Low offset frequency 1/f flicker noise in spin-torque vortex oscillators

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Outline:

- Spin torque oscillators (STO)
- Nonlinearity
- Noise in STOs
- Spectral shape

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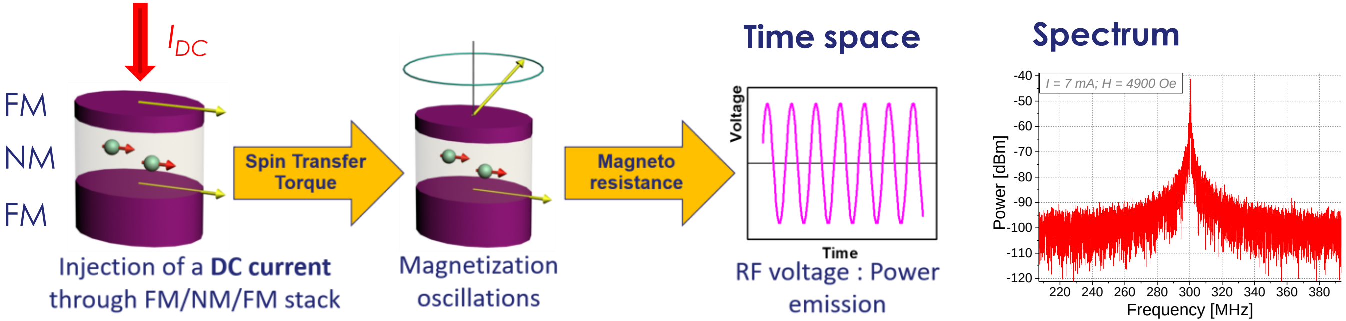
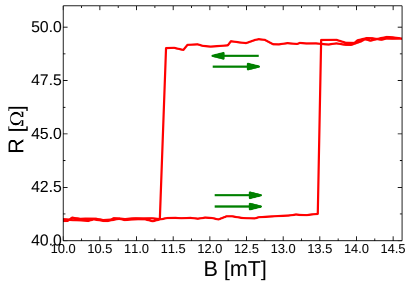
Spin Torque Nano Oscillator (STNO)

Principle

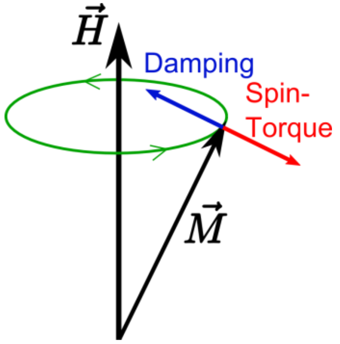
- Conversion of magnetization dynamics into an electrical rf signal



TMR effect



Magnetization dynamics



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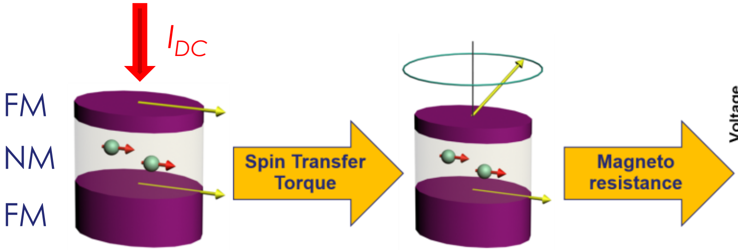
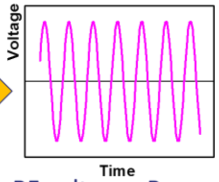


