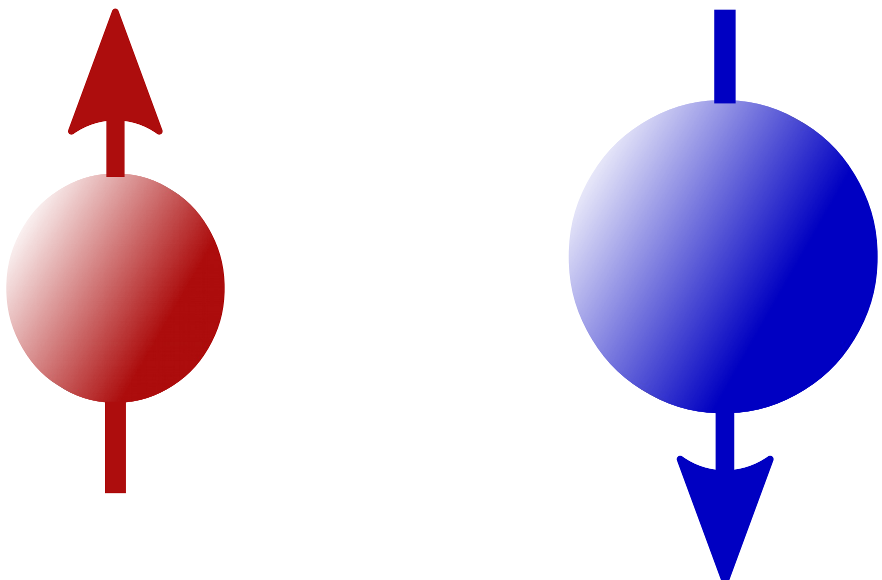
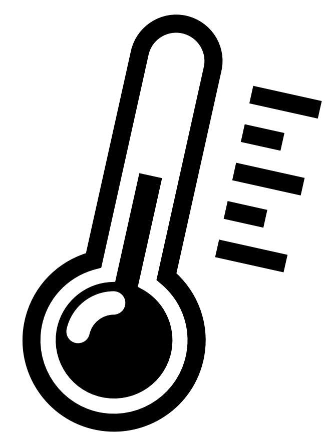
Spin thermometry of individual neutral impurities coupled to a Bose-Einstein condensate





Jens Nettersheim
nettersh@rhrk.uni-kl.de

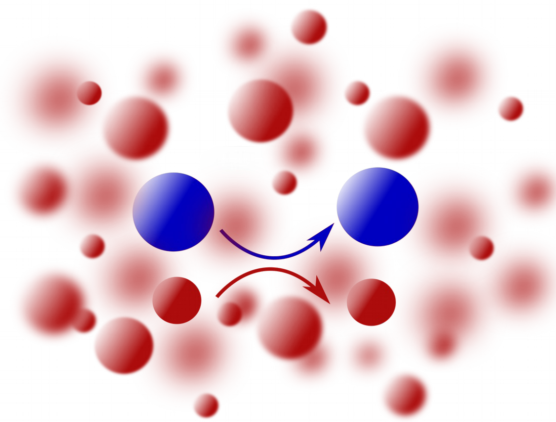
Widera group
Technische Universität Kaiserslautern, Germany

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

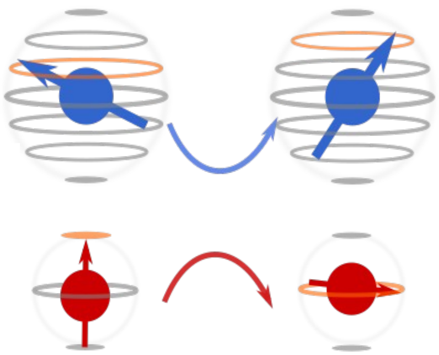
individual quantum systems

This is an experimental work!

Outline

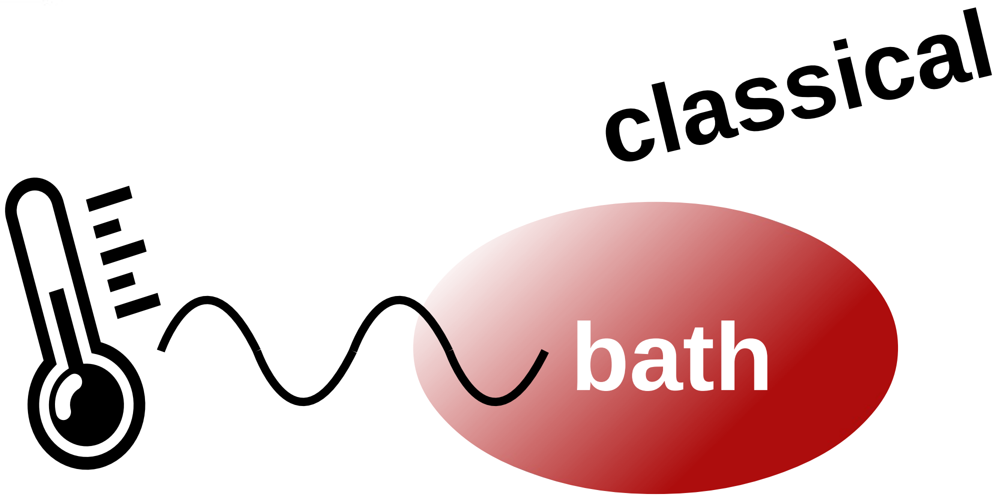


- Single-spin quantum probe
- Single impurities in an ultra-cold gas
- Spin-exchange collisions including model



- Mapping temperature onto spin distribution
- Sensitivity & extension to quantum probing
- Summary

Thermometer



$$\langle E_{kin} \rangle \sim T$$

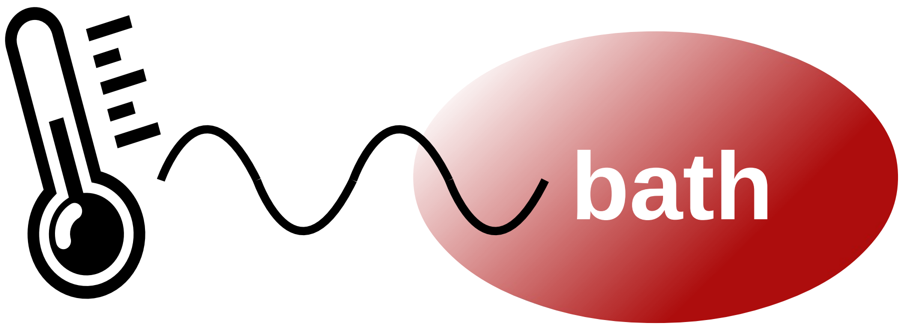
Standard method:

thermalization of motional degree of freedom

Spiegelhalder et al., PRL 103, 223203 (2009)
Lous et al., PRA **95** , 053627 (2017)
Olf et al., Nature phys. 11,720 (2015)

Thermometer

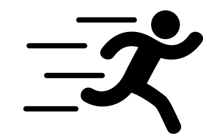
classical



$$\langle E_{kin} \rangle \sim T$$

Standard method:

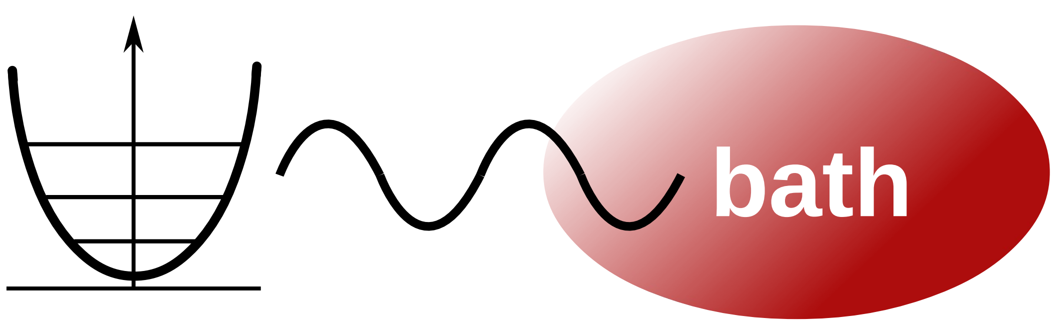
thermalization of motional degree of freedom



Spiegelhalder et al., PRL 103, 223203 (2009)
Lous et al., PRA **95** , 053627 (2017)
Olf et al., Nature phys. 11,720 (2015)

Correa et al., PRL 114, 220405 (2015)
Johnson et al., PRA 93, 053619 (2016)
Mehboudi et al., arXiv: 1811.03988

quantum



$$\sum_n p_n E_n \sim T$$

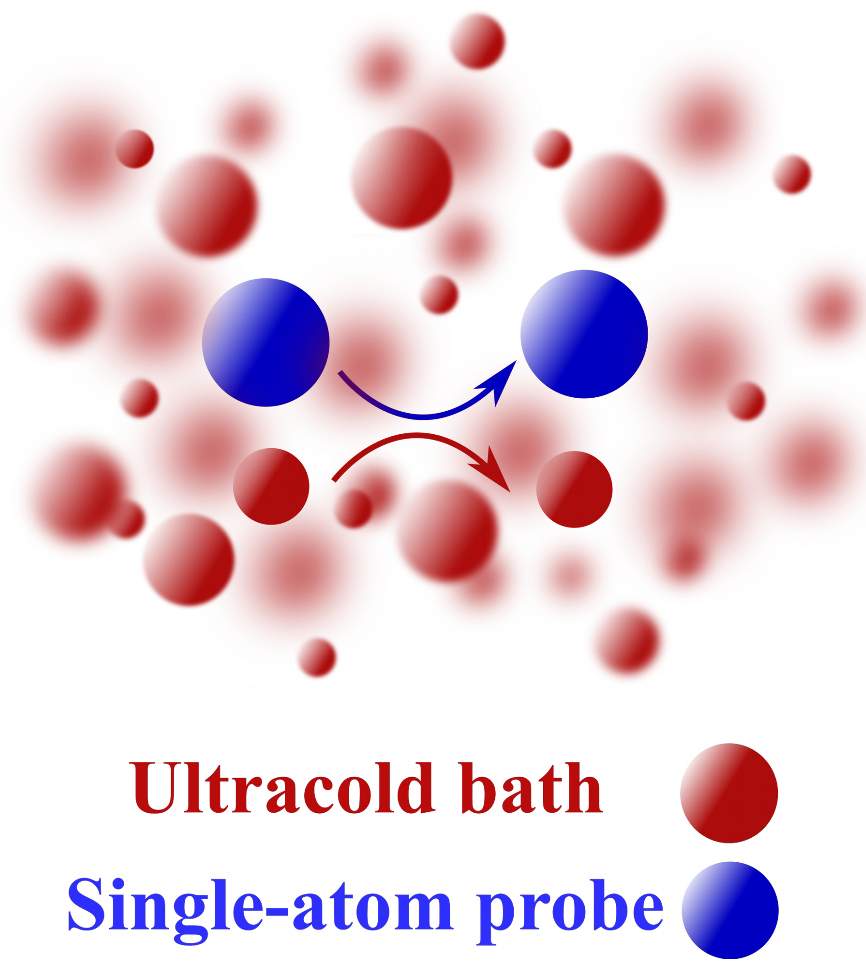
Proposal:

zeeman quasi-spin state coupling

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

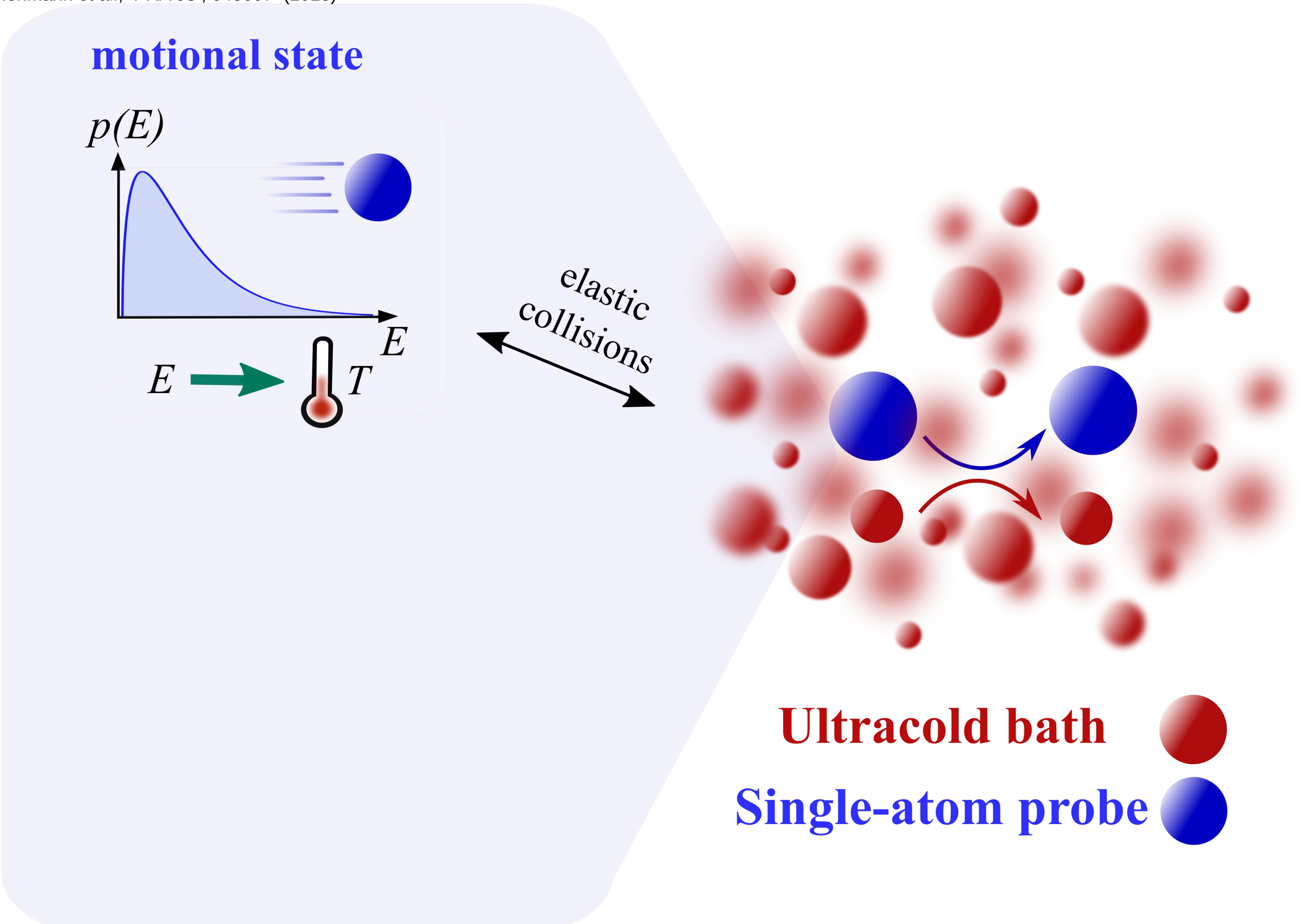
Single-spin quantum probe

individual quantum systems



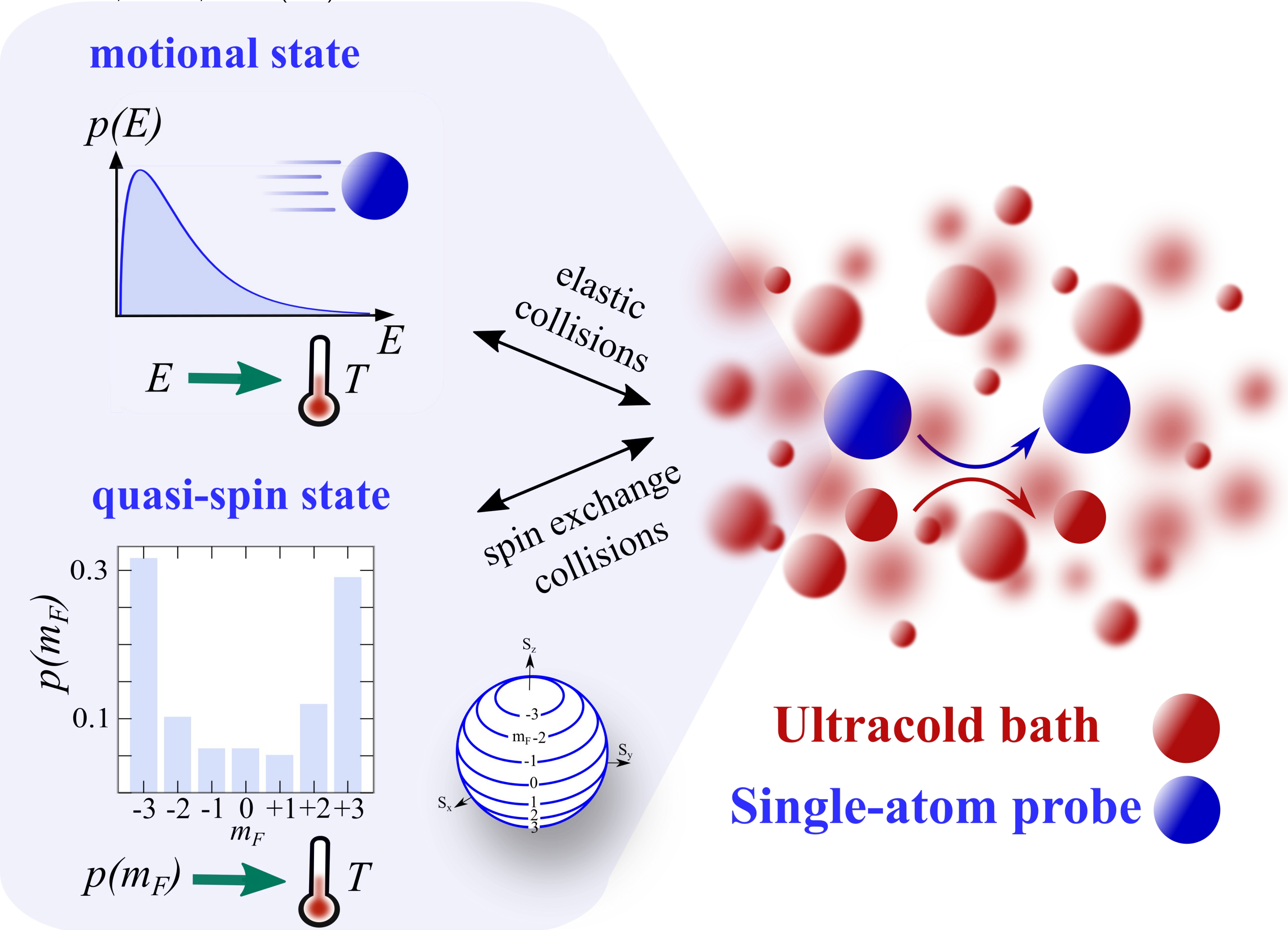
Single-spin quantum probe

Hohmann et al., PRA **93** , 043607 (2018)

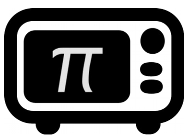


Single-spin quantum probe

Hohmann et al., PRA **93** , 043607 (2018)



Spin impurities in an ultracold gas



Cs m_F resolution

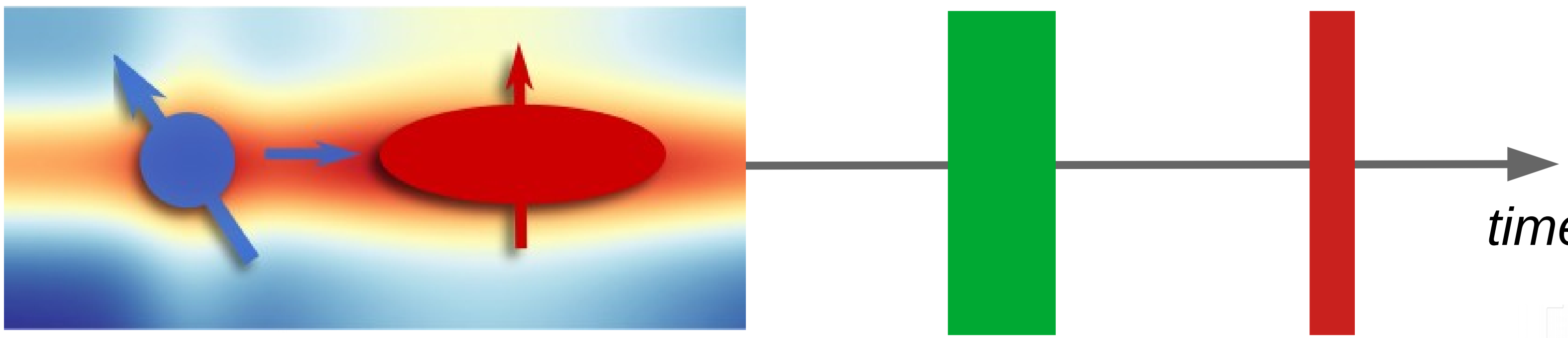
Cs prep.
$m_F = +2, F = 3$

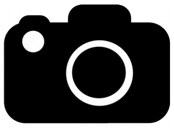
Rb prep.
$m_F = 0, F = 1,$
$N = 7$ k
$T = 200 – 1000$ nK

Cs-Rb Interaction

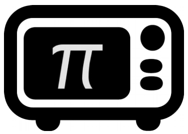
Rb push-out

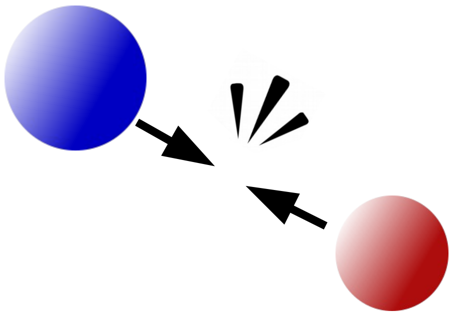
Readout

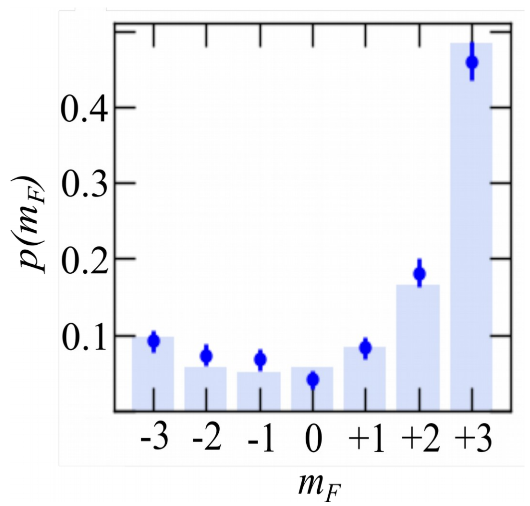




imaging fluorescence







Schmidt et al., PRL **121**, 130403 (2018)

