

Mesoscopic Stoner Instability in Metallic Nanoparticles Revealed by Shot Noise

Jürgen König
Theoretische Physik, Universität Duisburg-Essen

Collaborators

- Björn Sothmann Geneva
- Yuval Gefen WIS Rehovot
- Philipp Stegmann Duisburg

Financial Support

- EU-STREP GEOMDISS
- DFG via SFB 491

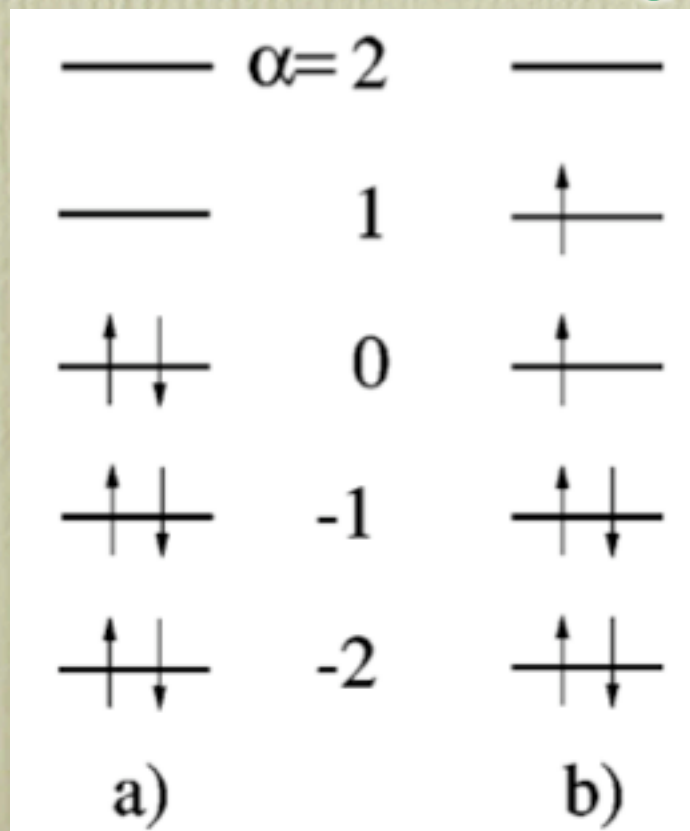
Macroscopic Stoner Instability in Bulk Metals *(Stoner '36)*

- exchange energy $\mathcal{J}$ favors ferromagnetic order
- kinetic energy Δ favors paramagnetic order
- (macroscopic) Stoner instability:
 - for $\mathcal{J} < \Delta$: spin $S=0$
 - for $\mathcal{J} > \Delta$: spin $S=\infty$ (macroscopically large)

Mesoscopic Stoner Instability

(Kurland, Aleiner, Altshuler, PRB '00)

- metallic nanoparticle or large quantum dot:
 - ▶ single-particle level spacing Δ : small spin S
 - ▶ exchange energy $\mathcal{J}$: large spin S
 - ▶ charging energy E_C : fixes charge N

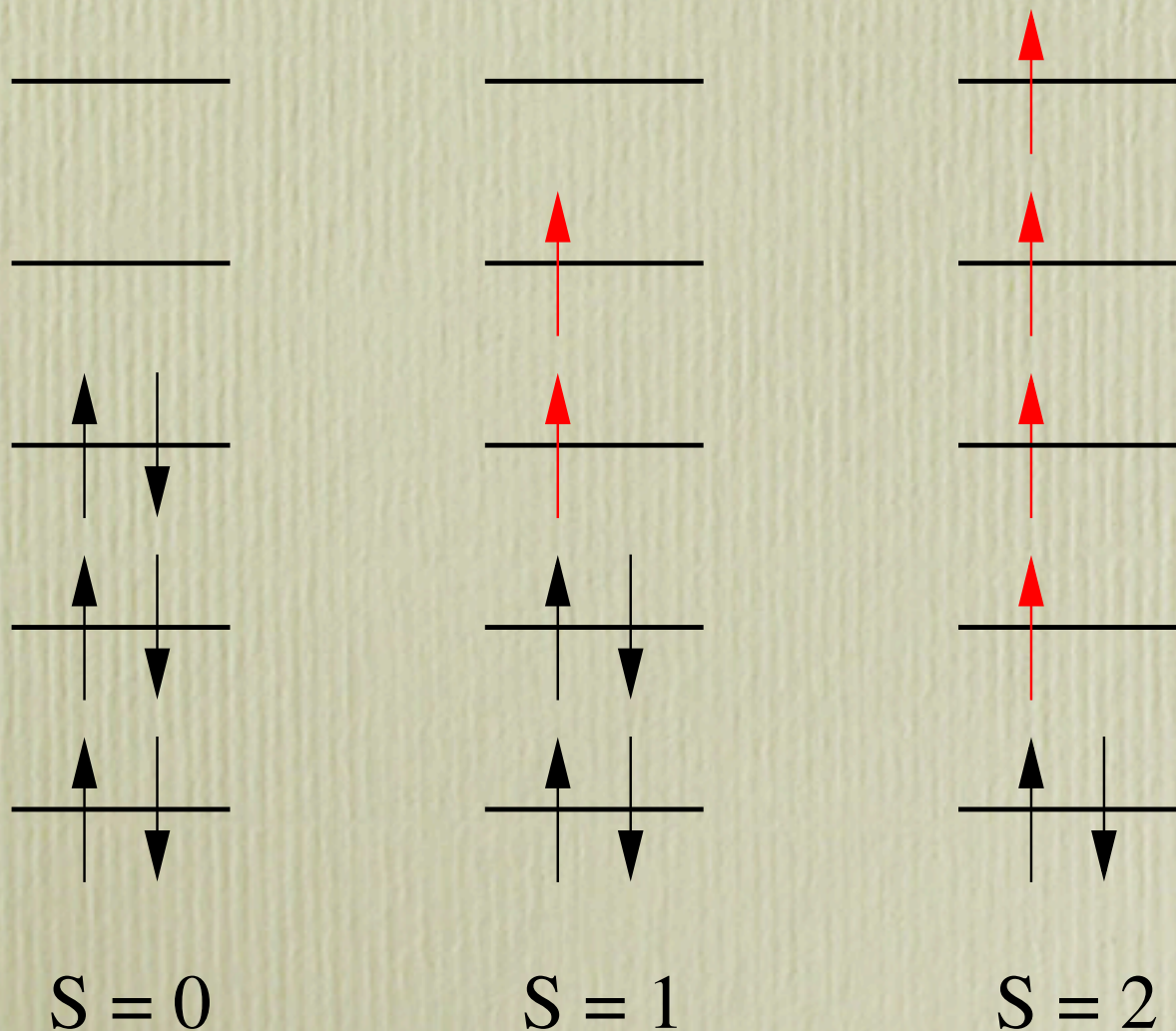


$$H = \sum_{\alpha\sigma} \varepsilon_{\alpha} c_{\alpha\sigma}^{\dagger} c_{\alpha\sigma} + E_C (N - N_G)^2 - J \mathbf{S}^2$$

- eigenstate characterized by:
 - ▶ charge N , spin S , spin projection S_z

eigenenergies for constant level spacing Δ :

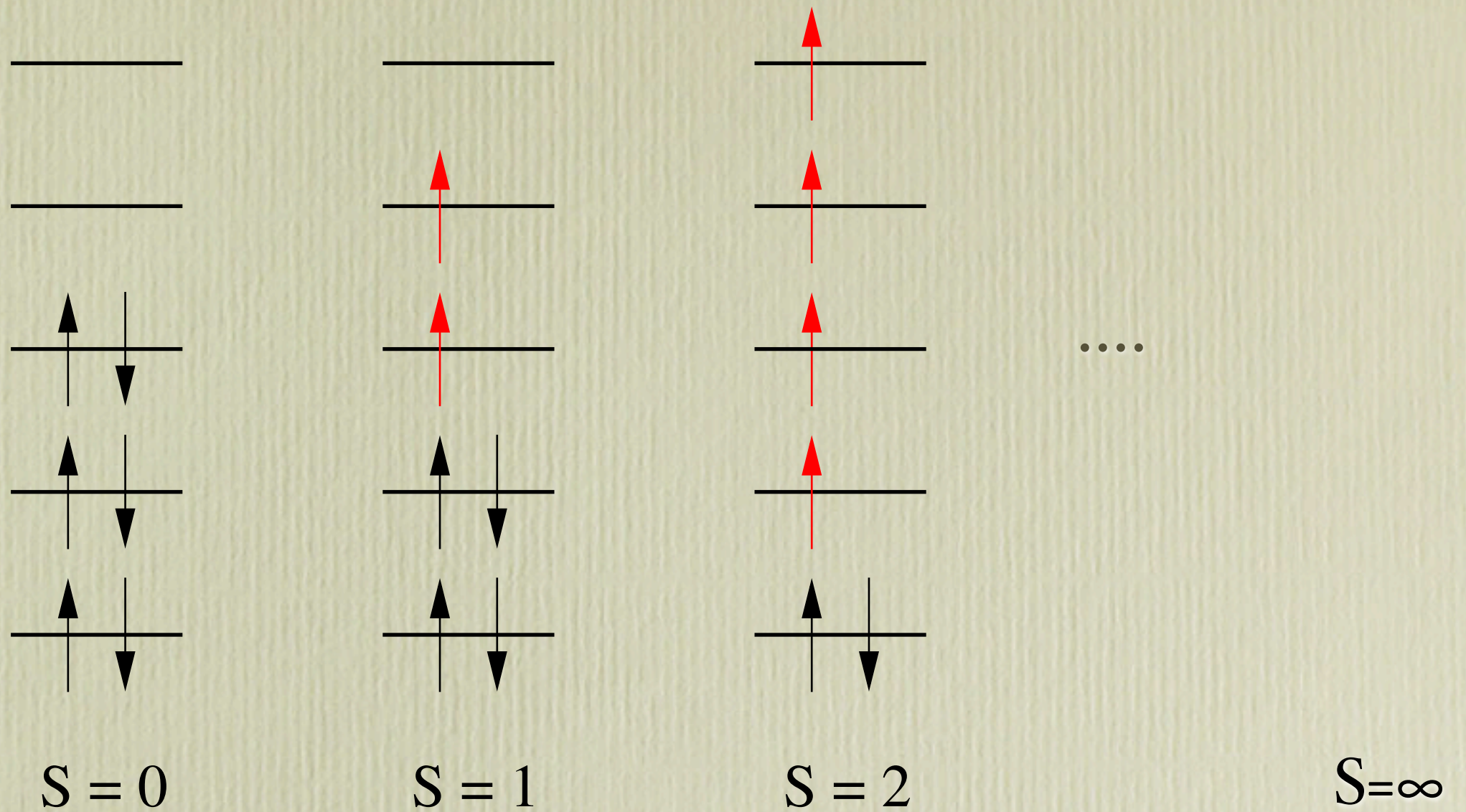
$$E_{N,S,S_z} = \Delta \left[\left(\frac{N}{2} \right)^2 + \frac{N}{2} + S^2 \right] + E_C (N - N_G)^2 - J S(S+1)$$