Injection of a **DC current** through FM/NM/FM stack

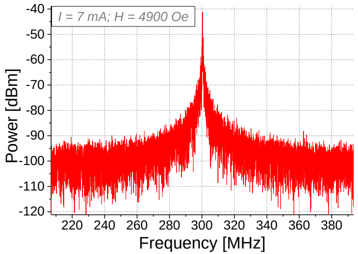
Magnetization oscillations

Time space

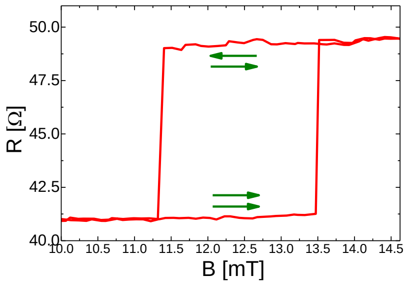


RF voltage : Power emission

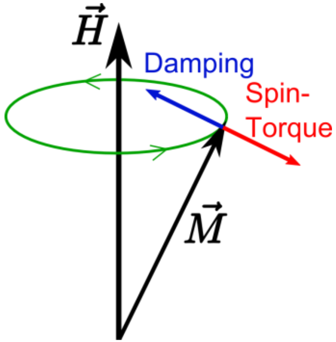
Spectrum



TMR effect



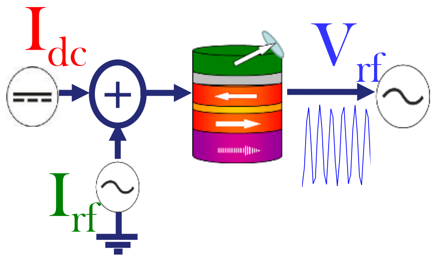
Magnetization dynamics

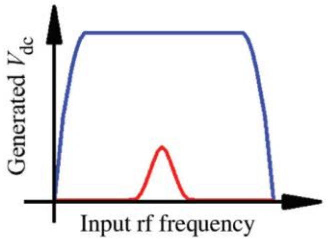


- ☺ Nano size (~100nm)
- ☺ Frequency range : [100 MHz, 60 GHz]
- ☺ Agility with current ΔI → Δf
- ☺ Radiation hard
- ☺ CMOS compatible
- ✘ Poor coherence
- ✘ Low output power ($\sim \mu W$)

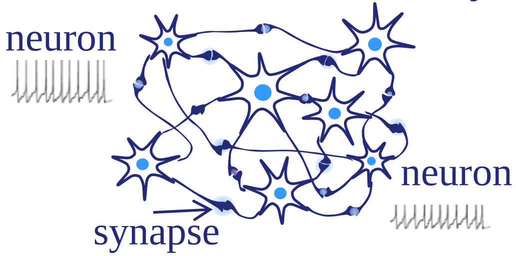
STNOs: The all-purpose swiss army knife?

- Towards rf applications & communication:
  Frequency shift keying, Mixing & Modulation, etc… *U. Ebels et al., Spintec Grenoble*
- High data transfer rate hard disk reading *Sato et al., IEEE Trans. Magn. 48, 1758, 2012*
- Magnonic logics *Kruglyak et al., JPD 43, 2010; Chumak et al., JPD 50, 2017*
- Broadband frequency detection *Jenkins et al., Nat. Nanotech. 11, 2016*
- Broadband microwave energy harvesting *Fang et al., PRAppl. 11, 2019*
- Bio-inspired computing *J. Grollier et al., CNRS/Thales*

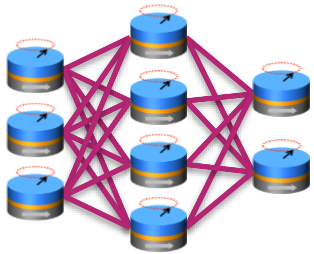




Brain: Neural assembly



Coupled spintronic nano-oscillators



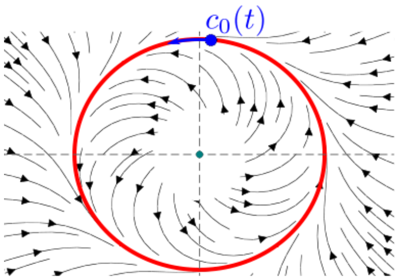
Torrejon et al., Nature 547, 2017

Nonlinearity of STNOs

- Nonlinear Langevin equation can be derived from the LLGS-equation:

$$\frac{dc}{dt} + i\omega(|c^2|)c + \Gamma_+(|c^2|)c - \Gamma_-(|c^2|)c = f(t)$$

A. Slavin, V. Tiberkevich, IEEE Trans. on Magn. 45, 2009



with the auto-oscillation $c(t) = c_0 e^{-i\omega t + i\phi_0}$

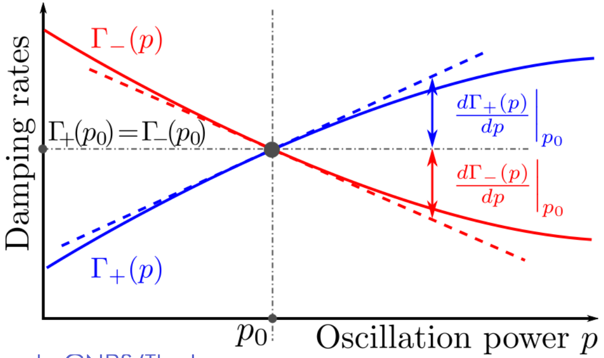
and output power $p = |c|^2$

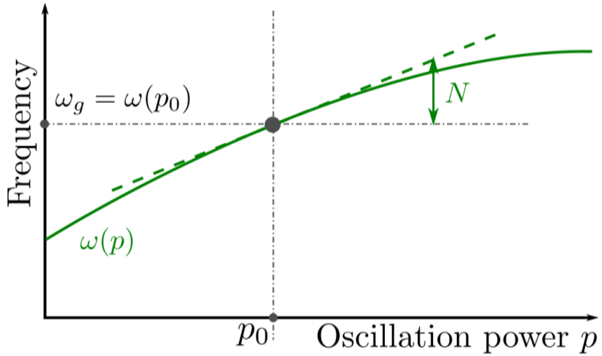
Nonlinearity

$$\omega(p) \approx \omega_0 + Np$$

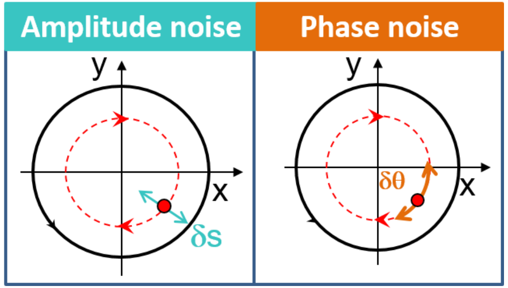
$$\Gamma_+(p) \approx \Gamma_G(1 + Qp)$$

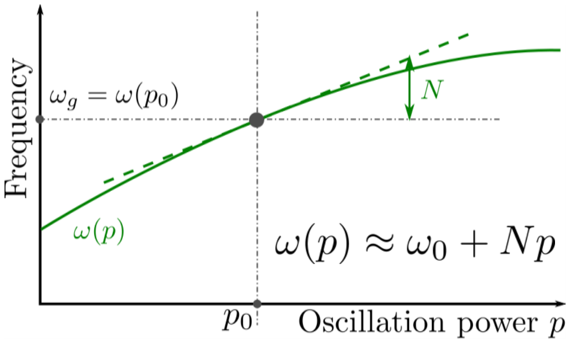
$$\Gamma_-(p) \approx \sigma I(1 - p)$$





Noise of a STNO (at high offset frequencies)





A. Slavin, V. Tiberkevich, IEEE Trans. on Magn. 45, 2009

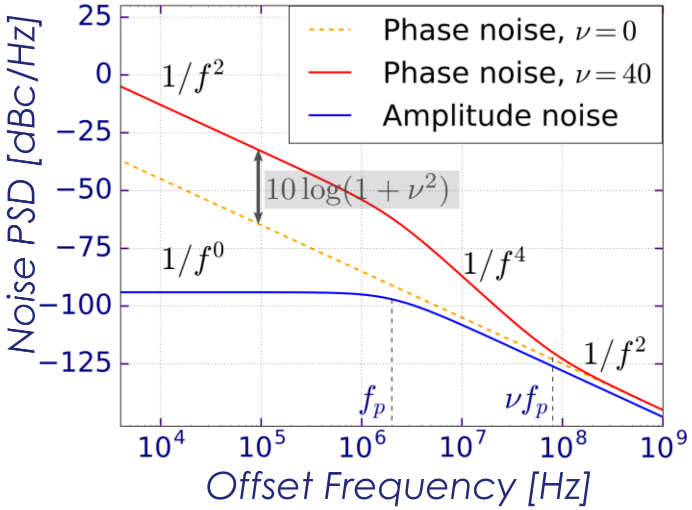
- In the presence of thermal noise, the noise Power Spectral density is:

$$S_{\delta\varepsilon}(f) = \frac{\Delta f_0}{2\pi} \frac{1}{{f_p}^2 + f^2}$$

$$S_{\delta\theta}(f) = \frac{\Delta f_0}{\pi f^2} + \nu^2 2 \frac{{f_p}^2}{f^2} S_{\delta\varepsilon}(f)$$

conversion

E. Grimaldi et al., PRB 89, 2014



- Relative damping always pulls the oscillation back to the limit circle with **damping rate f_p**
- Normalized **nonlinearity factor**: $\nu = \frac{N}{\pi f_p} p_0$