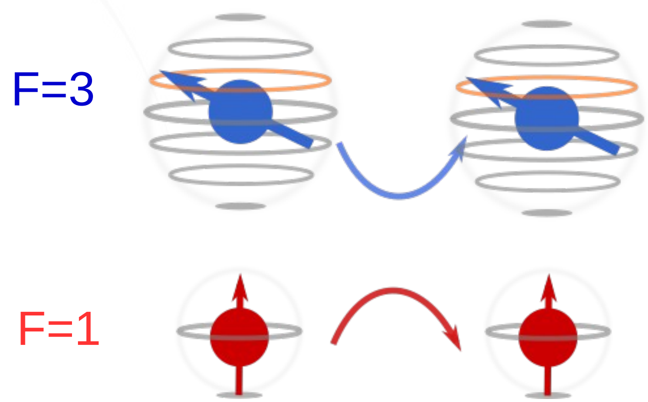
Interaction - Collisions

Cs-Rb collision

Ratio

10 : 1

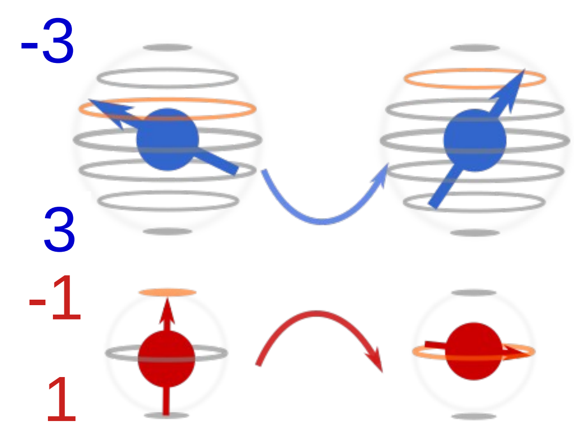
Elastic collisions



$$\Delta m_F = 0$$

thermalization of motional degree of freedom

Spin-Exchange collisions



$$\Delta m_F = 1$$

spin dynamics

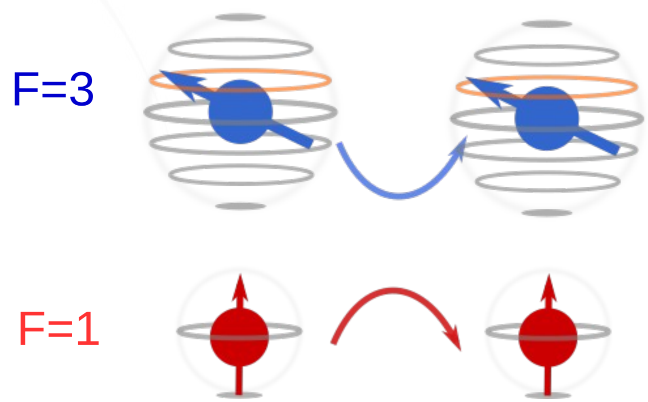
Interaction - Collisions

Cs-Rb collision

Ratio

10 : 1

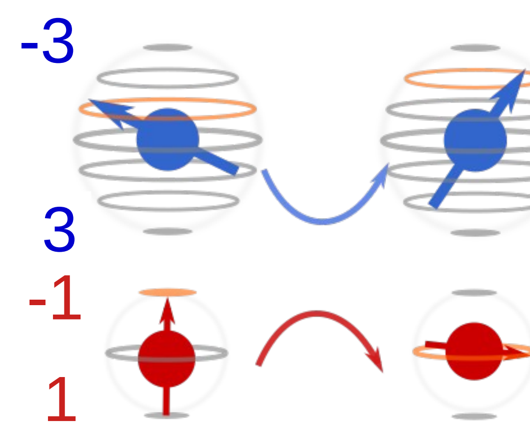
Elastic collisions



$$\Delta m_F = 0$$

thermalization of motional degree of freedom

Spin-Exchange collisions



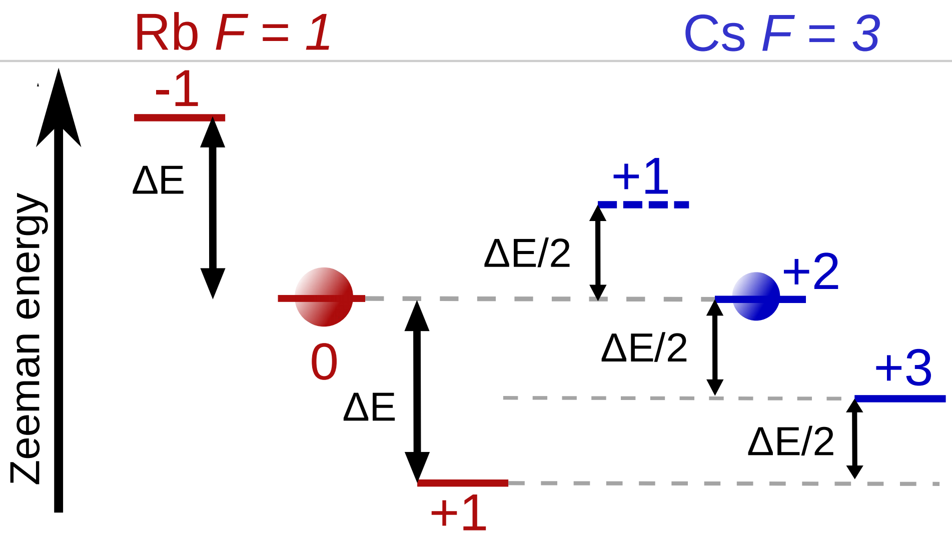
$$\Delta m_F = 1$$

spin dynamics

Investigate Spin-Exchange collisions

Spin-Exchange collisions

$$\Delta E = h \cdot B \cdot 700 \frac{kHz}{G}$$

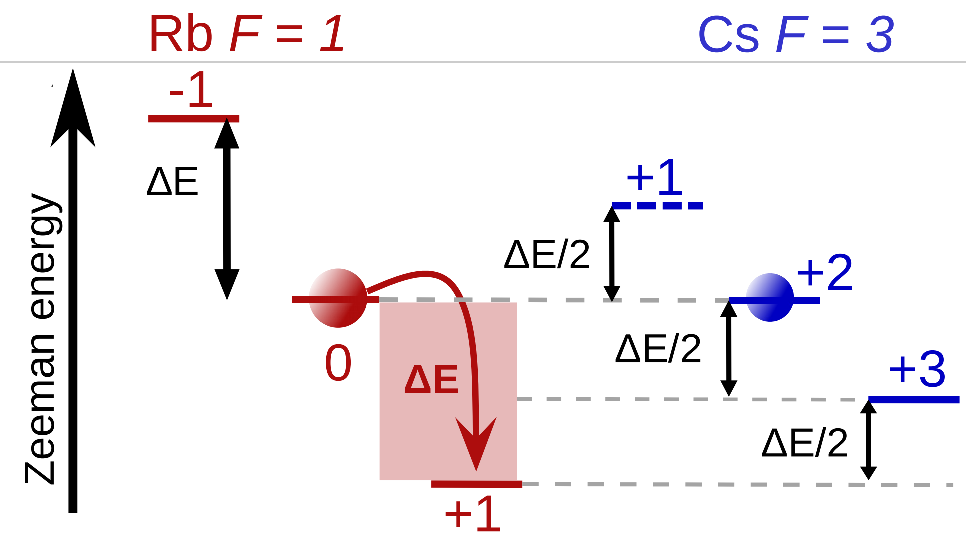


- different energy splittings due to different Landé factors

exoergic spin exchange

Spin-Exchange collisions

$$\Delta E = h \cdot B \cdot 700 \frac{kHz}{G}$$

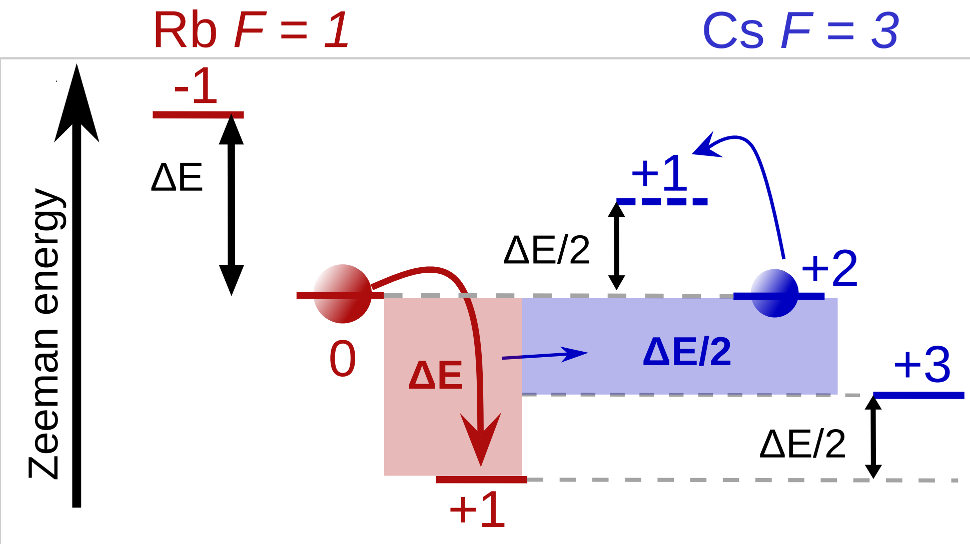


- energy released by Rb
  → decrease internal state

exoergic spin exchange

Spin-Exchange collisions

$$\Delta E = h \cdot B \cdot 700 \frac{kHz}{G}$$

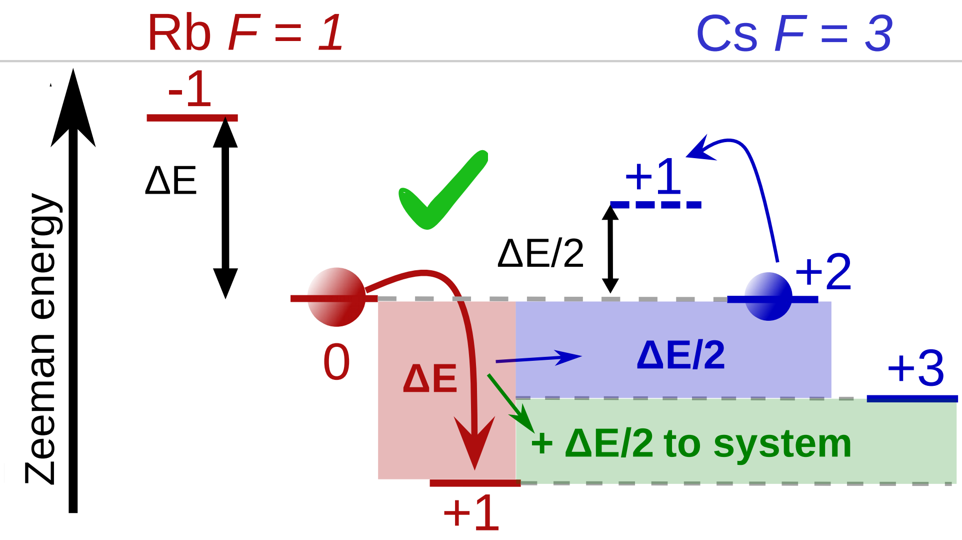


- Cs take a part of that energy → increase internal state

exoergic spin exchange

Spin-Exchange collisions

$$\Delta E = h \cdot B \cdot 700 \frac{kHz}{G}$$

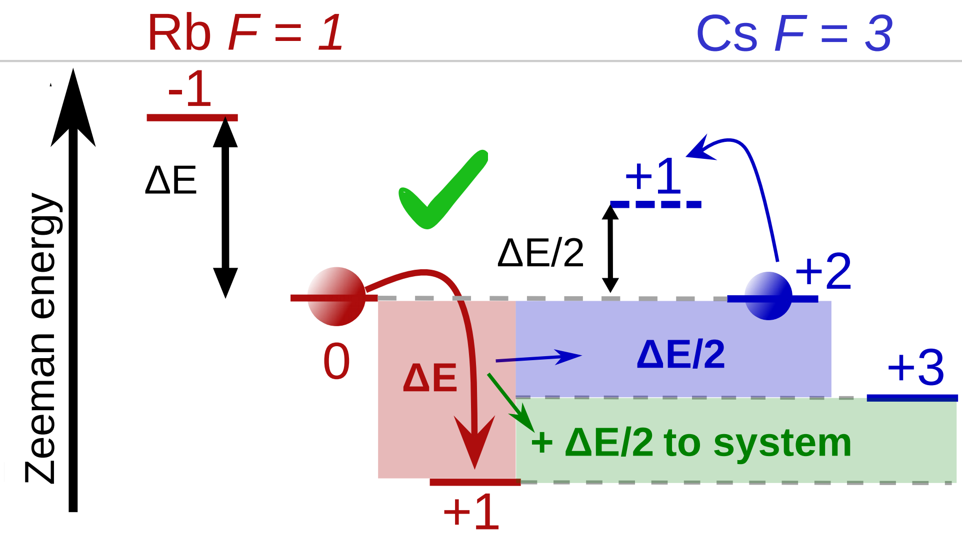


- rest of energy is given to the system
- collision energetically allowed ✓

exoergic spin exchange

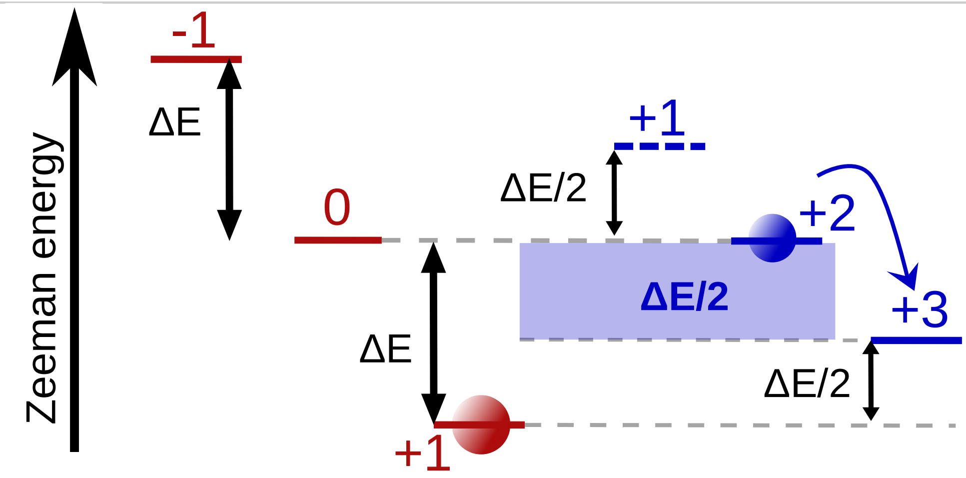
Spin-Exchange collisions

$$\Delta E = h \cdot B \cdot 700 \frac{kHz}{G}$$



- rest of energy is given to the system
- collision energetically allowed

exoergic spin exchange

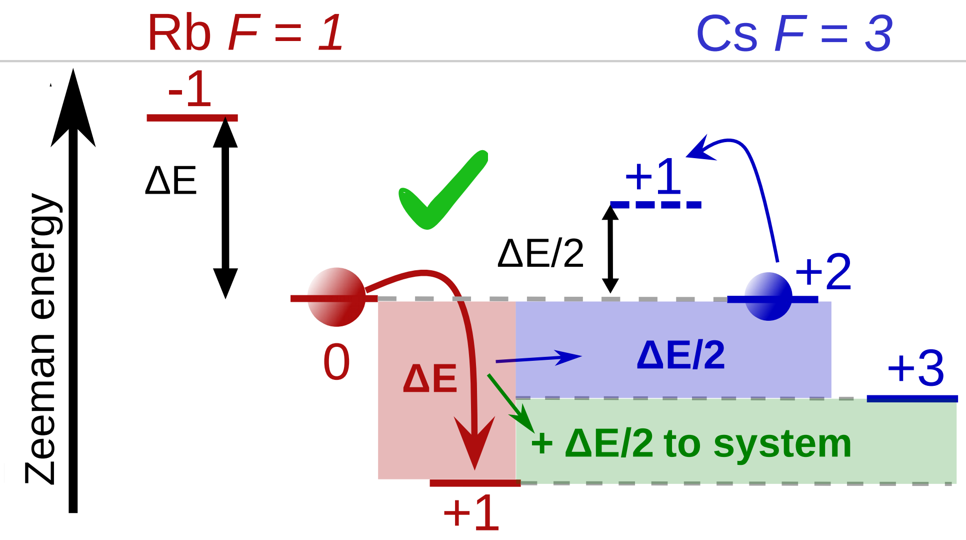


- energy released by Cs
  → decrease internal state

endoergic spin exchange

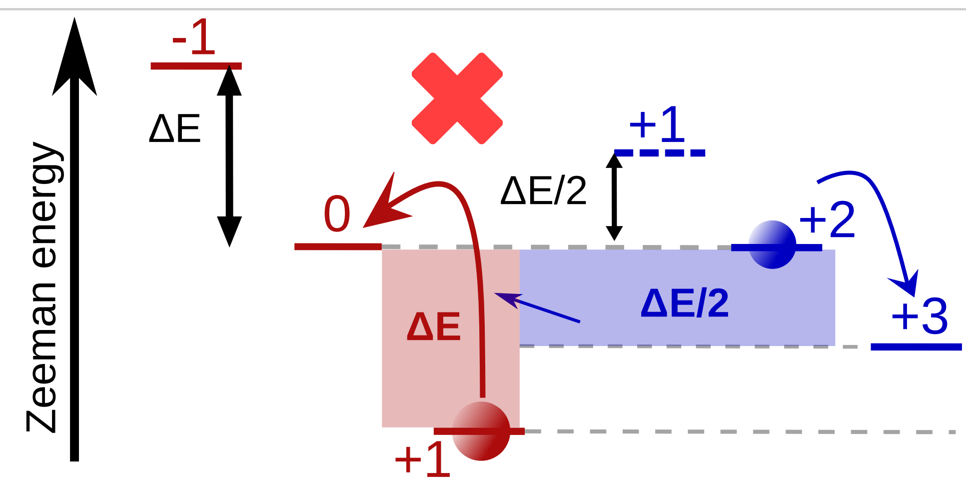
Spin-Exchange collisions

$$\Delta E = h \cdot B \cdot 700 \frac{kHz}{G}$$



- rest of energy is given to the system
- collision energetically allowed

exoergic spin exchange

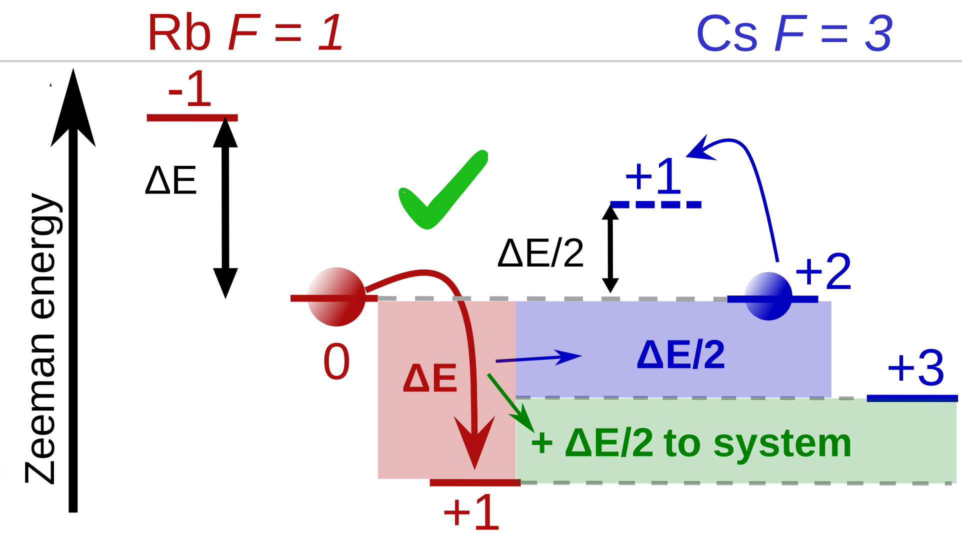


- energy missing for Rb
  → collision energetically forbidden

endoergic spin exchange

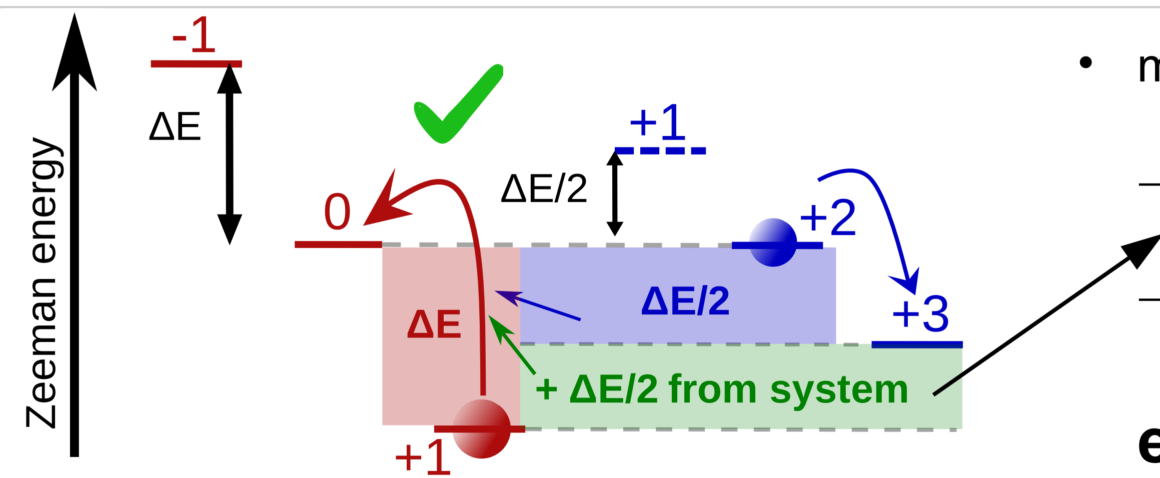
Spin-Exchange collisions

$$\Delta E = h \cdot B \cdot 700 \frac{kHz}{G}$$



- rest of energy is given to the system
- collision energetically allowed

exoergic spin exchange



- missing energy taken from system

$\rightarrow E_{Coll} \geq \Delta E/2$ allowed

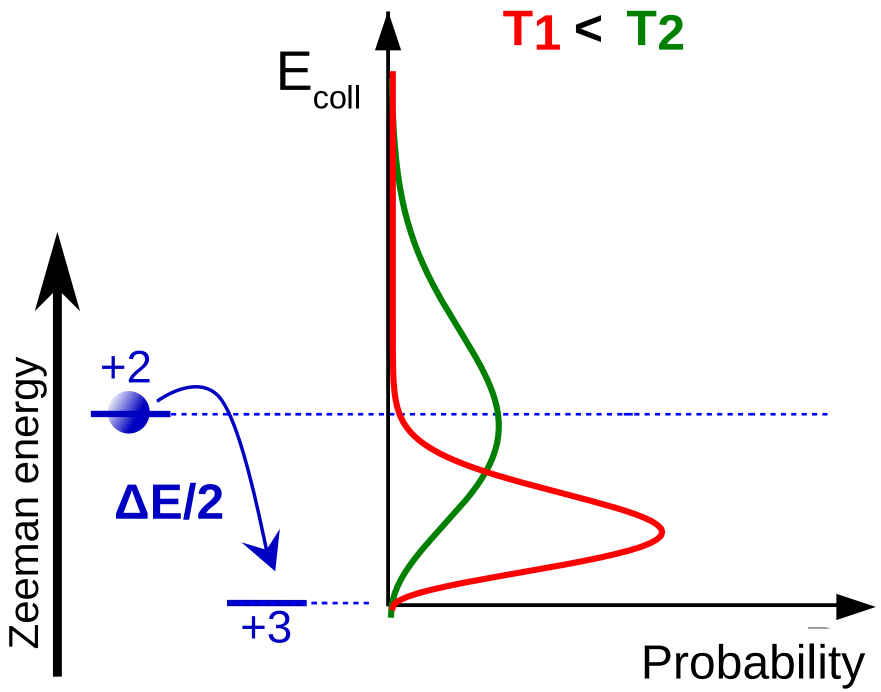
$\rightarrow E_{Coll} < \Delta E/2$ forbidden

