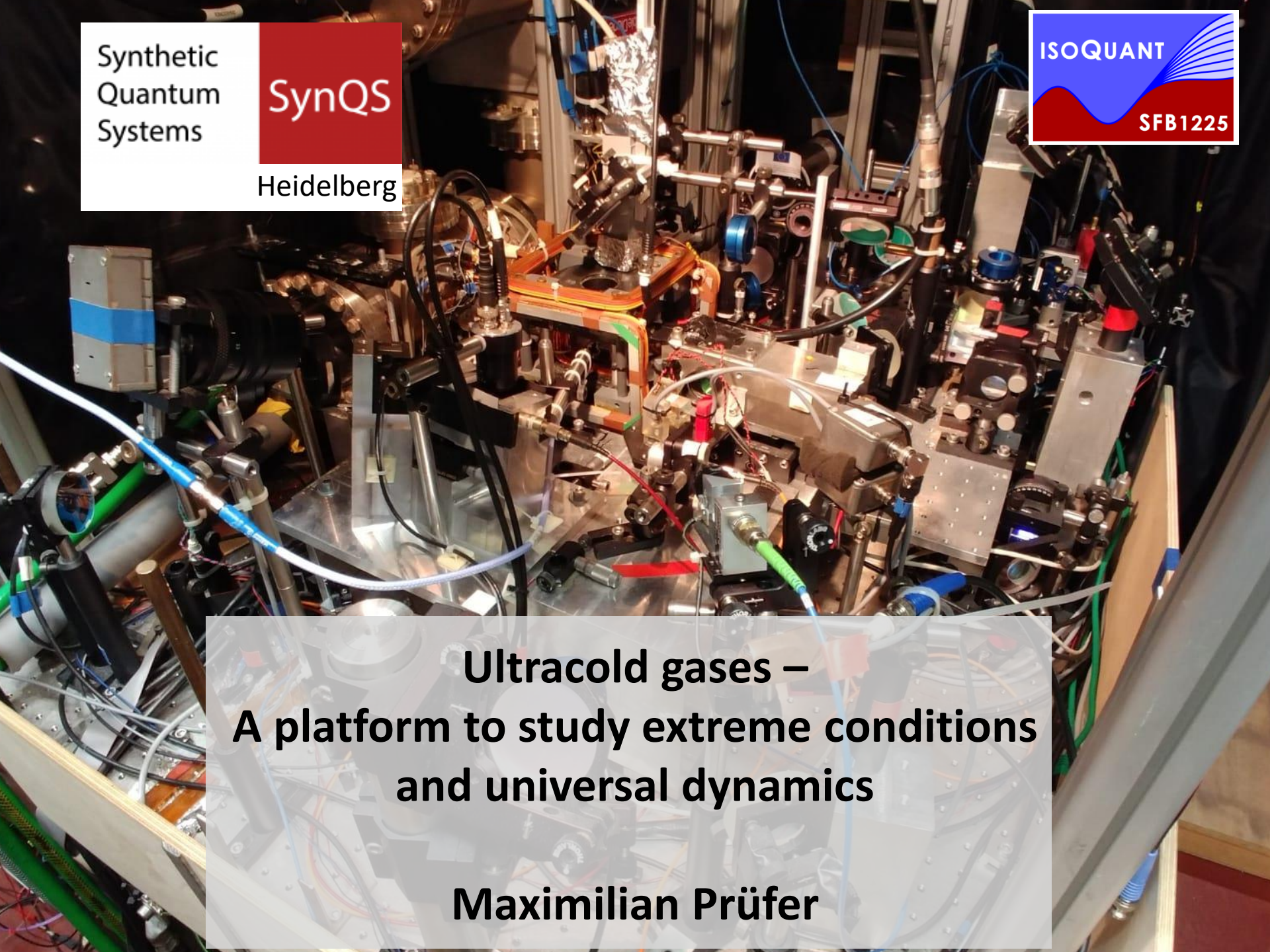


Ultracold gases –
A platform to study extreme conditions and universal dynamics

Maximilian Prüfer

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Synthetic Quantum Systems

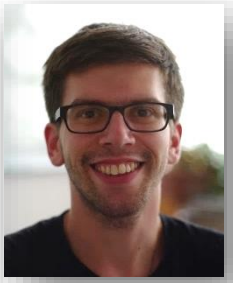
SynQS

Heidelberg

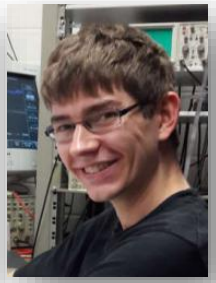
KIRCHHOFF-INSTITUTE FOR PHYSICS

Bosonic Quantum Gases

Maximilian Prüfer



Philipp Kunkel



Stefan Lannig

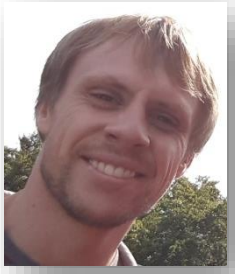
Daniel Linnemann

Alexis Bonnin

Helmut Strobel

Markus Oberthaler

Theory



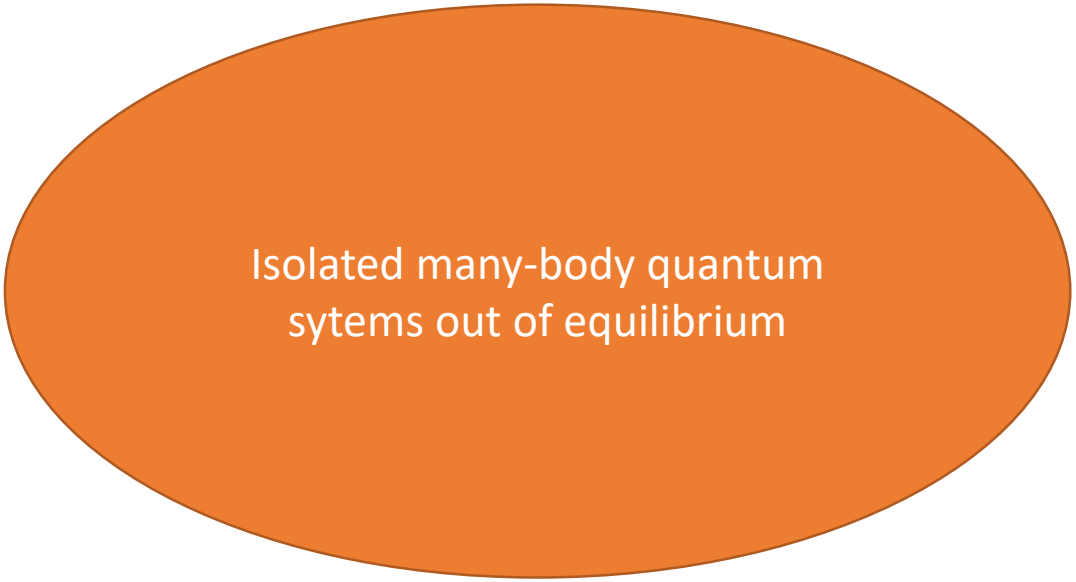
Christian-Marcel Schmied

Thomas Gasenzer

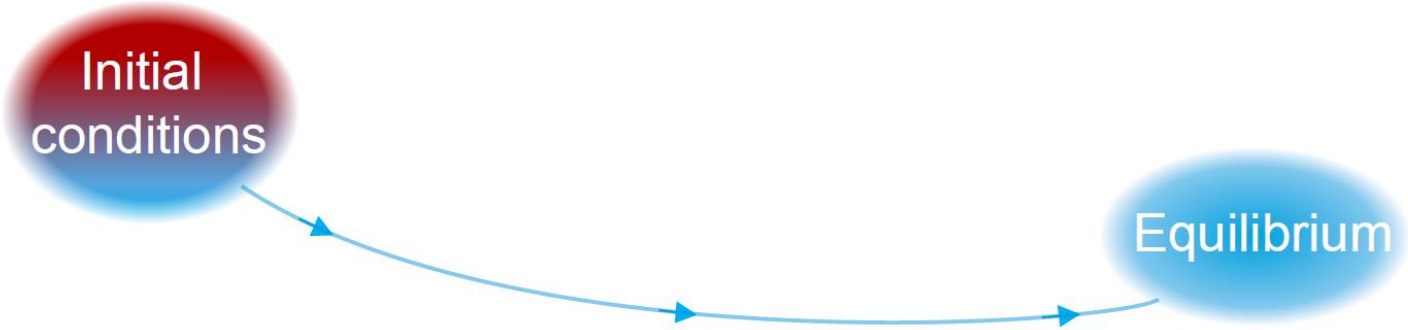
Jürgen Berges

ITP

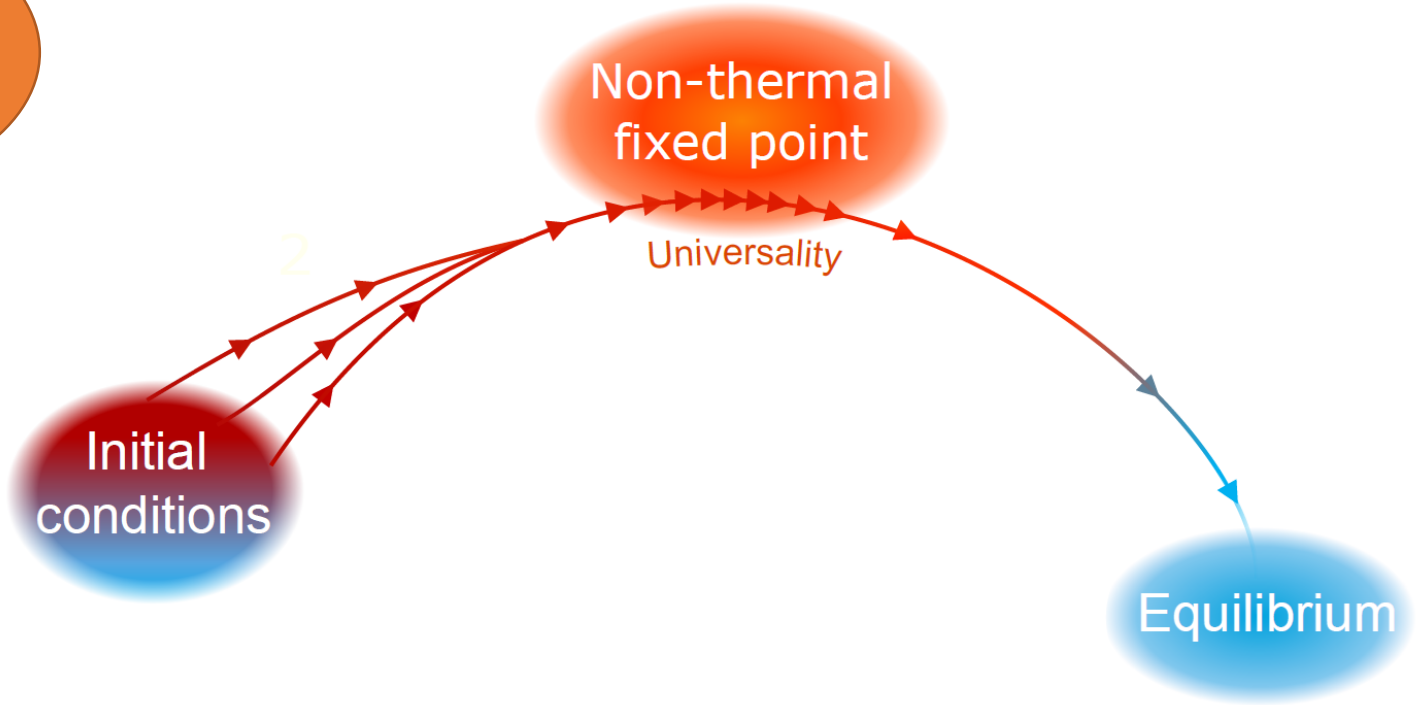
ISOQUANT SFB1225


Isolated many-body quantum
sytems out of equilibrium

Isolated many-body quantum sytems out of equilibrium

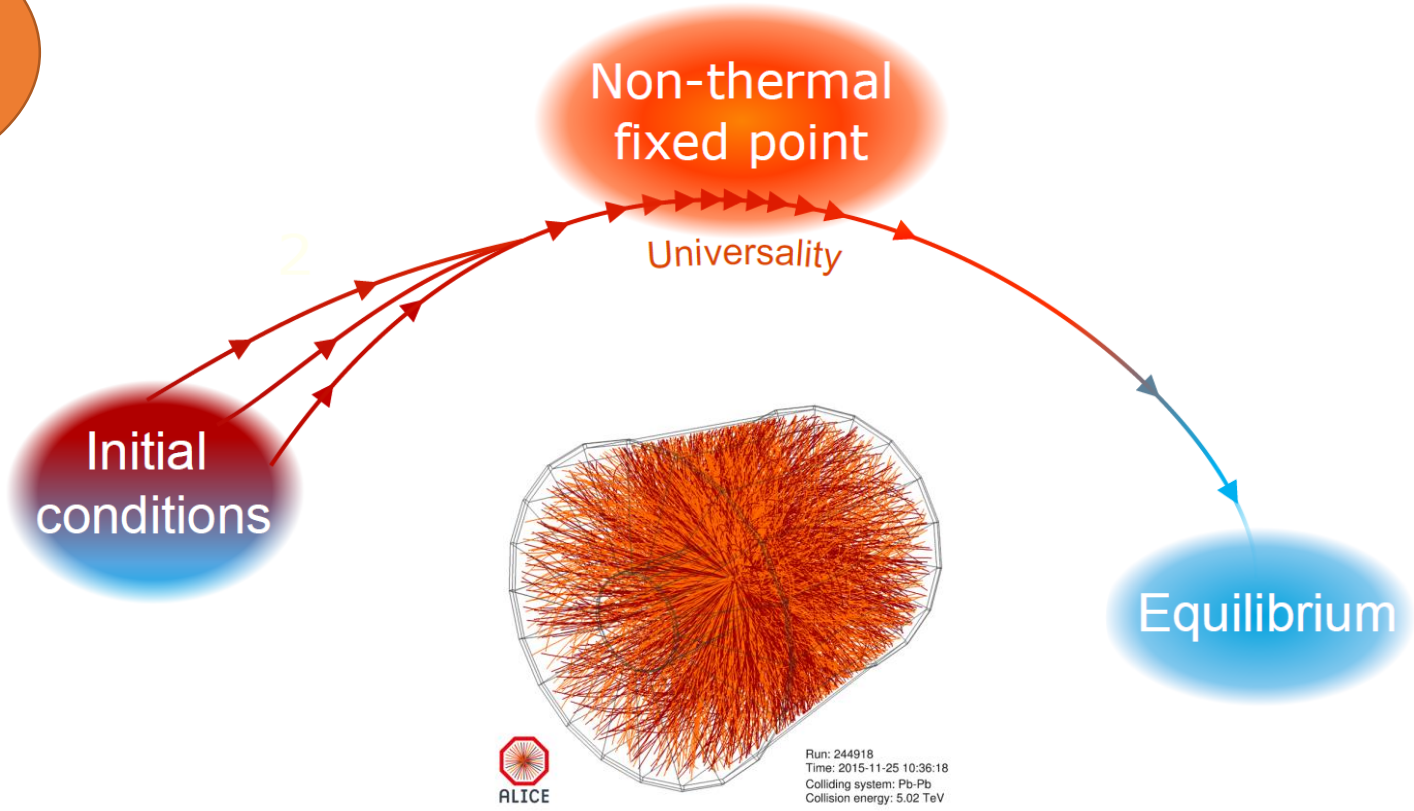


Isolated many-body quantum sytems out of equilibrium



Berges, Rothkopf, Schmidt, PRL 101, 041603(2008)

Isolated many-body quantum sytems out of equilibrium



Berges, Rothkopf, Schmidt, PRL 101, 041603(2008)

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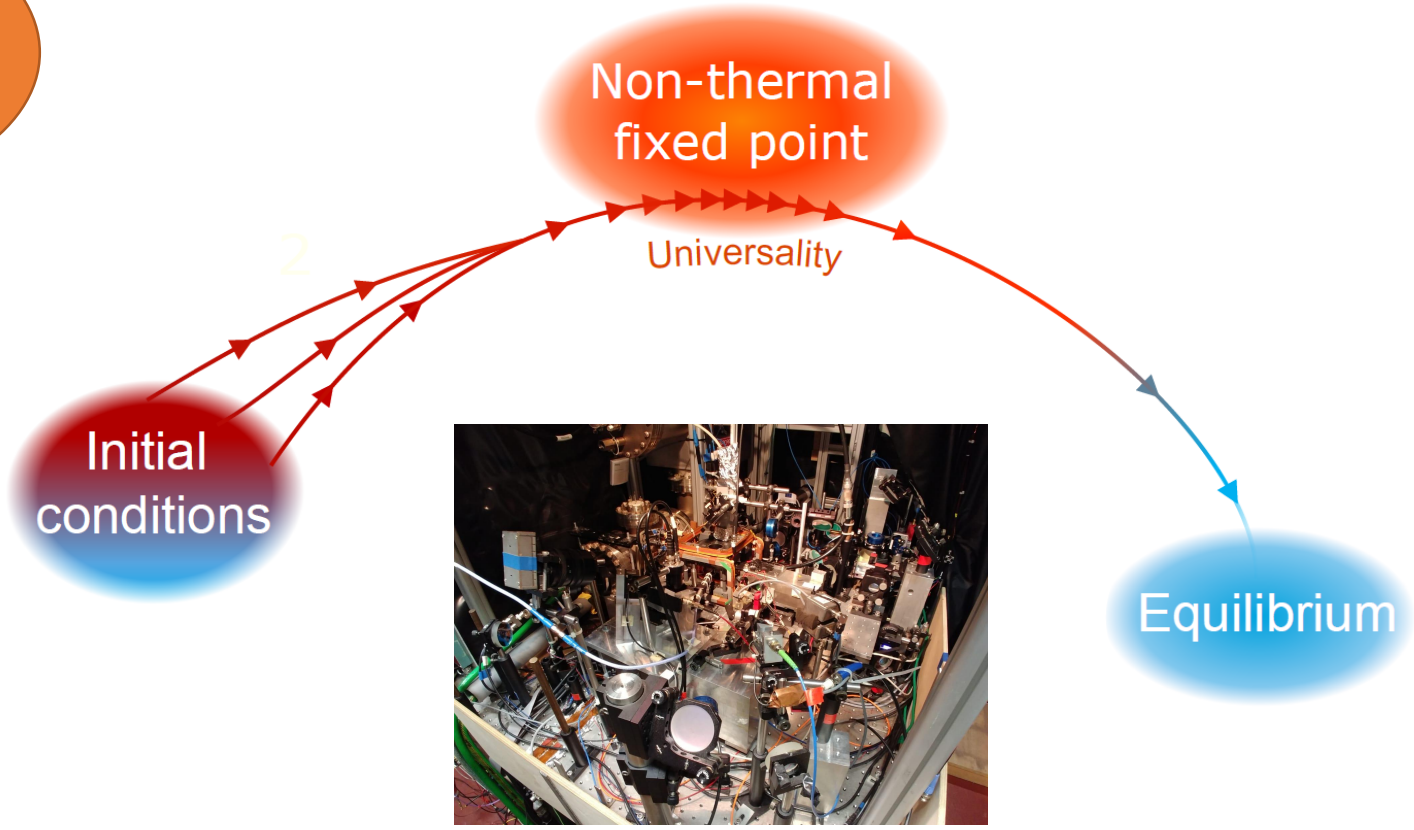