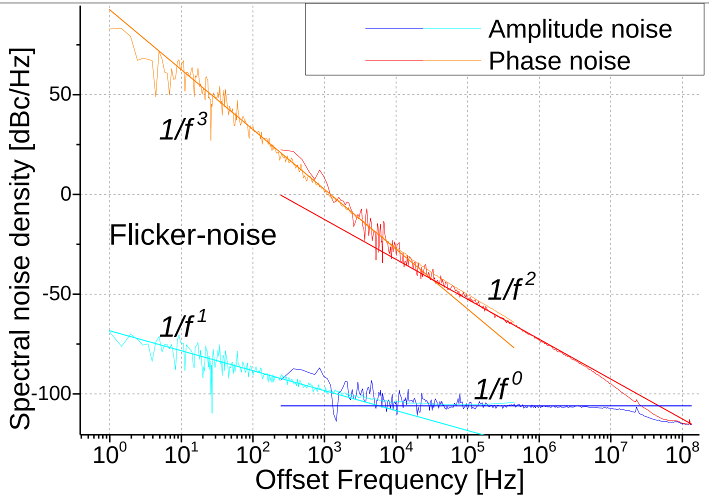
Flicker noise: Measurement

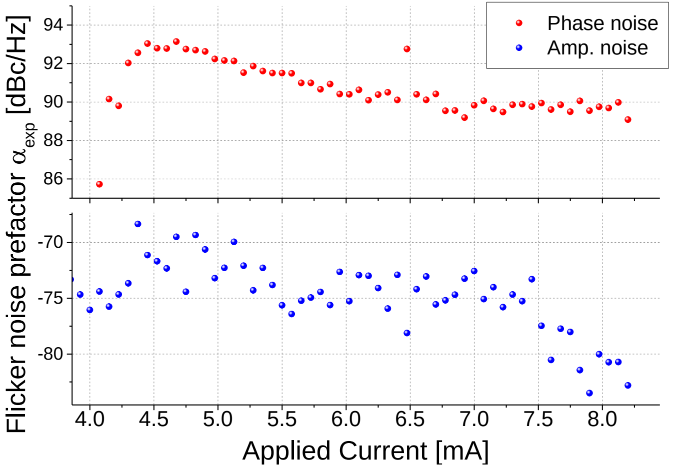
- Measured sample: *MTJ based sample at $T = 300\ K$ from* AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

- Different noise parts can be fitted by a power law:

$$S \sim \frac{\alpha_{exp}}{f^{\gamma}}$$

- Parameter $\boldsymbol{\alpha}$ gives a scale for the noise contribution





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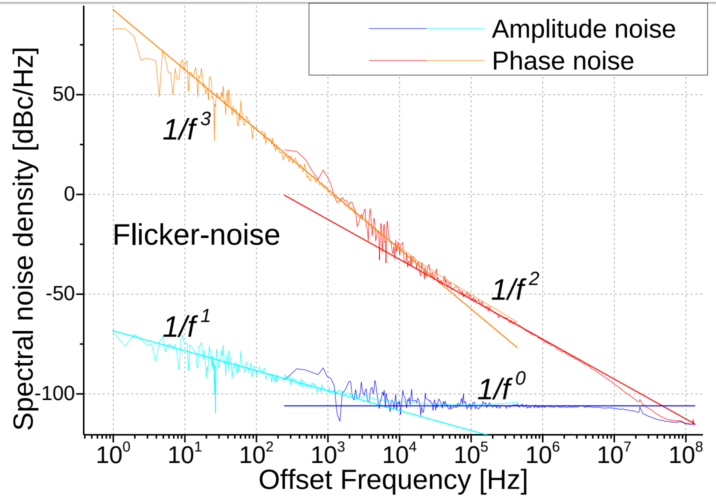
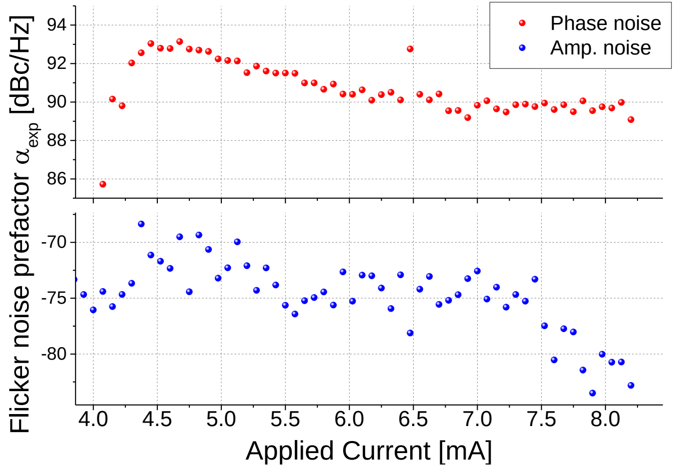




