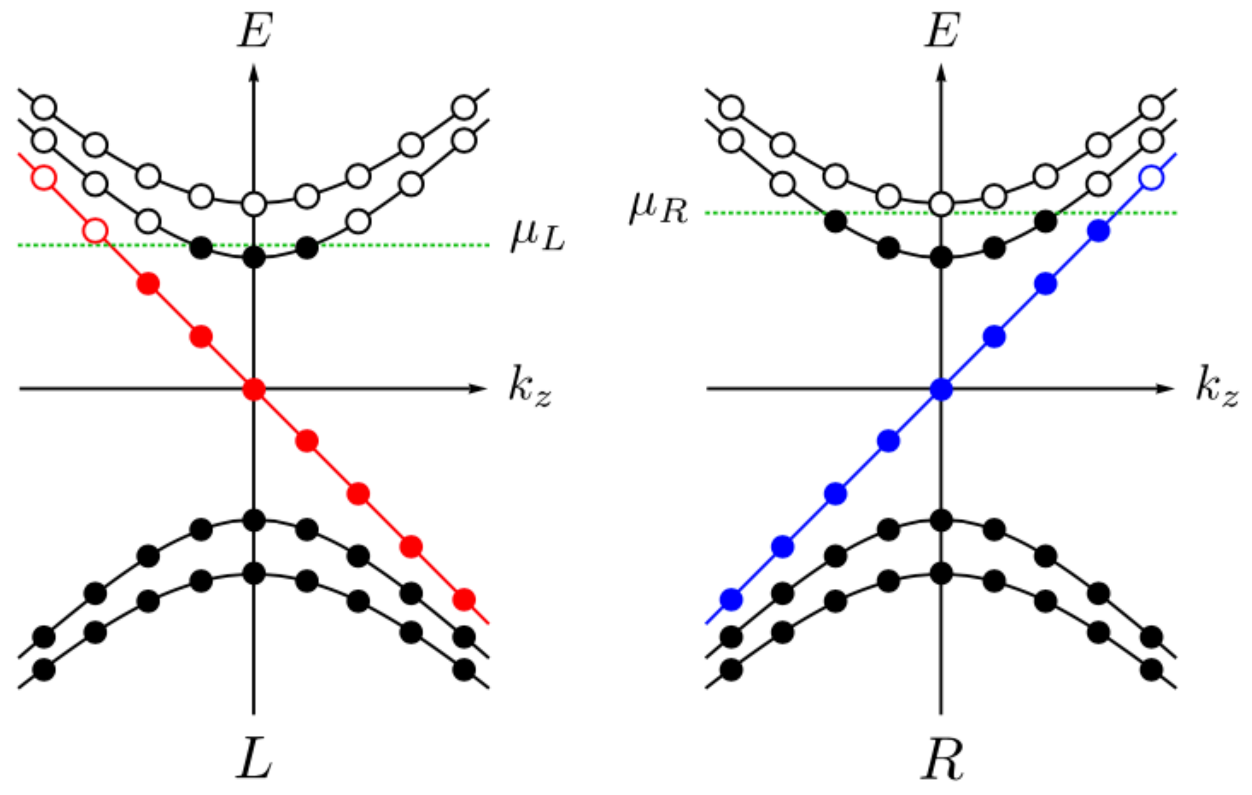


- Allow a single pair of valleys
- Valleytronics + Spintronics
- Interplay between band topology and magnetic textures

Nonlocal valley transport

Parameswaran, Grover, Abanin, Pesin and Vishwanath, 2014





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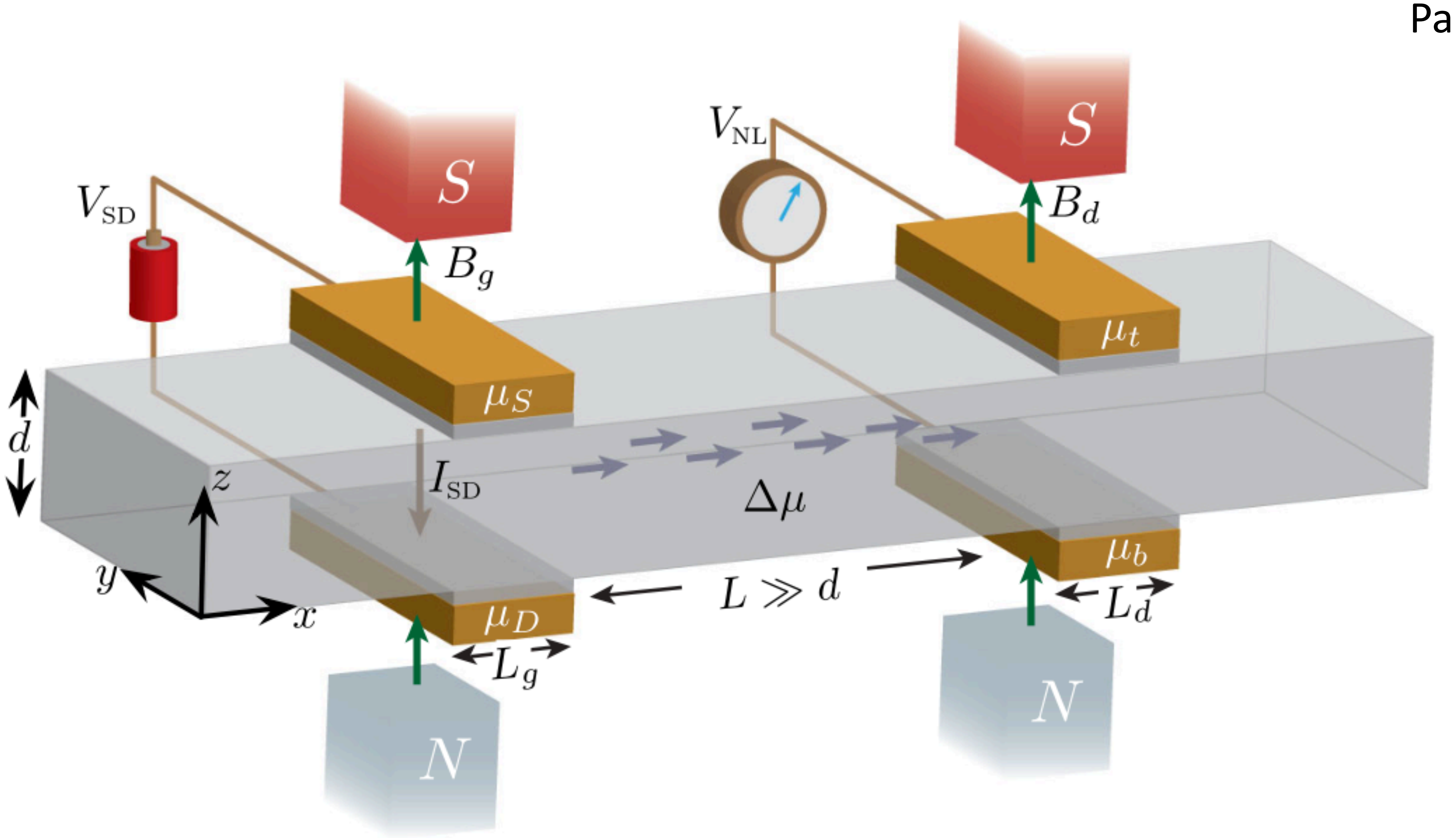
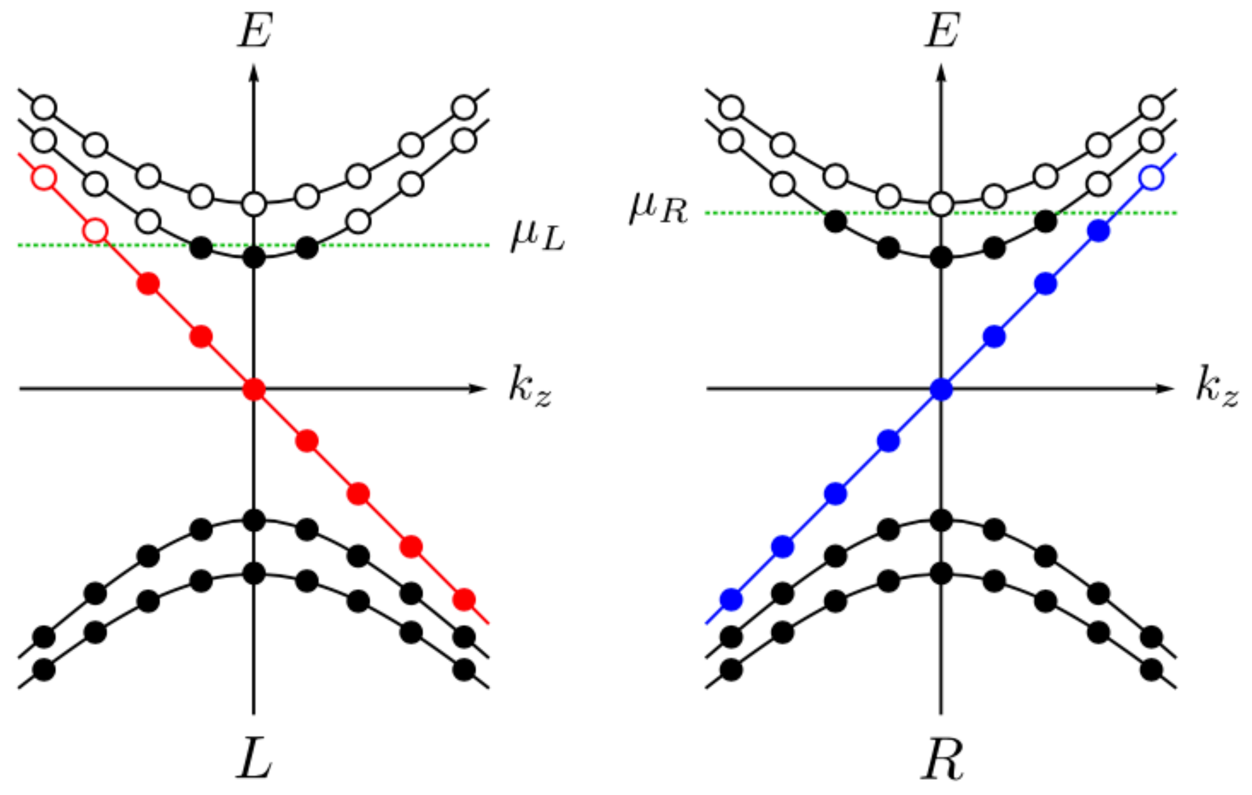