► N fixed for $E_C \gg \mathcal{J}, \Delta$

► S depends on $\mathcal{J}/\Delta$

► energy independent of S_z



kinetic energy:

$+\Delta$

$+3\Delta$

$+5\Delta$

....

exchange energy:

$-2\tilde{J}$

$-4\tilde{J}$

$-6\tilde{J}$

....

transition at $\tilde{J}/\Delta =$

$1/2$

$3/4$

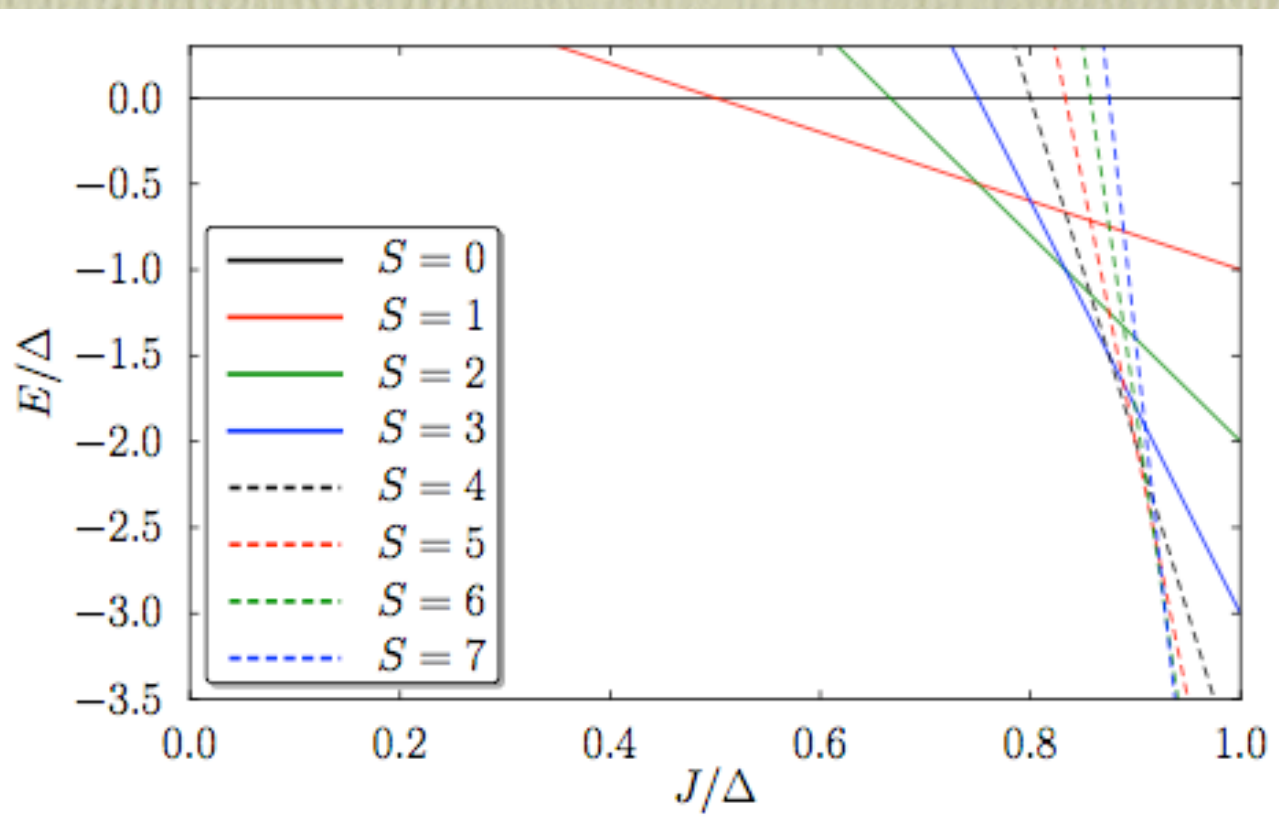
$5/6$

....

I

mesoscopic Stoner instability

Mesoscopic Stoner Instability



- mesoscopic Stoner instability for $1/2 < \mathcal{J}/\Delta < 1$
 - spin very sensitive to $\mathcal{J}/\Delta$
 - large spin fluctuations
-
- question: how to detect mesoscopic Stoner instability?
 - problems:
 - ▶ magnetic moment of individual nanoparticle small
 - ▶ $\mathcal{J}/\Delta$ interaction not tunable

Signatures of Mesoscopic Stoner Instability - I

- statistics of linear conductance peaks

Albassid, Rupp, PRL '03

- interplay with Coulomb charging

*Kiselev, Gefen, PRL '06; Burmistrov, Kiselev, Gefen, JETP Lett. '10;
Burmistrov, Kiselev, Gefen, PRB '12*

- interplay with Kondo effect

Murthy, PRL '05; Rotter, Türeci, Albassid, Stone, PRL '08

- influence of spin-orbit interaction

Gorokhov, Brouwer, RPB '04; Türeci, Albassid, PRB '06

Signatures of Mesoscopic Stoner Instability - 2

- competition with superconducting pairing
Falci, Fazio, Mastellone, PRB '03; Schmidt, Alhassid, PRL '08
- sensitivity to degree of chaos
Ullmo, Nagano, Tomsovic, PRL '03
- implications on thermopower
Billings, Stone, Alhassid, PRB '10
- role of Berry phase
Saha, Gefen, Burmistrov, Shnirman, Altland, arXiv '12
- ...

Mesoscopic Stoner Instability in Metallic Nanoparticles Revealed by Shot Noise

Björn Sothmann,¹ Jürgen König,² and Yuval Gefen³

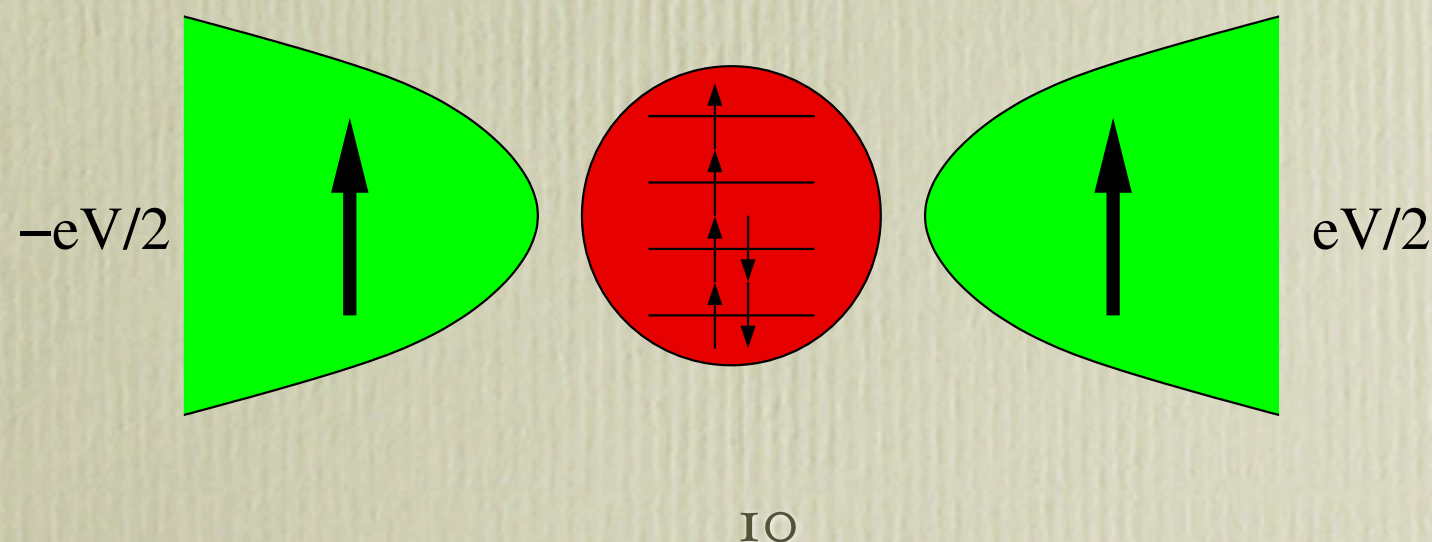
¹*Département de Physique Théorique, Université de Genève, CH-1211 Genève 4, Switzerland*

²*Theoretische Physik, Universität Duisburg-Essen and CeNIDE, 47048 Duisburg, Germany*