- Noise is decreasing for increasing bias currents
  - → Nonlinearity?
  - → Volume, following the Hooge-formula?

Flicker noise: Theory & Parameters

- Evaluate Langevin Diff. Equation assuming
  - A stationary process f_n for the $1/f$ noise
  - Wiener-Khintchine-theorem with a phenomenological approach: $S(f) = \int \langle f_n(t) f_n^*(t-t') \rangle \cdot e^{2\pi i f t} dt = \frac{\alpha}{f^\beta}$

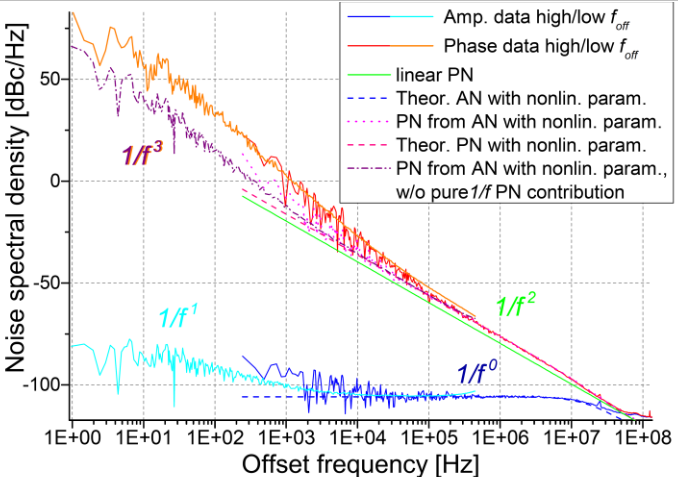
→ Total noise spectral density:

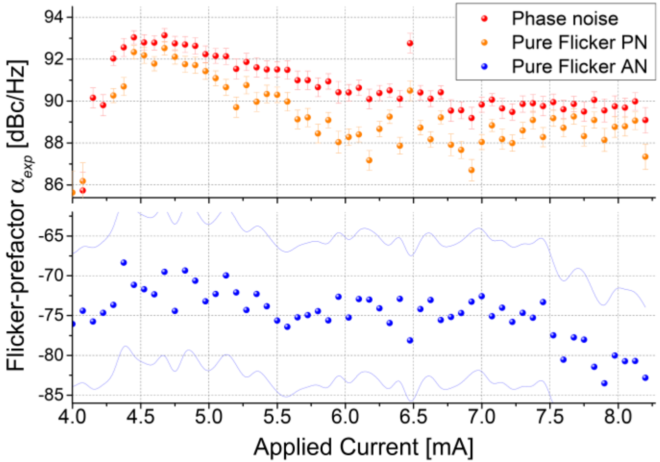
thermal — Low frequency Flicker

$$S_{\delta\epsilon} = \frac{\Delta f_0}{\pi} \cdot \frac{1}{f^2 + f_p^2} + \frac{1}{4 p_0 \pi^2 \left(f_p^2 + f^2\right)} \cdot \frac{\alpha}{f^\beta}$$

$$S_{\delta\phi} = \frac{\Delta f_0}{\pi f^2} + \frac{1}{4 p_0 \pi^2 f^2} \cdot \frac{\alpha}{f^\beta} + \frac{\nu^2 f_p^2}{f^2} S_{\delta\epsilon}$$