- Multiple diffusive degrees of freedom?

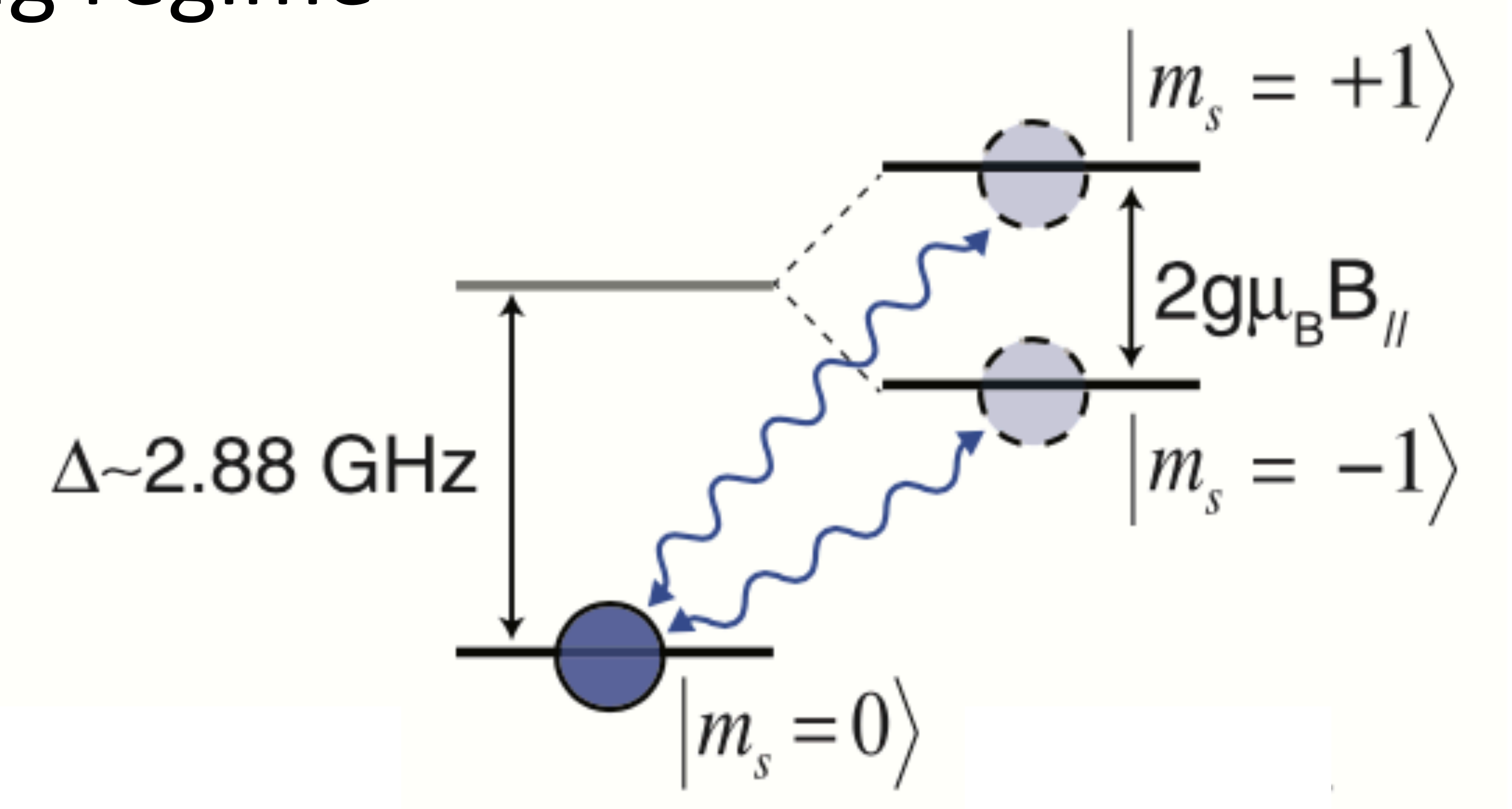
Magnetic noise spectroscopy

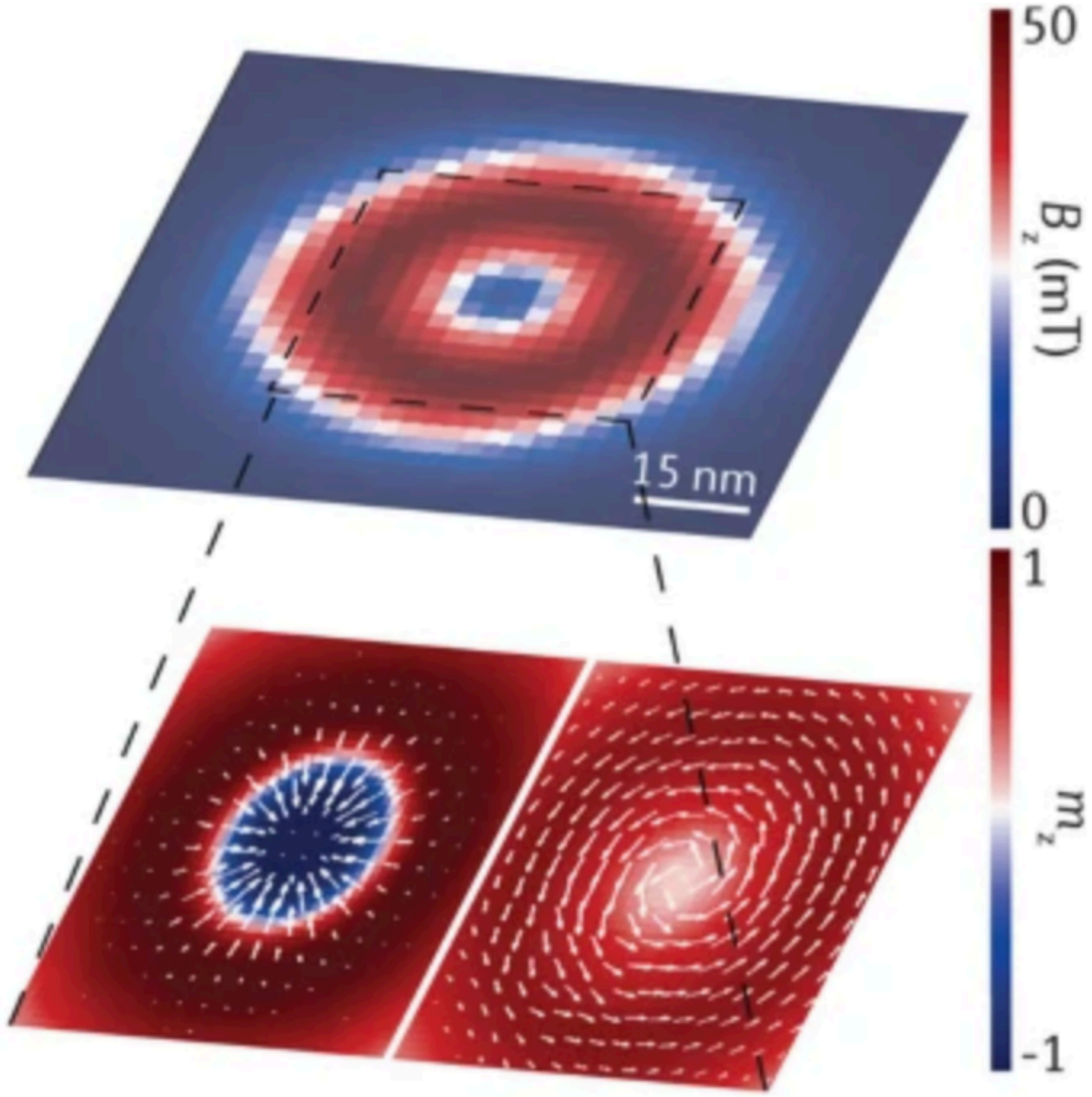
Single-qubit relaxometry with NV center:

Relaxation rate ~ magnetic field fluctuation ~ $\chi''(k \sim 1/d, \omega)$