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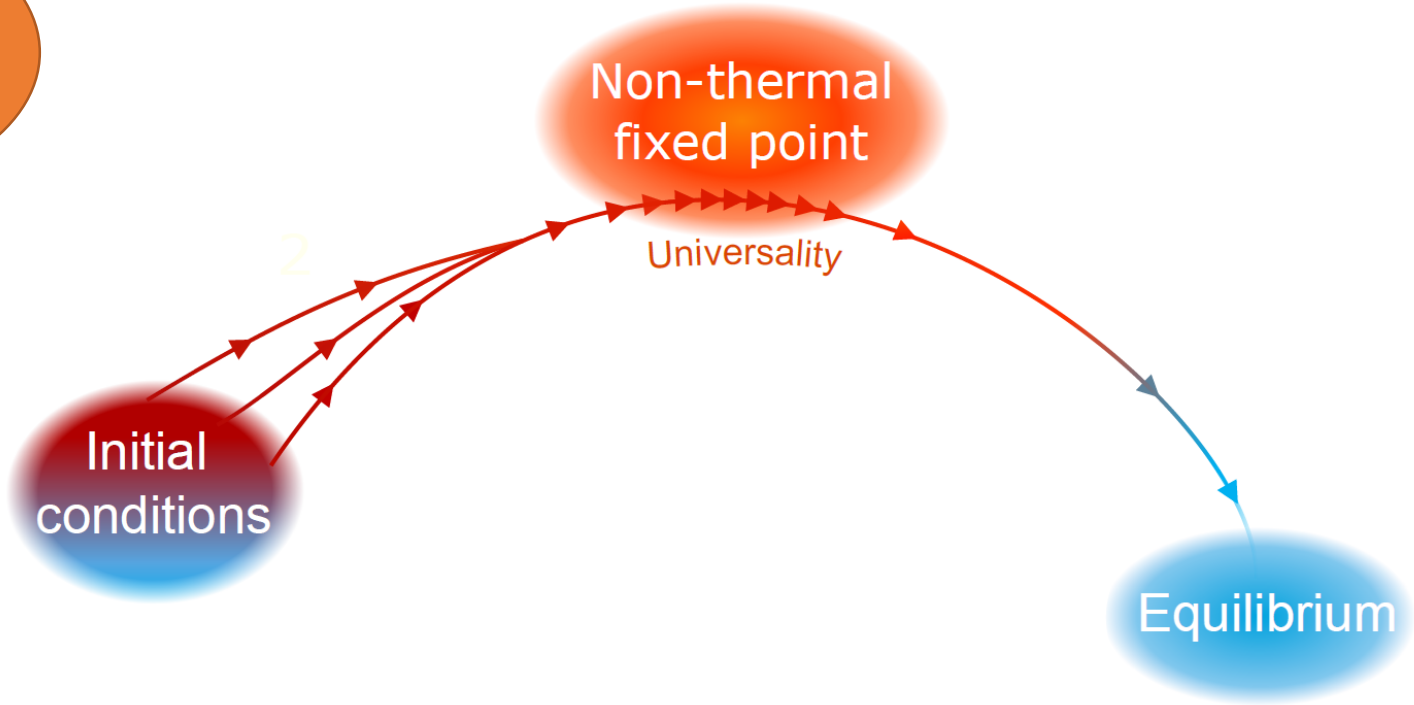
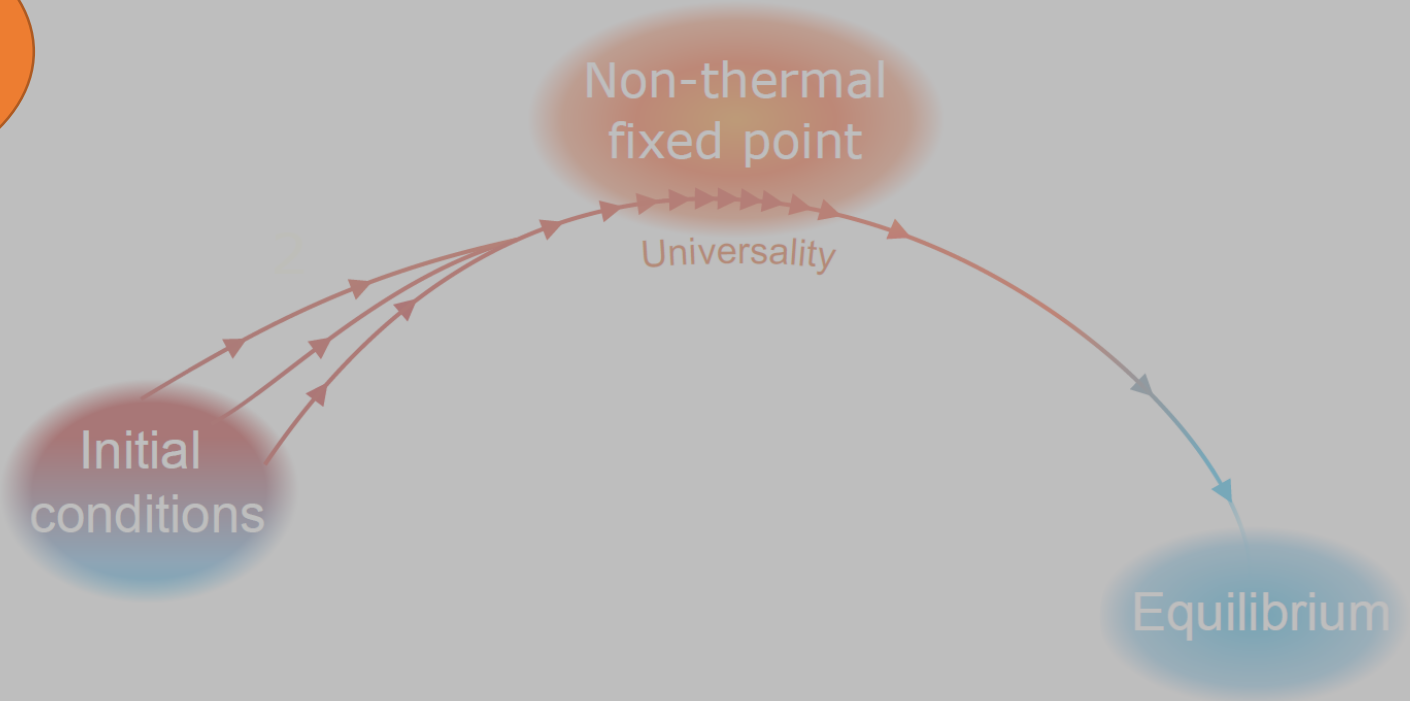
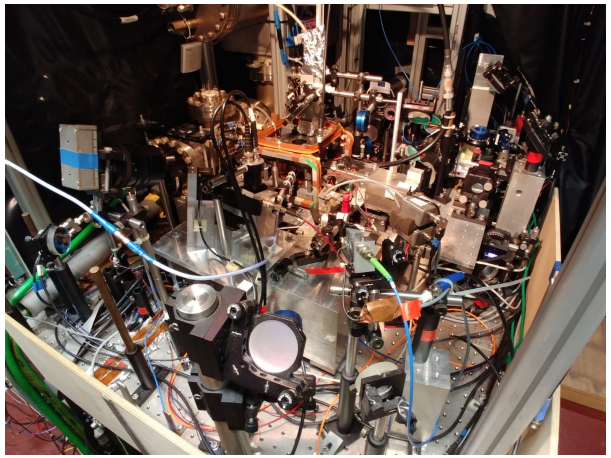
Isolated many-body quantum sytems out of equilibrium

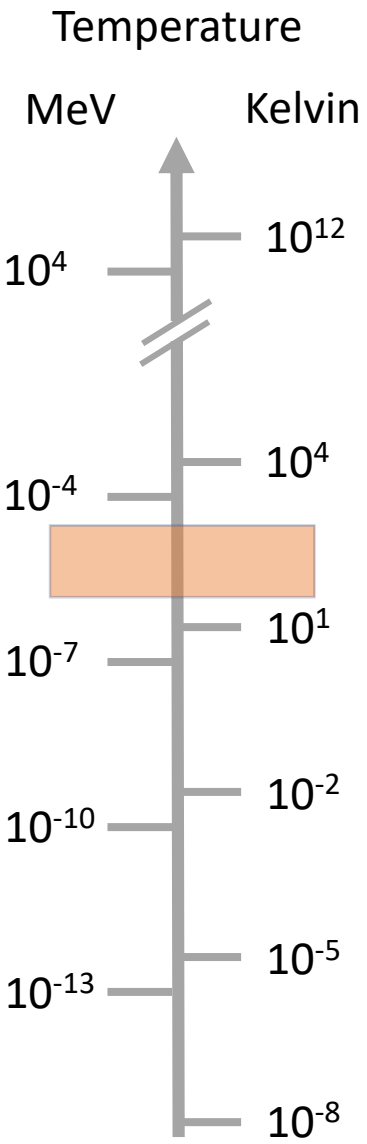


Isolated many-body quantum sytems out of equilibrium

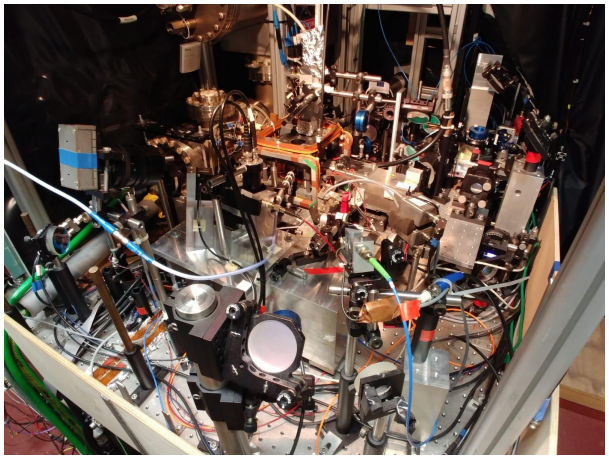


$^{87}\mathrm{Rb}$

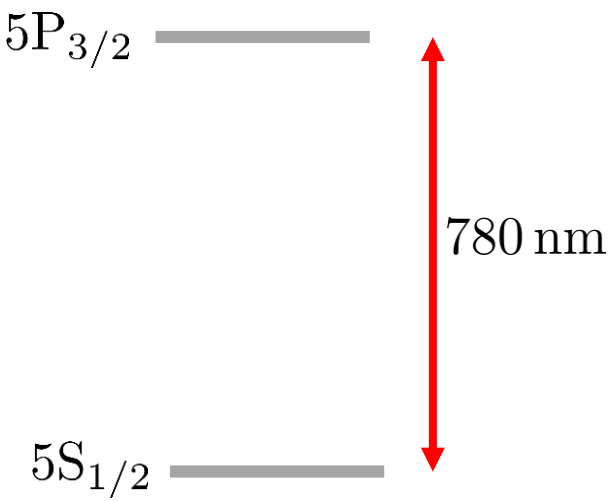



Temperature
MeV
Kelvin
10^{4}
10^{12}
10^{4}
10^{-4}
10^{1}
10^{-7}
10^{-2}
10^{-10}
10^{-5}
10^{-13}
10^{-8}

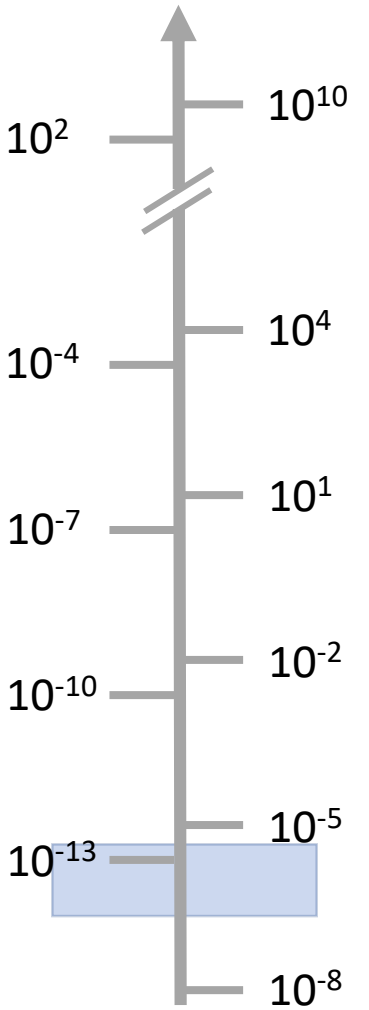
$^{87}\mathrm{Rb}$



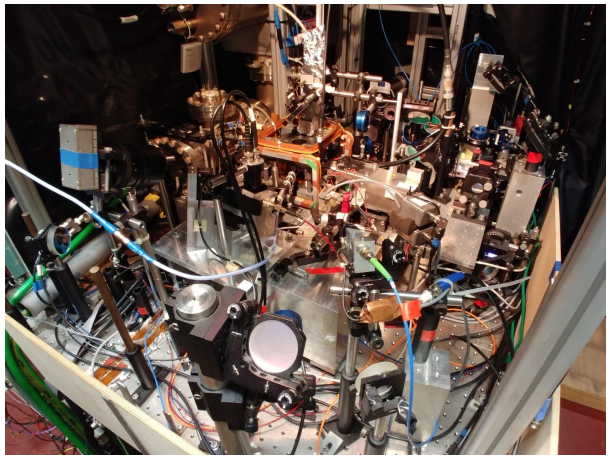
Laser cooling

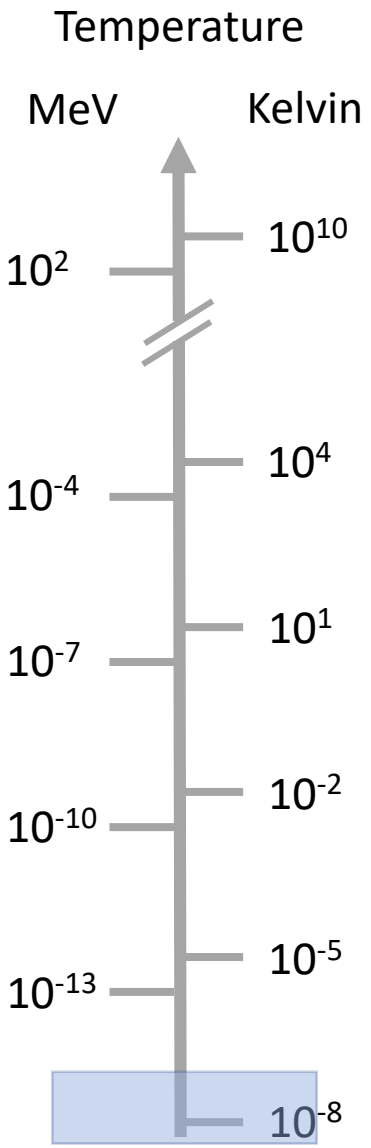


Temperature

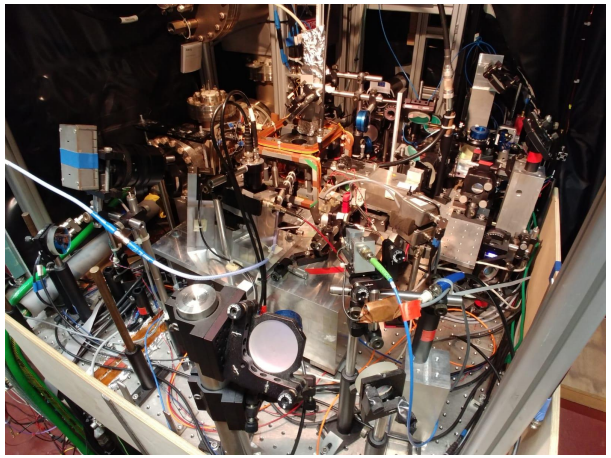


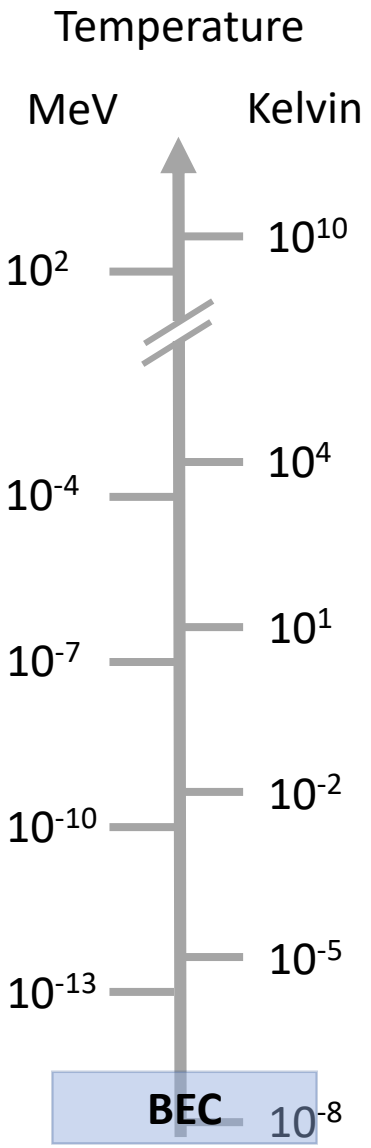
$^{87}\mathrm{Rb}$




Temperature
MeV
Kelvin
10^{2}
10^{10}
10^{4}
10^{-4}
10^{1}
10^{-7}
10^{-2}
10^{-10}
10^{-5}
10^{-13}
10^{-8}