endoergic spin exchange

Mapping temperature onto spin distribution

endoergic spin exchange

Zeeman energy vs. thermal energy

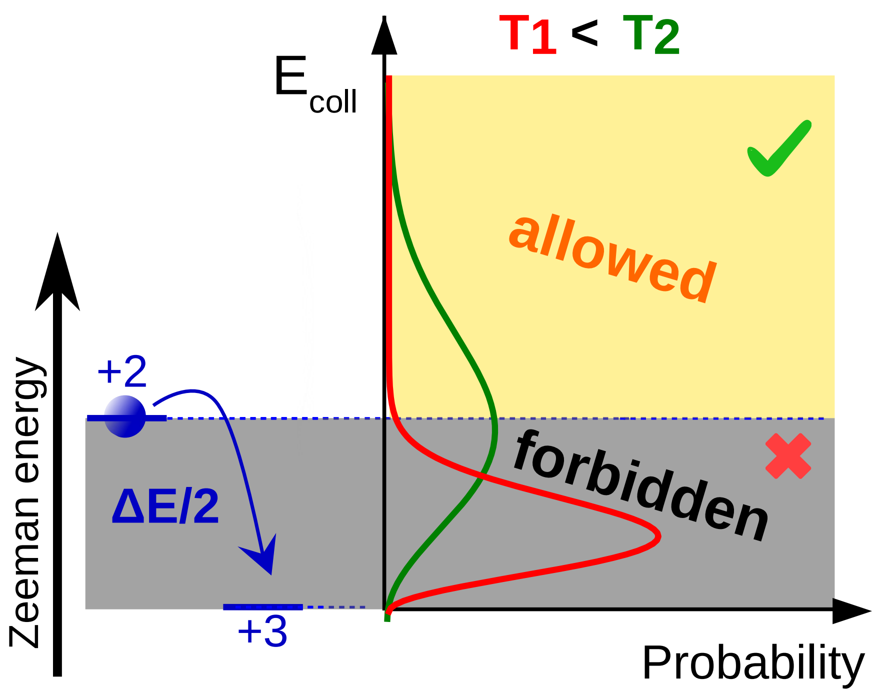


Mapping temperature onto spin distribution

endoergic spin exchange

Zeeman energy vs. thermal energy

$$E_{Coll} \geq \Delta E/2$$ ✓



$$E_{Coll} < \Delta E/2$$ ✖

Mapping temperature onto spin distribution

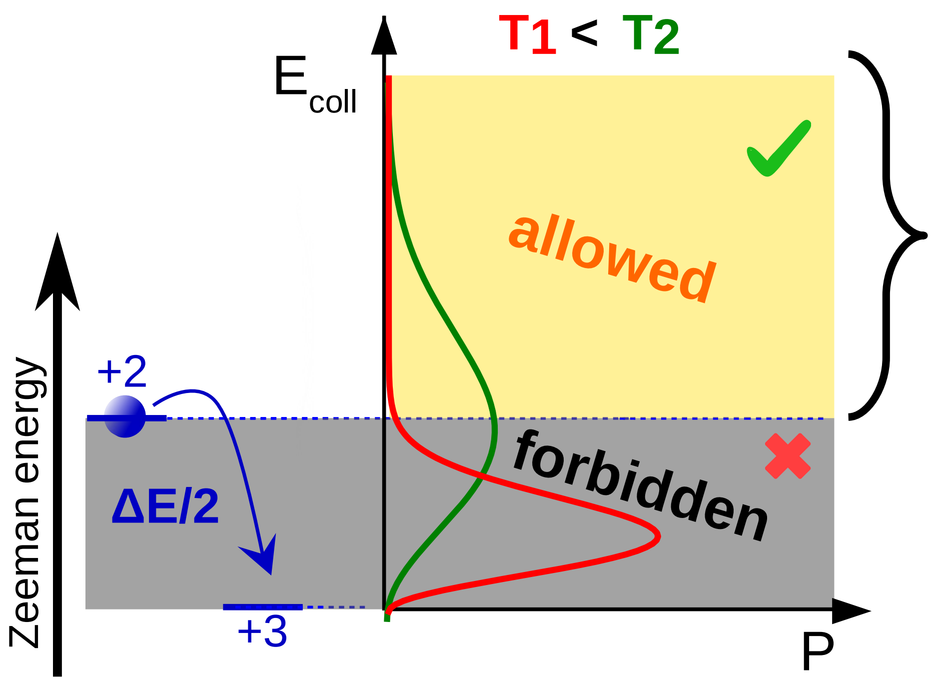
TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

individual quantum systems

endoergic spin exchange

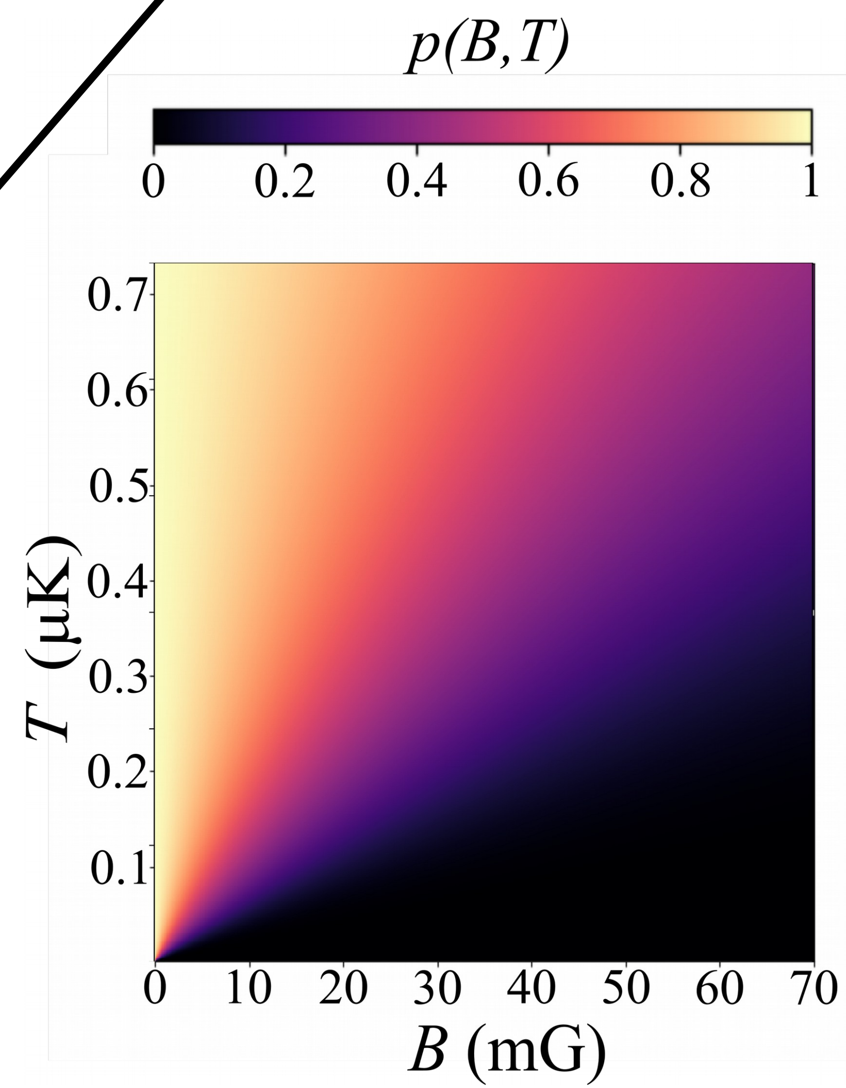
Zeeman energy vs. thermal energy

$E_{Coll} \geq \Delta E/2$ ✓

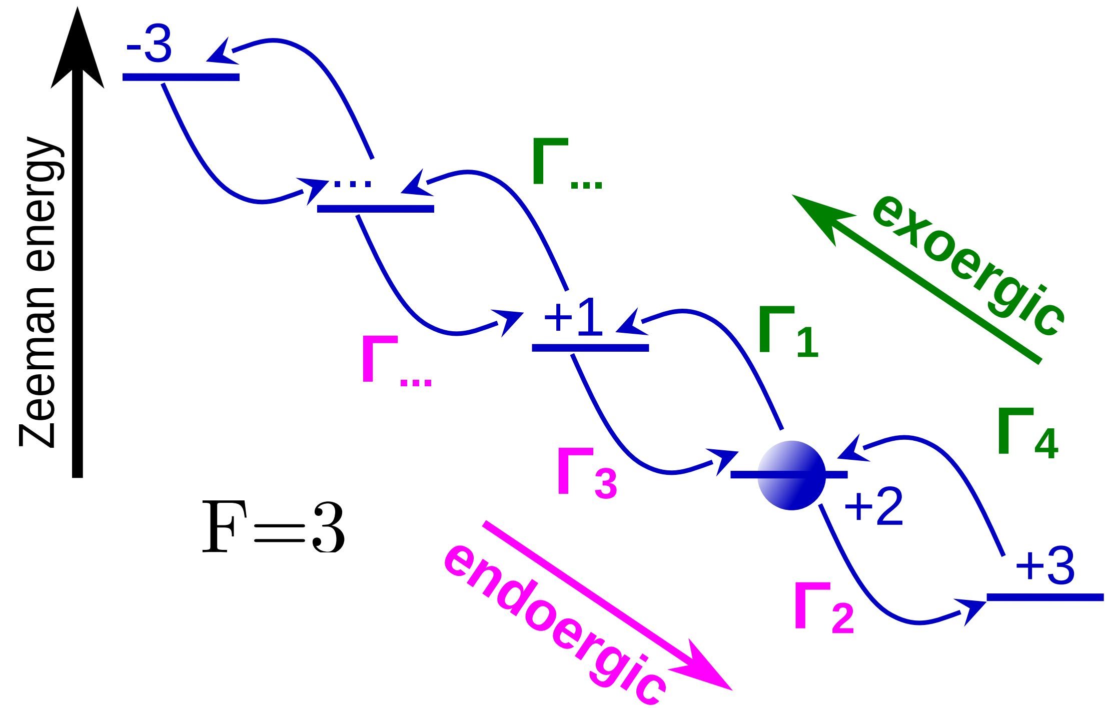


$E_{Coll} < \Delta E/2$ ✖

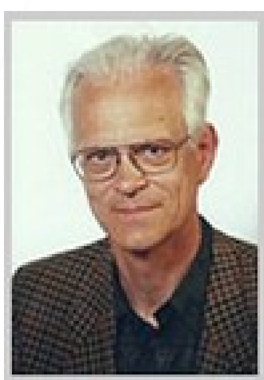
$$p(B,T) = \int_{\Delta E/2}^{\infty} p(E_c)\,dE_c$$



Mapping temperature onto spin distribution



Rates:



Eberhard Tiemann,
Universität Hannover

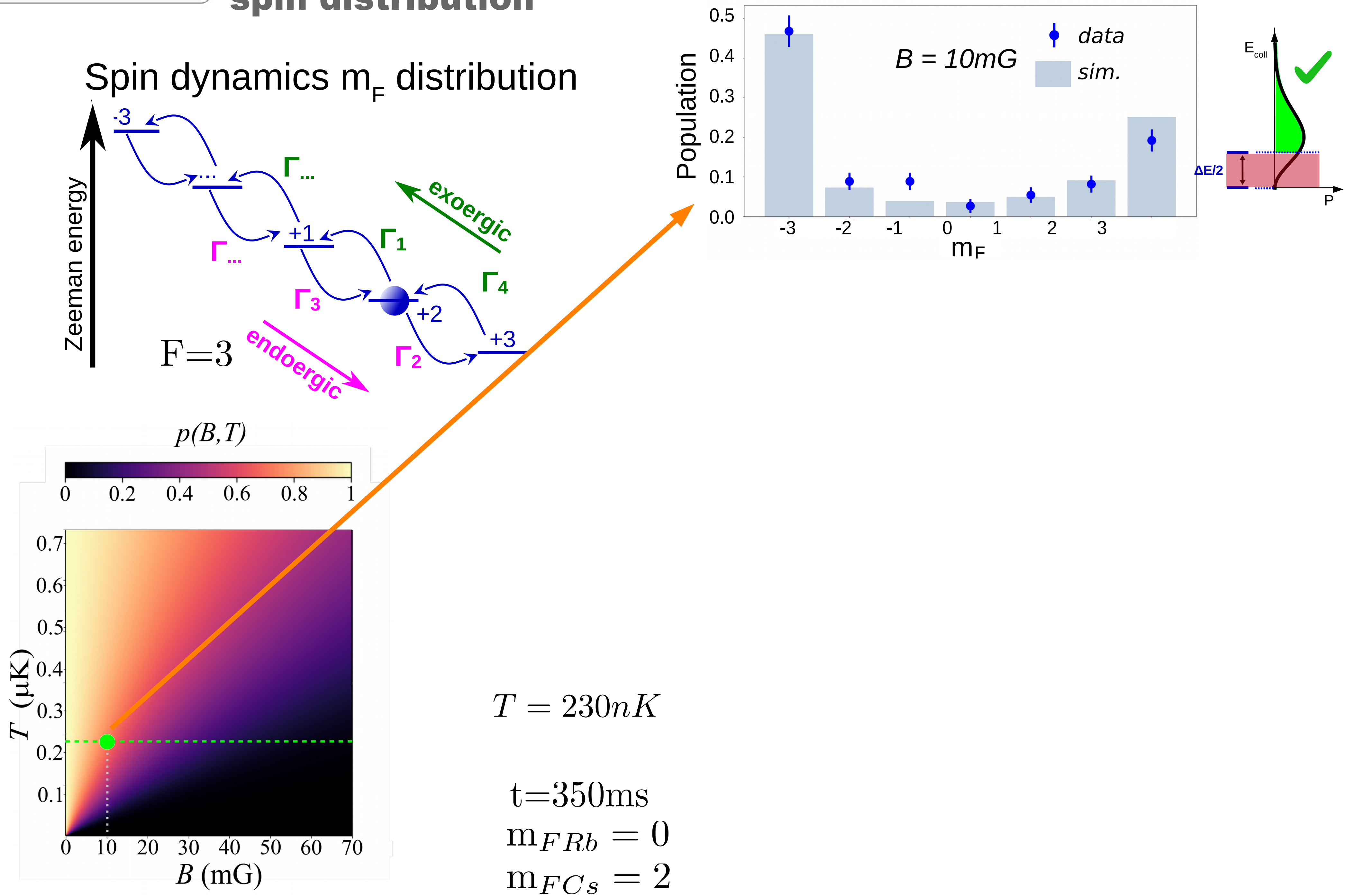
$$\Gamma_i = \sigma_i \langle n \rangle v$$

$$\sigma_i(T, B, m_F) \qquad v(T)$$

Schmidt et al., PRL **122**, 013401 (2019)