Casola, van der Sar, Yacoby, 2018

- Sensitive to weak magnetic field
- High frequency resolution
- Tunable probing regime
- Noninvasive





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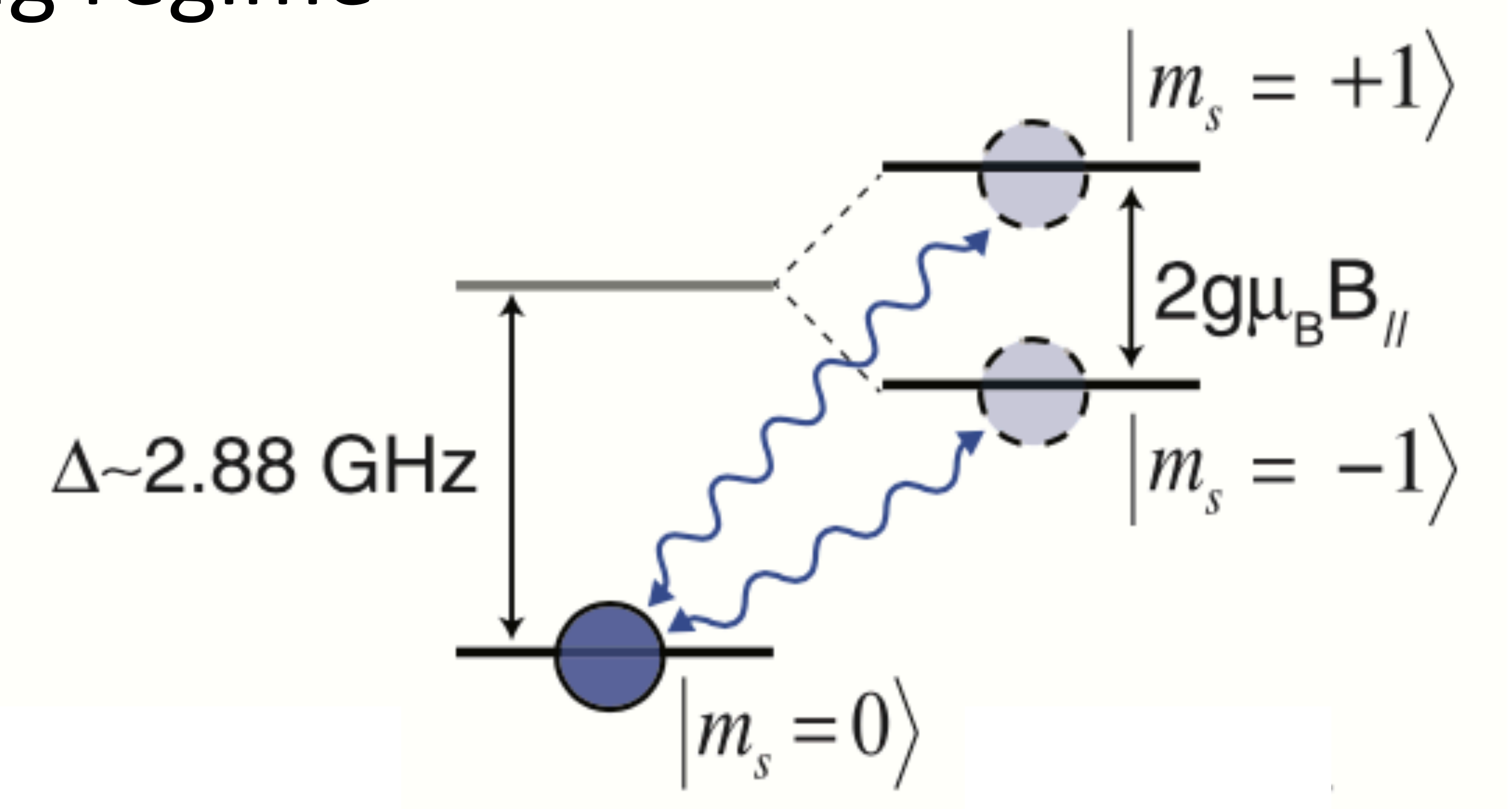