$^{87}\mathrm{Rb}$




Temperature
MeV
Kelvin
10^{2}
10^{10}
10^{4}
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10^{1}
10^{-7}
10^{-2}
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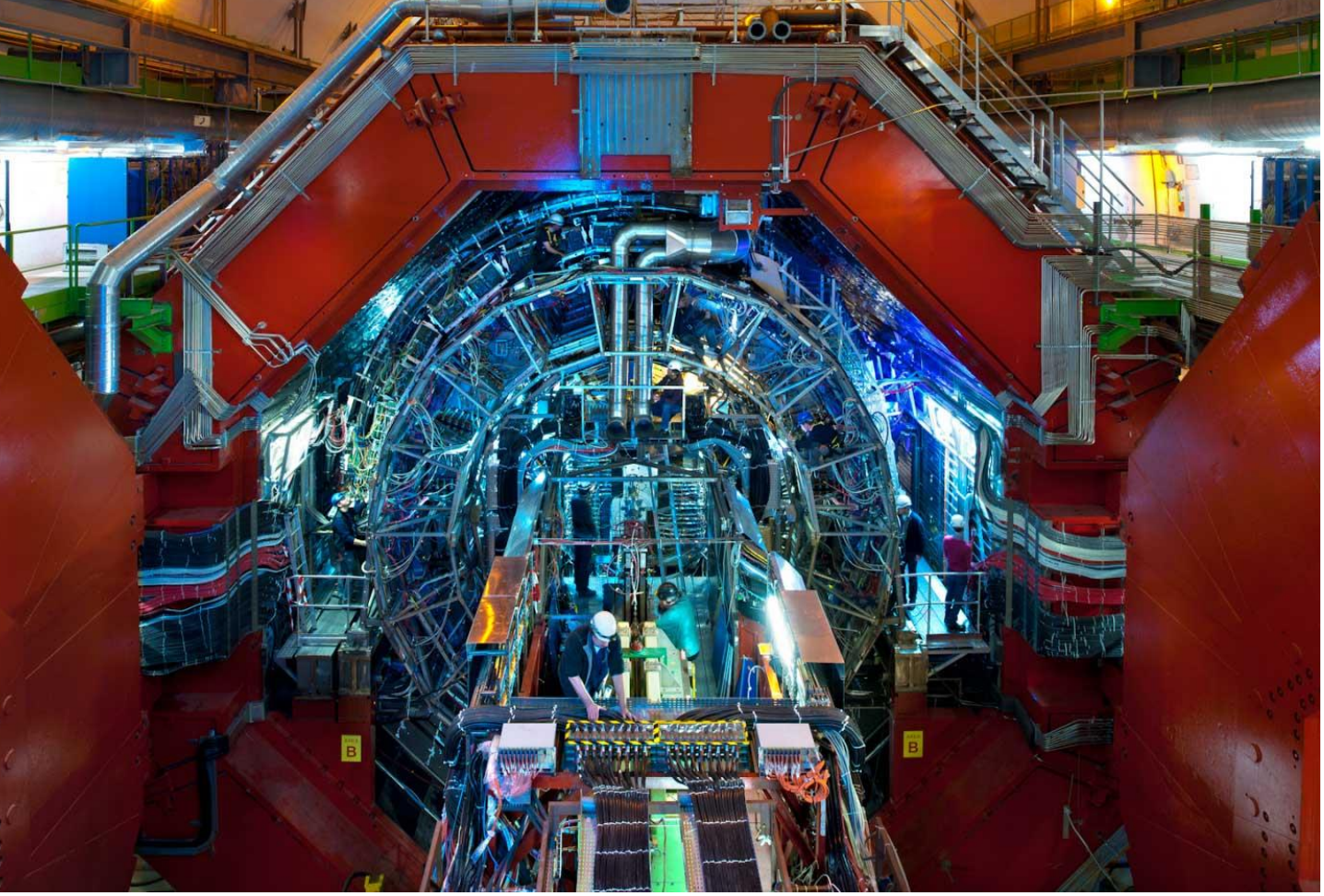
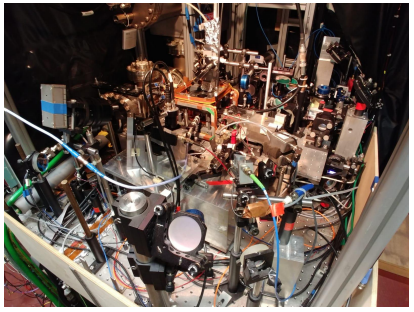
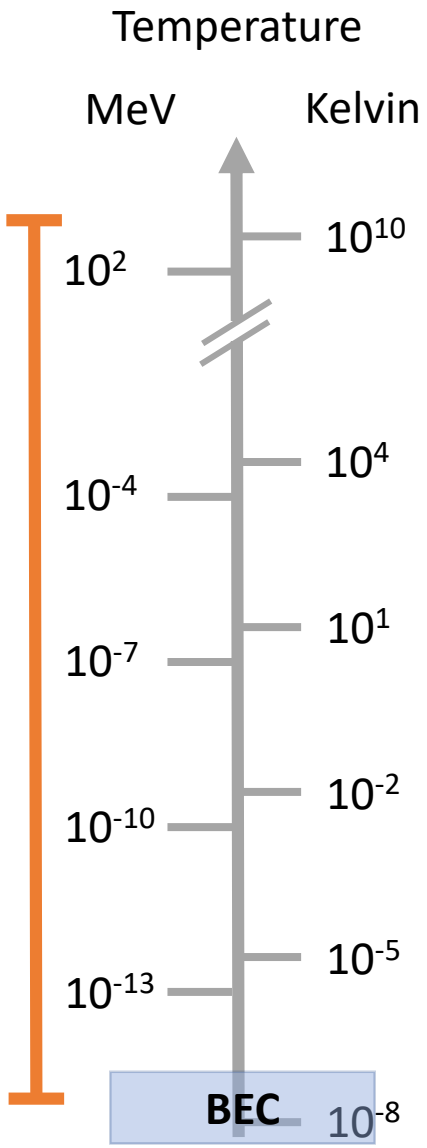
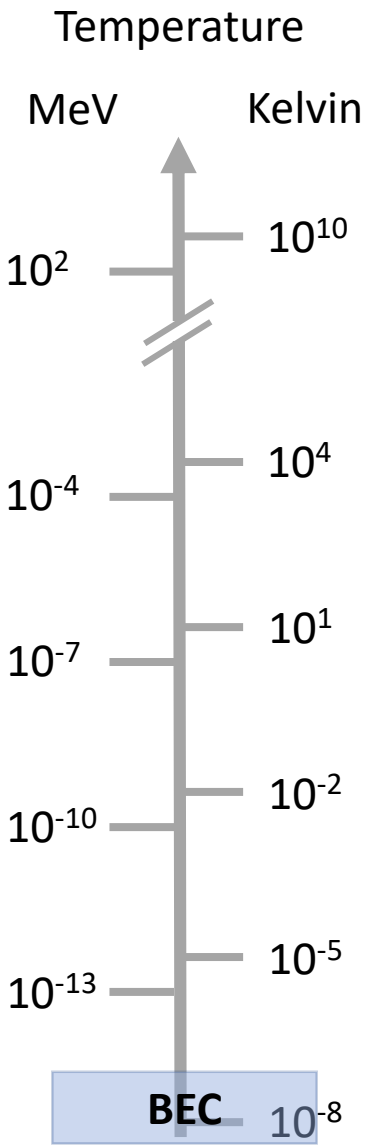
10^{-5}
10^{-13}
BEC
10^{-8}

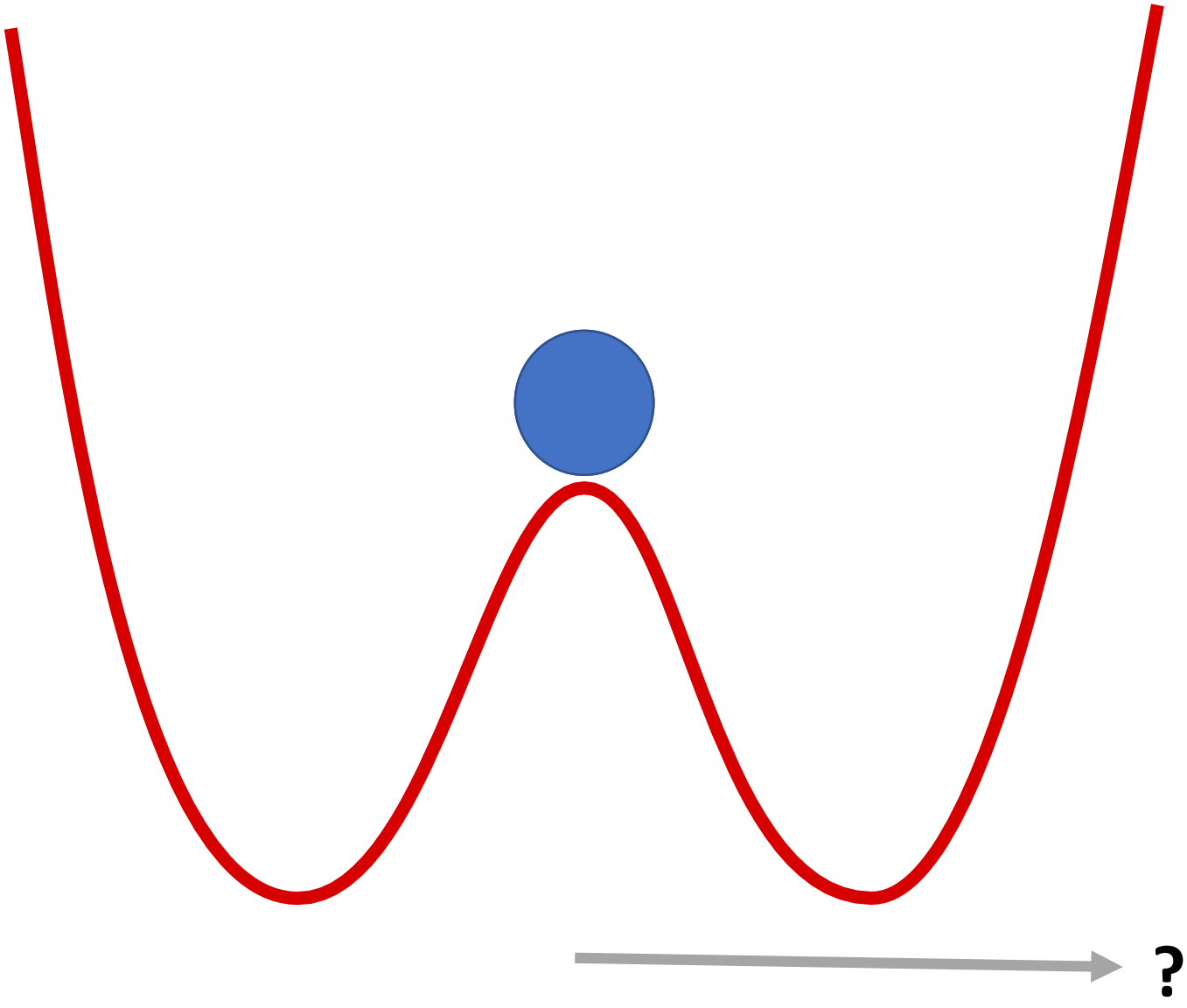






20 orders
of magnitude


Temperature
MeV
Kelvin
10^{2}
10^{10}
10^{4}
10^{-4}
10^{1}
10^{-7}
10^{-2}
10^{-10}
10^{-5}
10^{-13}
BEC
10^{-8}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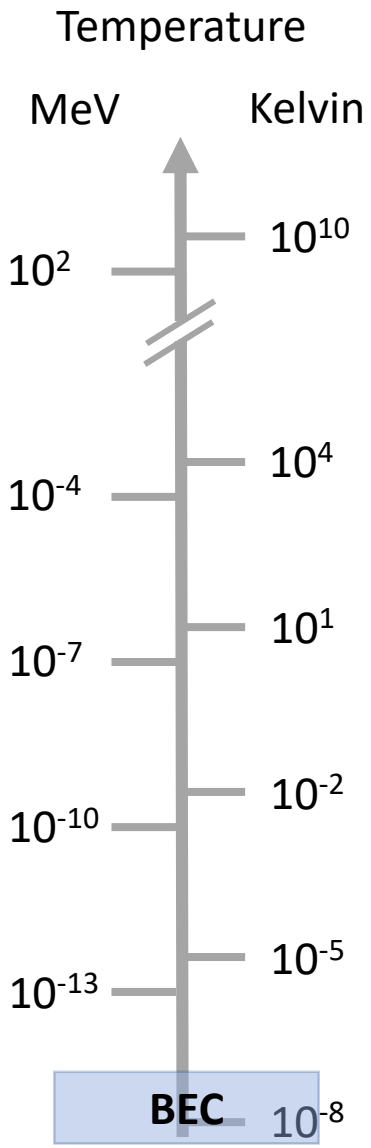
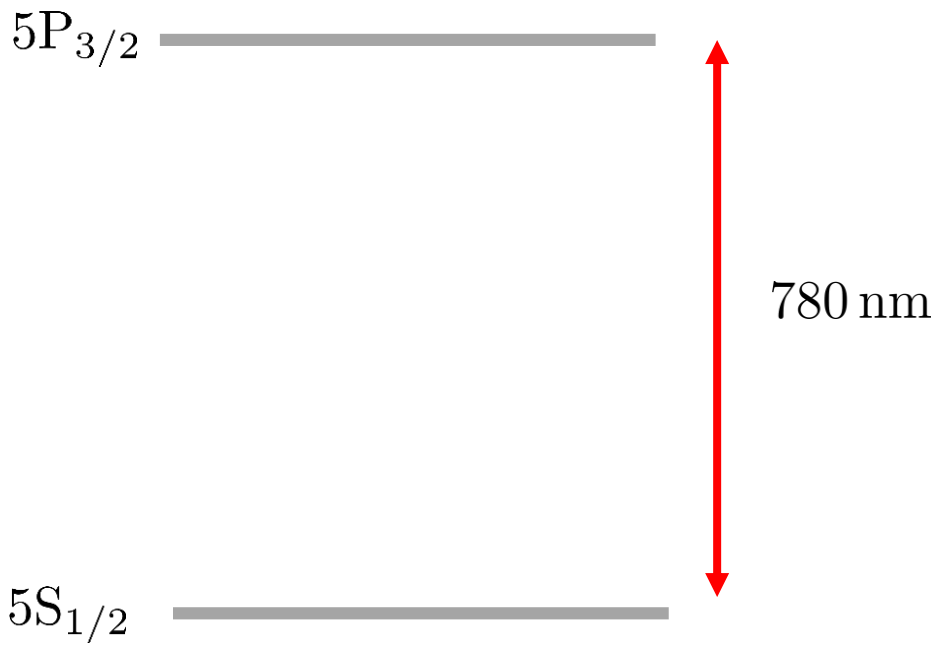
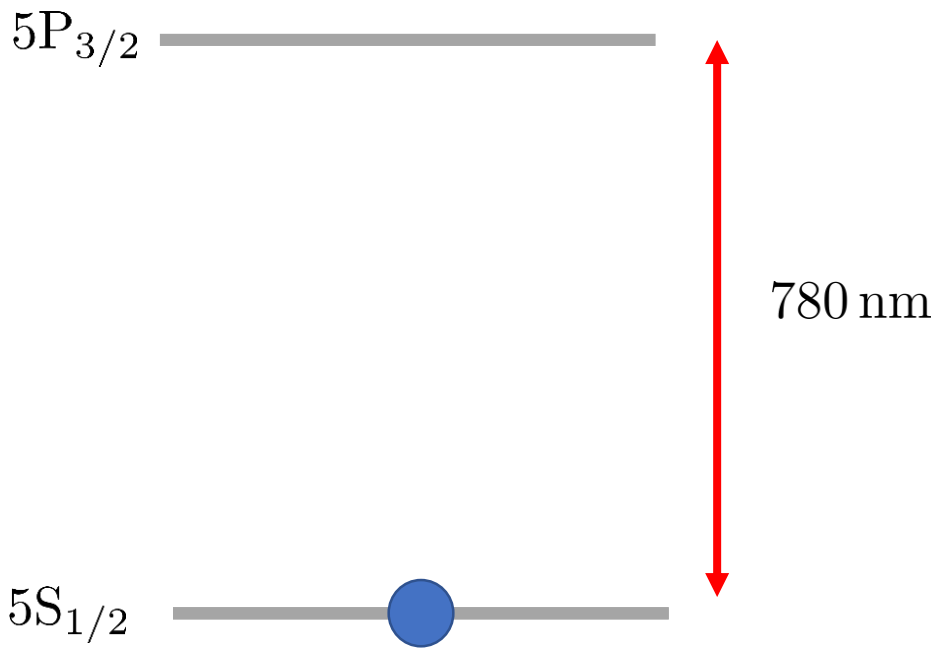

Temperature
MeV
Kelvin
10^{2}
10^{10}
10^{4}
10^{-4}
10^{1}
10^{-7}
10^{-2}
10^{-10}
10^{-5}
10^{-13}
BEC
10^{-8}