Mapping temperature onto spin distribution

Spin dynamics m_F distribution



$T = 230nK$

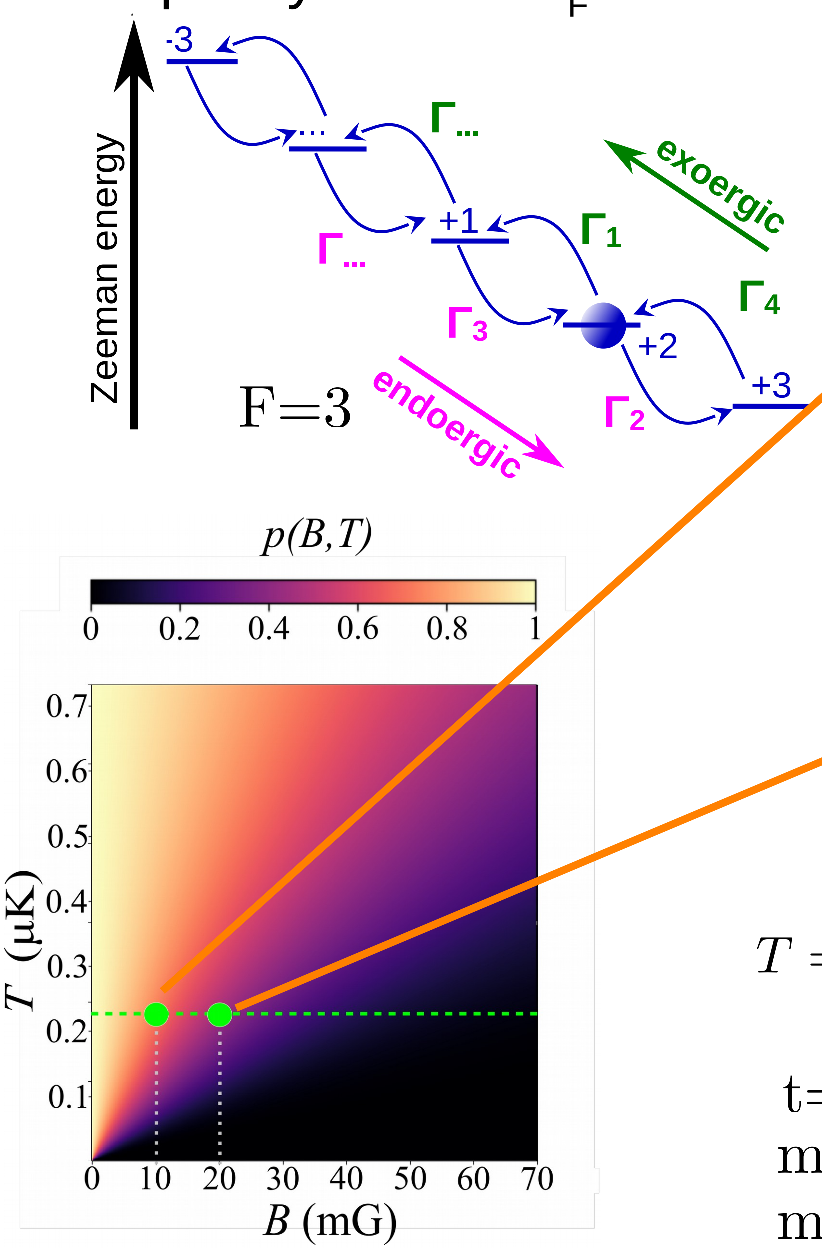
t=350ms

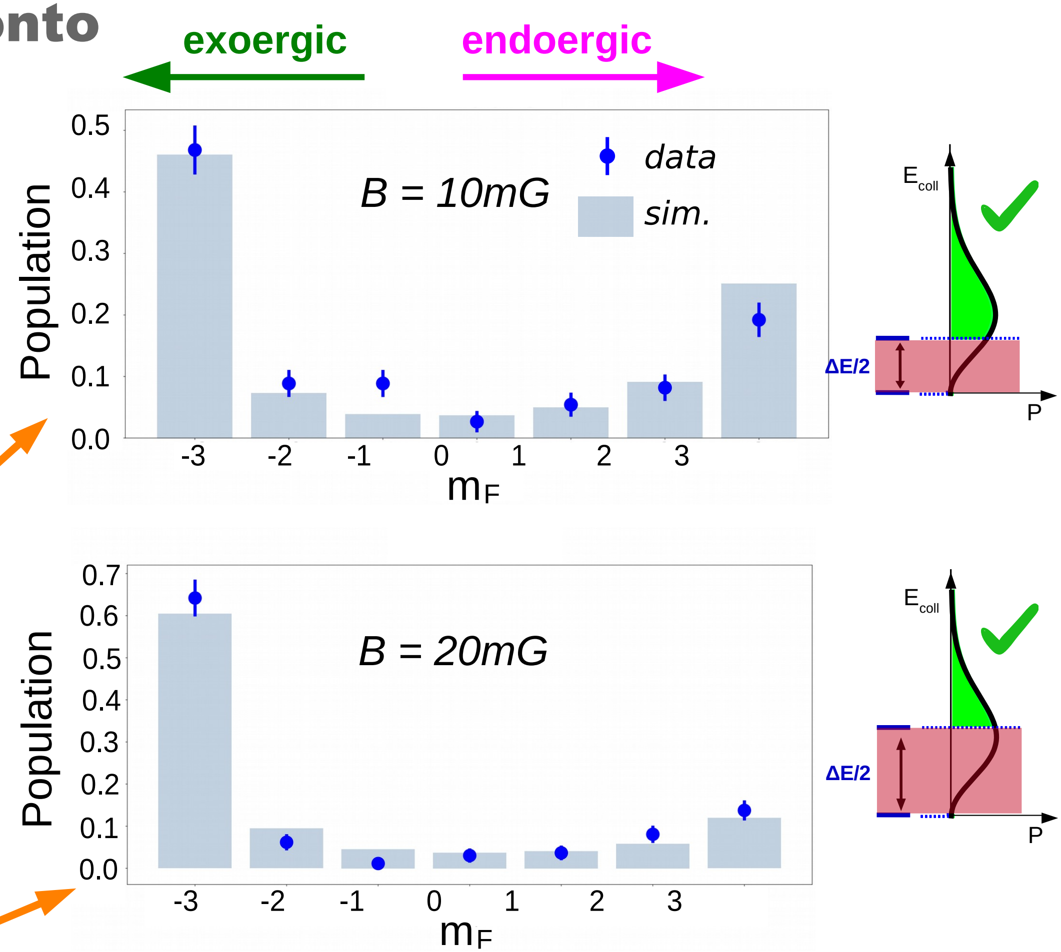
$m_{F Rb} = 0$

$m_{F Cs} = 2$

Mapping temperature onto spin distribution

Spin dynamics m_F distribution





$T = 230nK$

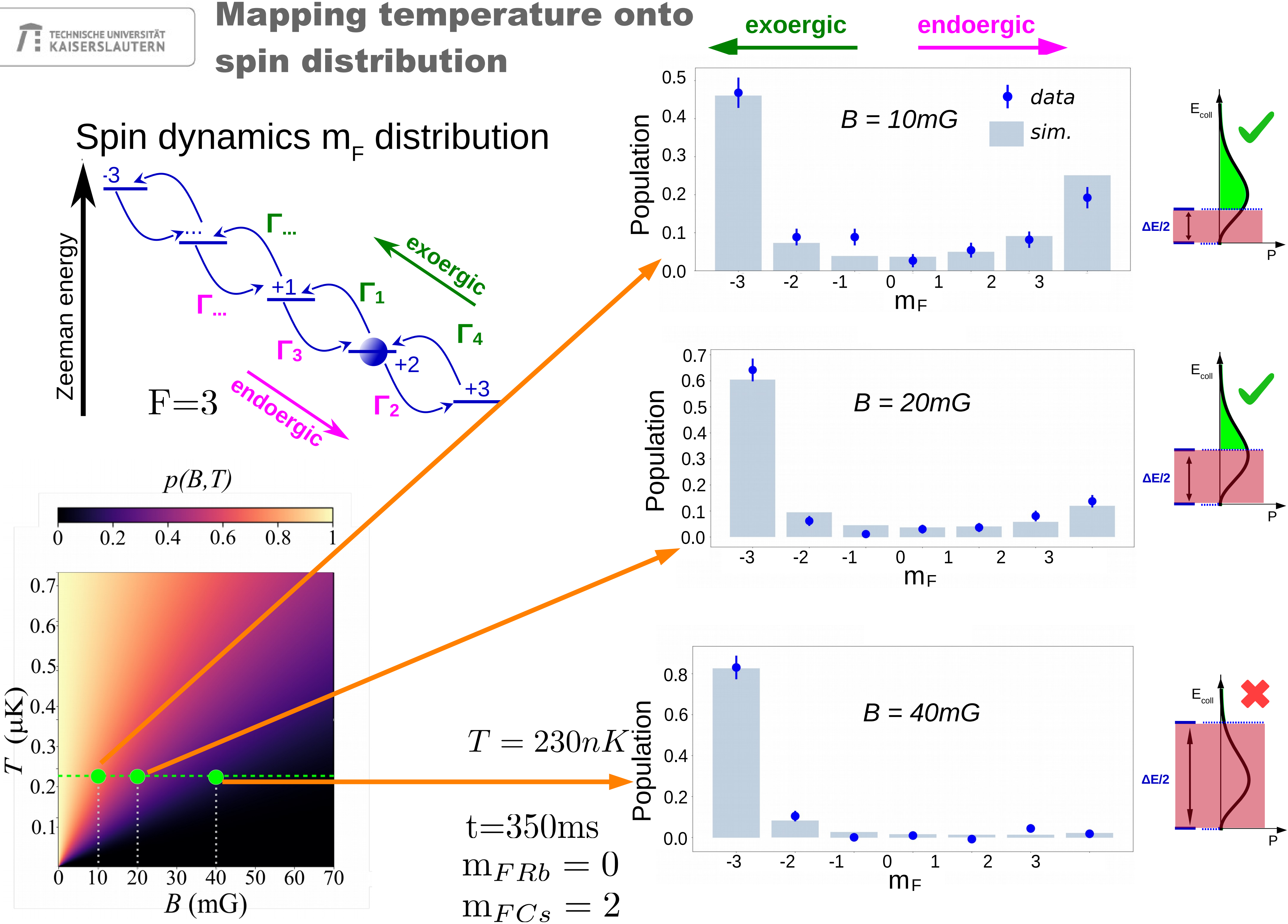
$t=350ms$

$m_{FRb} = 0$

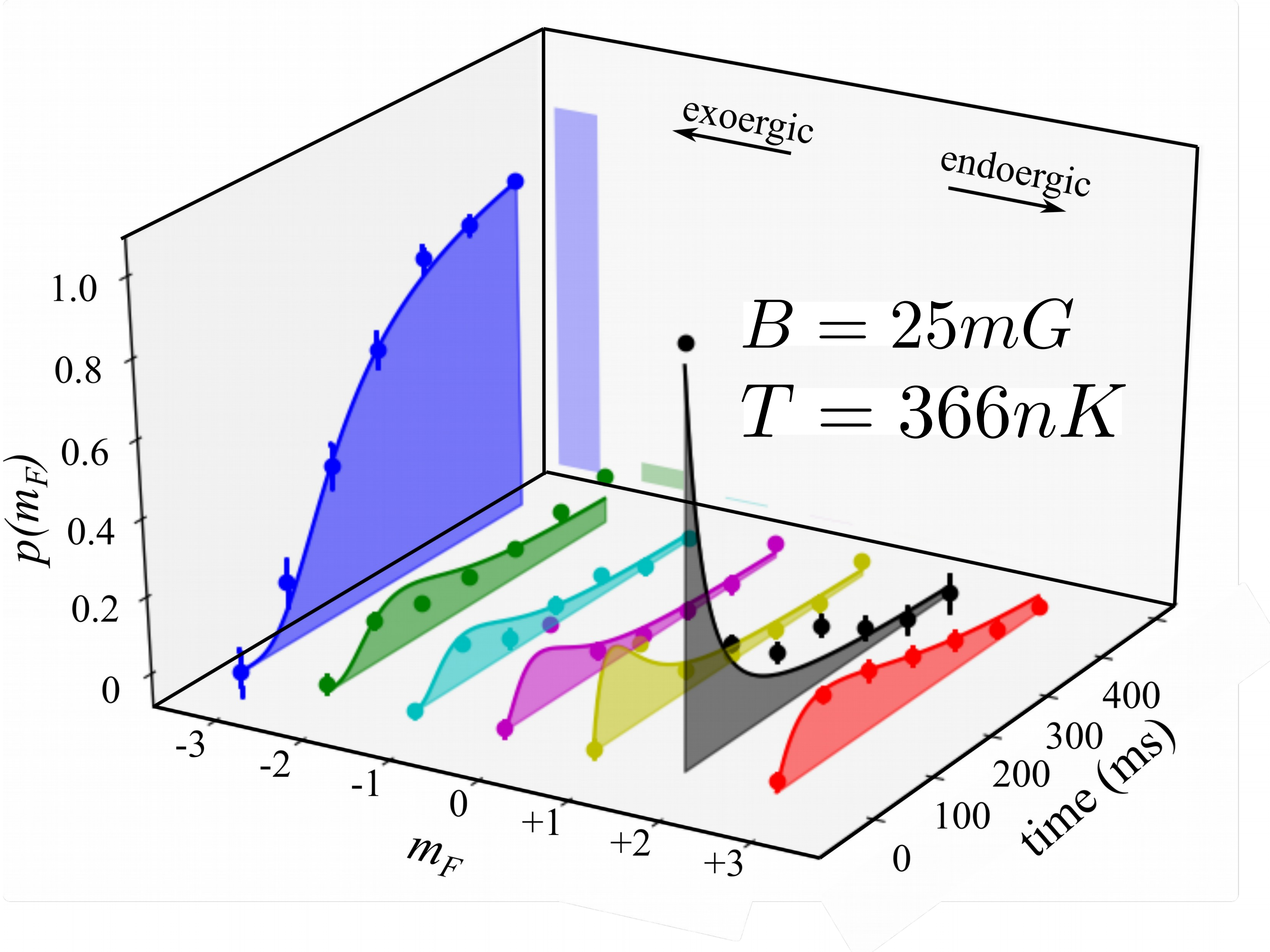
$m_{FCs} = 2$

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

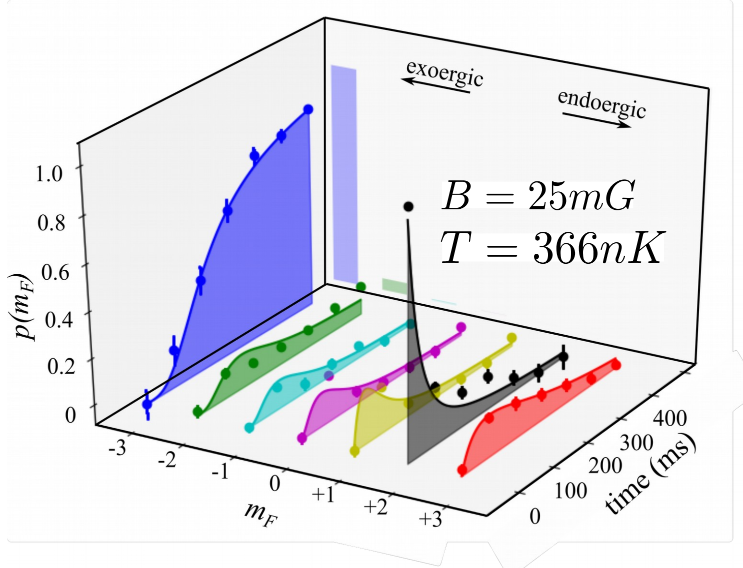
Mapping temperature onto spin distribution