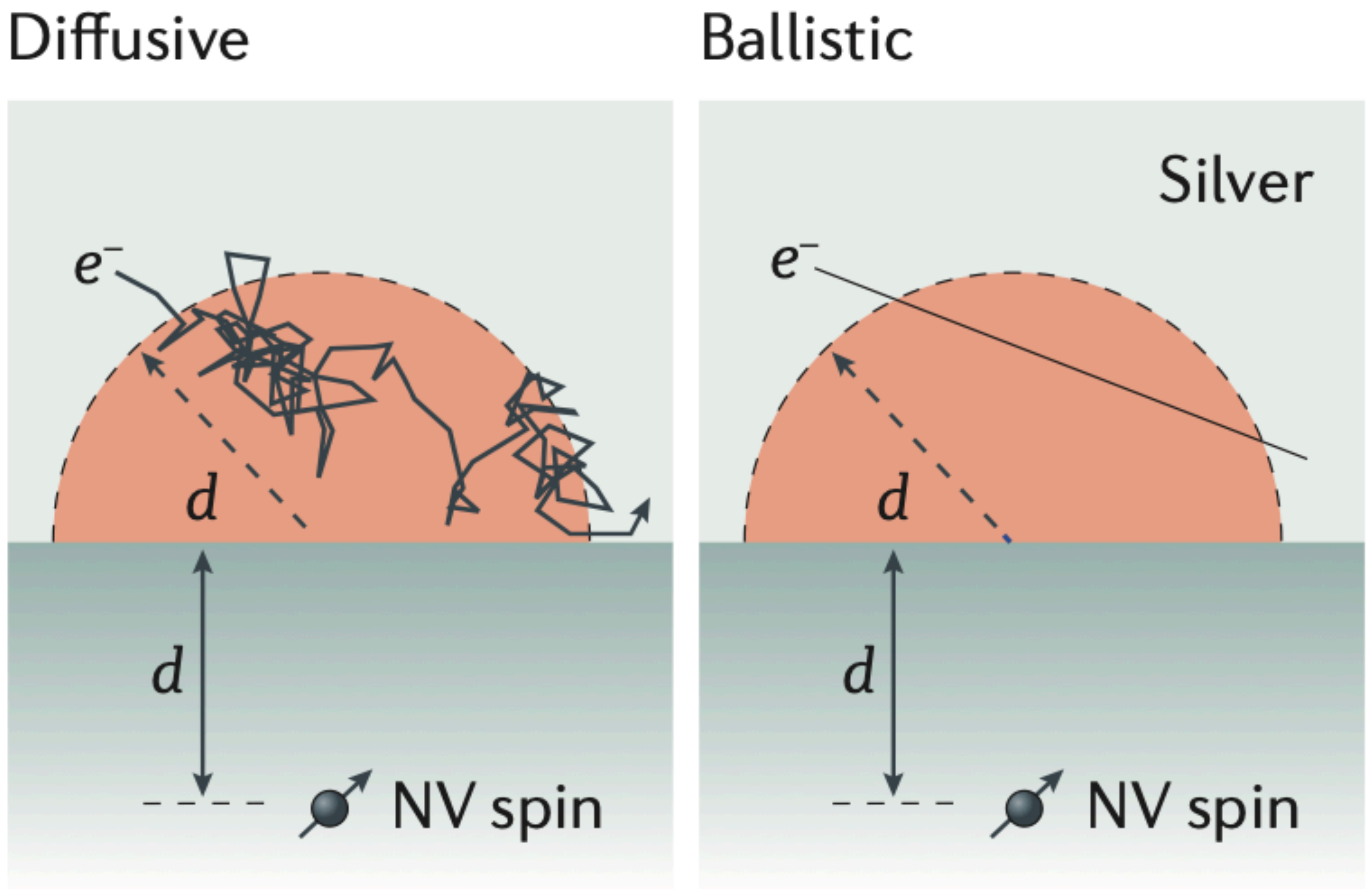

Magnetic noise spectroscopy

Kolkowitz et. al. 2015
Du et. al. 2017

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