Experimental system



Experimental system

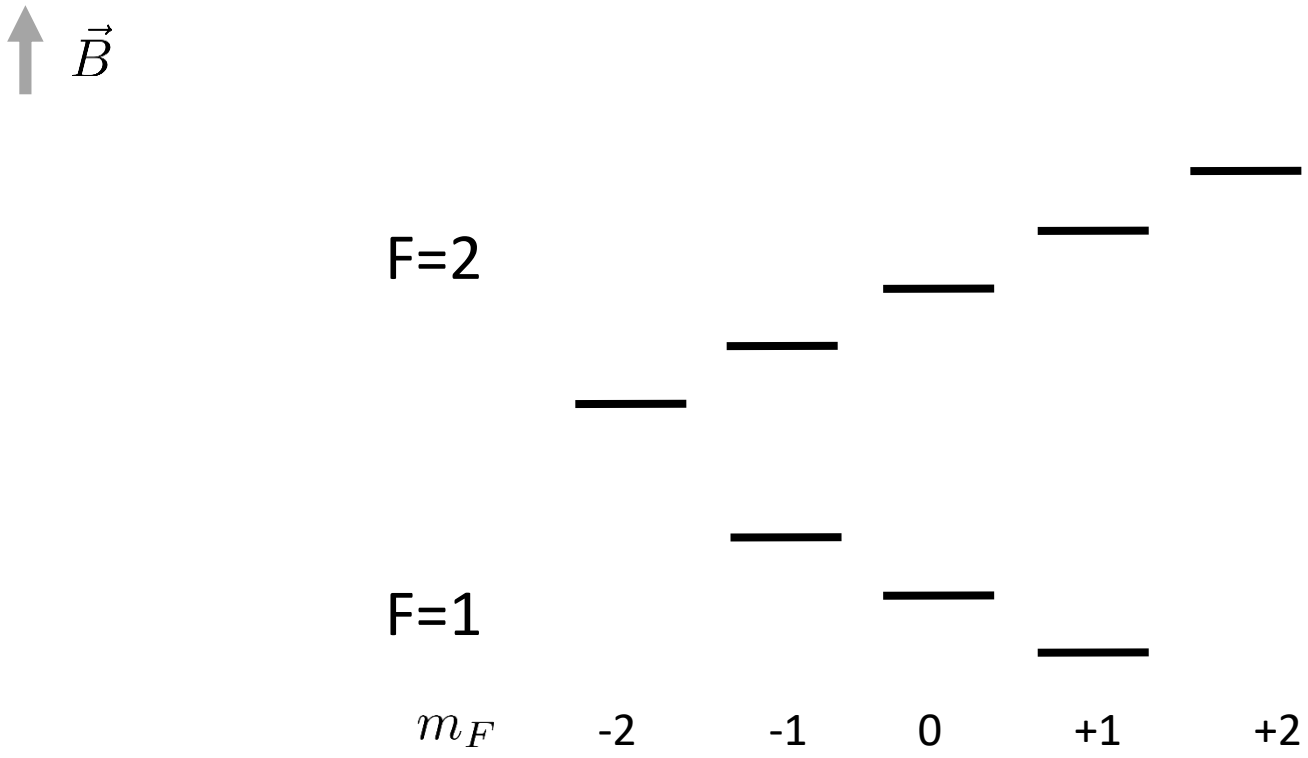


Experimental system

Hyperfine groundstate manifold of $^{87}\mathrm{Rb}$

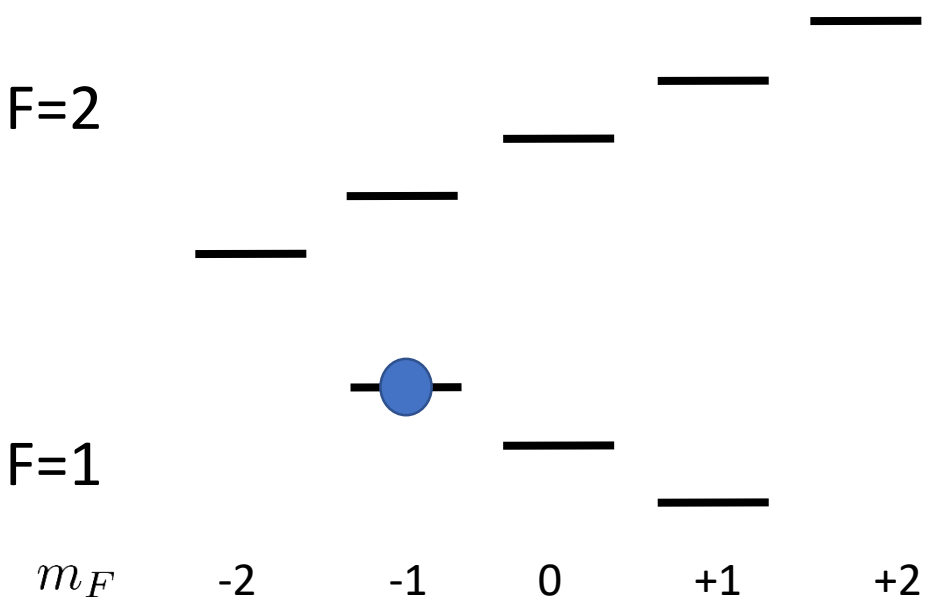
Experimental system

Hyperfine groundstate manifold of $^{87}\mathrm{Rb}$



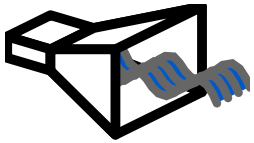
Experimental system

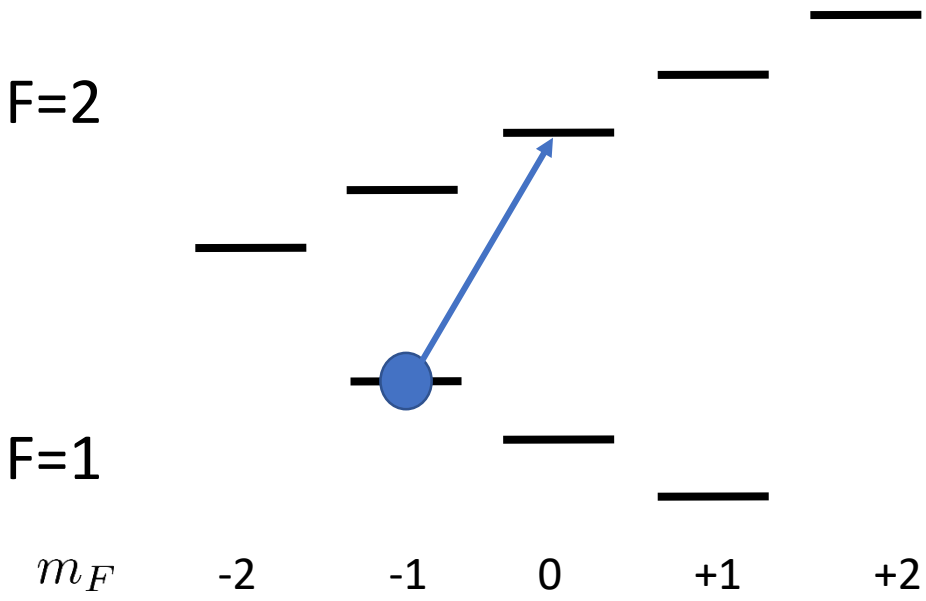
Hyperfine groundstate manifold of $^{87}\mathrm{Rb}$



Experimental system

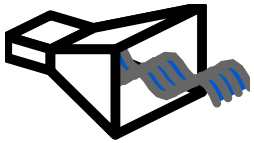
Microwave

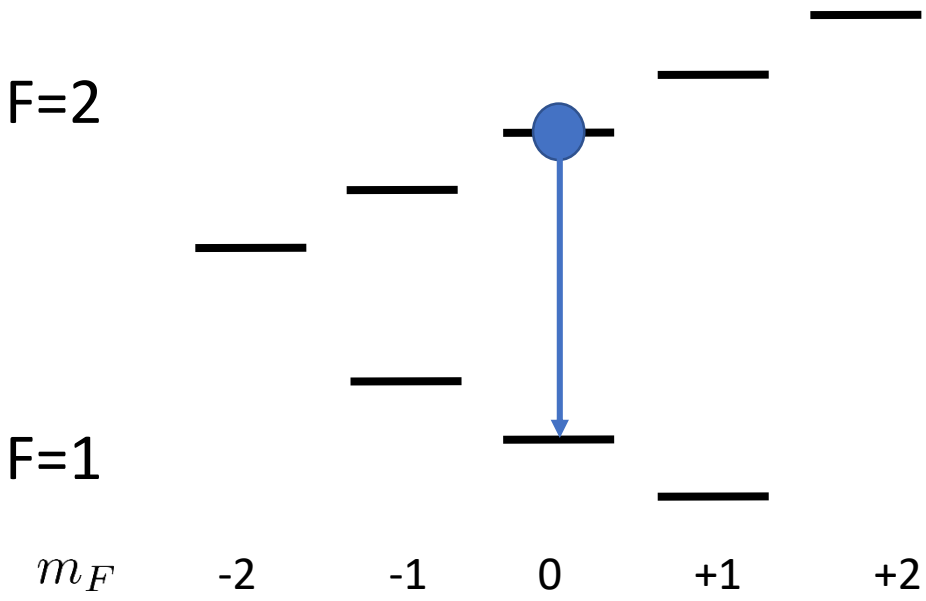




Experimental system

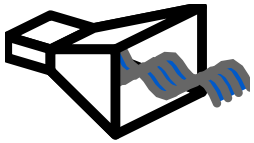
Microwave

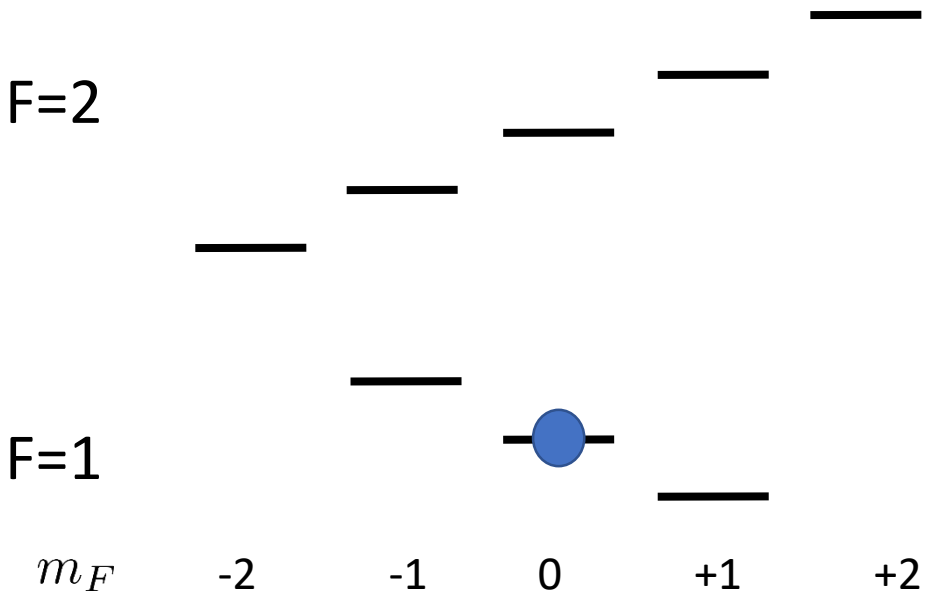




Experimental system

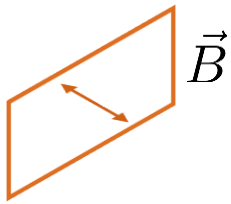
Microwave

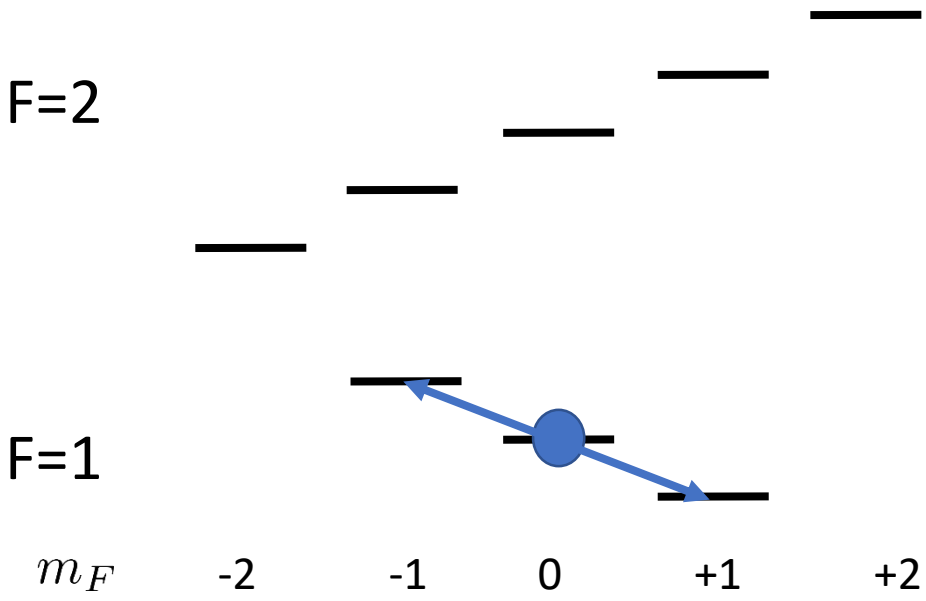




Experimental system

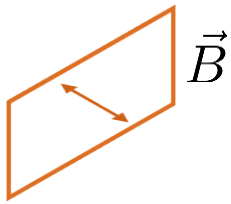
Radio-frequency

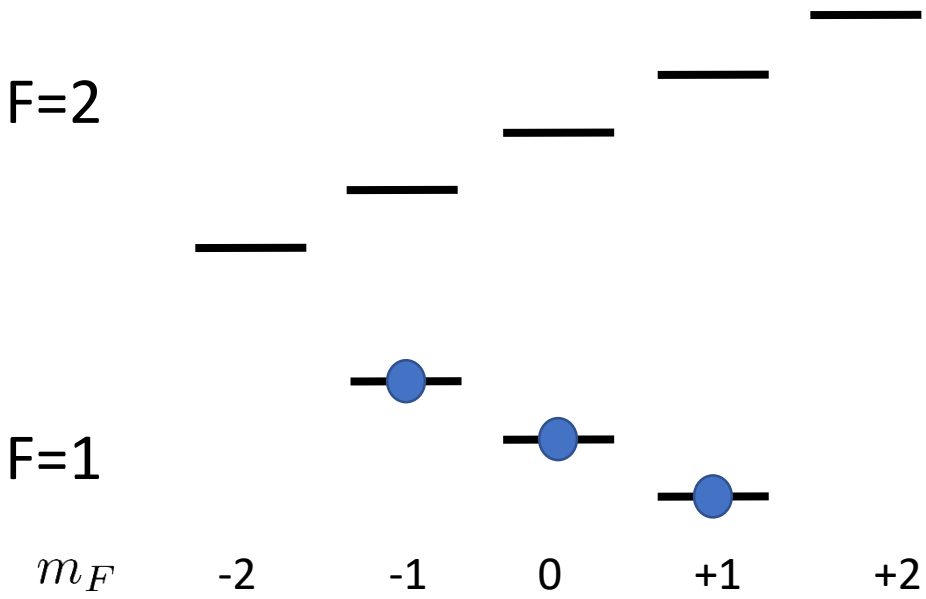




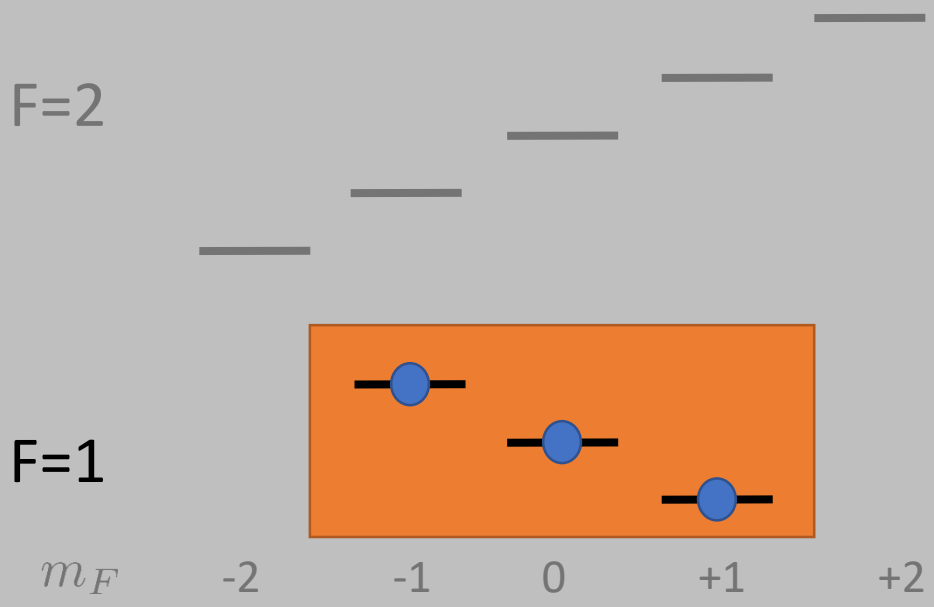
Experimental system

Radio-frequency



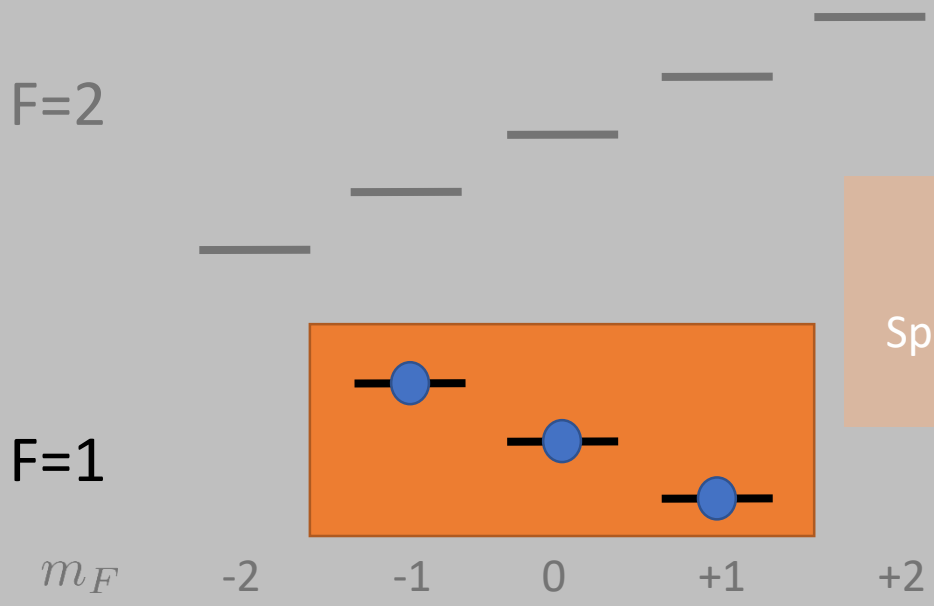


Spinor Bose gas



Stamper-Kurn and Ueda, Rev. Mod. Phys 85, 1191 (2013)