with $\alpha \sim \frac{V^2}{A(I_{dc})}$





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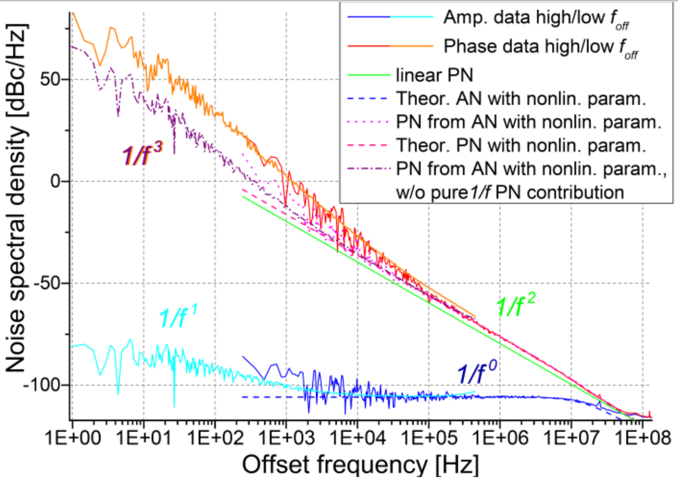
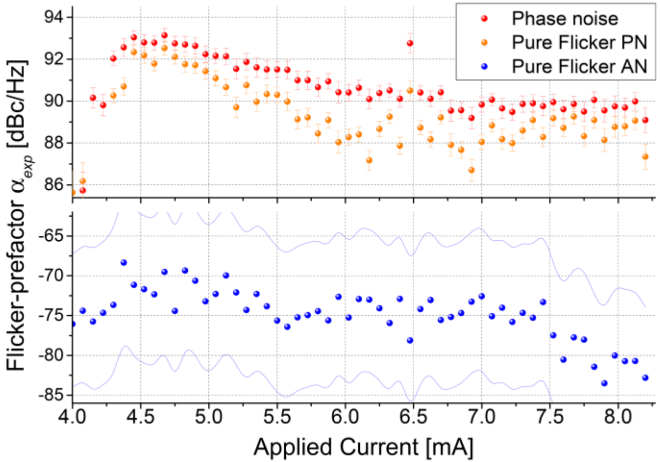




Main results:

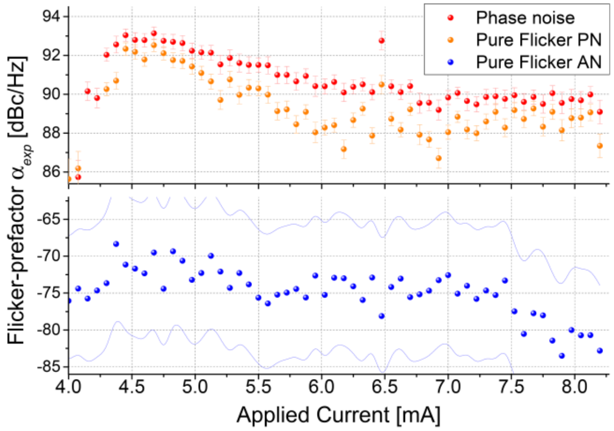
→ We find $\beta \sim 1$, similar to GMR/TMR sensors
→ Conversion of $1/f^1$ amplitude noise into $1/f^3$ phase noise
→ Dominant $1/f^3$ ***pure phase flicker noise*** contribution

Flicker noise parameters: Nonlinearity ↔ Hooge

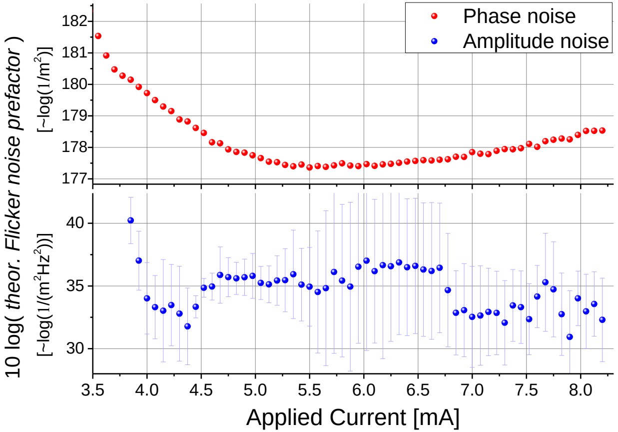
- Evaluate the whole prefactor of the Flicker noise terms:

St. Wittrock et al., PRB 99, 2019

Experimental Evaluation



Theoretical Prediction, All prefactors



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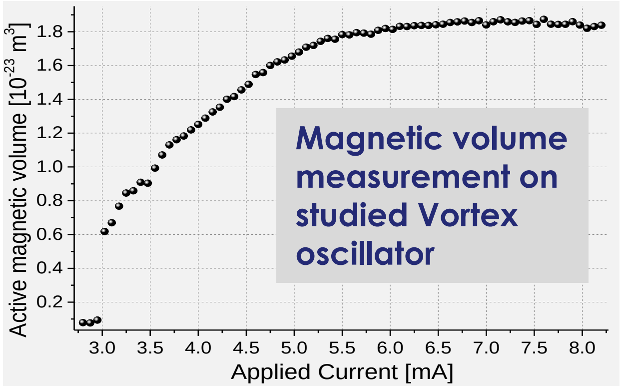
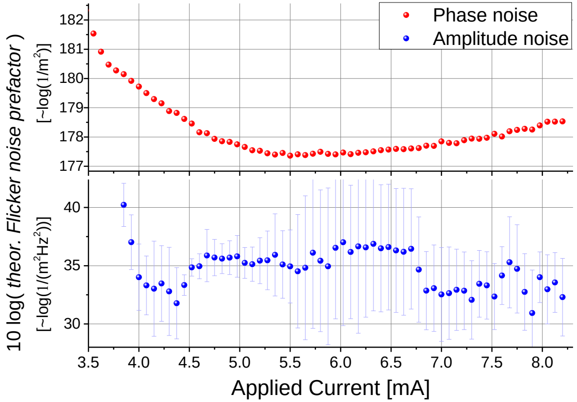
With $\alpha \sim \alpha_H \cdot \frac{V^2}{A}$

→ **Hooge-behaviour and nonlinear properties qualitatively determine the flicker noise**

→ **Especially the active magnetic oscillation surface A and f_p are important parameters**

Influence of the oscillator volume





St. Wittrock et al., in preparation

→ **Magnetically active volume plays an important role**

→ **When nonlinear volume evolution reaches saturation, an increase of the flicker noise with applied current is predicted**

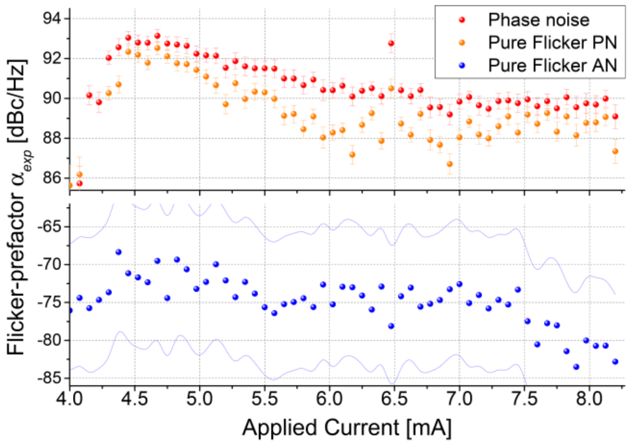
Low Frequency Flicker noise in STNOs: Conclusion

- **Comprehension of the noise parameter space due to our model**
- **Nonlinear noise-conversion less pronounced at low frequency offsets**
- **Lowest flicker noise level determined by competition between nonlinear effects & classical Hooge-like behavior**
- **$1/f$ noise leads to complex spectral shape dependent on the measurement duration ***

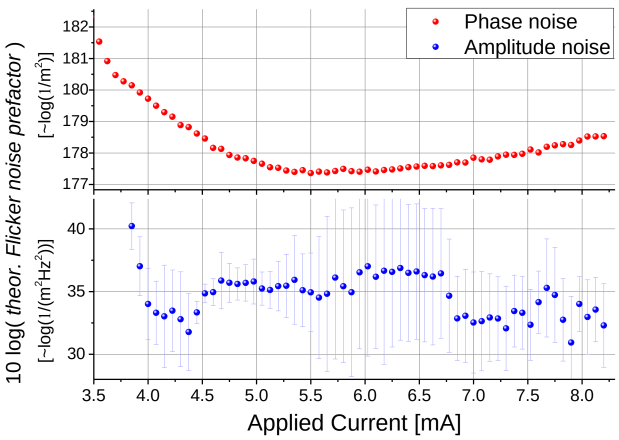
St. Wittrock et al., PRB 99, 2019
St. Wittrock et al., Sci.Rep., to be submitted

Thank you for your attention!

Experimental Evaluation



Theoretical Prediction



* Slides treating this point were removed for the publication of this presentation