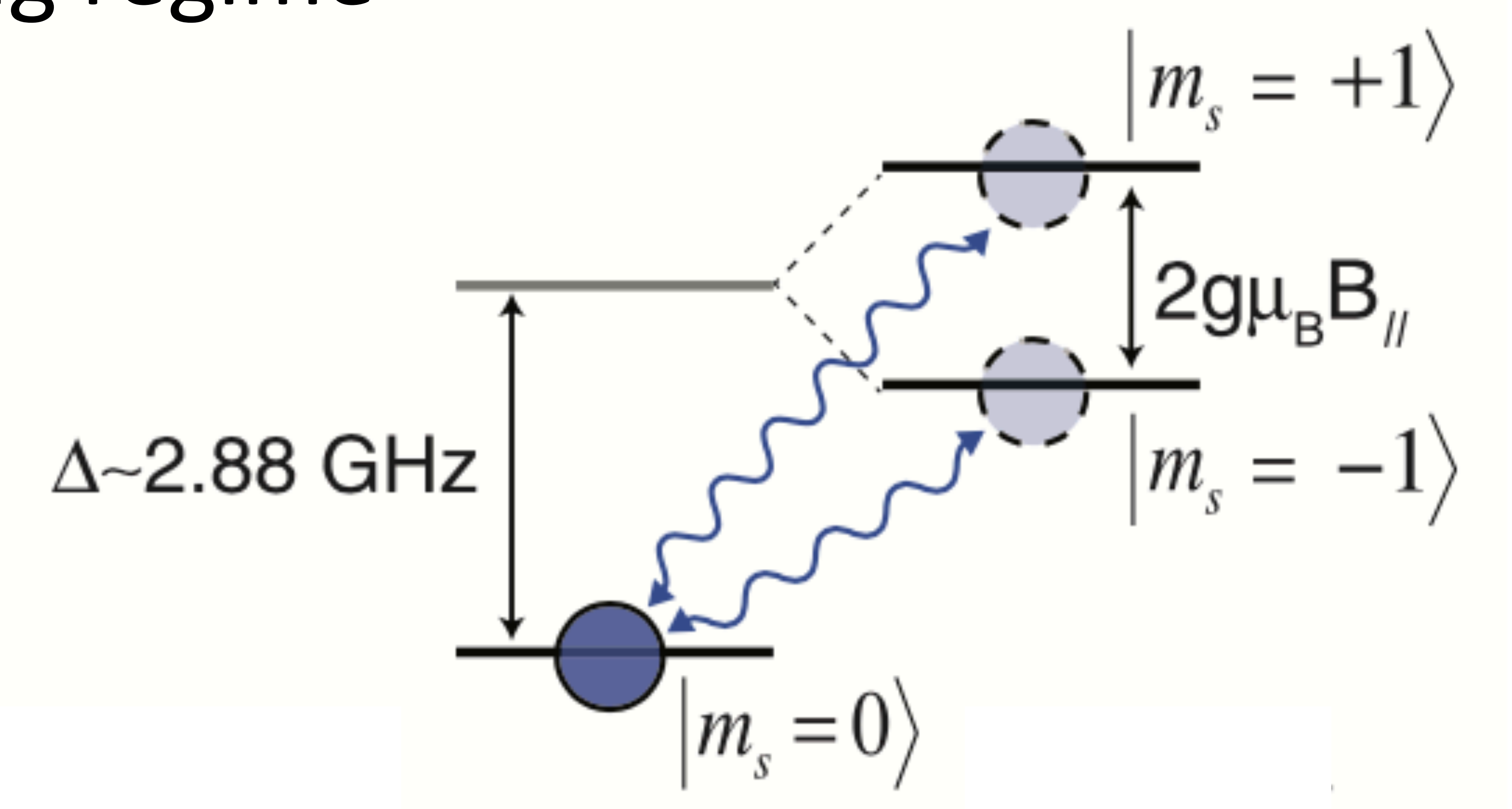
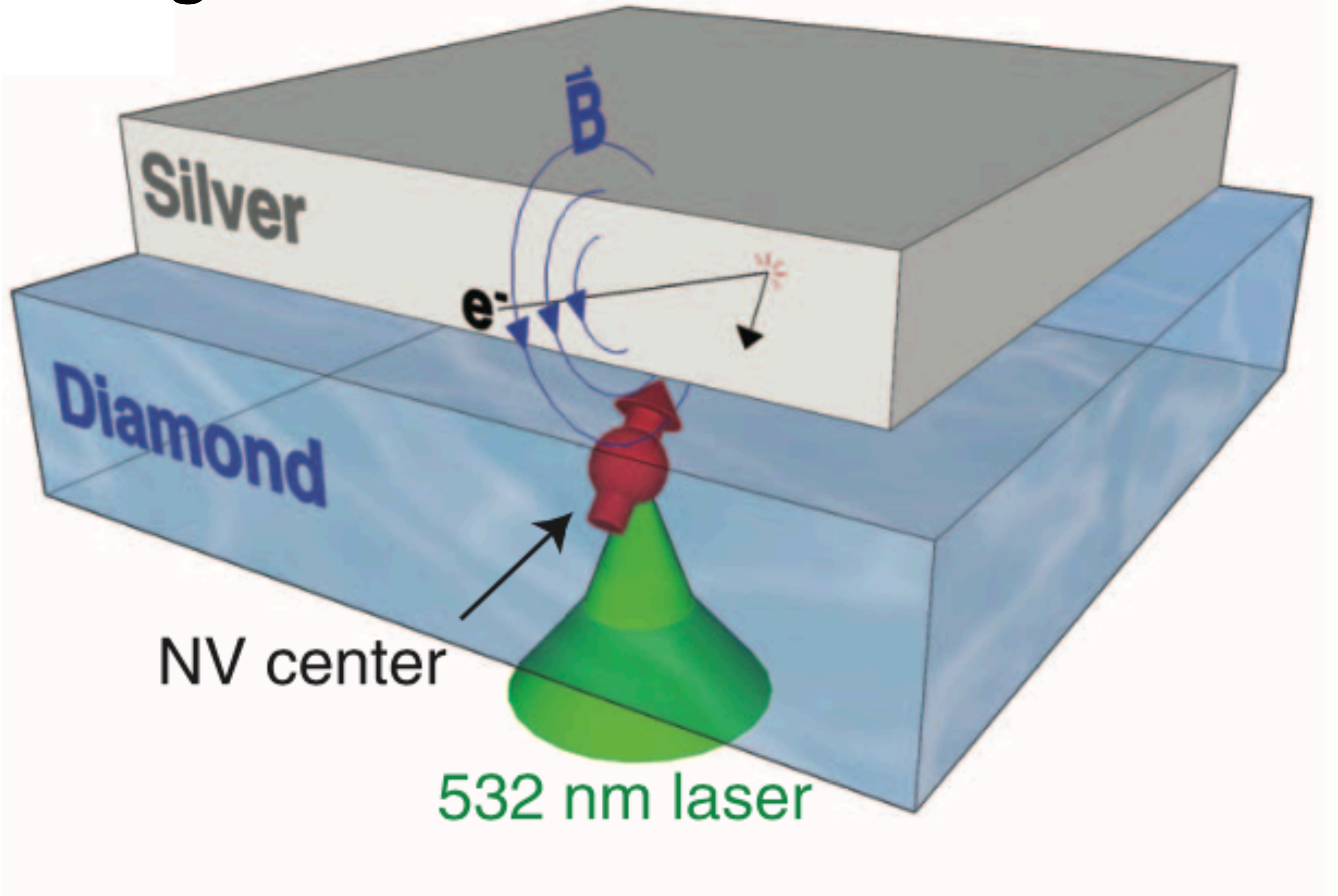
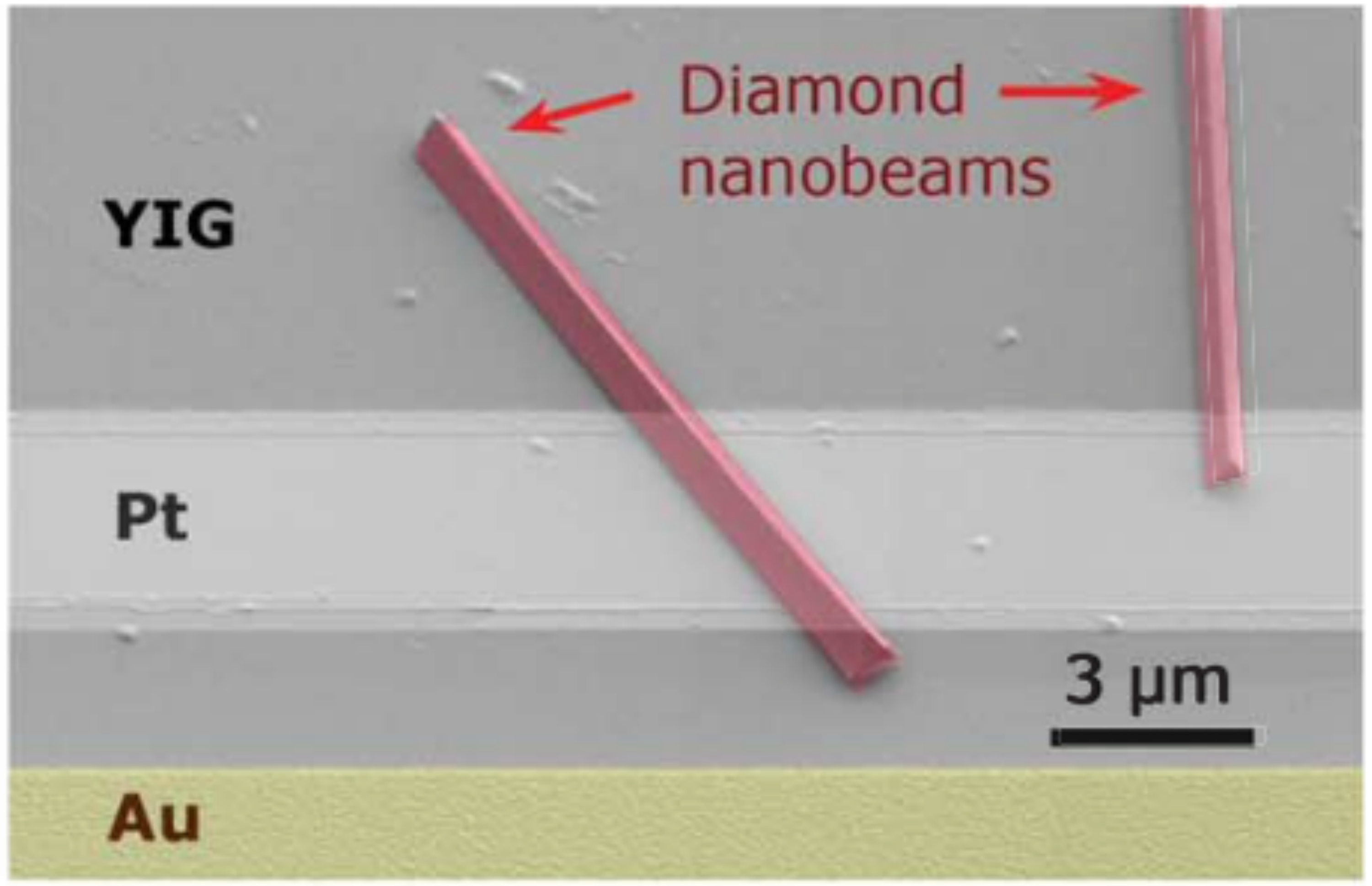