³*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel*

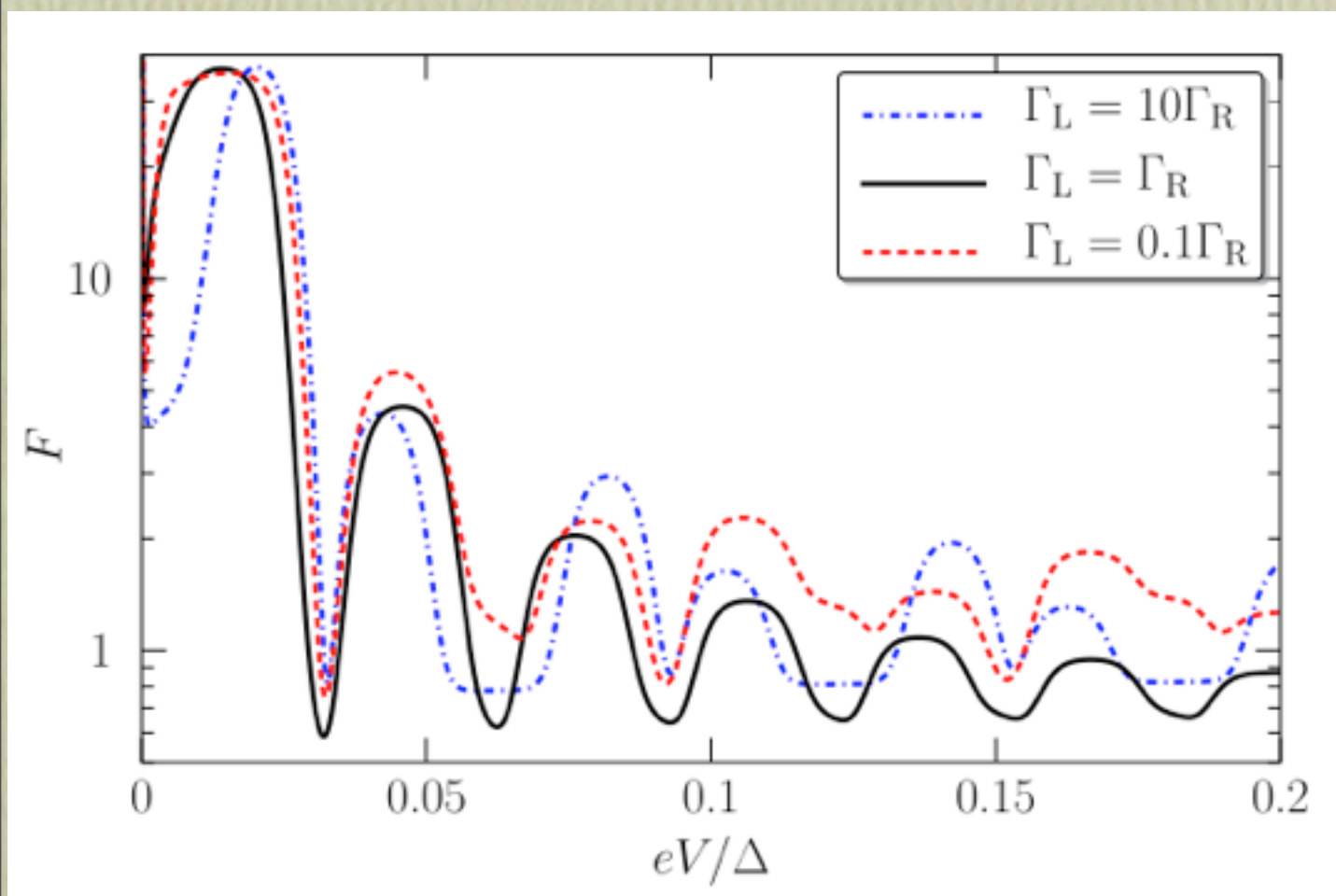
(Received 12 October 2011; published 19 April 2012)

- attach ferromagnetic leads with parallel magnetization
- bias voltage eV generates spin excitations
- measure shot noise for $E_C, \Delta, \mathcal{J} \gg eV \geq \Delta - \mathcal{J} \gg k_B T$



Main Result: Smoking Gun Signature

Fano factor $F = \frac{\int dt \langle \delta \hat{I}(0) \delta \hat{I}(t) + \delta \hat{I}(t) \delta \hat{I}(0) \rangle}{2e \langle \hat{I} \rangle}$



- **oscillates** as function of eV
- between **super-Poissonian** and **sub-Poissonian** values

Parameter Regime

- $E_C \gg eV$: only two charge states $N, N+1$
- $\Delta \gg eV$: no particle-hole excitations
- $eV \geq \Delta - \mathcal{J}$: spin excitations available
- $\Delta - \mathcal{J} \gg k_B T$: no thermal smearing

tunneling Hamiltonian:

$$H = H_{\text{dot}} + H_{\text{leads}} + H_{\text{tunn}}$$

leads' spin polarization:

$$p = \frac{\rho_{\text{maj}} - \rho_{\text{min}}}{\rho_{\text{maj}} + \rho_{\text{min}}}$$

Method

- **master equation** (sequential tunneling)
 - ▶ states $|N, S, S_z\rangle$
- **tunneling rates** include:
 - ▶ **spin-dependent tunnel couplings**
 - ▶ **Clebsch-Gordan coefficients**
- **current, noise power and Fano factor**

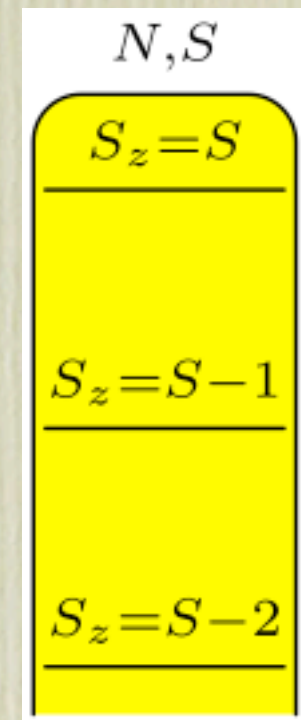
$$I = \langle \hat{I} \rangle$$

$$S = \int dt \langle \delta \hat{I}(0) \delta \hat{I}(t) + \delta \hat{I}(t) \delta \hat{I}(0) \rangle$$

$$F = \frac{S}{2eI}$$

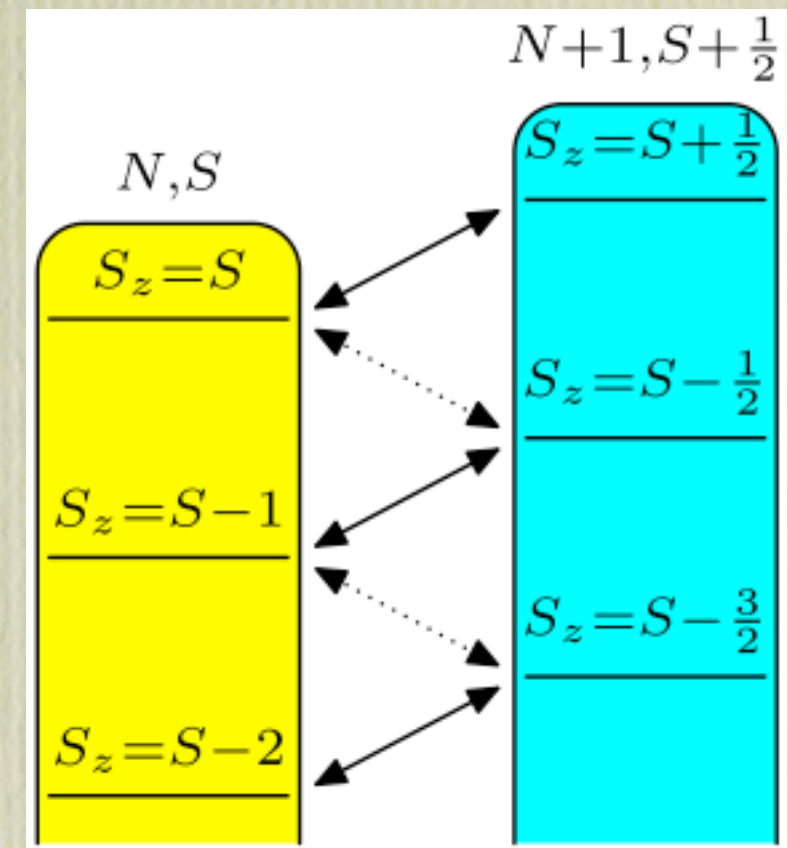
Available Charge and Spin States

- small bias voltage:
 - ▶ charge N and spin S fixed
 - ▶ spin projections S_z equally occupied (isotropic spin state)
 - ▶ no current



Available Charge and Spin States

- increase bias voltage:
 - ▶ **two** states N, S and $N+1, S+1/2$
 - ▶ spin projections S_z **equally occupied** (isotropic spin state)
 - ▶ **super-Poissonian Fano factor**



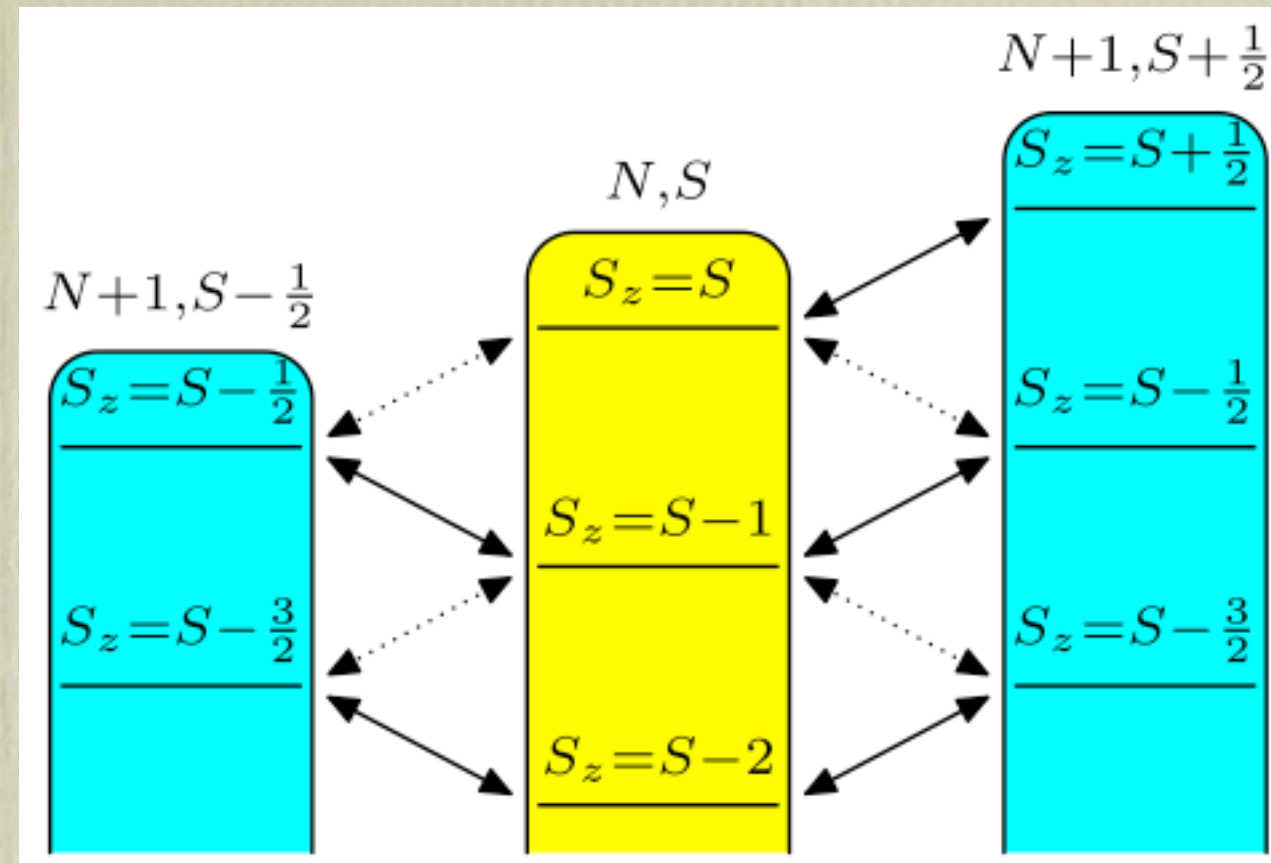
Available Charge and Spin States

- increase bias voltage further:

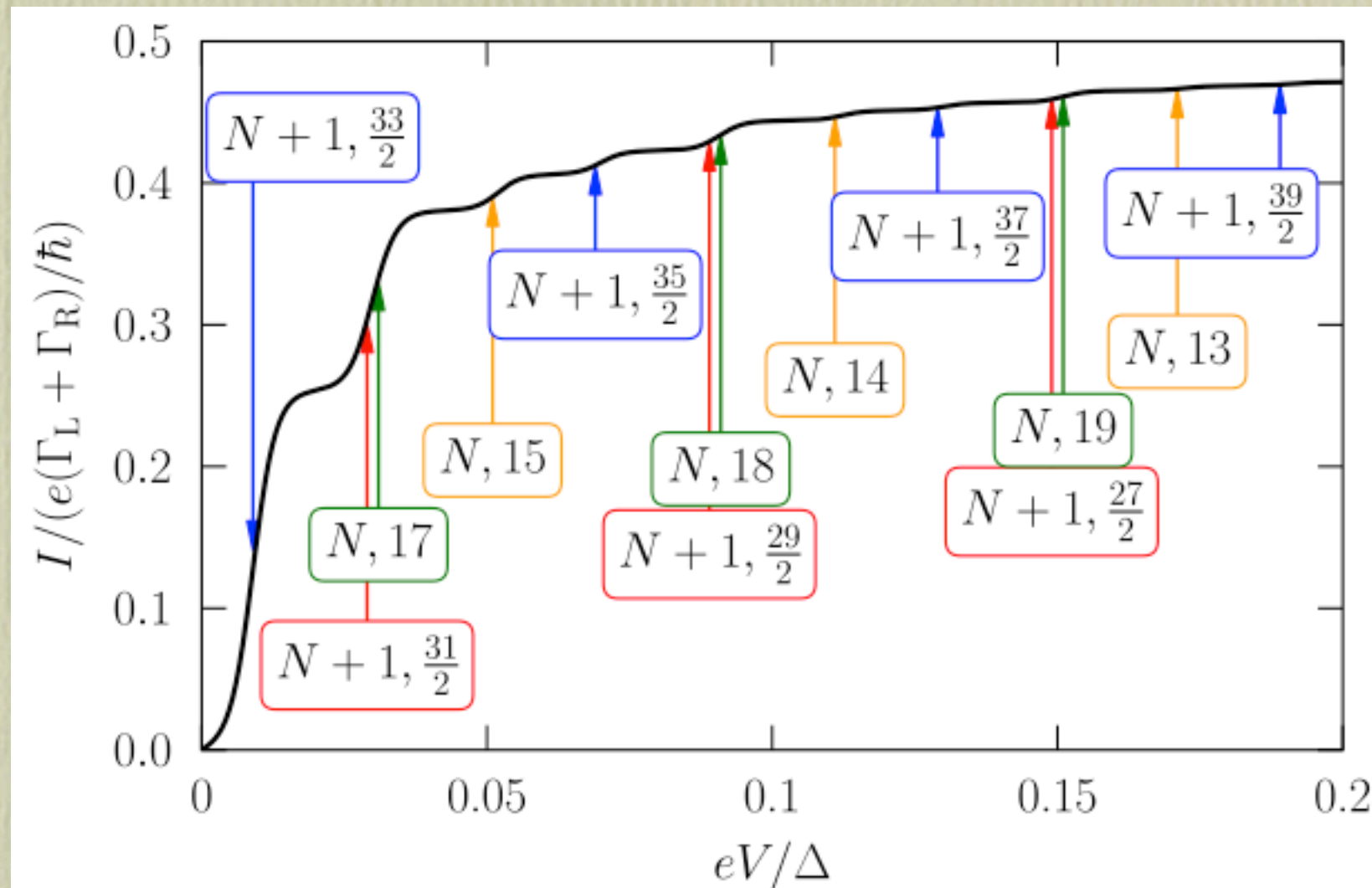
- ▶ **three** states

- ▶ spin projections S_z **equally occupied**
(isotropic spin state)

- ▶ **sub-Poissonian Fano factor**

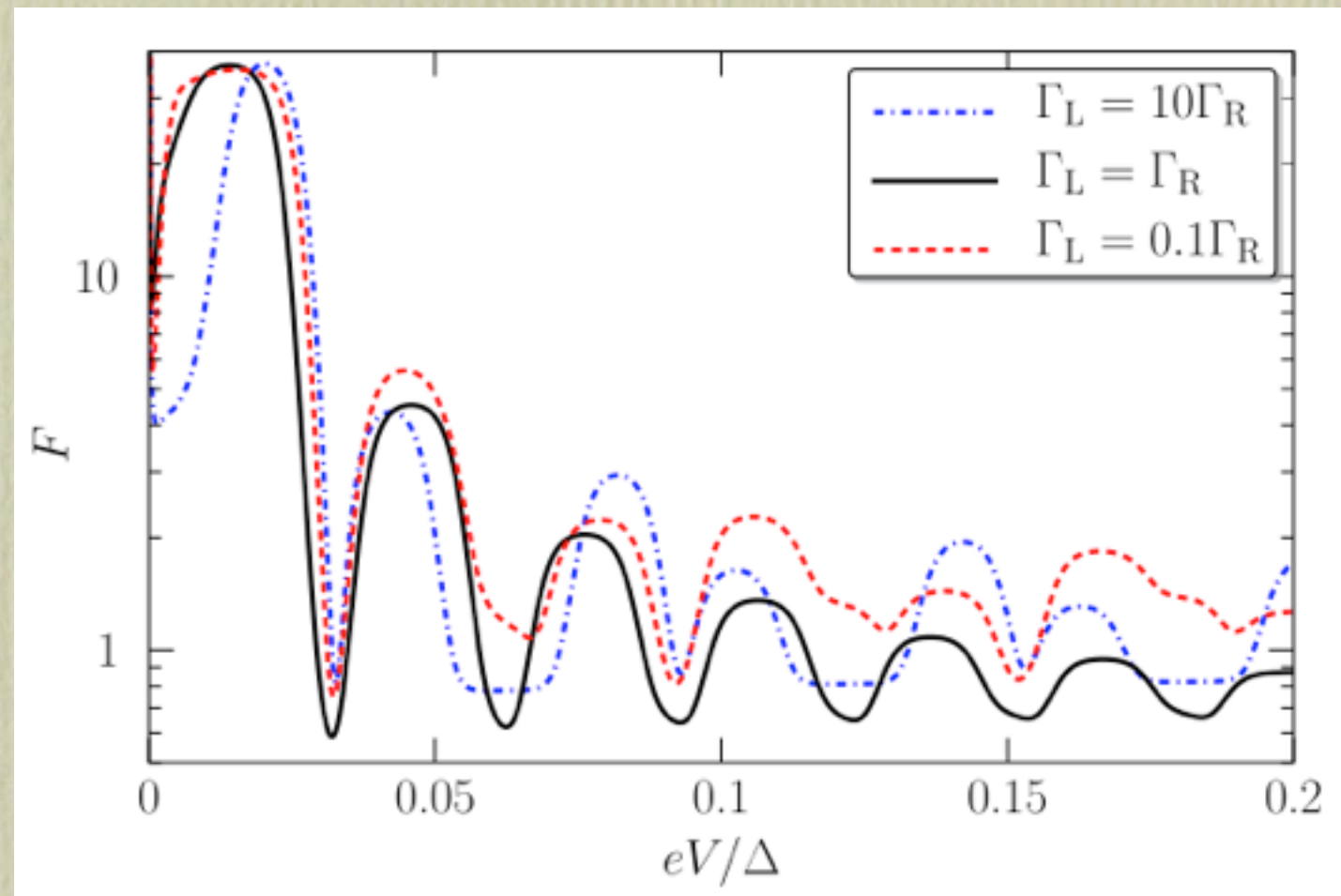


Current



- steps at spin excitation energies
- no unique signature for mesoscopic Stoner regime

Noise and Fano Factor



- **super-Poissonian** for **even number of states**
- **sub-Poissonian** for **odd number of states**
- **robust against asymmetry in tunnel couplings**

Fano Factor

analytic results for two states N, S and $N+I, S+I/2$:

$$F(S, p) = \frac{1}{1 - p^2} \left\{ \frac{\gamma_L^2 + \gamma_R^2}{(\gamma_L + \gamma_R)^2} + p^2 \left[\frac{4S^2}{3} + 2S + \left(\frac{4S}{3} + 1 \right) \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R} \right] \right\}$$

$$\gamma_L = (2S + 2)\Gamma_L$$

$$\gamma_R = (2S + 1)\Gamma_R$$

- nonmagnetic leads $p=0$:

► sub-Poissonian

$$F = \frac{\gamma_L^2 + \gamma_R^2}{(\gamma_L + \gamma_R)^2}$$

- ferromagnetic leads, large S :