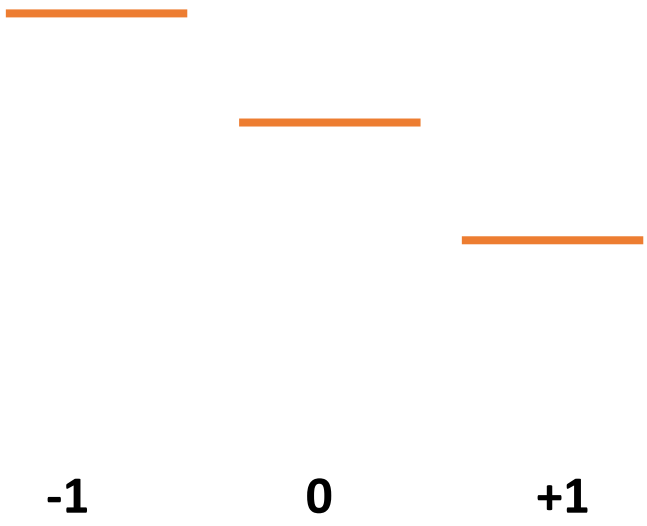
Spinor Bose gas



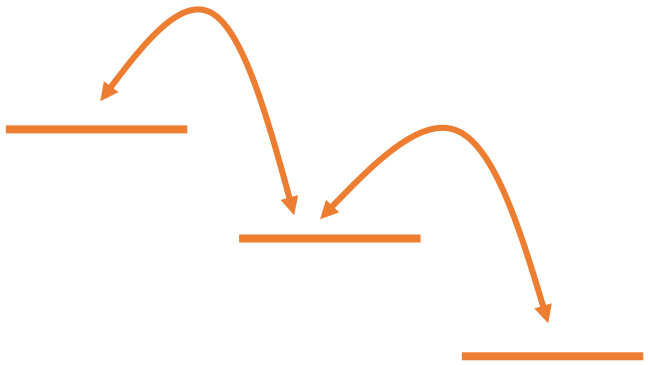
Bose gas +
Spin degree of freedom

Stamper-Kurn and Ueda, Rev. Mod. Phys 85, 1191 (2013)