Charge fluctuations in metal

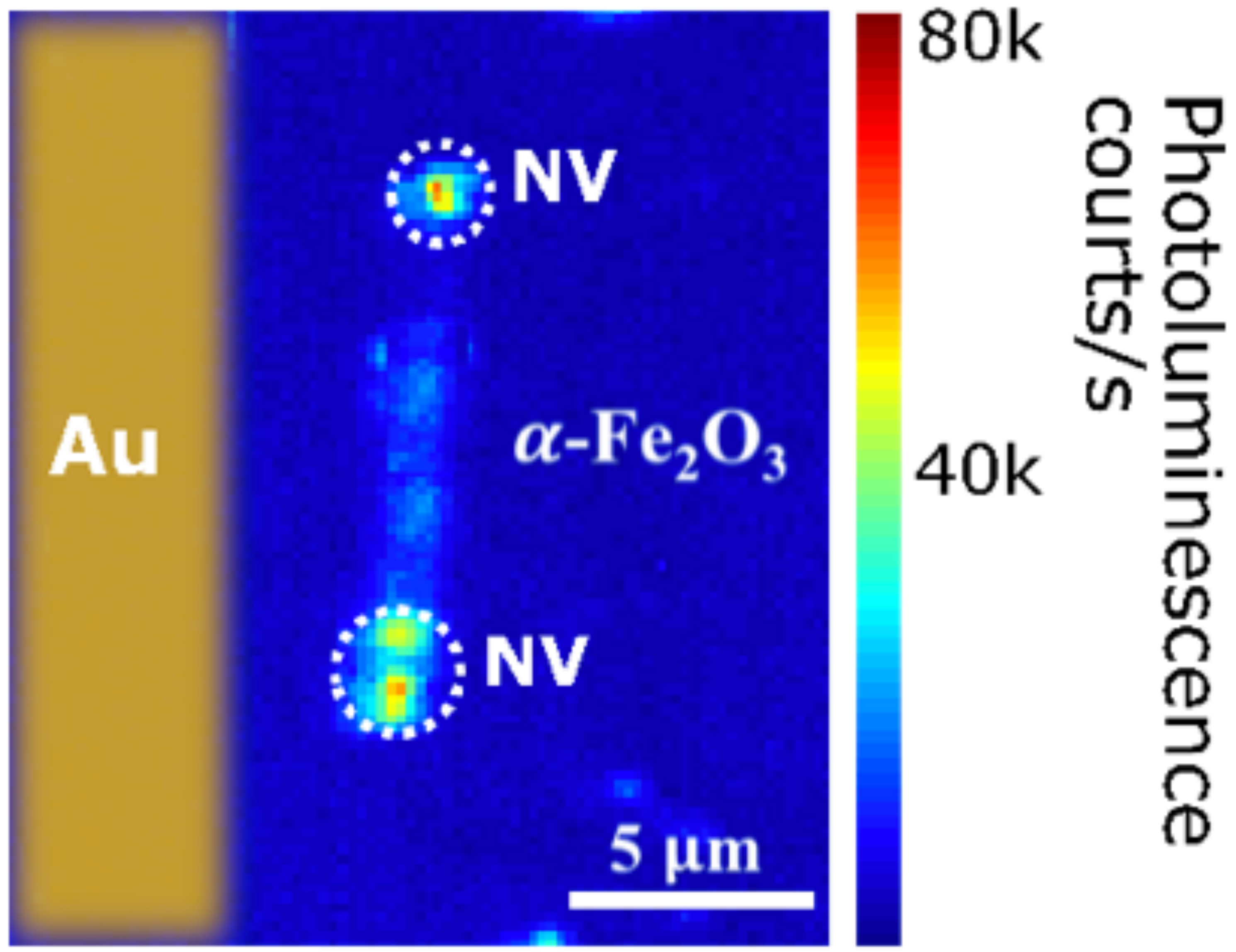


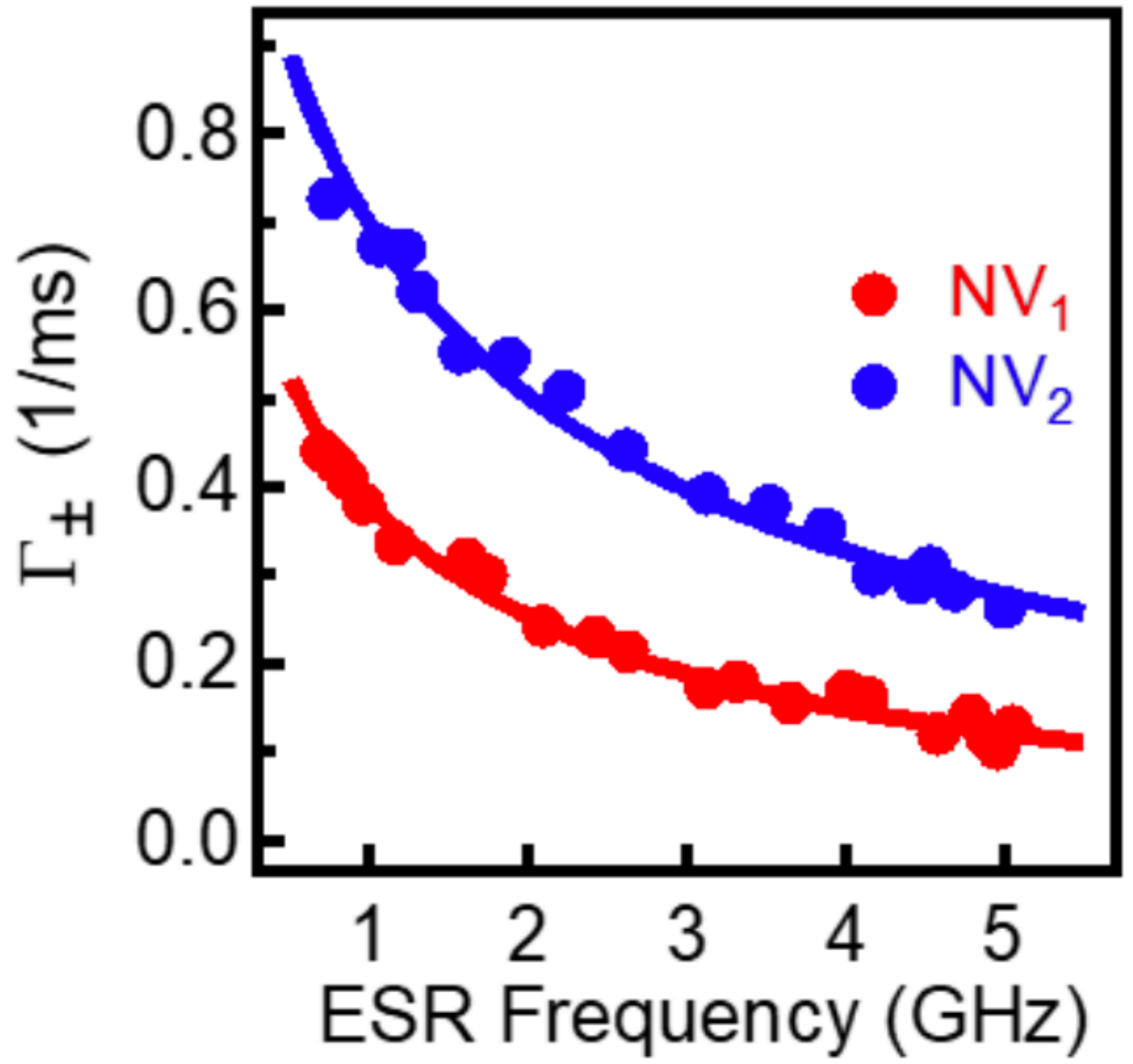
Spin fluctuations in magnetic insulator



Magnetic noise spectroscopy

Wang, SZ, … Tserkovnyak, Du, 2022

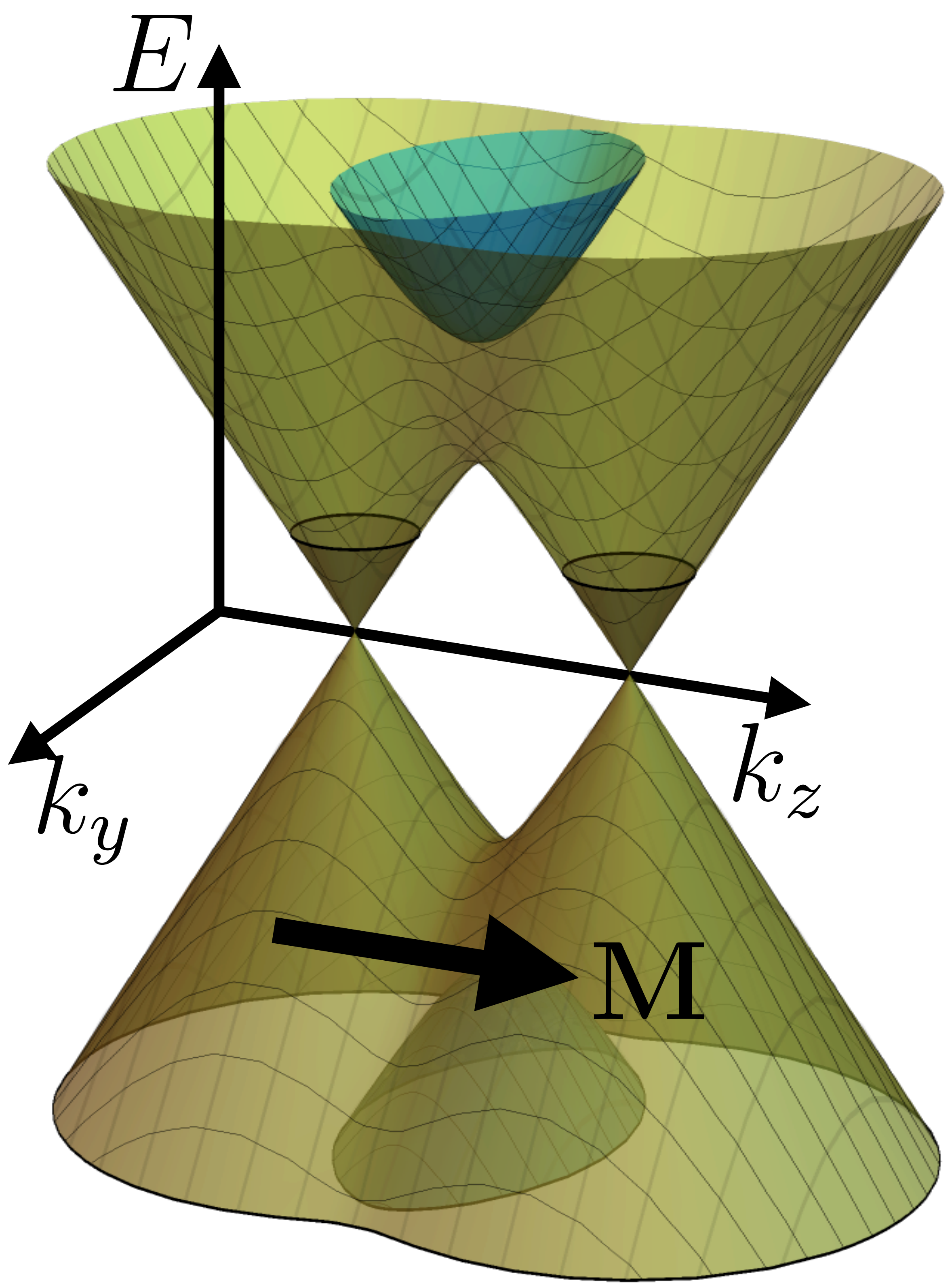




Diffusion of longitudinal spin fluctuations $\partial_t s_\parallel - D\nabla^2 s_\parallel = -\frac{1}{\tau_s} s_\parallel$