► super-Poissonian

$$F = \frac{4}{3} \cdot \frac{p^2}{1 - p^2} \cdot S^2$$

Explanation - I

- system's dynamics:

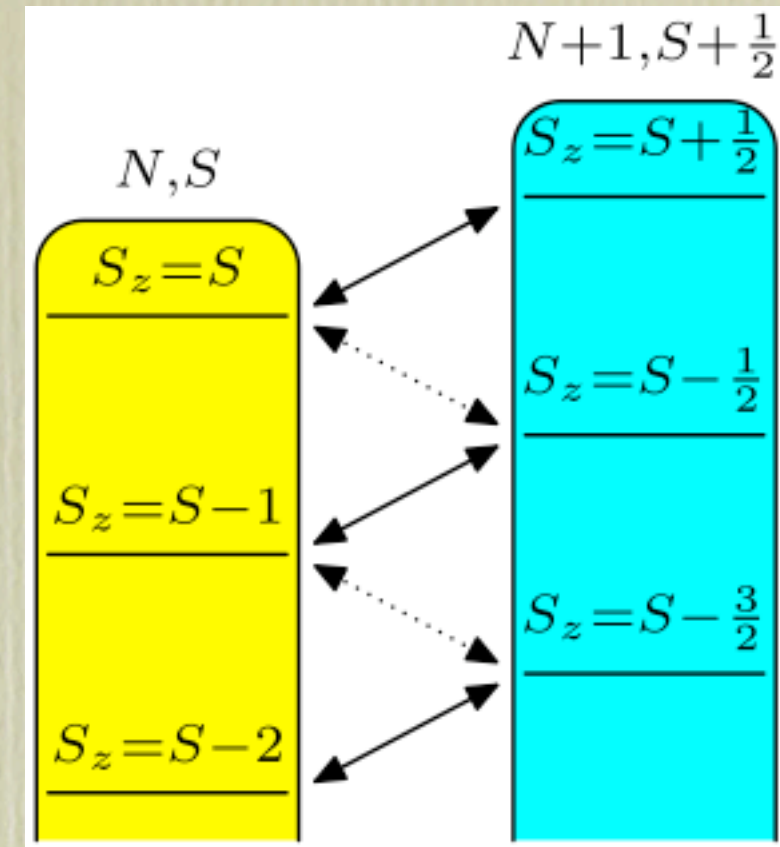
- ▶ random walk in spin space

- ▶ spin projections S_z equally occupied

- ▶ switching time from $S_z=+S$ to $-S$ scales with $\tau \sim \frac{S^2}{(1-p^2)\Gamma}$

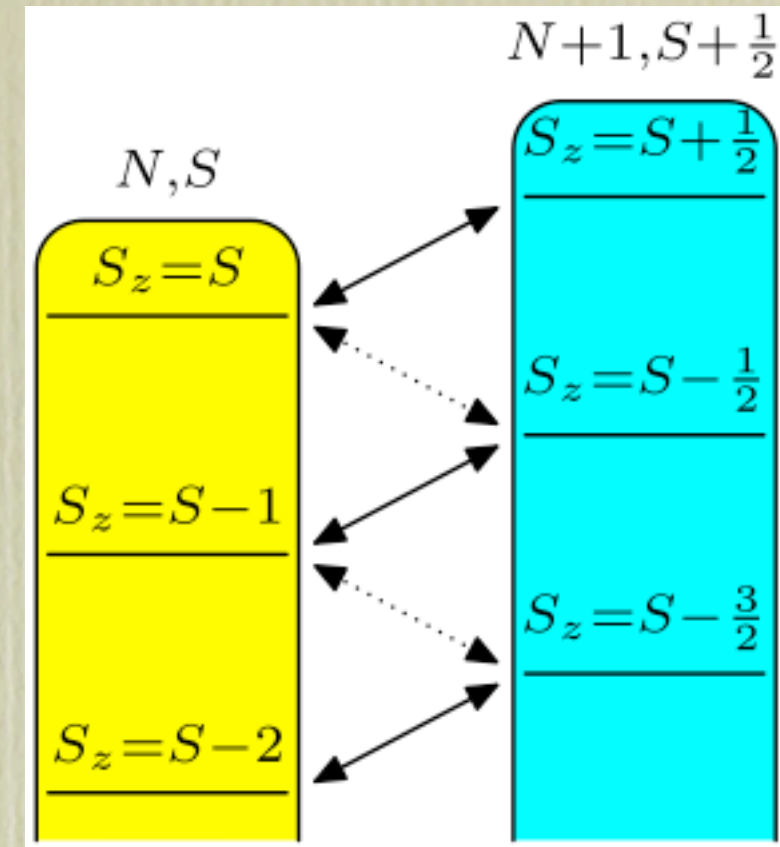
- current

- generalized random-telegraph noise



Explanation - 2

- system's dynamics
- current: Glebsch-Gordan coefficients
 - ▶ for $S_z > 0$ dominated by majority spins
 - ▶ for $S_z < 0$ dominated by minority spins
 - ▶ current S_z -dependent: $I_{\pm} \sim \left(1 \pm \frac{p}{2}\right) \Gamma$
- generalized random-telegraph noise

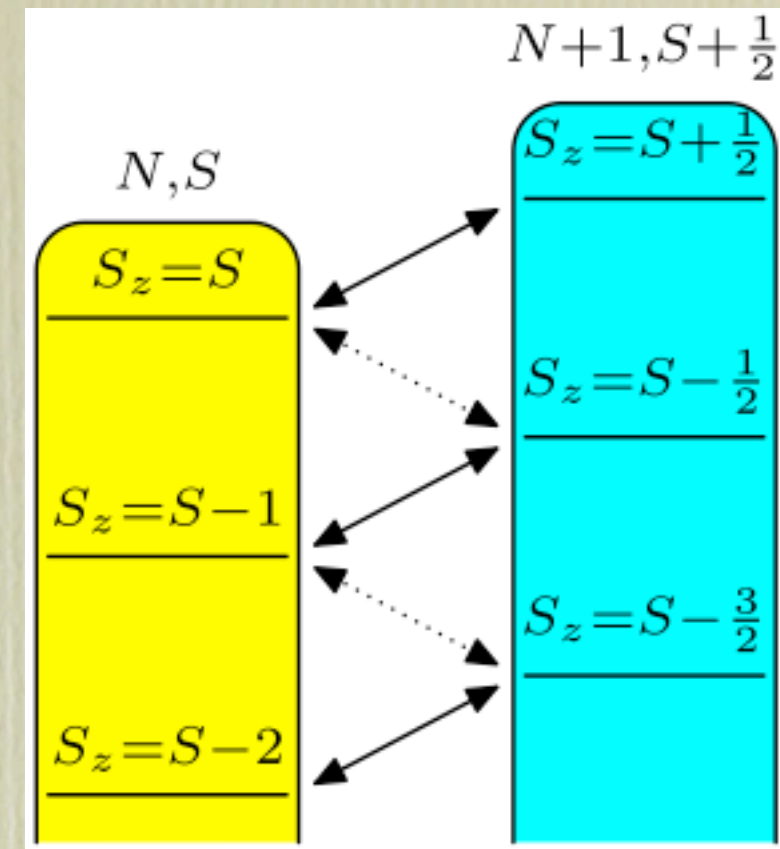


Explanation - 3

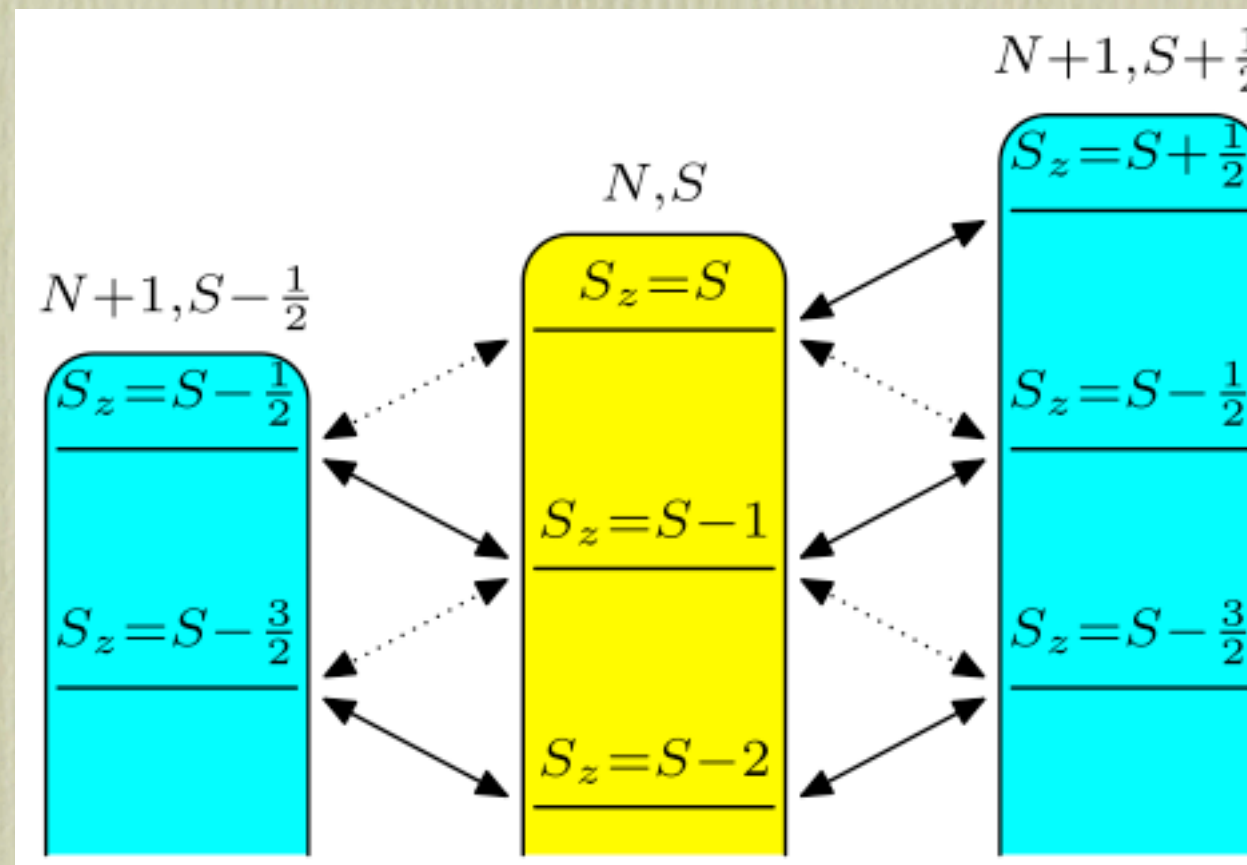
- system's dynamics
- current
- generalized random-telegraph noise:

$$F = \frac{(I_+ - I_-)^2 \tau}{I_+ + I_-} \sim \frac{p^2}{1 - p^2} \cdot S^2$$

increased Fano factor, scales with S^2



Explanation - 4



- for three states:

S_z -dependence of current averages out

- no random-telegraph noise, no enhanced Fano factor

Outlook

(Stegmann, Sothmann, König, Gefen, work in progress)

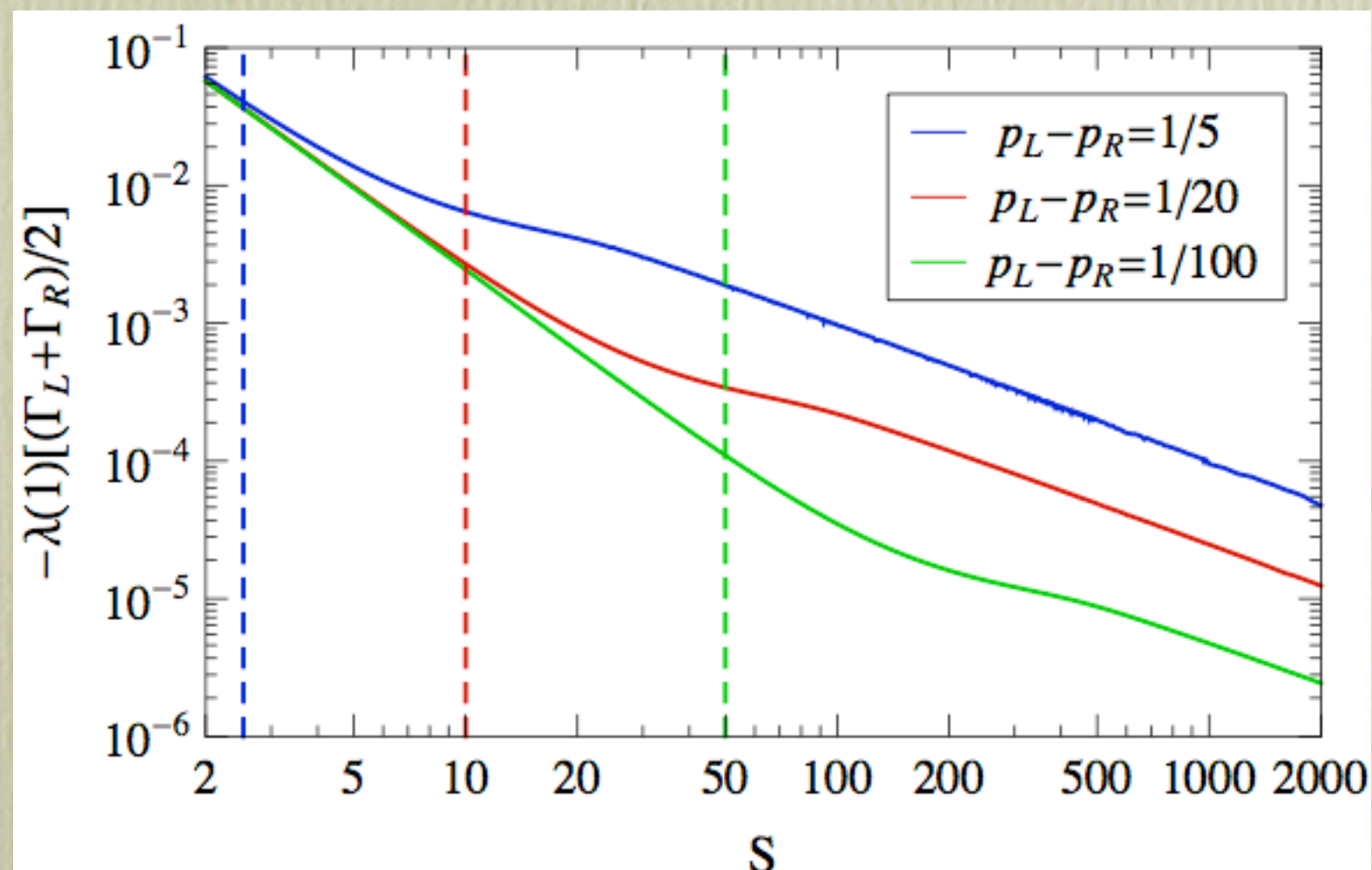
- allow for $p_L \neq p_R$ and **noncollinear** leads:
drift and **diffusion**
- **Fokker-Planck** description
- generation of states with **magnetic quadrupole**
moment dominating over **dipole**

Drift vs Diffusion - I

- allow for $p_L \neq p_R$
- random walk in spin space
 - ▶ drift: switching time scales with S
 - ▶ diffusion: switching time scales with S^2
 - ▶ crossover drift/diffusion as function of S
 - ▶ visible in Fano factor

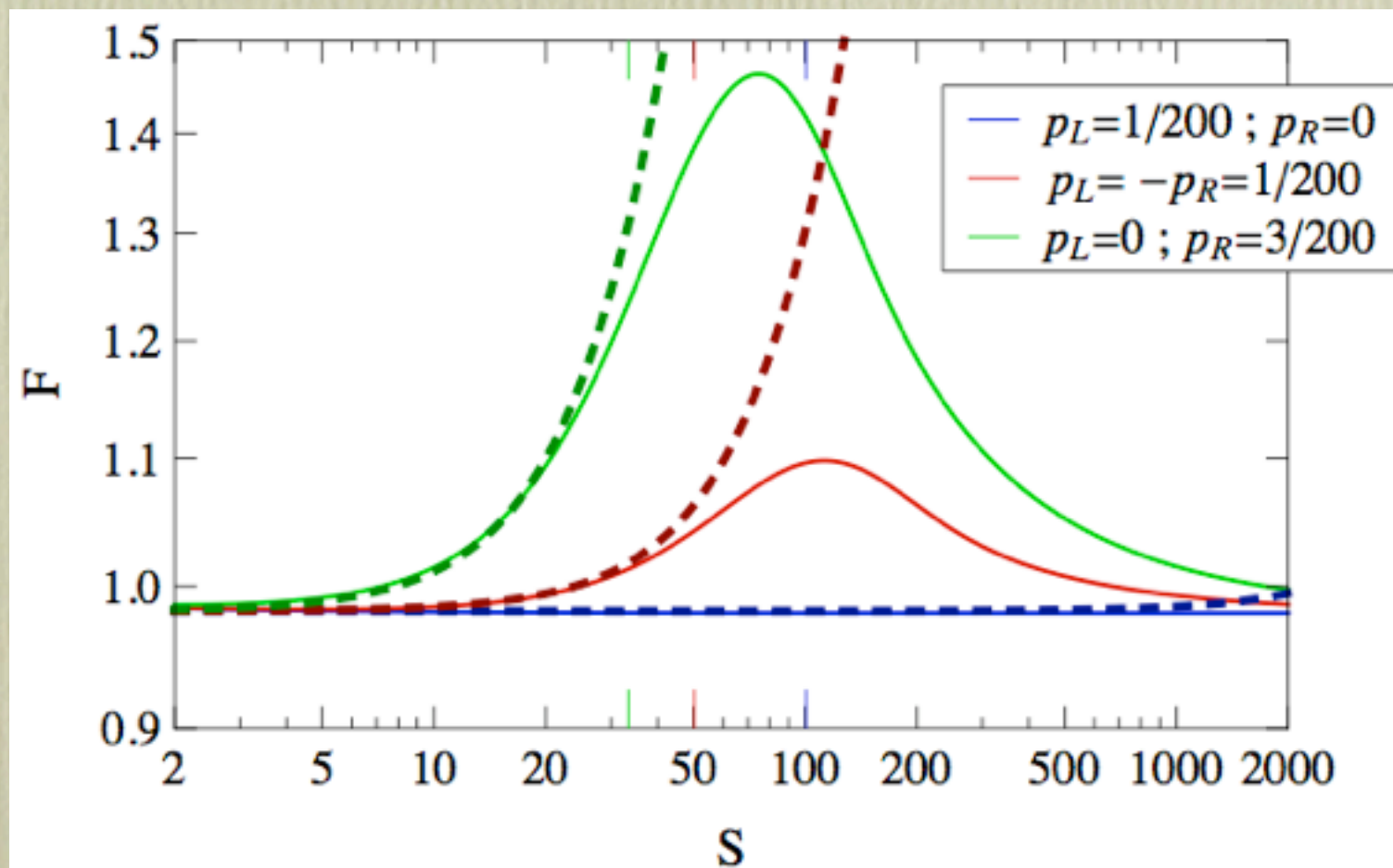
Drift vs Diffusion - 2

- identify switching time by largest relaxation time
- scales with S^2 for $S < S_{\text{cross}}$: diffusion
- scales with S for $S > S_{\text{cross}}$: drift