Spin-1 system



Spin-1 system

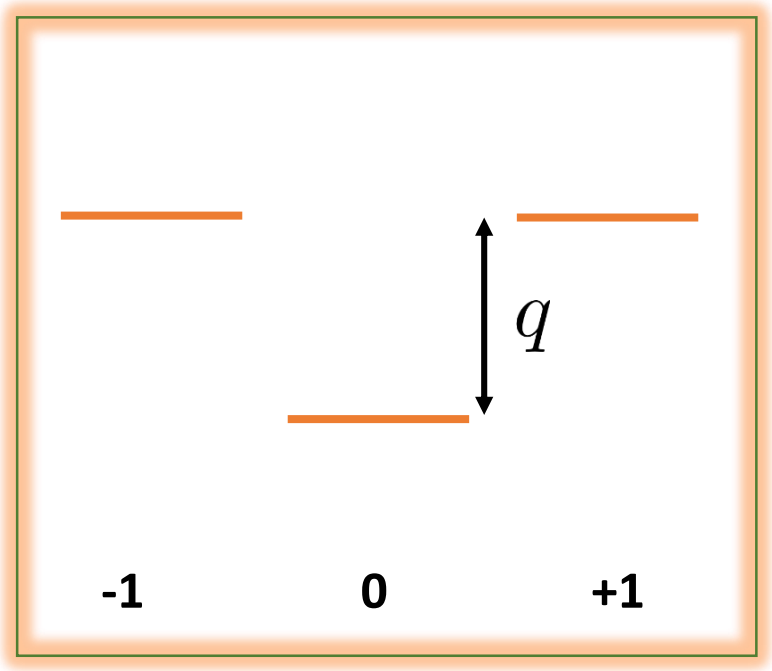


-1 **0** **+1**

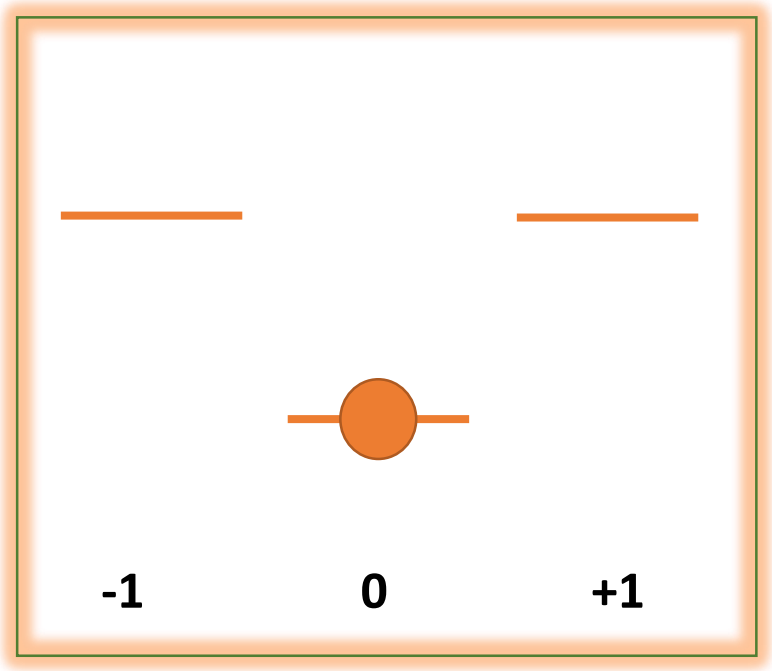
Spin-1 system

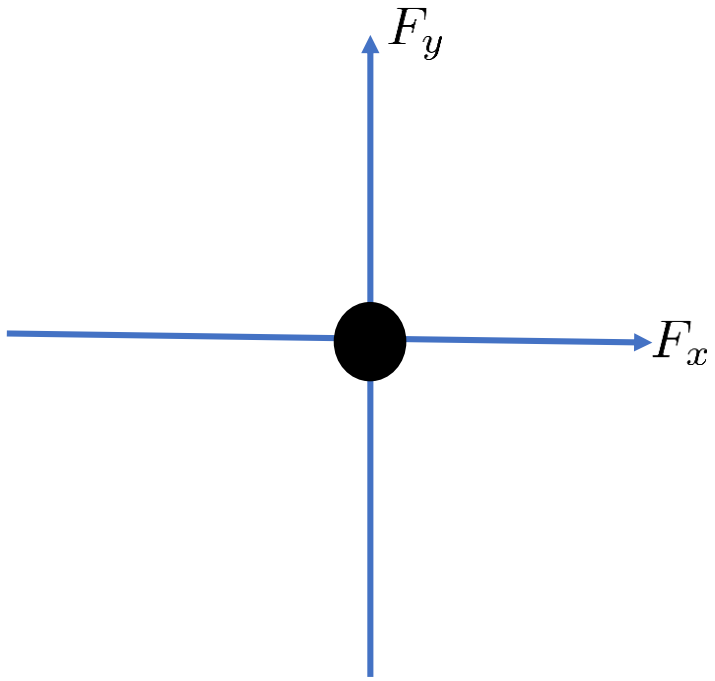
-1 **0** **+1**

Spin-1 system



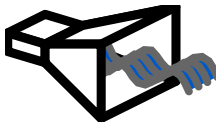
Spin – 1 system

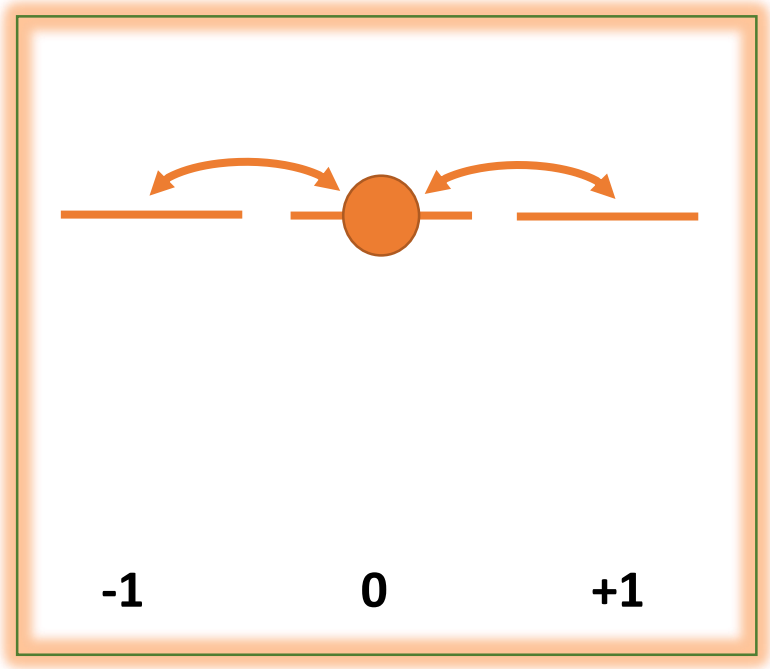


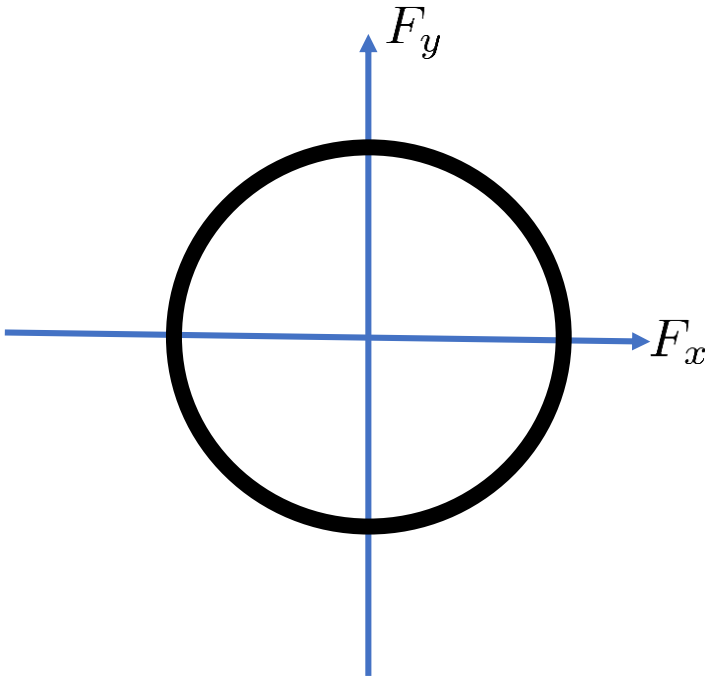


Spin – 1 system

Microwave

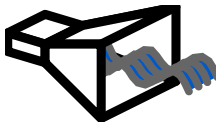


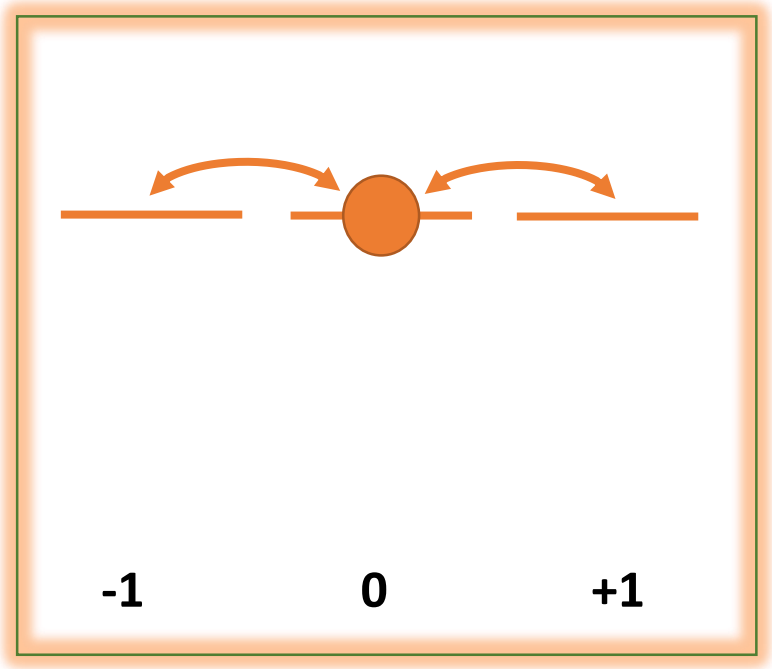


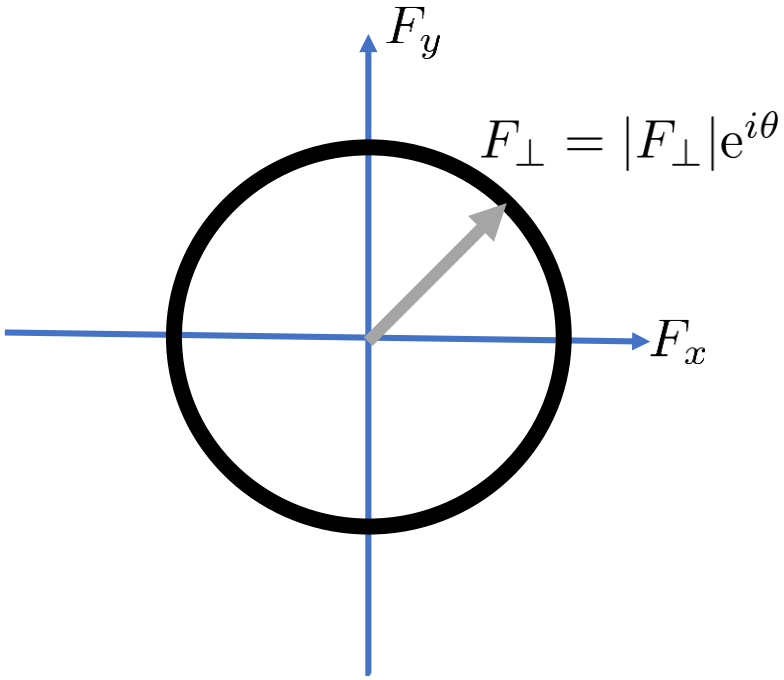


Spin – 1 system

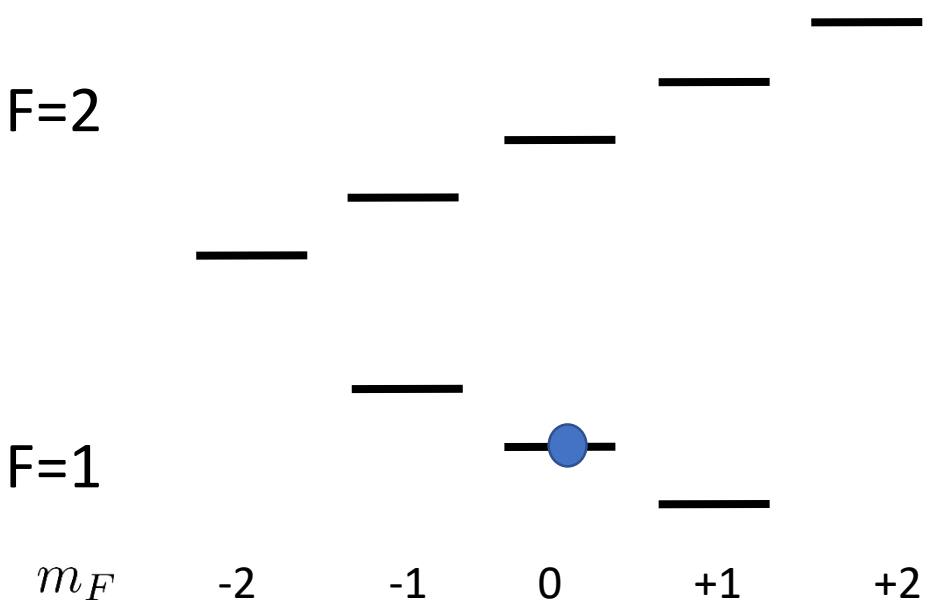
Microwave



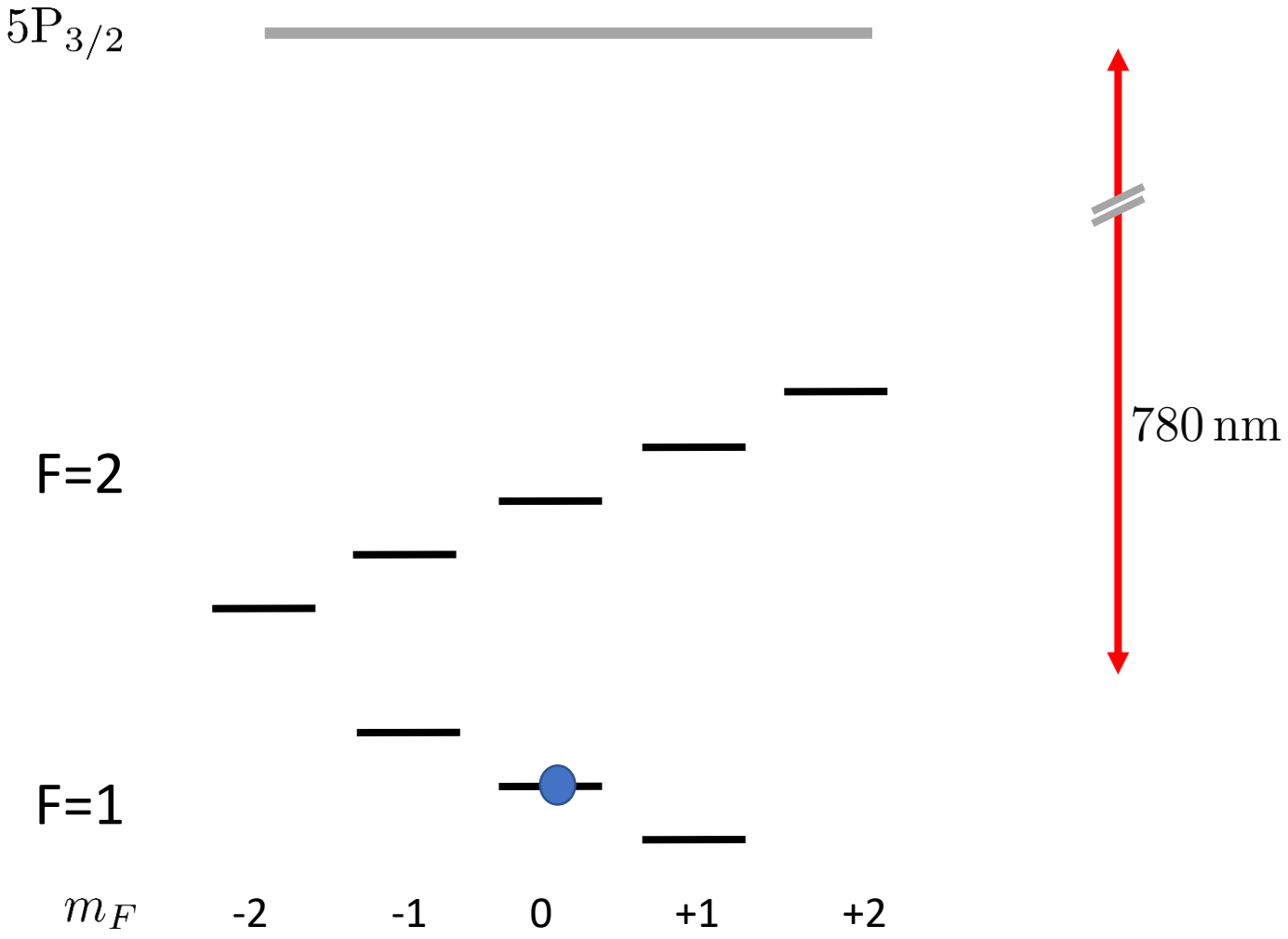




Readout

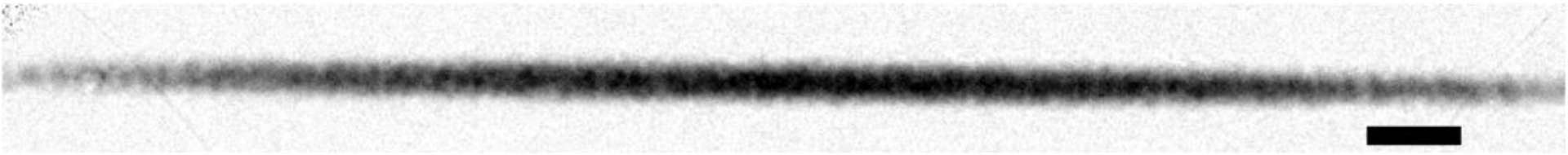


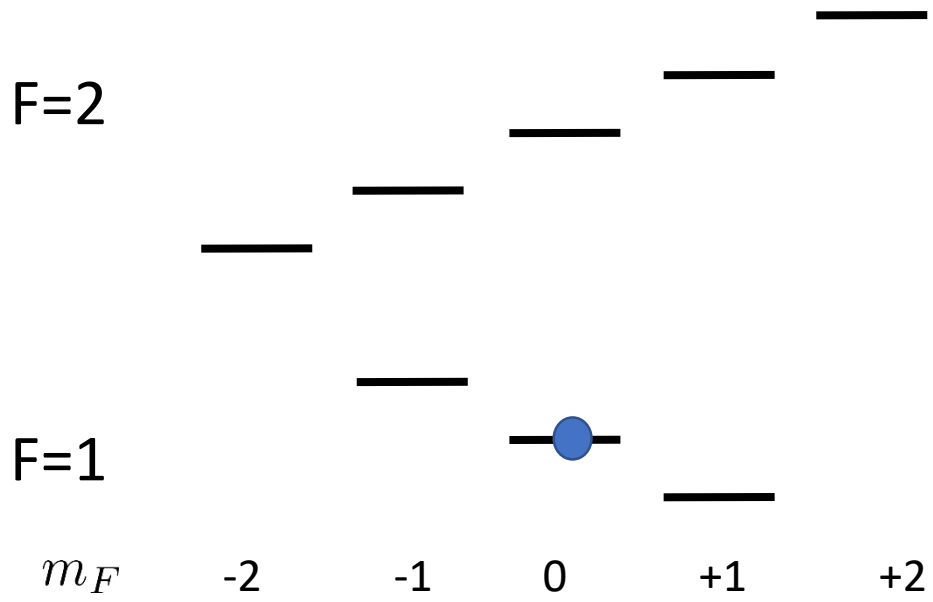
Readout



Readout

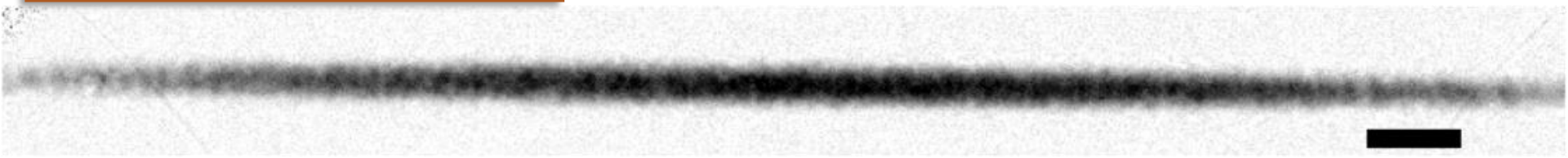
Resolution $\approx 1.1\,\mu\mathrm{m}$

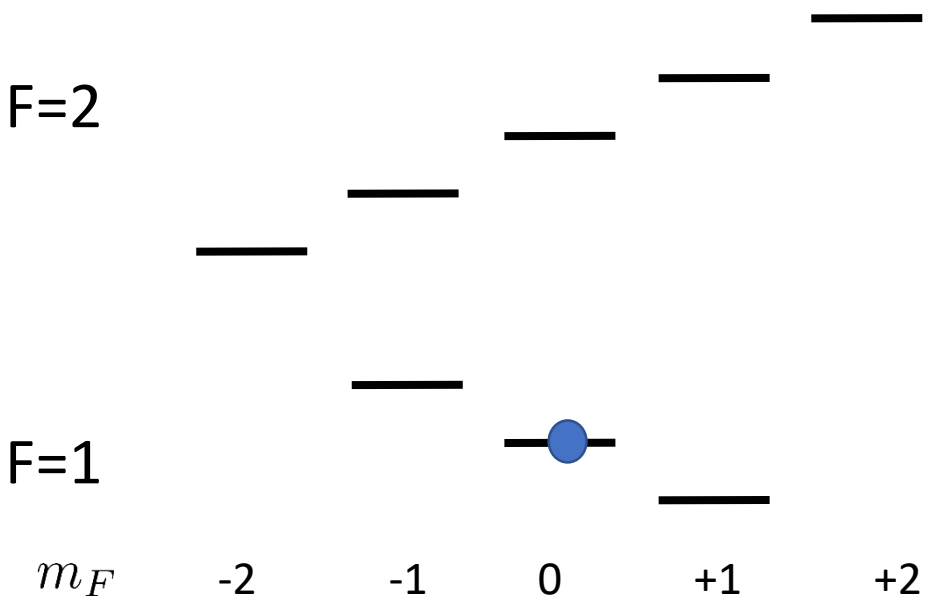




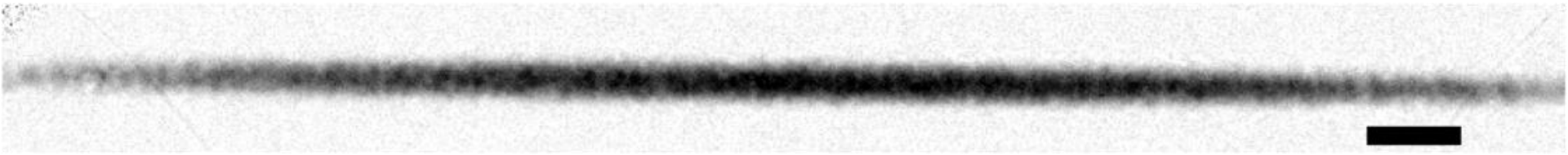
Readout

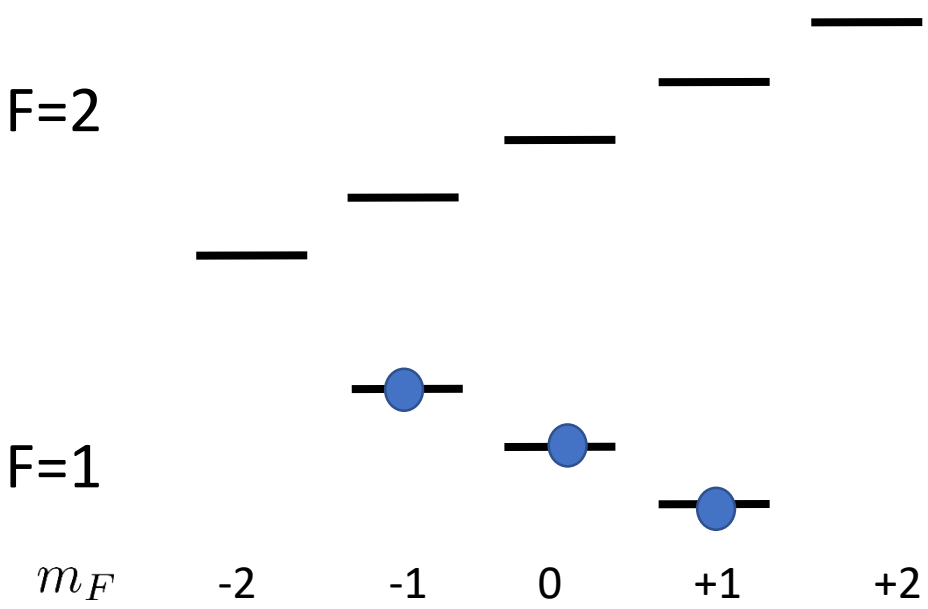
1+1 dimensional setup



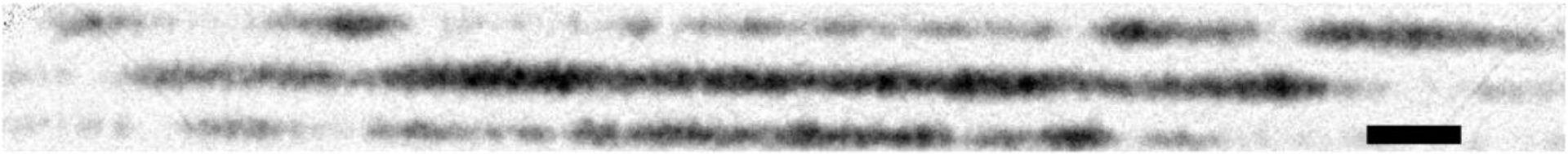


Readout



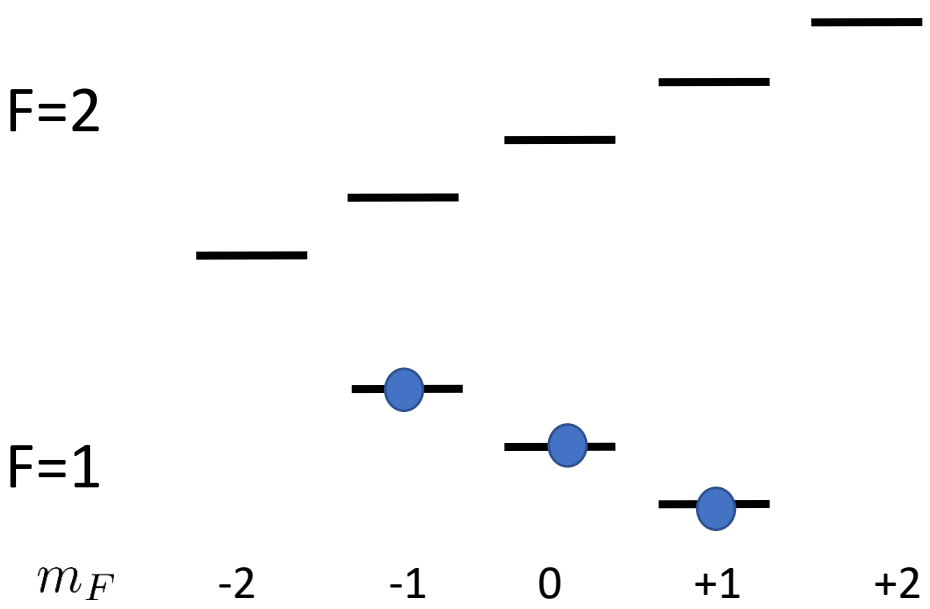


Readout

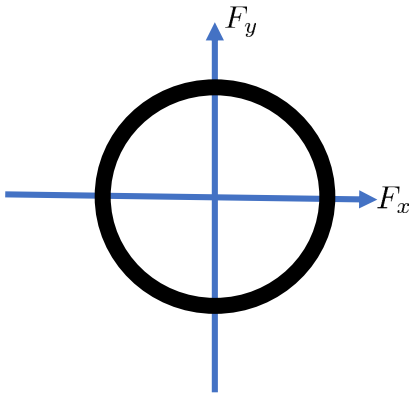


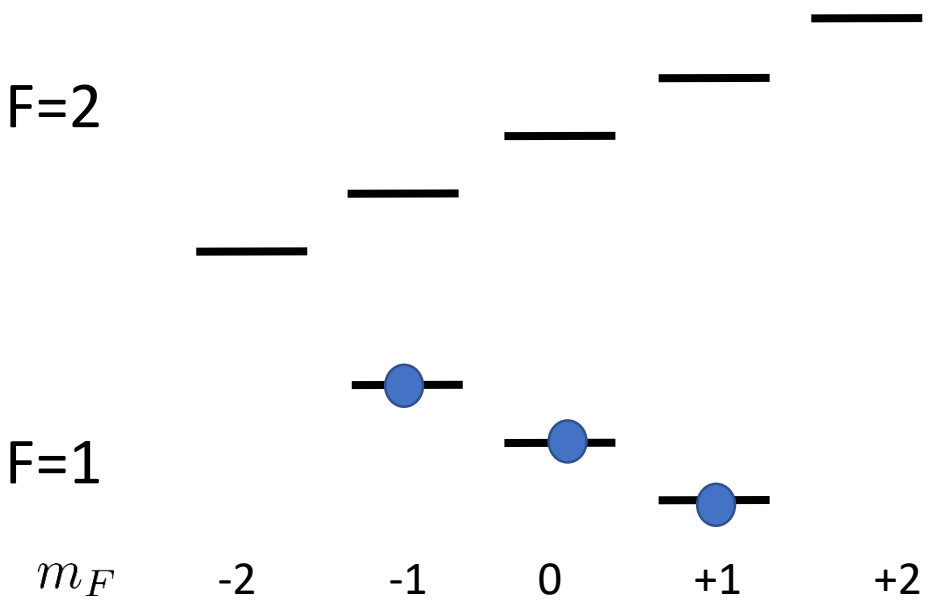
Magnetic
Fiel gradient

ΔB



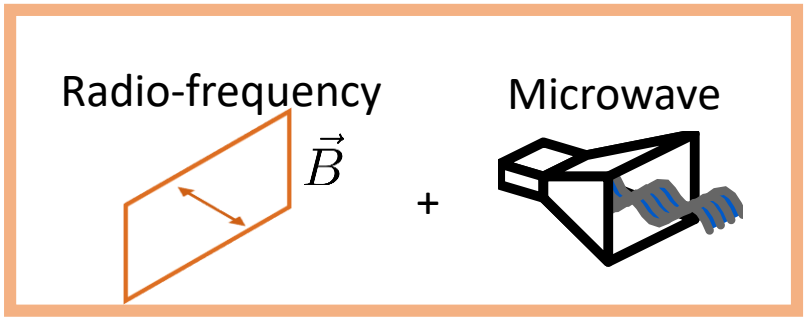
Readout



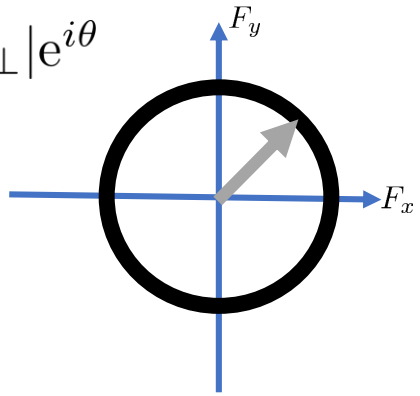


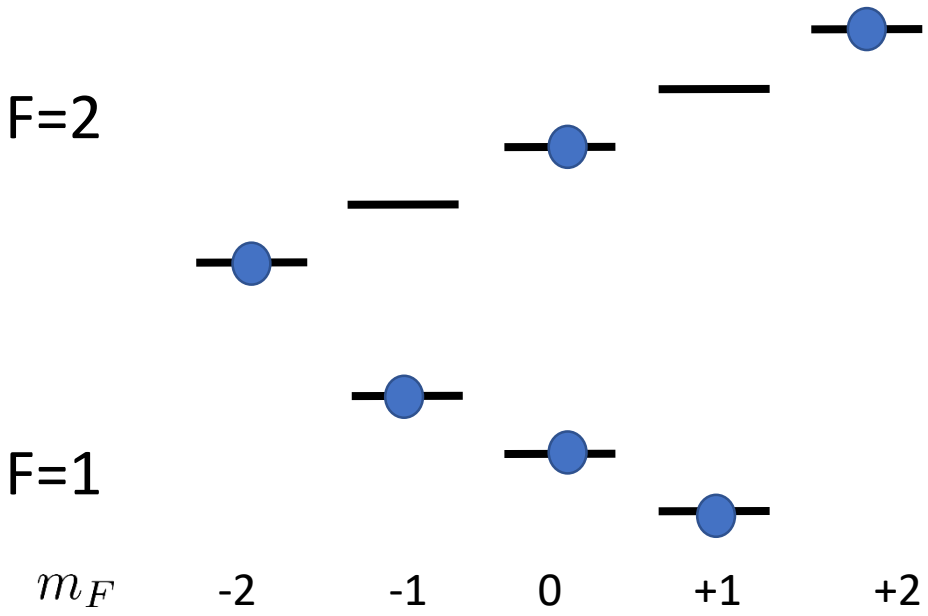
Kunkel et al., in preparation (2018)