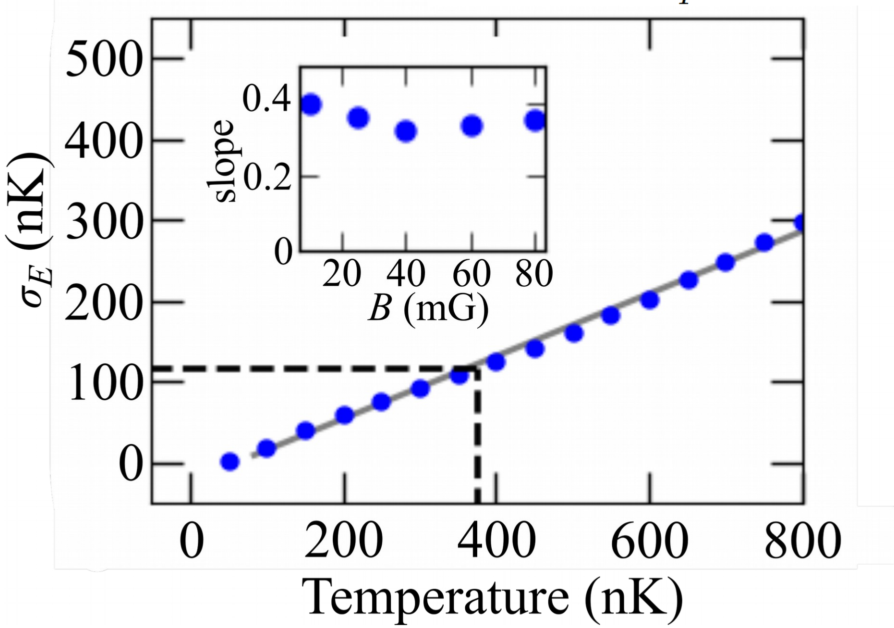
Mapping temperature onto spin distribution



Mapping temperature onto spin distribution



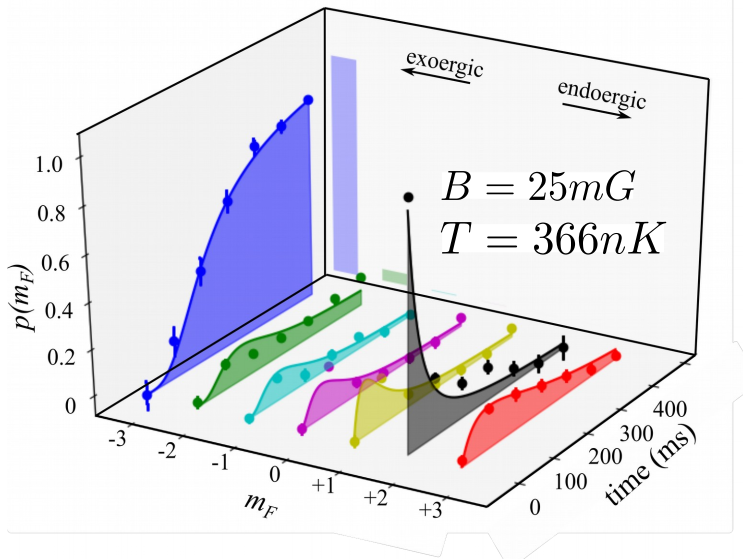
$$\sigma_E^2 = \langle E^2 \rangle - \langle E \rangle^2 \qquad \langle E^2 \rangle = \sum_{m_F} E_{m_F}^2 p(m_F)$$



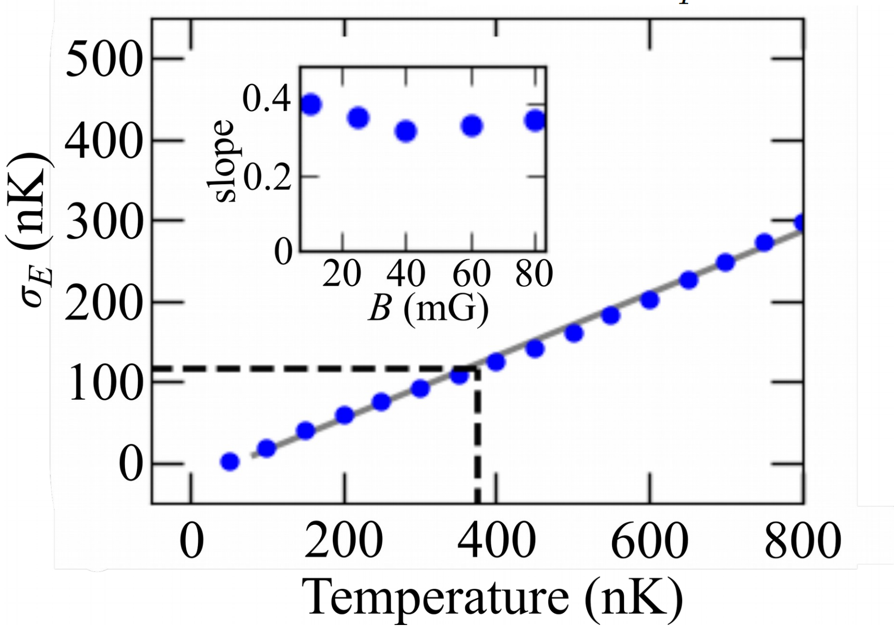
steady state (theoretically)

Bouton et al., arXiv: 1906.00844 (2019)

Mapping temperature onto spin distribution

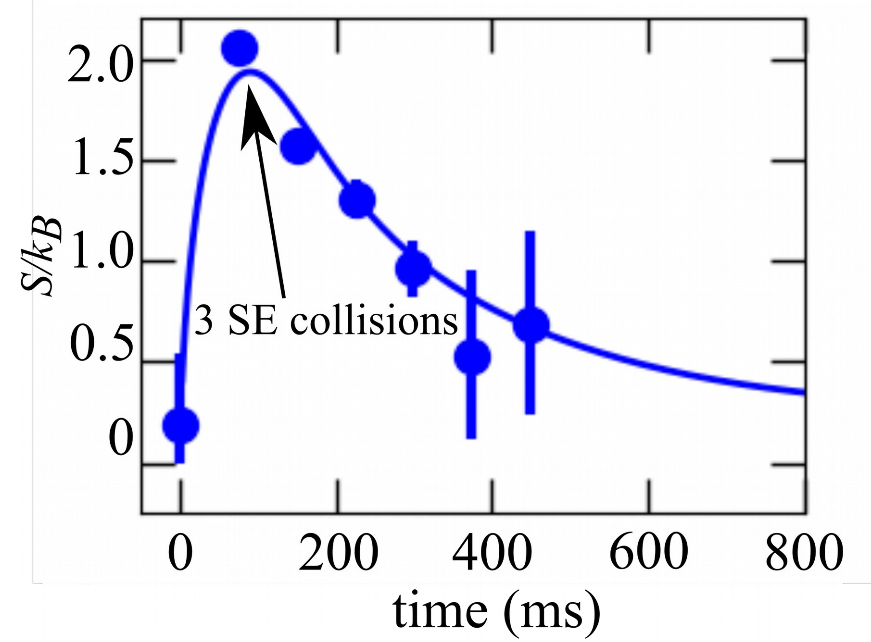


$\sigma_E^2 = \langle E^2 \rangle - \langle E \rangle^2$ $\langle E^2 \rangle = \sum_{m_F} E_{m_F}^2 p(m_F)$



steady state (theoretically)

$S = -k_B \sum_{m_F} p(m_F) \log(p(m_F))$

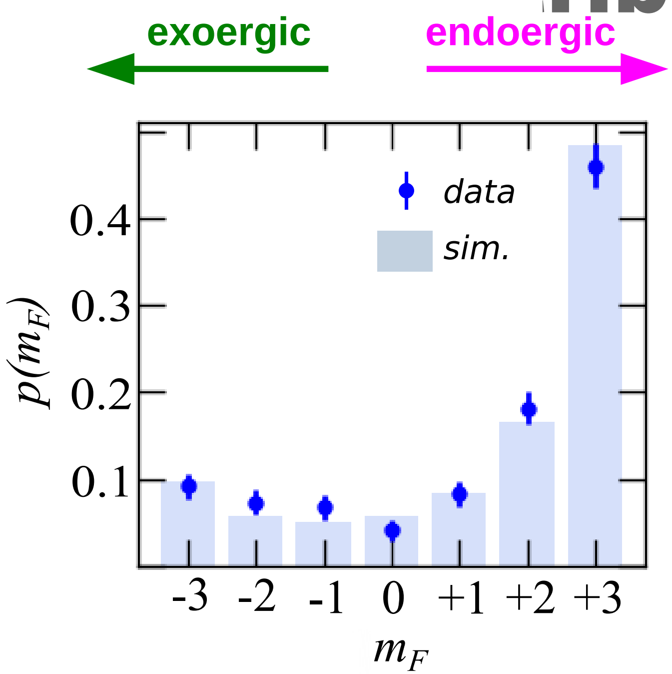


dynamic (exp. & theor.)

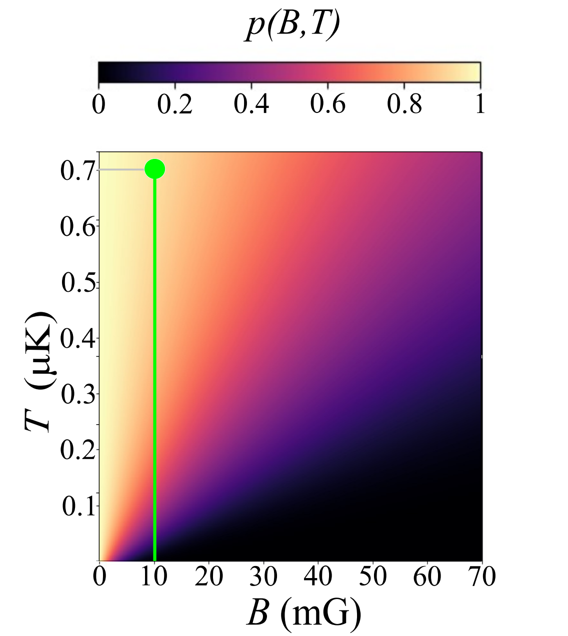
Bouton et al., arXiv: 1906.00844 (2019)

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

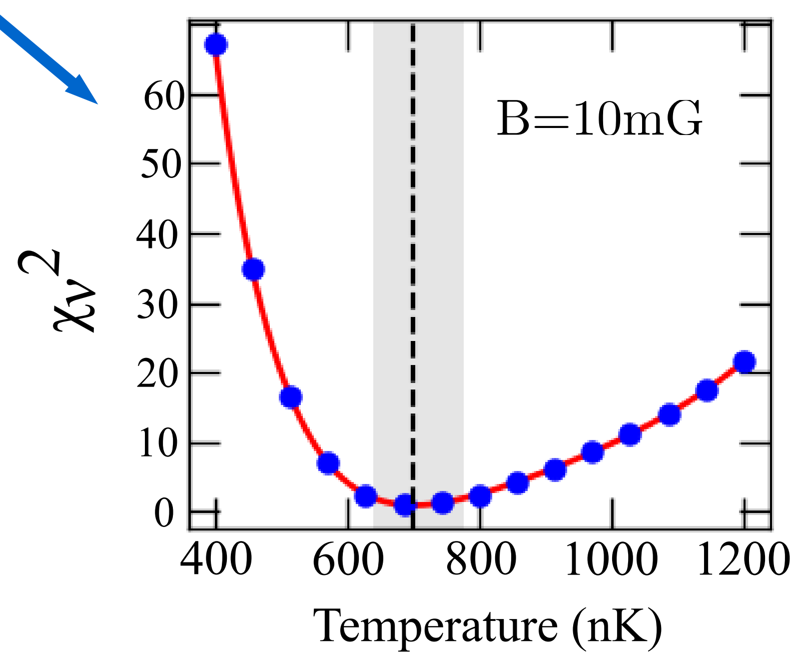
Mapping temperature onto spin distribution



$$\chi^2_\mu = \frac{1}{\nu} \sum_i \left(\frac{p_{meas.} - p_{theo.}}{\sigma_{meas}} \right)^2$$



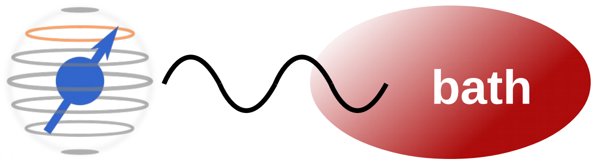
$$\mathrm{T}_{Spin} = 702^{+60}_{-76} nK$$



Determine temperature via spin dynamic

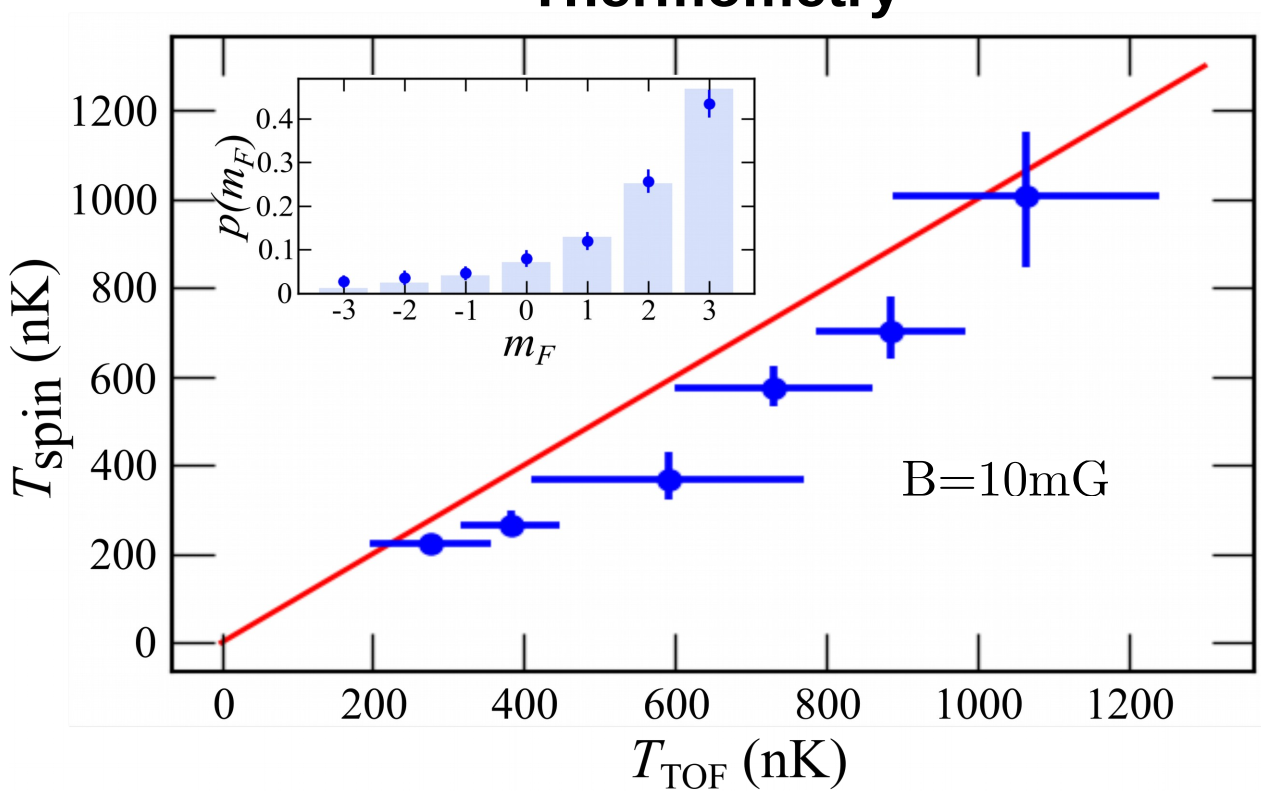
Compare Cs distributions for different simulated temperatures with measured distribution

Mapping T & B onto spin distribution



Single atom coupled to the bath
allows thermometry via spin dynamic

Thermometry



Next step: Investigate the sensitivity

Bouton et al., arXiv: 1906.00844 (2019)

Sensitivity

Bures distance

$$d^2_{\text{Bures}}(\delta T) = 2 - 2\sum_{m_F}\left[P_{m_F}(T)P_{m_F}(T+\delta T)\right]^{1/2}$$

$$d_{\text{Bures}}(\delta T) = \sqrt{F_T}\,\delta T \; + \; \mathcal{O}(\delta T)^2$$