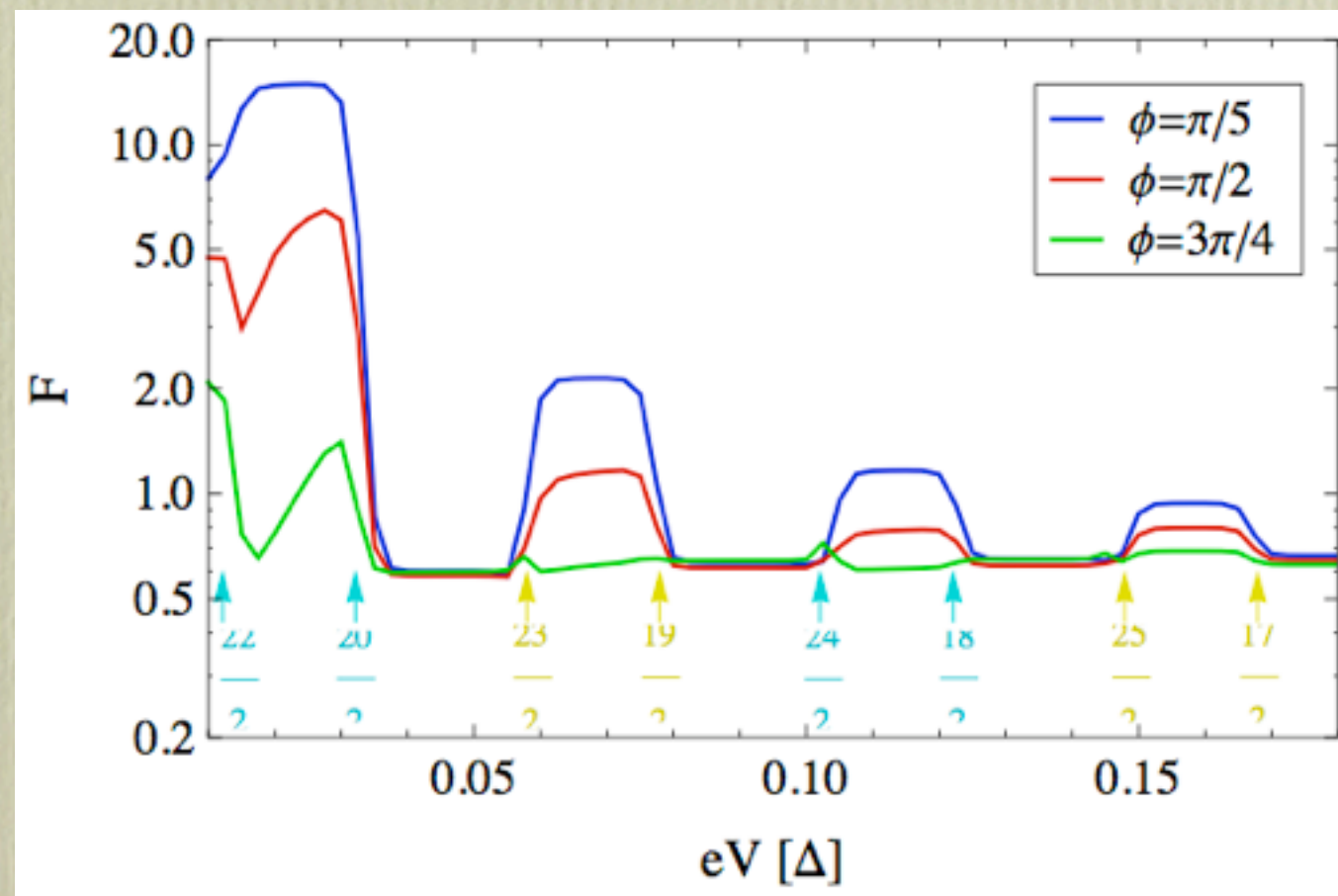
Drift vs Diffusion - 3

- crossover visible in Fano factor
- F scales with S^2 for $S < S_{\text{cross}}$: diffusion
- F goes down for S for $S > S_{\text{cross}}$: drift



Drift vs Diffusion - 4

- allow for **non-collinear** leads
 - ▶ **parallel**: only diffusion, enhanced F
 - ▶ **non-collinear**: drift and diffusion
 - ▶ **antiparallel**: drift dominates, reduced F



Fokker-Planck Description - I

- two states, large S

$$\frac{d}{dt}P(S_z) = \frac{d}{dS_z} [A(S_z)P(S_z)] + \frac{d^2}{dS_z^2} [D(S_z)P(S_z)]$$

- drift and diffusion constants:

$$A(S_z) = \Gamma \frac{(p_L - p_R)(S^2 - S_z^2)}{2S [2S + (p_L + p_R)S_z]}$$

$$D(S_z) = \Gamma \frac{(1 - p_L p_R)(S^2 - S_z^2)}{4S [2S + (p_L + p_R)S_z]}$$

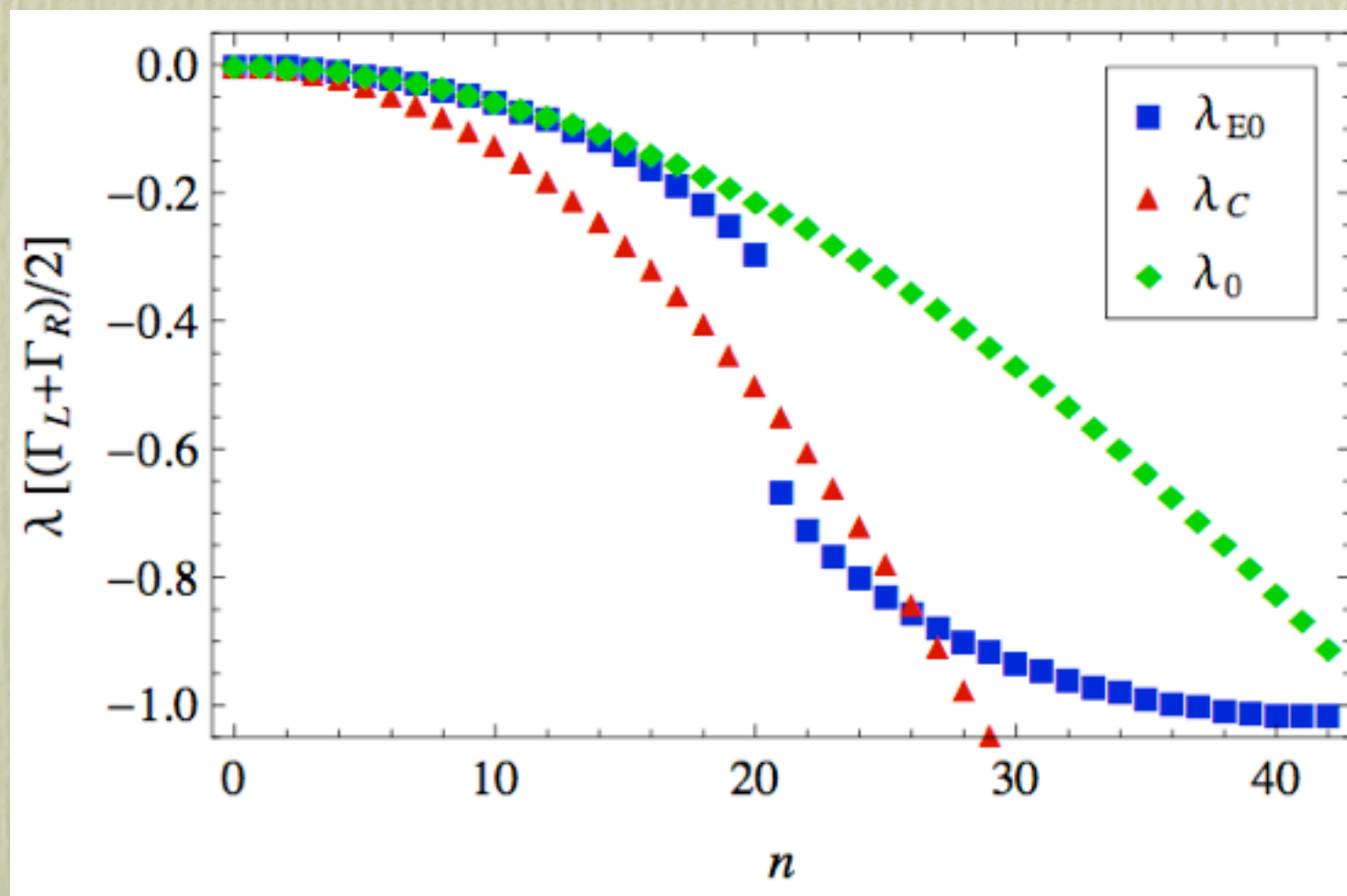
- neglecting Clebsch-Gordan coefficients:

$$A(S_z) = \Gamma \frac{(p_L - p_R)}{4}$$

$$D(S_z) = \Gamma \frac{(1 - p_L p_R)}{4}$$

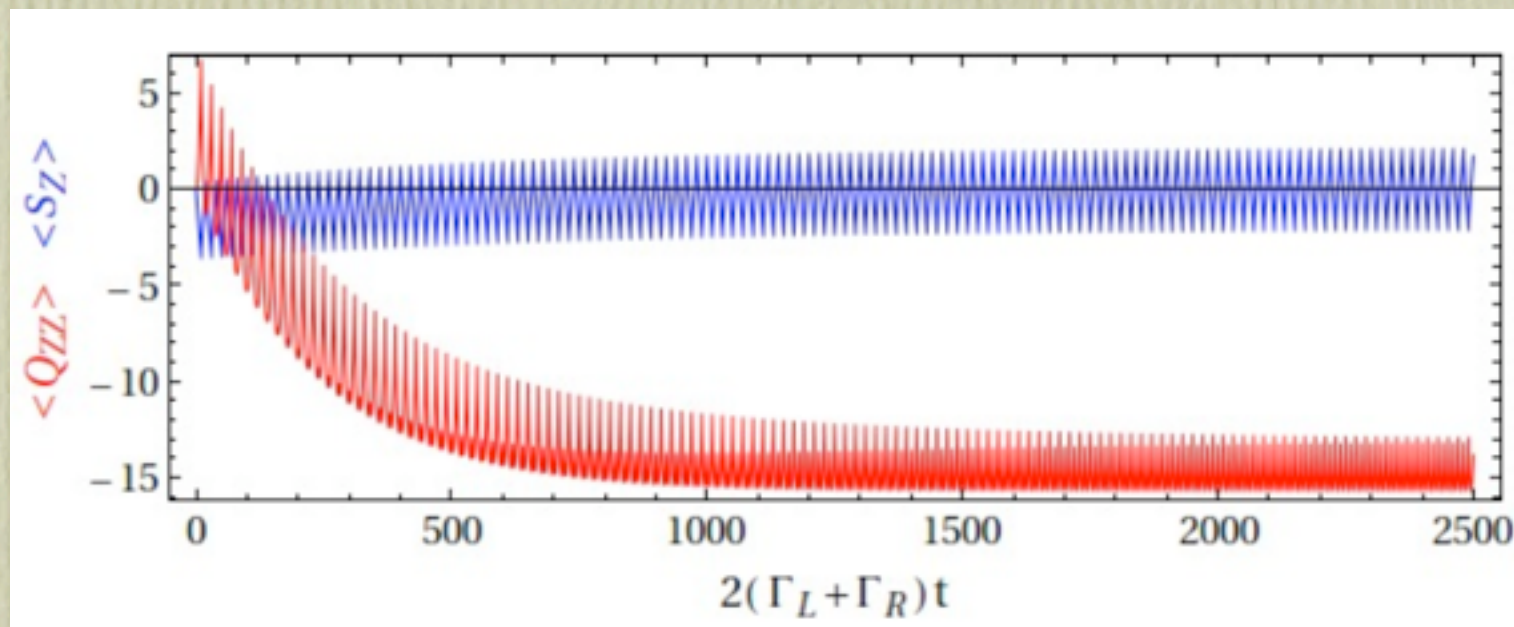
Fokker-Planck Description - 2

- compare set of relaxation rates
 - exact, Fokker-Planck, Fokker-Planck without CG