Readout



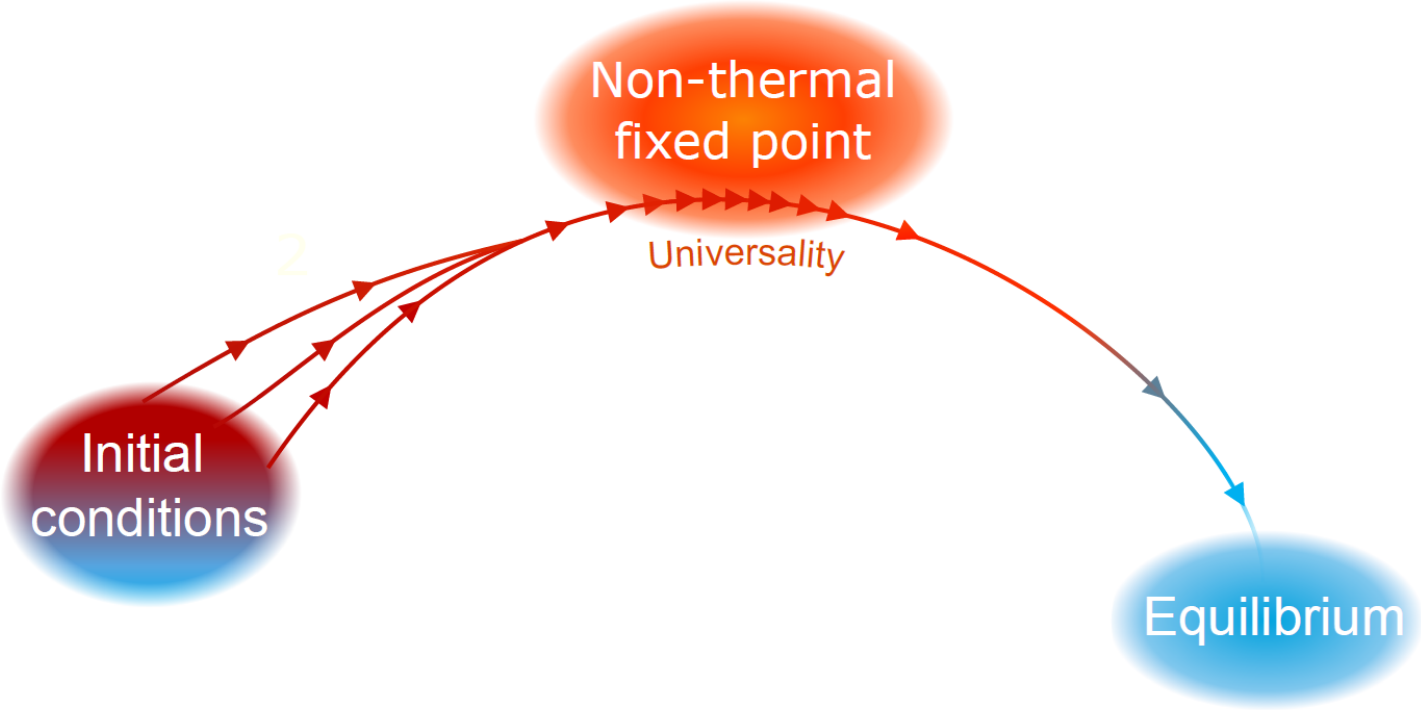
$$F_\perp = |F_\perp| e^{i\theta}$$



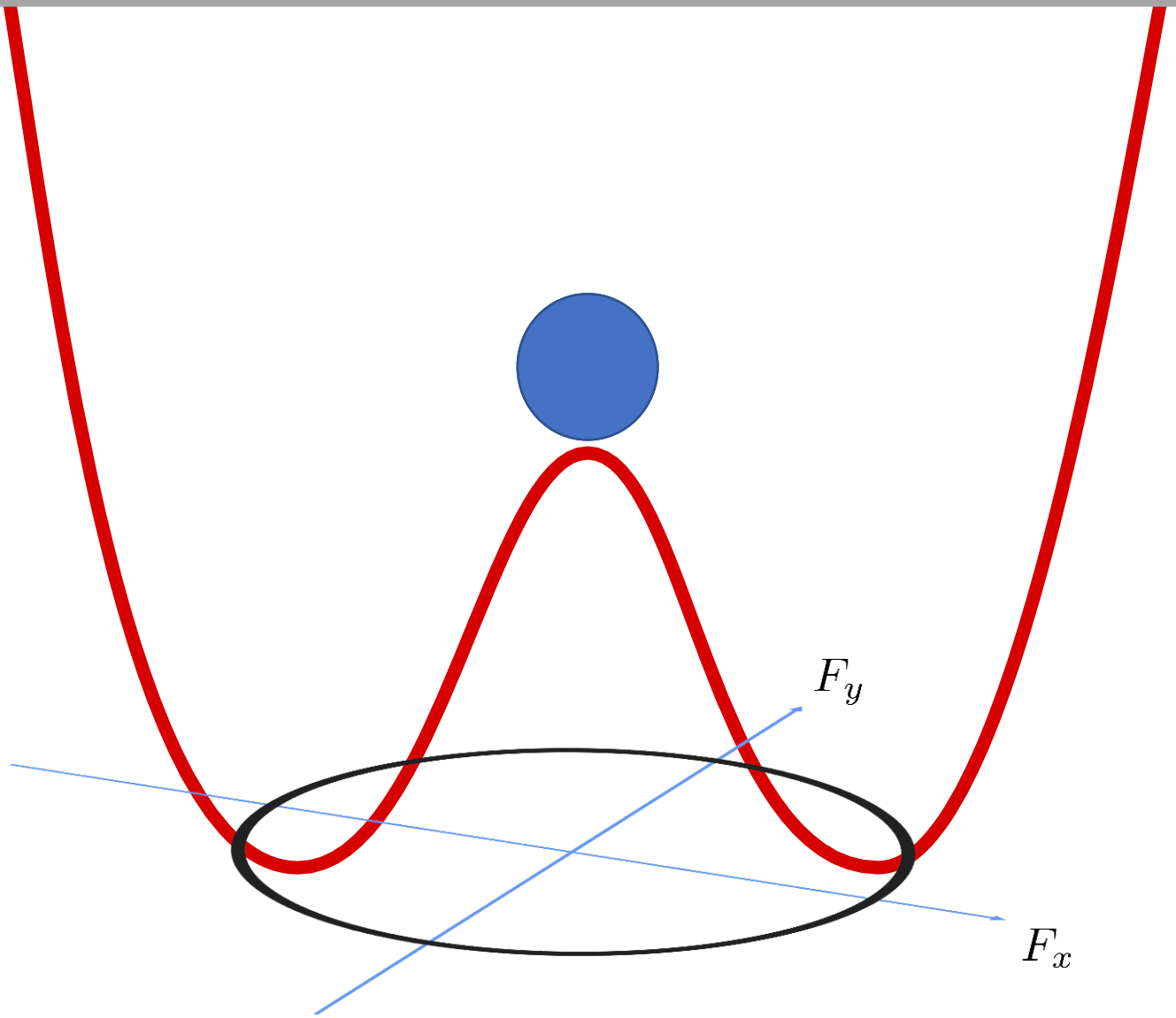


Kunkel et al., in preparation (2018)

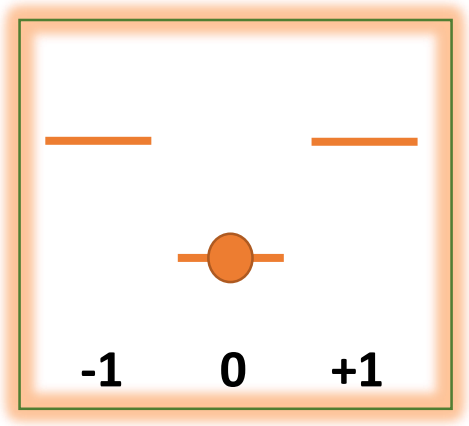
Isolated many-body quantum sytems out of equilibrium

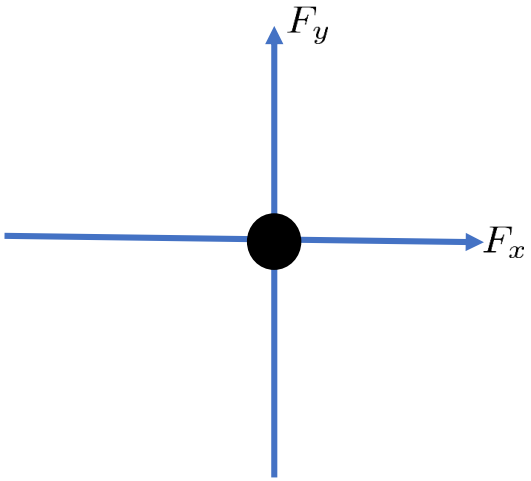


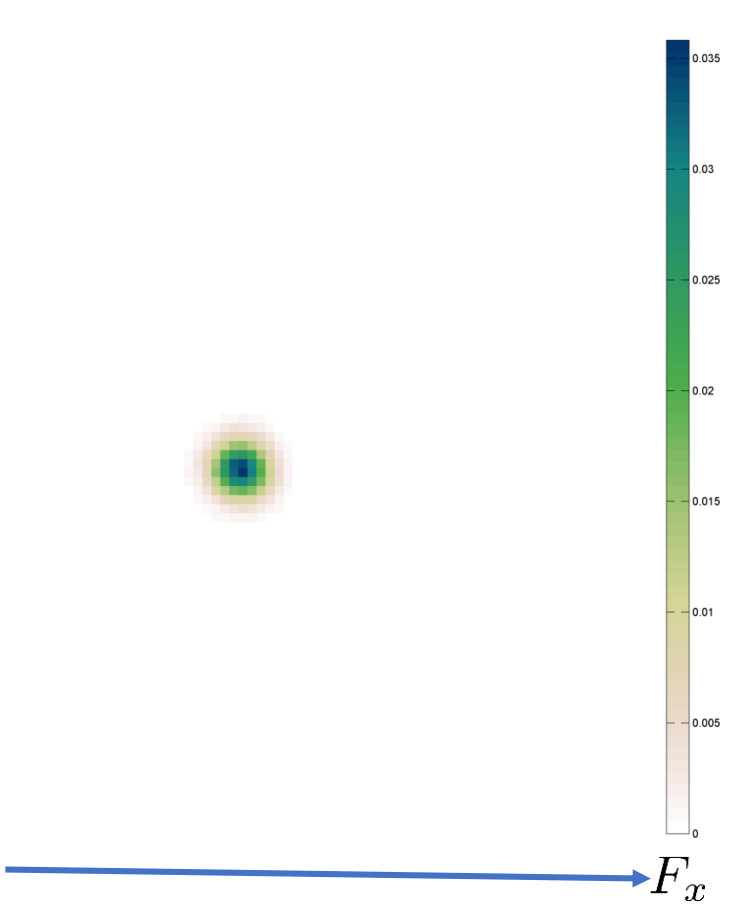
Extreme conditions



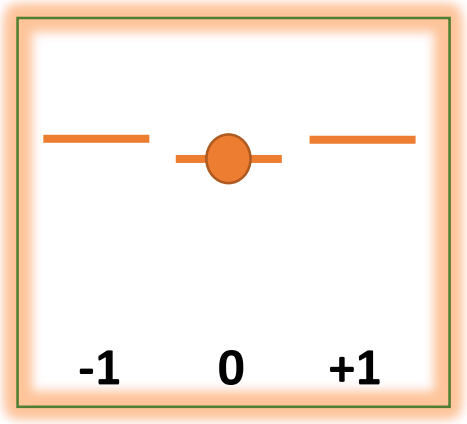
Extreme conditions

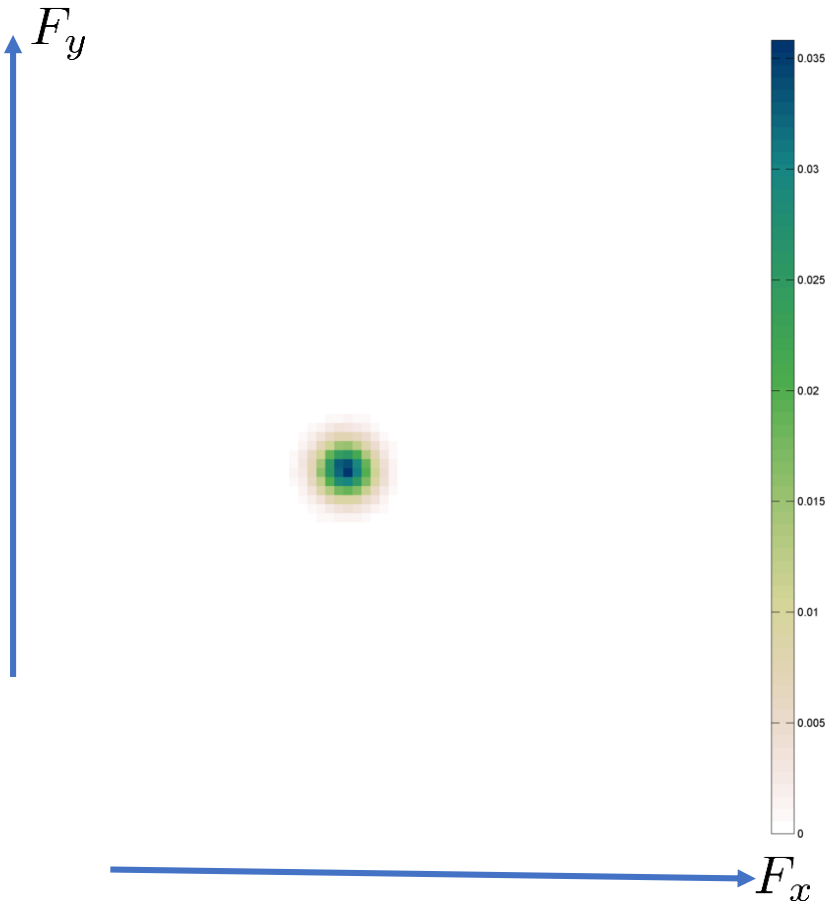






Extreme conditions





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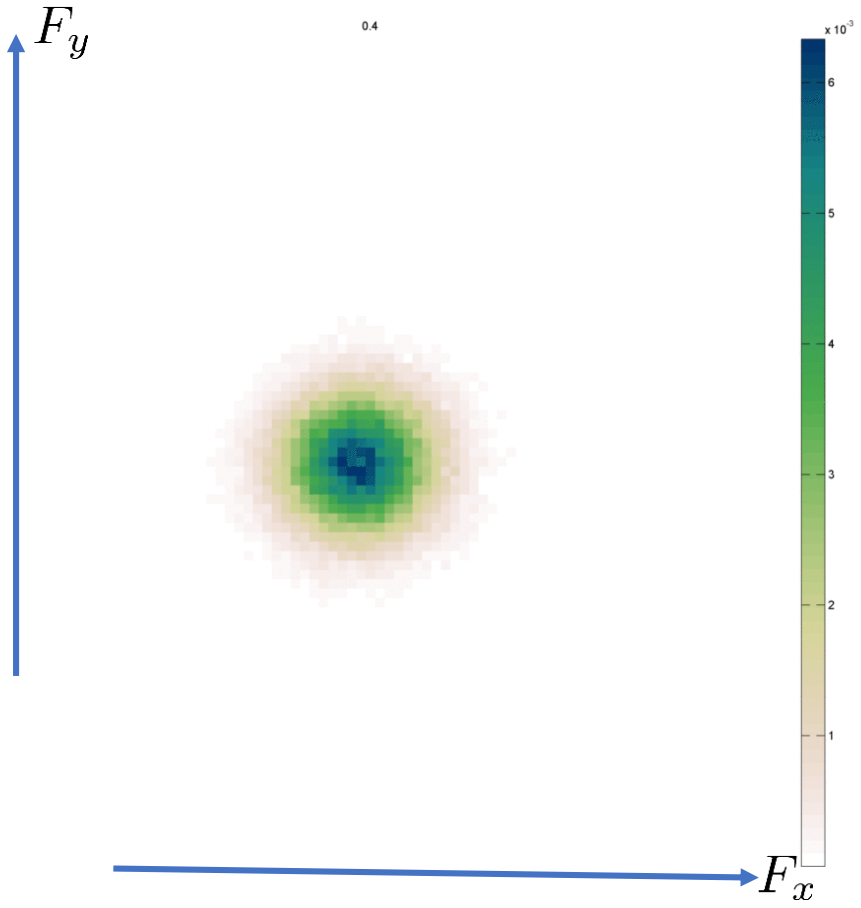
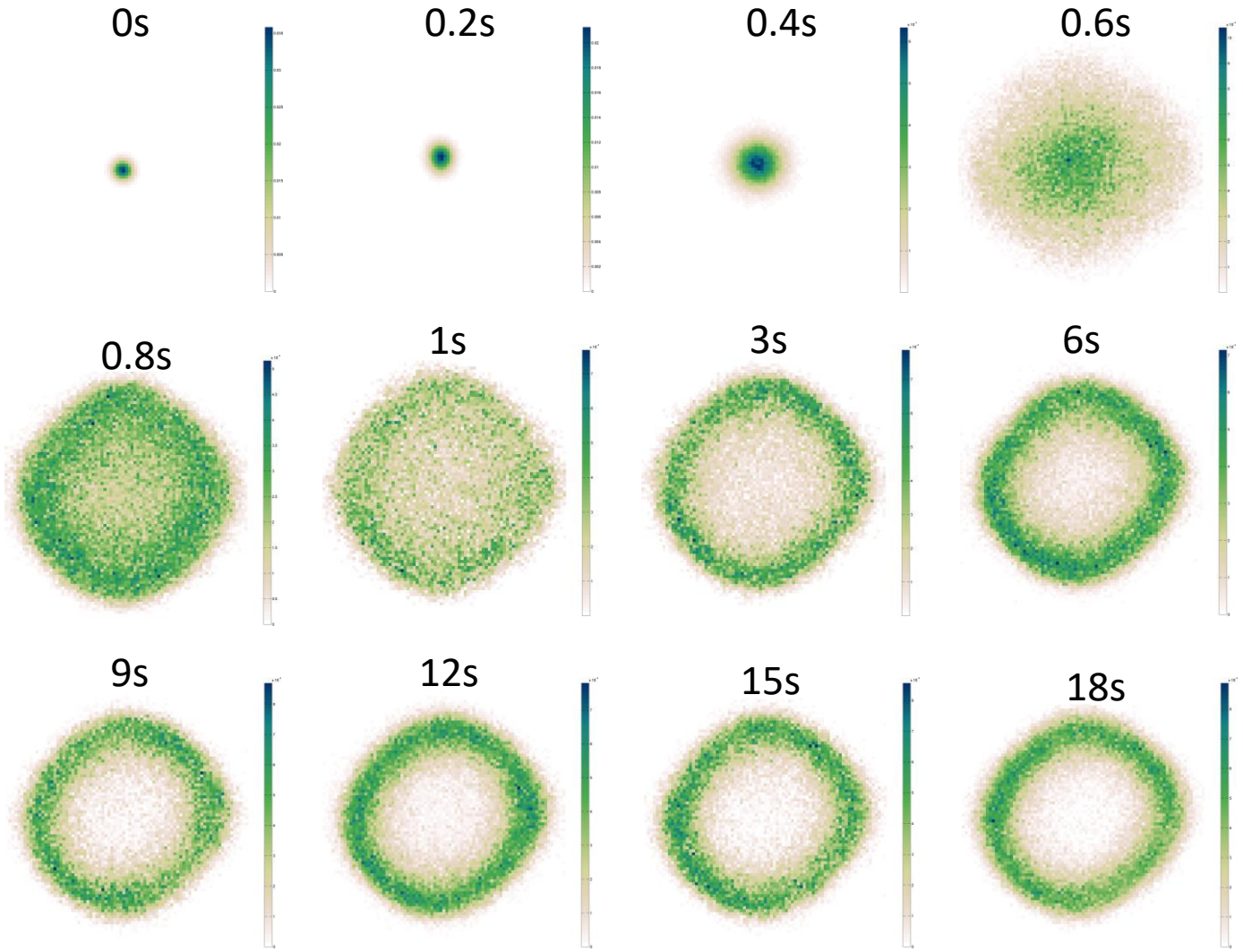
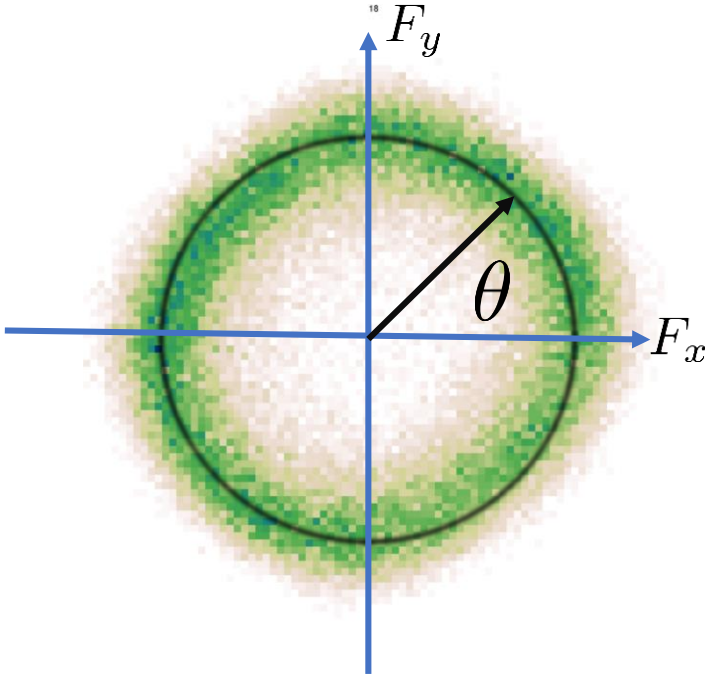