Sensitivity

$$\partial d_{\text{Bures}}/\partial \delta_T = \sqrt{F_T}$$

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

Sensitivity

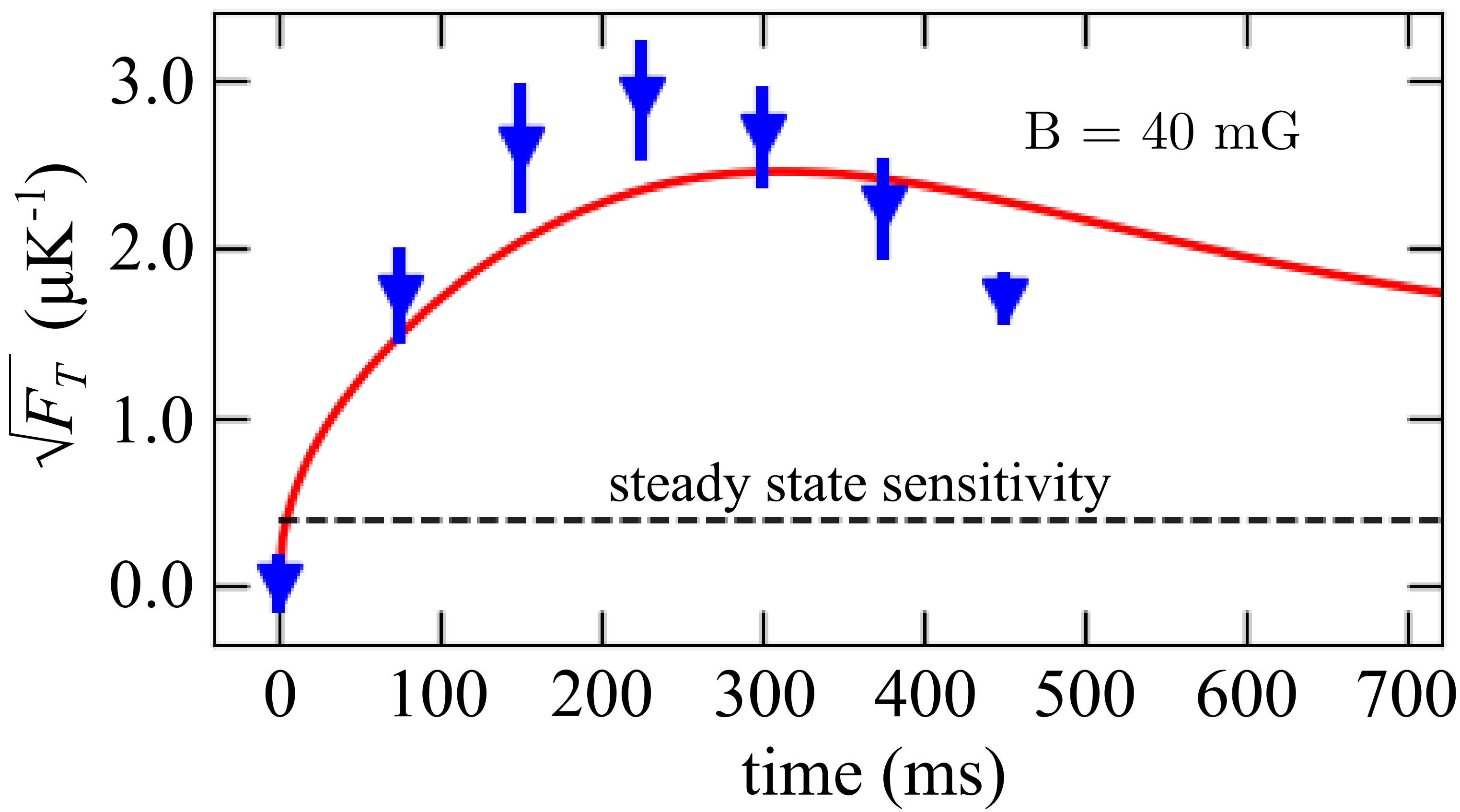
Bures distance

$$d^2_{\mathrm{Bures}}(\delta T) = 2 - 2\sum_{m_F}\left[P_{m_F}(T)P_{m_F}(T+\delta T)\right]^{1/2}$$

$$d_{\mathrm{Bures}}(\delta T) = \sqrt{F_T}\,\delta T \ + \ \mathcal{O}(\delta T)^2$$

Sensitivity

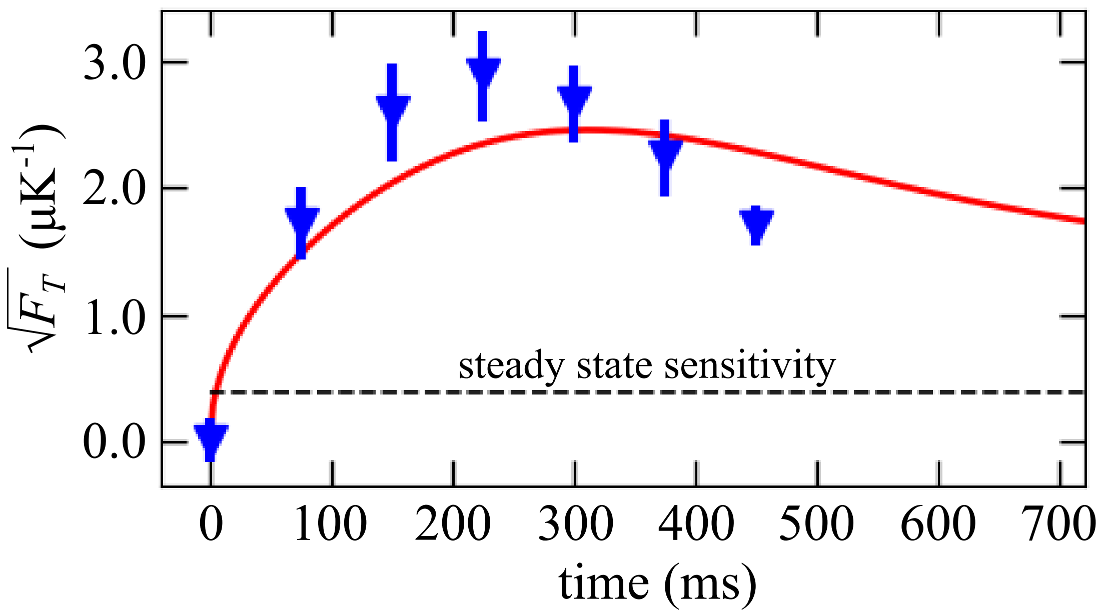
$$\partial d_{\mathrm{Bures}}/\partial\delta_T = \sqrt{F_T}$$



Bouton et al., arXiv: 1906.00844 (2019)

Sensitivity

Bouton et al., arXiv: 1906.00844 (2019)



Sensitivity

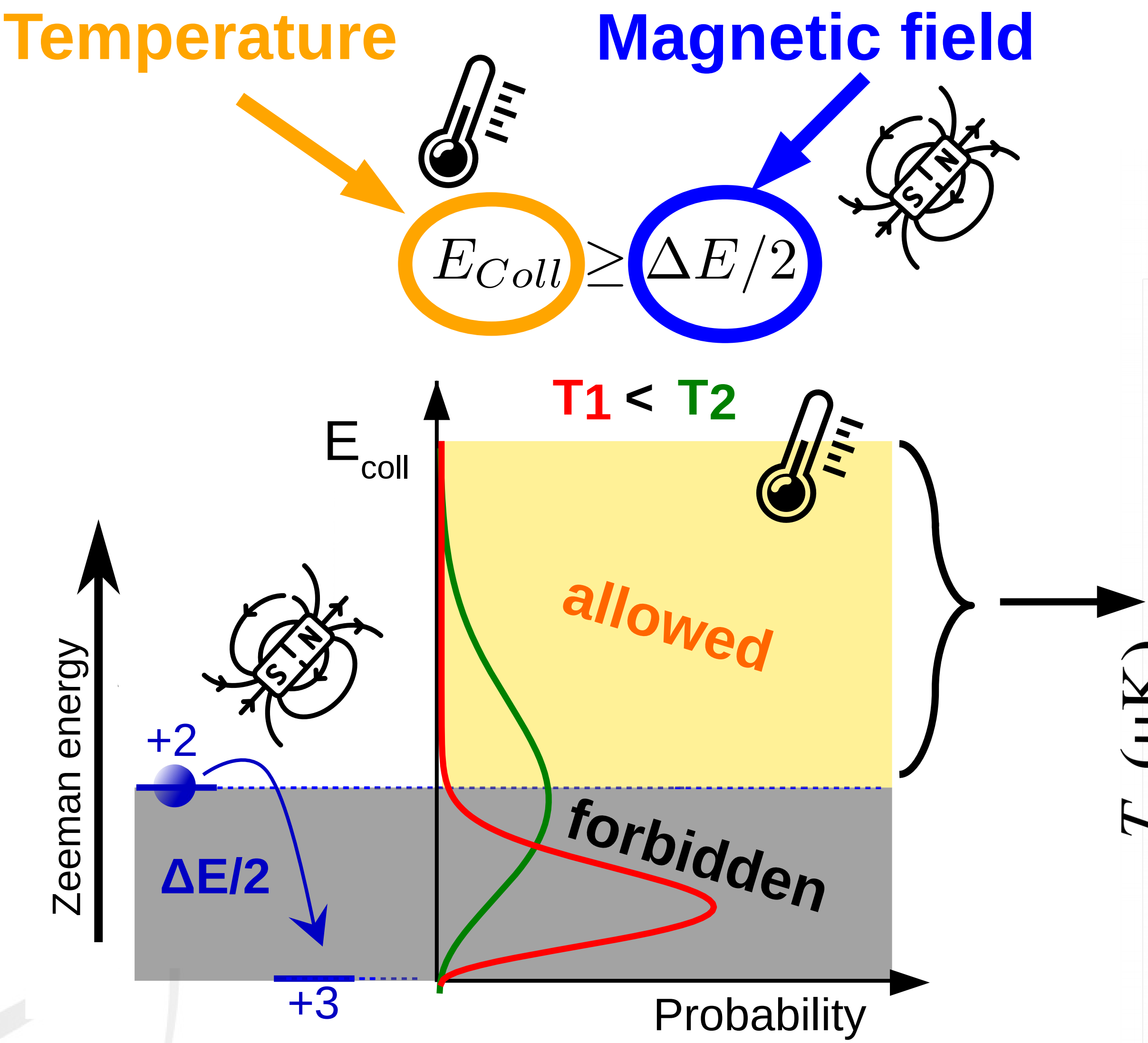
$$\partial d_{\text{Bures}} / \partial \delta_T = \sqrt{F_T}$$