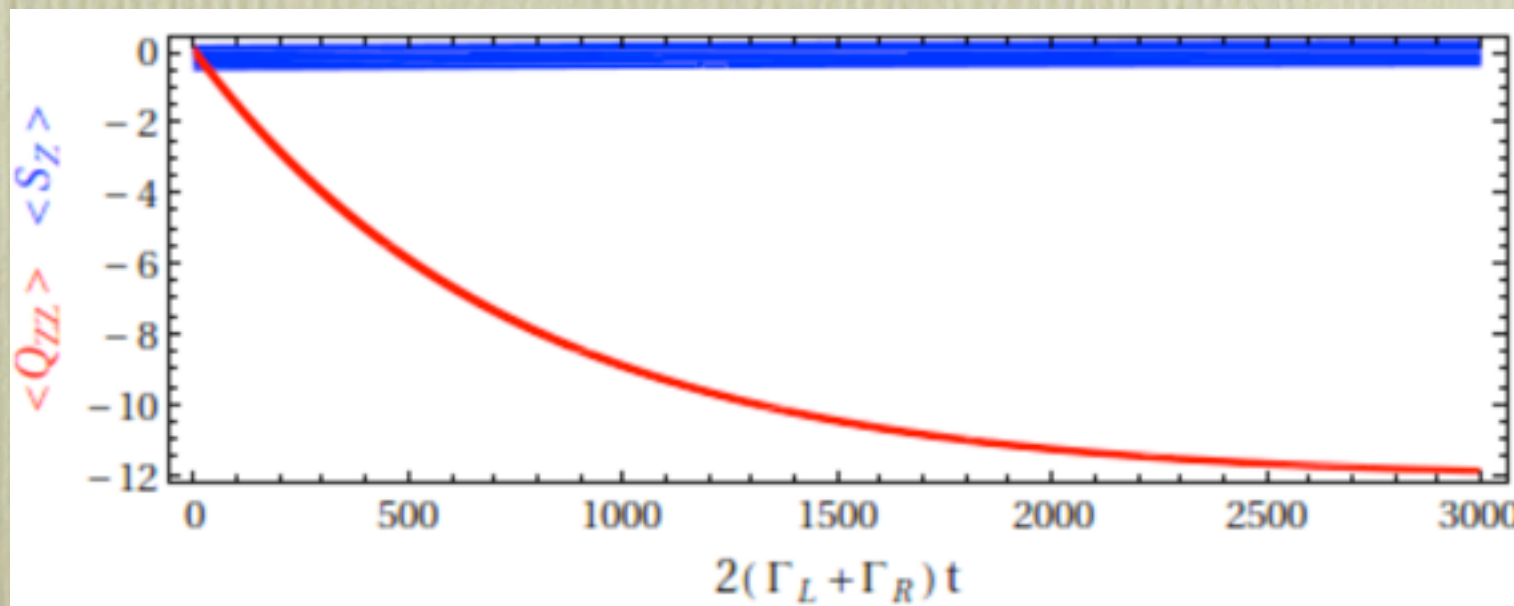


Generation of Quadrupole - I

- oscillate bias voltage with period T : $\langle Q_{zz} \rangle \gg \langle S_z \rangle$



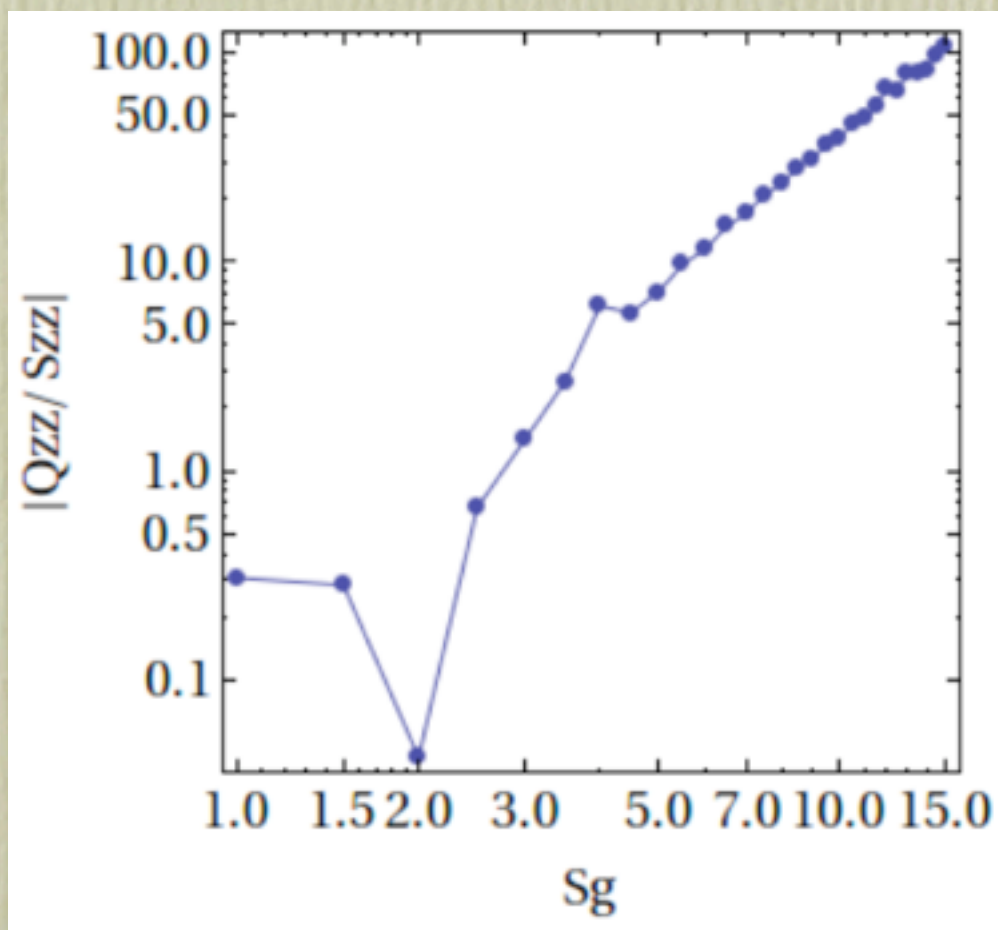
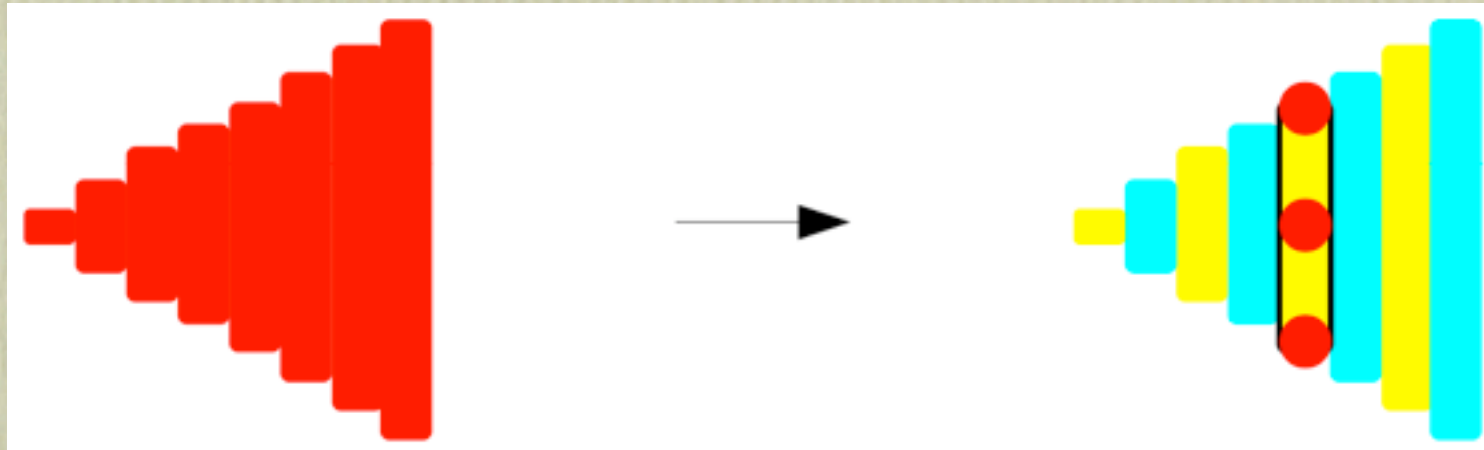
$$T = 10(\Gamma_L + \Gamma_R)$$



$$T = \Gamma_L + \Gamma_R$$

Generation of Quadrupole - 2

- switch off bias voltage:



$$\langle Q_{zz} \rangle \gg \langle S_z \rangle$$

Conclusion

- mesoscopic Stoner instability revealed by shot noise:
 - ▶ Fano factor oscillates between super-Poissonian and sub-Poissonian values
- Fokker-Planck description, drift and diffusion
- generation of quadrupoles dominating over dipoles