↓ spin diffusion constant

Magnetic Weyl semimetal



A minimal four-band model:

Burkov, Hook, Balents, 2011

$$H = v\tau_z \otimes (\boldsymbol{\sigma} \cdot \hbar\mathbf{k}) + \Delta\tau_x + J\boldsymbol{\sigma} \cdot \mathbf{M}$$

↓ Valley ↓ Spin

charge current $\mathbf{j}^c = \mathbf{j}^+ + \mathbf{j}^-$

valley current $\mathbf{j}^v = \mathbf{j}^+ - \mathbf{j}^-$

$$= \langle \tau_z \partial_{\mathbf{k}} H/\hbar \rangle = v\langle \boldsymbol{\sigma} \rangle$$

↓ Local itinerant spin density

Langevin approach in diffusive regime

Magnetic noise contribution from charge, valley, and spin

Langevin approach in diffusive regime

Flavor	Charge
Diffusion equation	$\nabla \cdot \mathbf{j}^c = 0$
Basic relations	$\mathbf{j}^c = -\sigma \nabla \mu^c + \boldsymbol{\epsilon}^c$
Langevin equation	$\sigma \nabla^2 \mu^c = \nabla \cdot \boldsymbol{\epsilon}^c$
Magnetic field Generation	Charge current Biot-Savart law

Coulomb screening

White noise

+ boundary conditions

Langevin approach in diffusive regime

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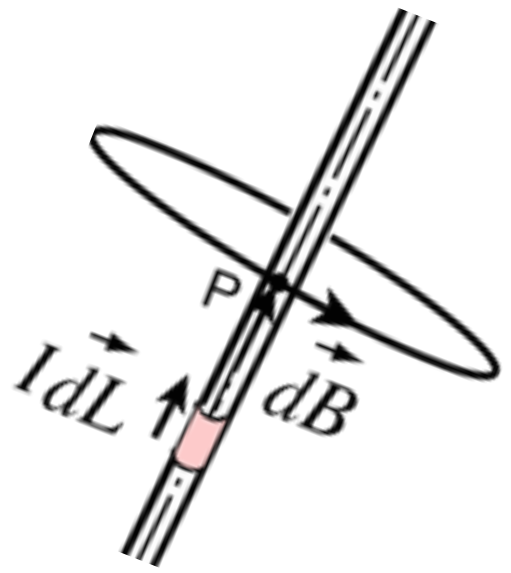


Spectral function for the magnetic noise

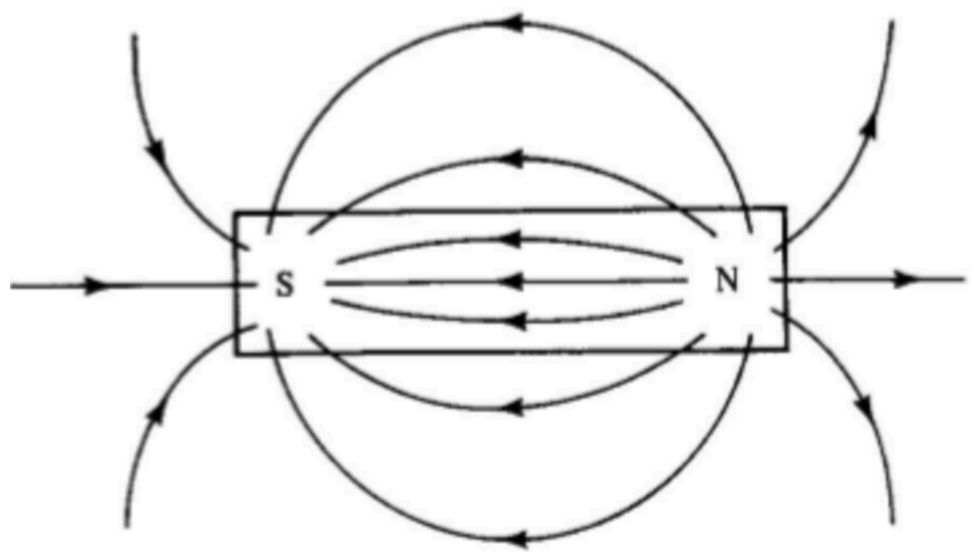
$$\mathcal{B}_{ii'}(\omega) = \int dt\, e^{i\omega t} \langle B_i(\mathbf{r}_{\rm NV}, t) B_{i'}(\mathbf{r}_{\rm NV}, 0) \rangle$$

Johnson-Nyquist noise $\sim \dfrac{\pi e^2 k_B T \sigma}{c^2 d}$ → Conductivity

Langevin approach in diffusive regime

Flavor	Charge	Valley
Diffusion equation	$\nabla \cdot \mathbf{j}^c = 0$	$\partial_t \rho^v + \nabla \cdot \mathbf{j}^v = -\frac{1}{\tau^v}\rho^v$
Basic relations	$\mathbf{j}^c = -\sigma \nabla \mu^c + \boldsymbol{\epsilon}^c$	$\rho^v = \frac{\nu}{2}\mu^v,\ \mathbf{j}^v = -\frac{\sigma}{2}\nabla \mu^v + \boldsymbol{\epsilon}^v$
Langevin equation	$\sigma \nabla^2 \mu^c = \nabla \cdot \boldsymbol{\epsilon}^c$	$\left(\partial_t + \frac{1}{\tau^v}\right)\mu^v - D\nabla^2 \mu^v = -\frac{2}{\nu}\nabla \cdot \boldsymbol{\epsilon}^v$
Magnetic field Generation	Charge current Biot-Savart law	Valley current —> itinerant spin density Demagnetization field

No screening (charge neutrality)