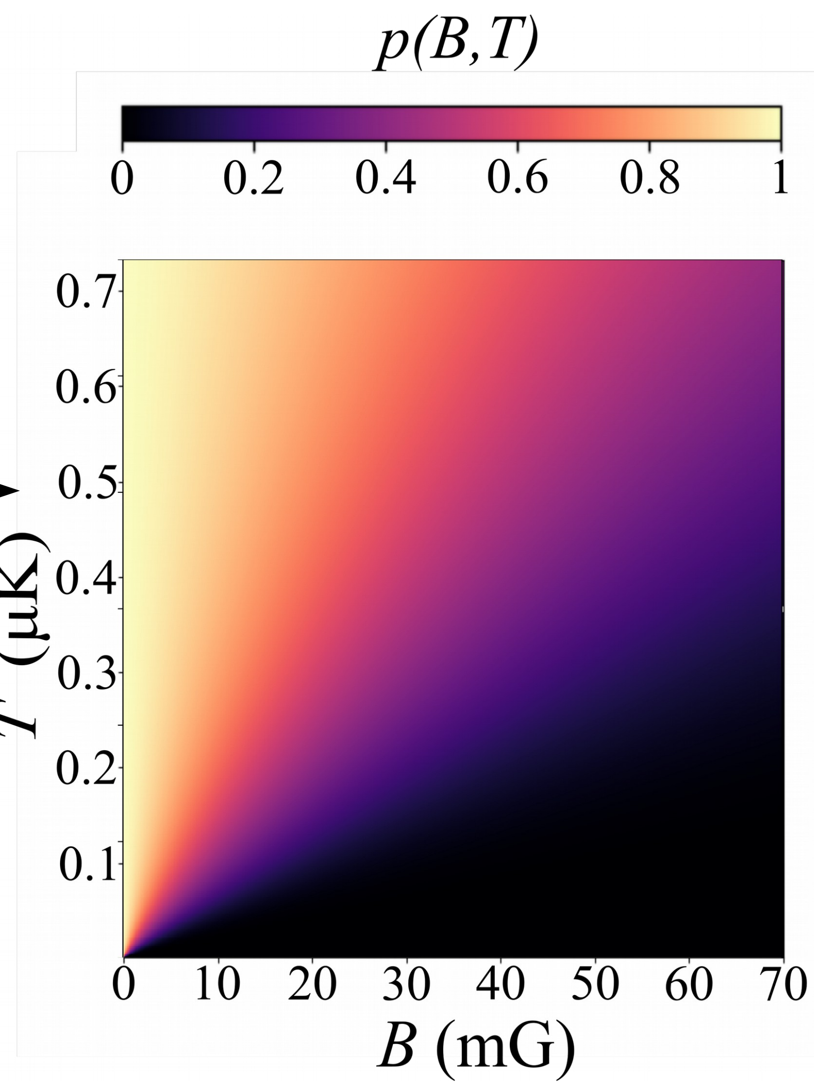
compared to steady state

thermometry 6.55 

boost in sensitivity

Magnetometry

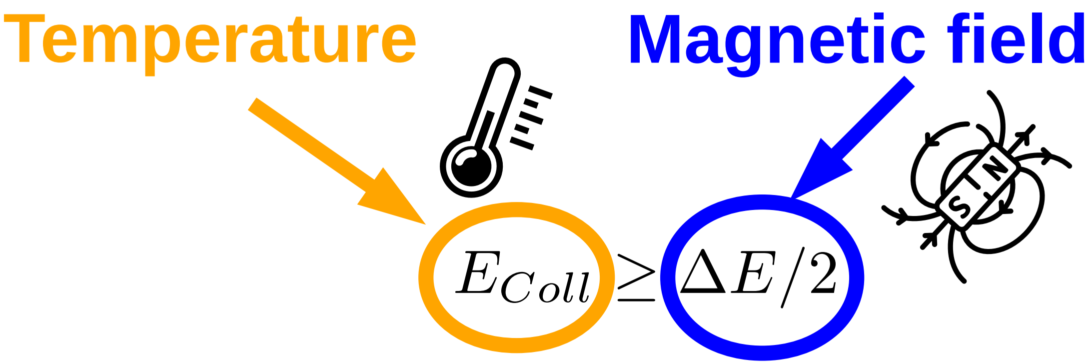


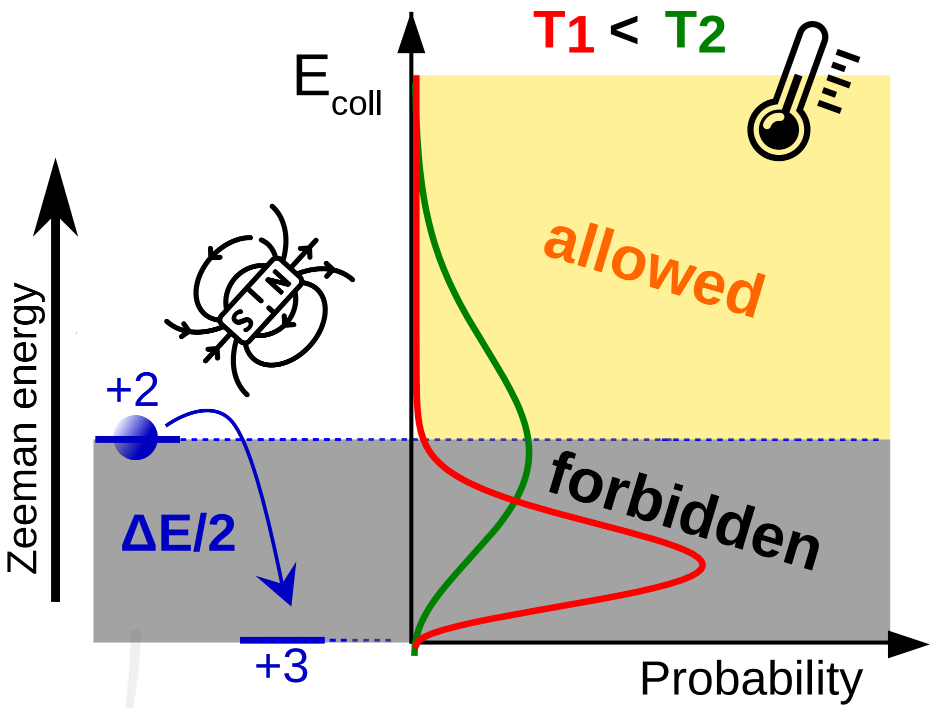


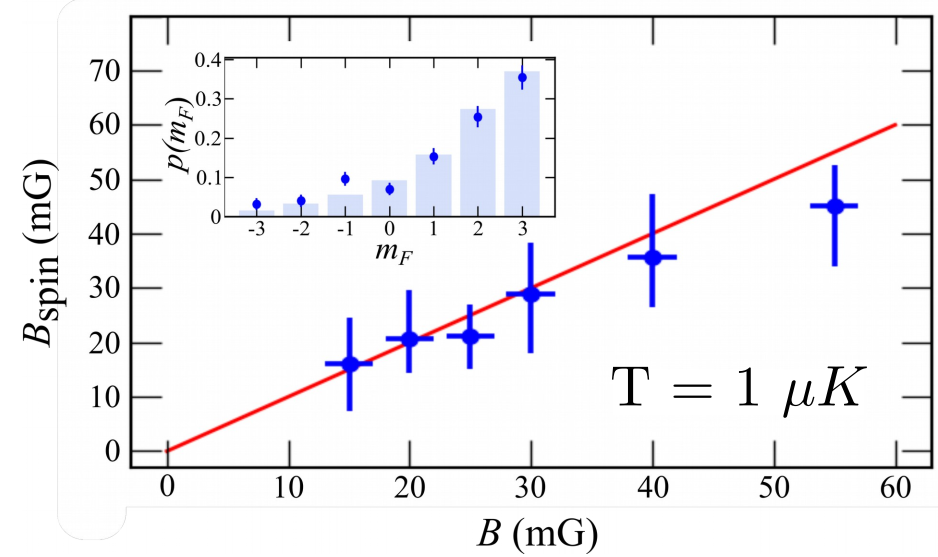
Bouton et al., arXiv: 1906.00844 (2019)
Evrard et. al., PRL **122**, 173601 (2019)
Correa et. al., PRL **114**, 220405 (2015)
Wasilewski et. al., PRL **104**, 133601 (2010)

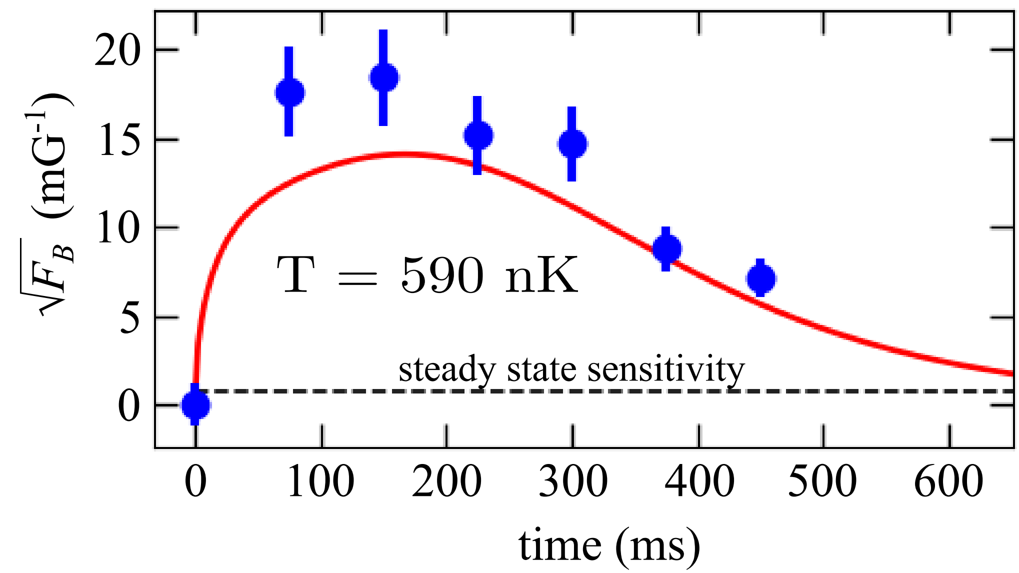
TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

Magnetometry

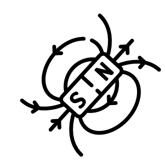








magnetometry 17.5

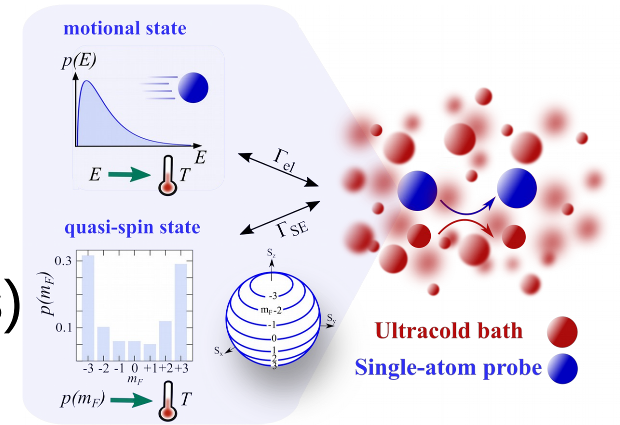


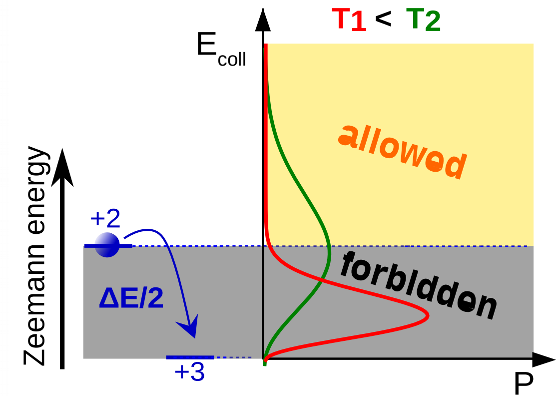
boost in sensitivity

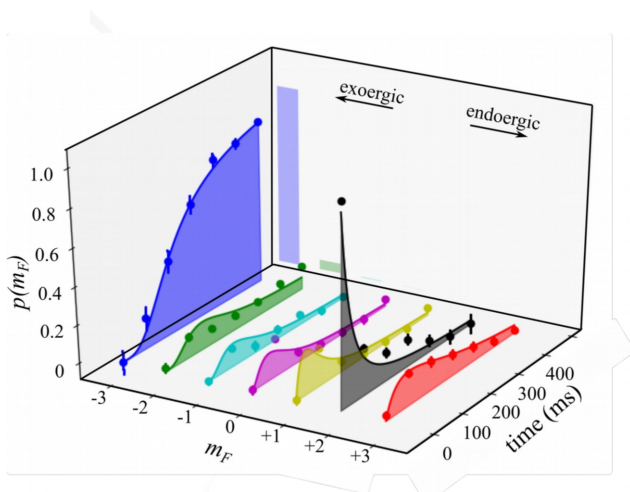
Bouton et al., arXiv: 1906.00844 (2019)
Evrard et. al., PRL **122**, 173601 (2019)
Correa et. al., PRL **114**, 220405 (2015)
Wasilewski et. al., PRL **104**, 133601 (2010)

Summary

- **motional** coupling
  quasi-spin state coupling
  (exo-/ and endoergic collisions)

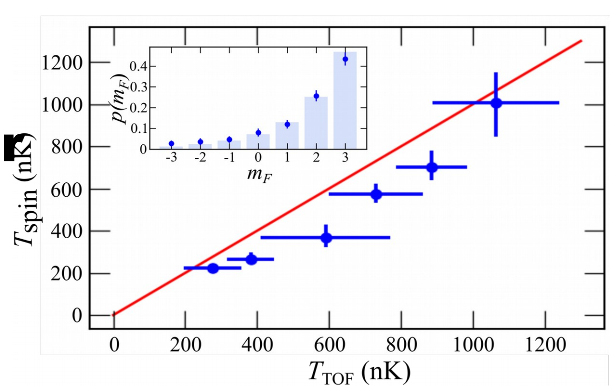


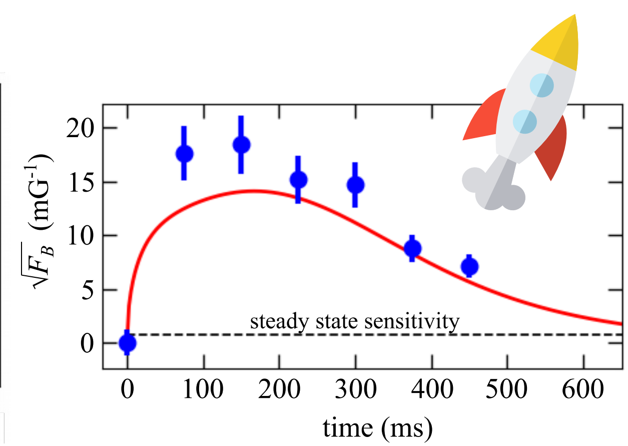




- T & B can be mapped onto spin (zeeman) states via **spin-exchange**

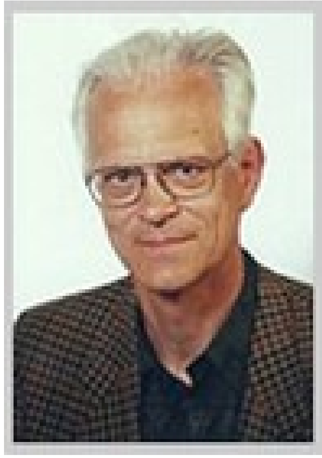
- realizing single atom **quantum thermometer/magnetometer** in spin space
- boost of **sensitivity by nonequilibrium dynamics**



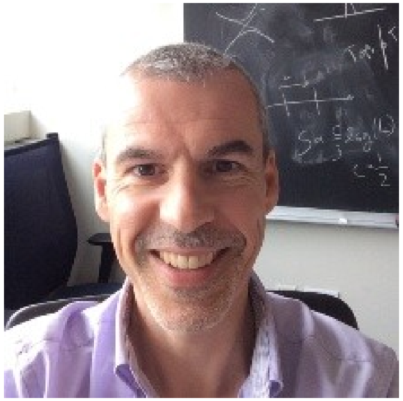


Thanks

Support



Eberhard Tiemann,
Universität Hannover

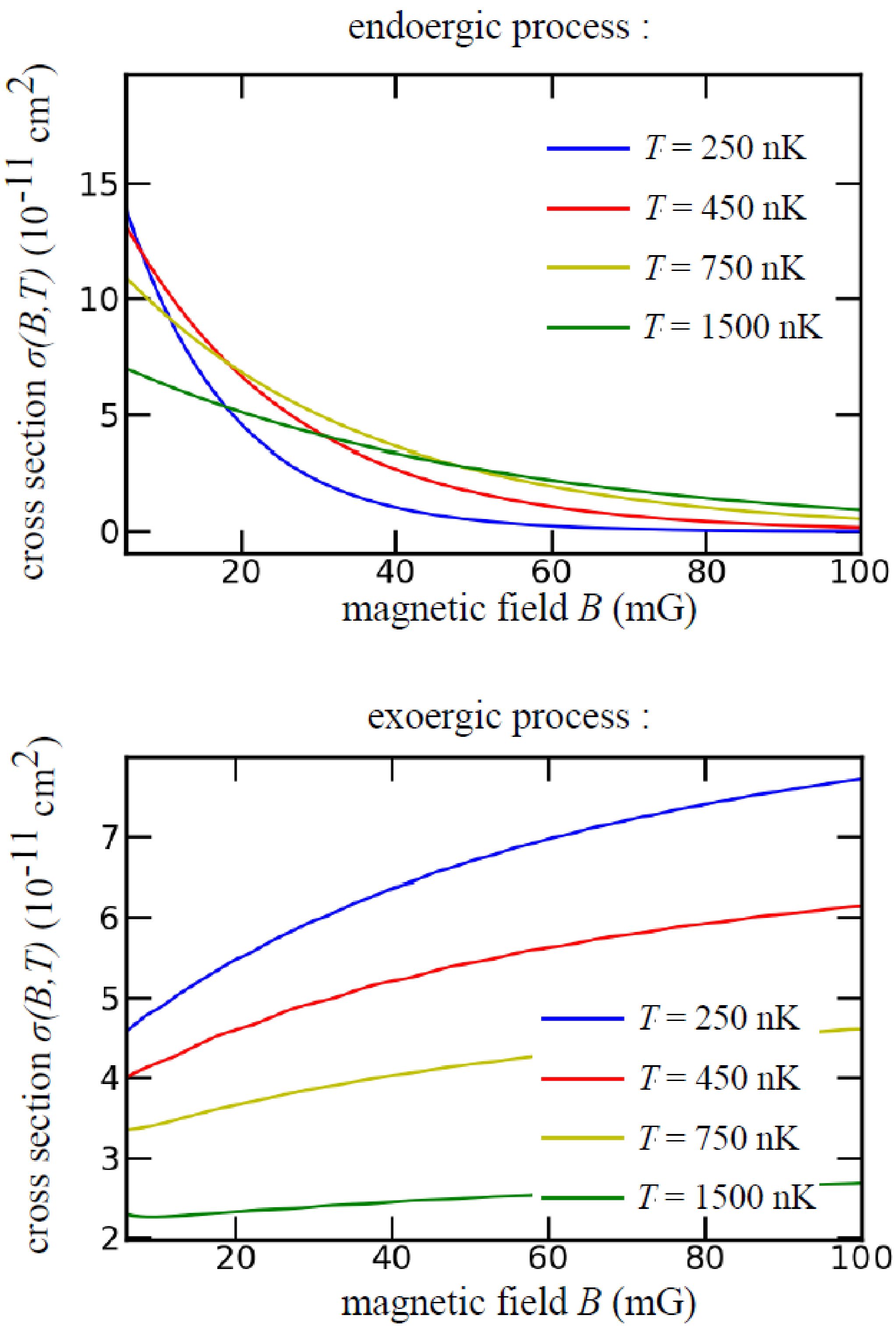


Eric Lutz,
Universität Stuttgart

DFG

GRADUATE SCHOOL OF EXCELLENCE
MATERIALS SCIENCE IN MAINZ

OPTIMAS
TU Kaiserslautern



$$m_{F,\mathrm{Cs}} = 2$$
$$m_{F,\mathrm{Rb}} = 0$$

$m_{F,\mathrm{Rb}} = 0,\ \Delta m_F = 1,\ \langle E_{\mathrm{coll}} \rangle = k_B \times 450$ nK