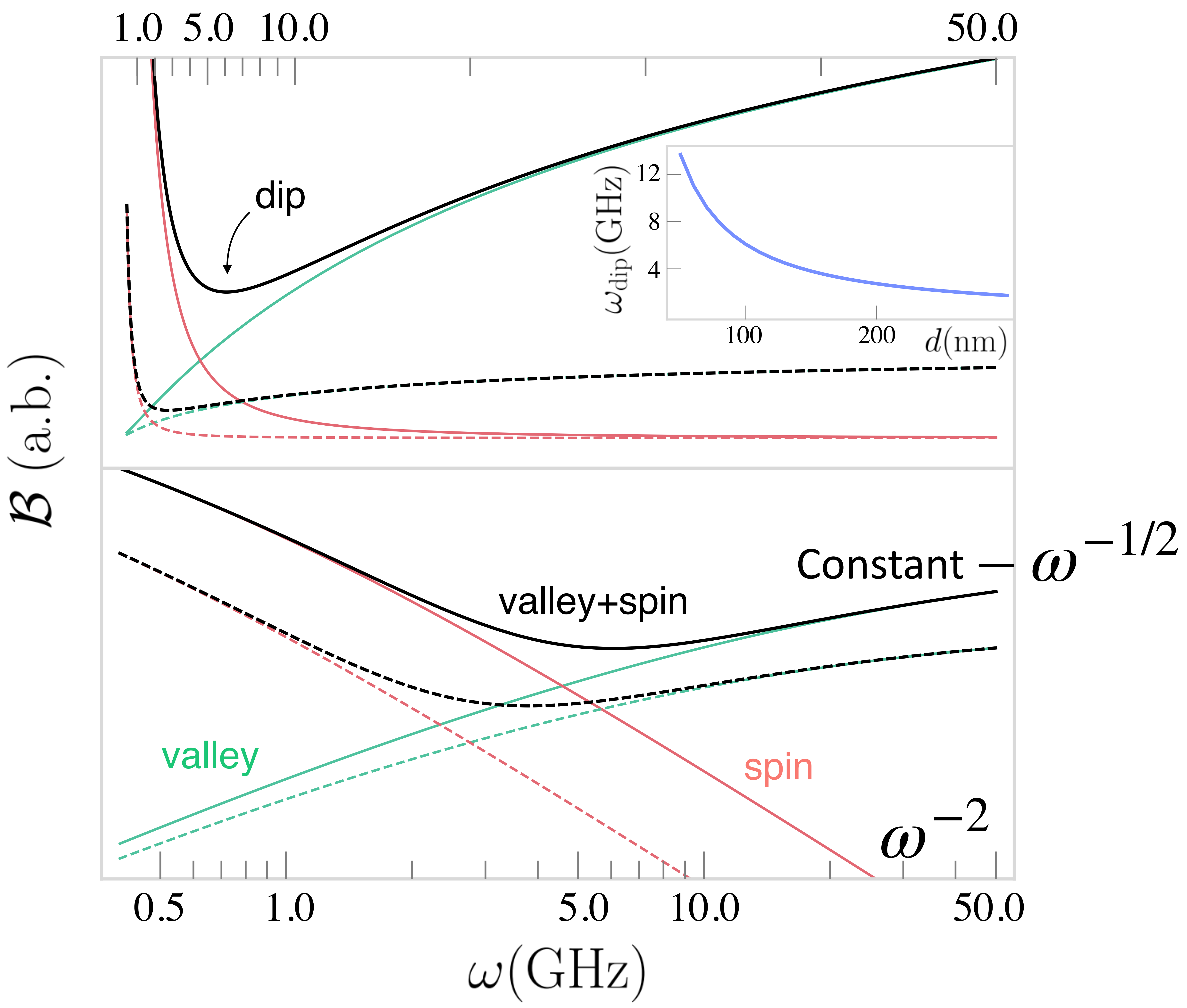


Langevin approach in diffusive regime

Flavor	Charge	Valley	Spin
Diffusion equation	$\nabla \cdot \mathbf{j}^c = 0$	$\partial_t \rho^v + \nabla \cdot \mathbf{j}^v = -\frac{1}{\tau^v}\rho^v$	$\partial_t s_z + \nabla \cdot \mathbf{j}^s = -\frac{1}{\tau^s} s_z$
Basic relations	$\mathbf{j}^c = -\sigma \nabla \mu^c + \boldsymbol{\epsilon}^c$	$\rho^v = \frac{\nu}{2}\mu^v, \; \mathbf{j}^v = -\frac{\sigma}{2}\nabla \mu^v + \boldsymbol{\epsilon}^v$	$\mathbf{j}^s = -D^s \nabla s_z$
Langevin equation	$\sigma \nabla^2 \mu^c = \nabla \cdot \boldsymbol{\epsilon}^c$	$\left(\partial_t + \frac{1}{\tau^v}\right)\mu^v - D\nabla^2 \mu^v = -\frac{2}{\nu}\nabla \cdot \boldsymbol{\epsilon}^v$	$\left(\partial_t + \frac{1}{\tau^s}\right) s_z - D^s \nabla^2 s_z = \epsilon^s$
Magnetic field Generation	Charge current Biot-Savart law	Valley current —> itinerant spin density Demagnetization field	Spin density Demagnetization field

Predictions for magnetic noise

SZ, Tserkovnyak arXiv:2108.07305



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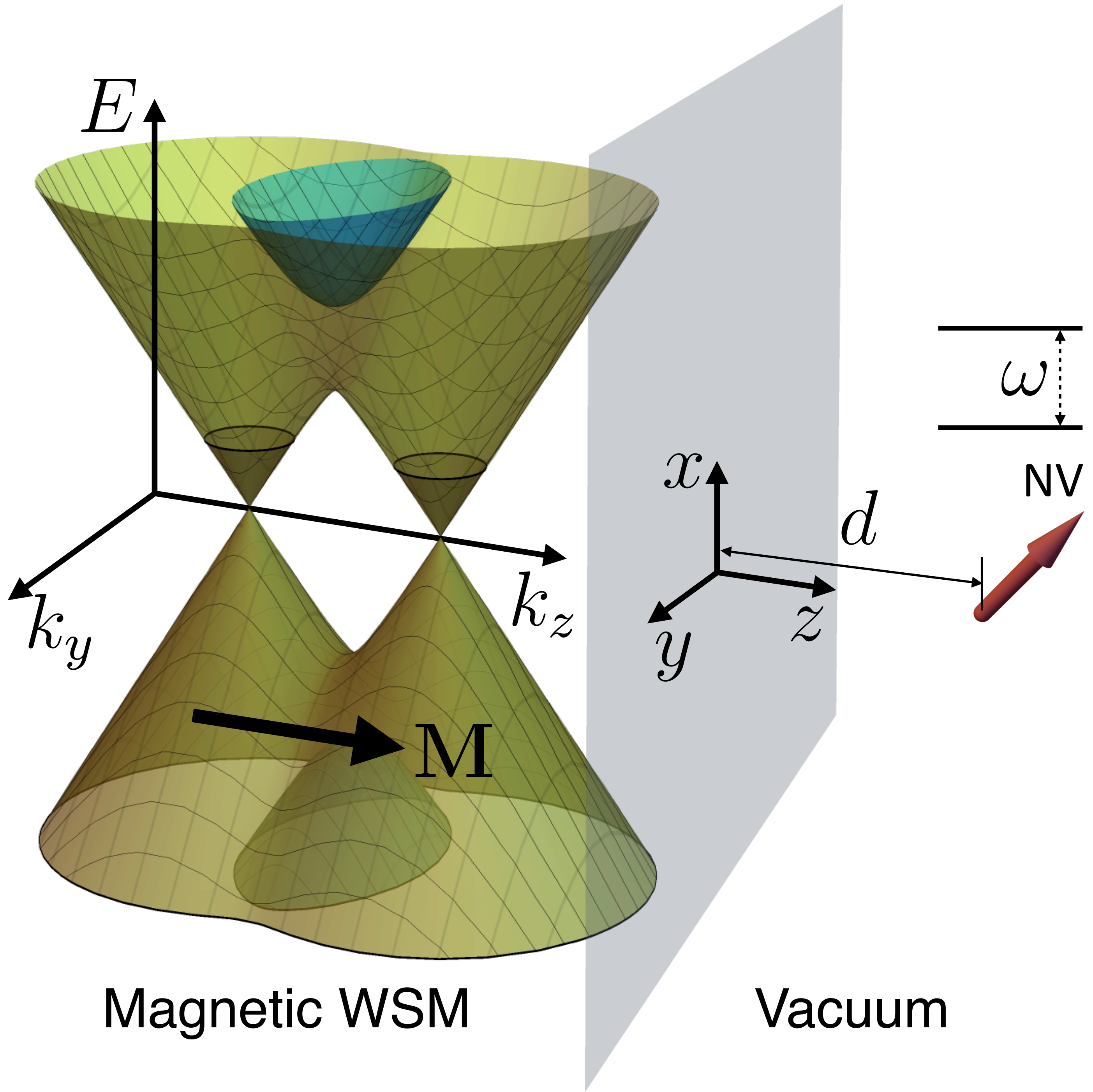

Summary

- Magnetic noise can be a versatile tool to study low-frequency transport in quantum materials
- Key: how the transport dof couples to magnetic field
- For a magnetic Weyl semimetal: charge, valley, and spin can have distinct spectral characters
- Outlook: hydrodynamic regime, near charge-neutrality, spin-valley coupled transport…

arXiv:2108.07305

Thank you!