Extreme conditions



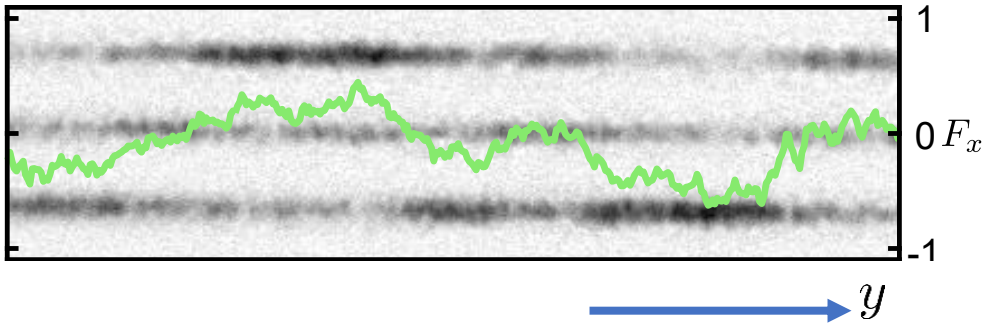
Observable

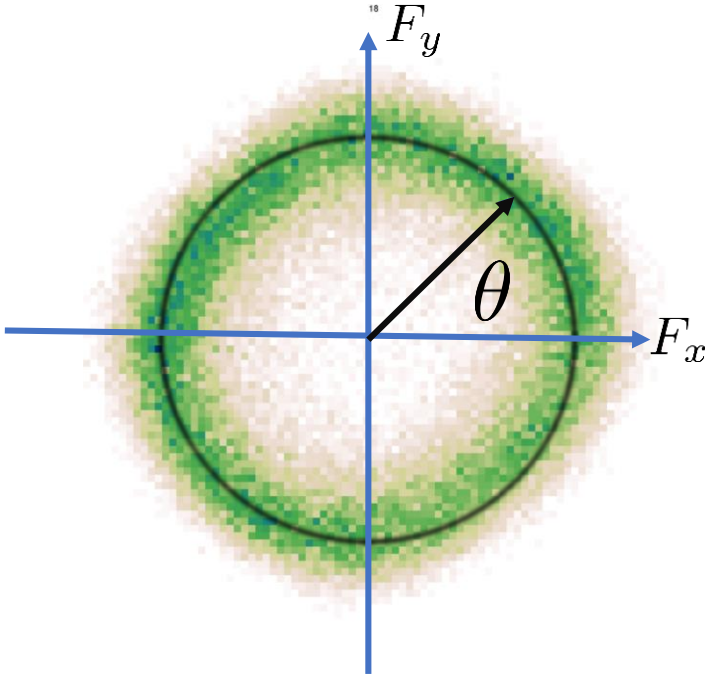
Angular orientation θ



Observable

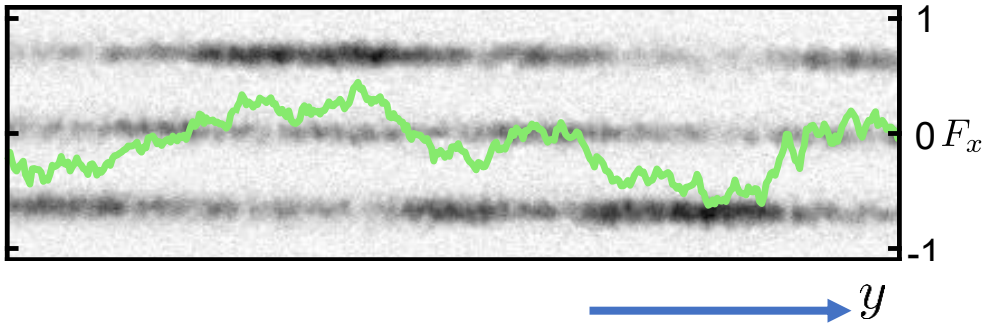
Angular orientation $\theta(y)$

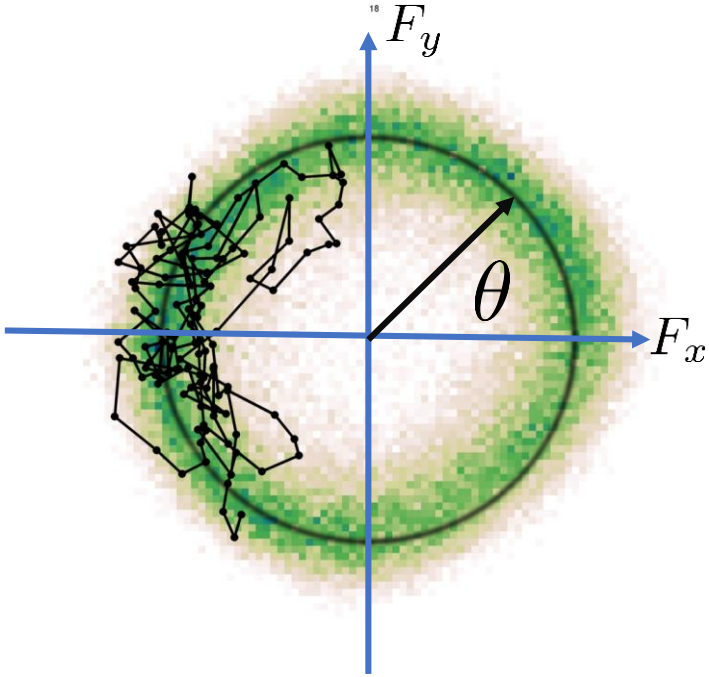




Observable

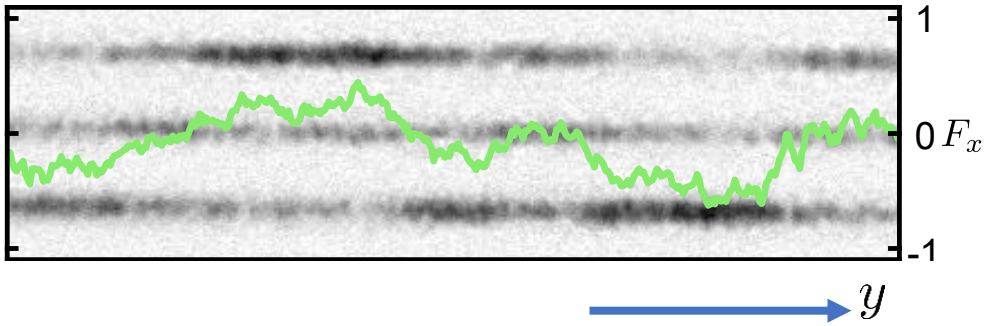
Angular orientation $\theta(y)$

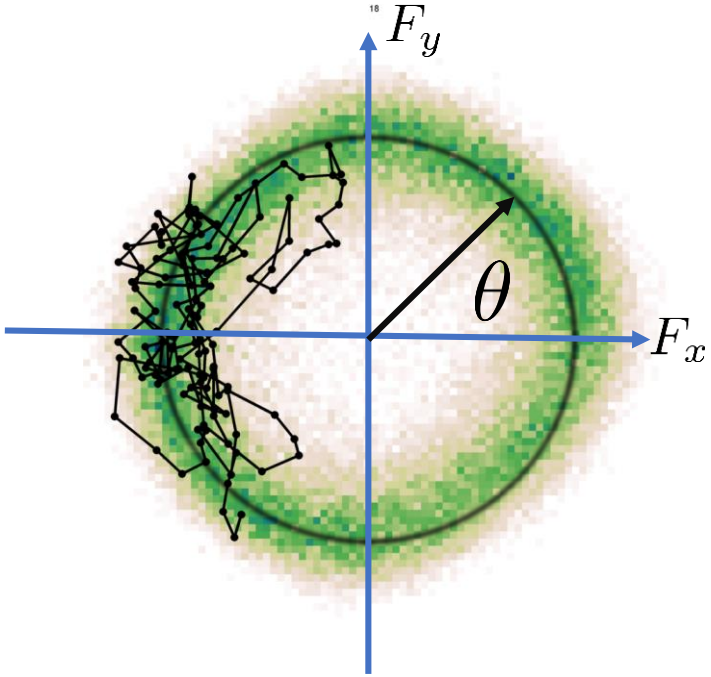




Observable

Angular orientation $\theta(y)$

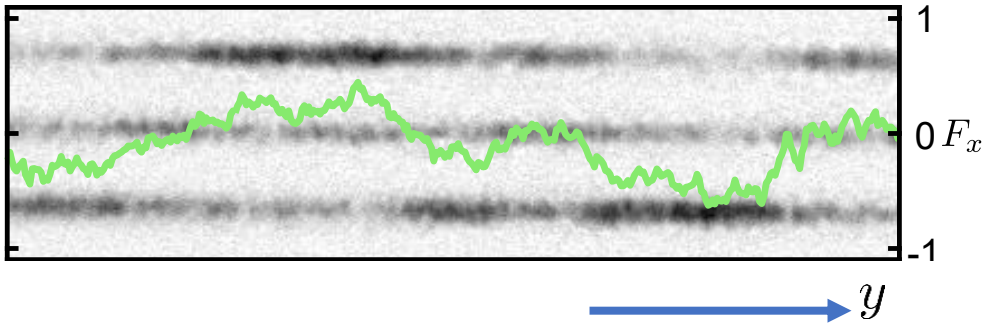


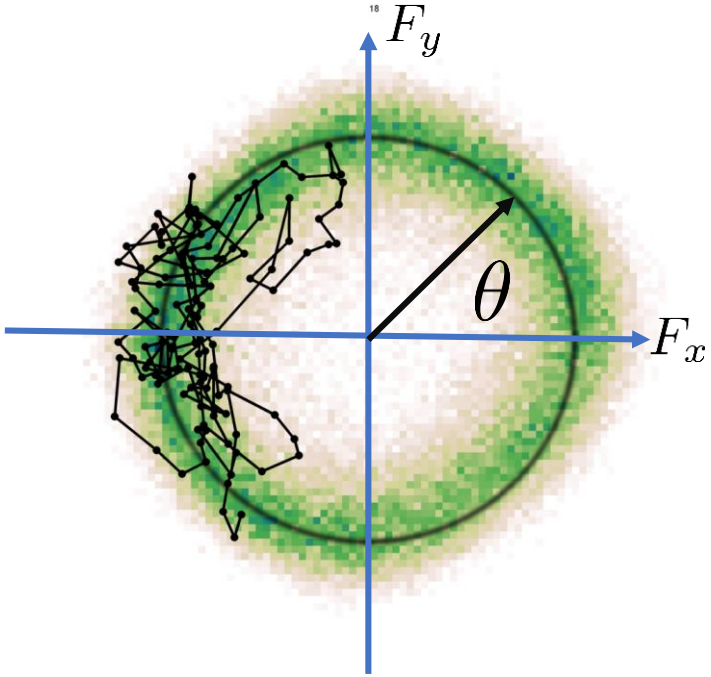


Correlation functions $\langle \theta(y)\theta(y') \rangle$

Observable

Angular orientation $\theta(y)$



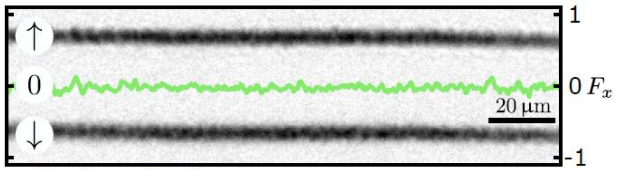


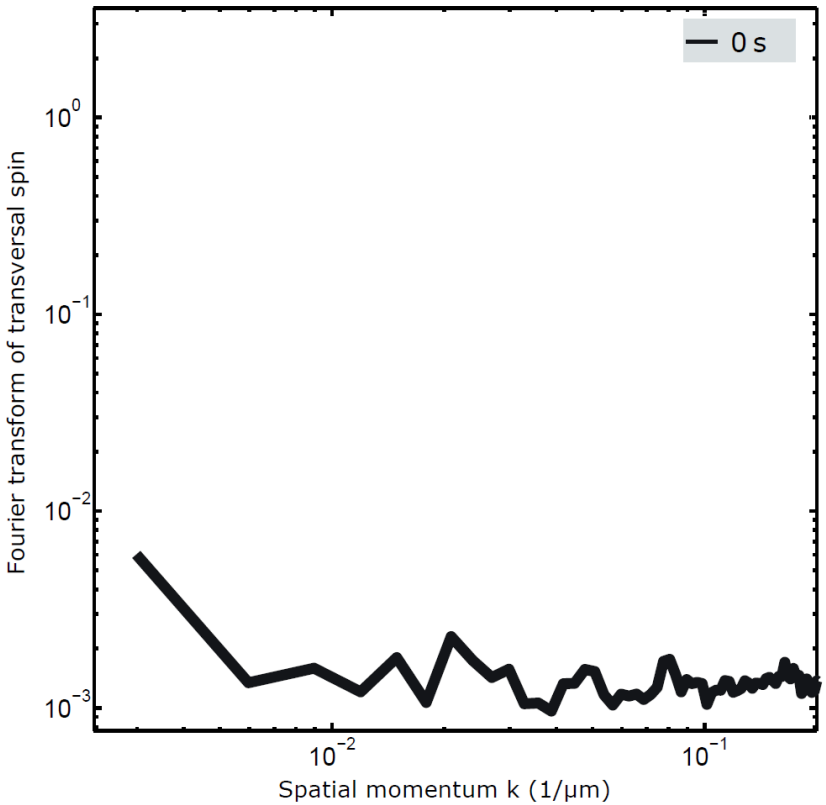
Correlation functions $\langle \theta(y)\theta(y') \rangle$

Fourier space $f_\theta(k)$

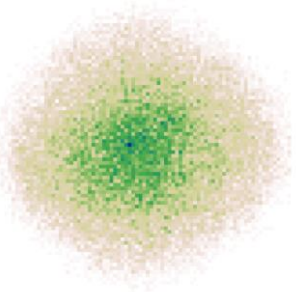
Going extreme

Structure factor $f_\theta(k)$

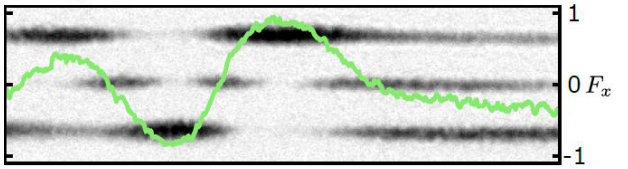


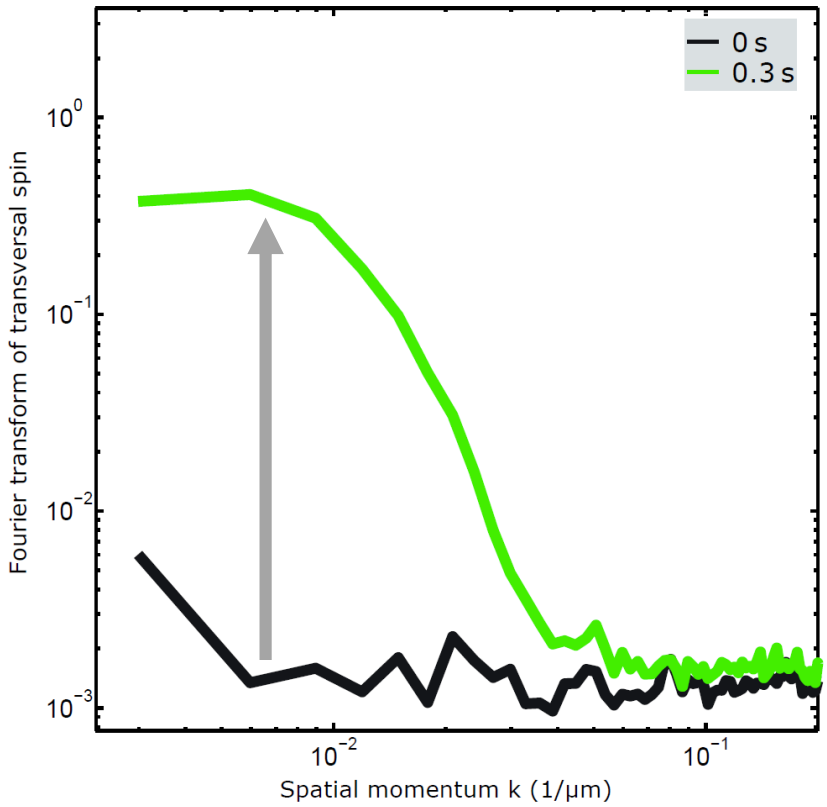


Going extreme

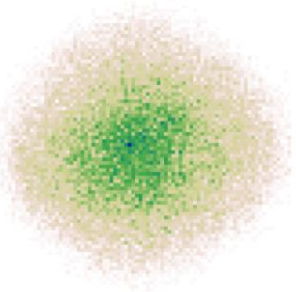


Structure factor $f_\theta(k)$

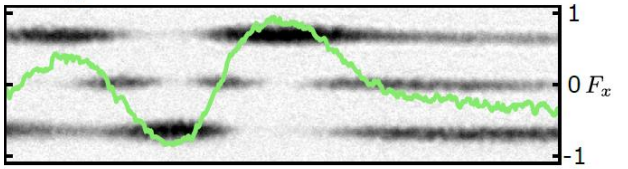


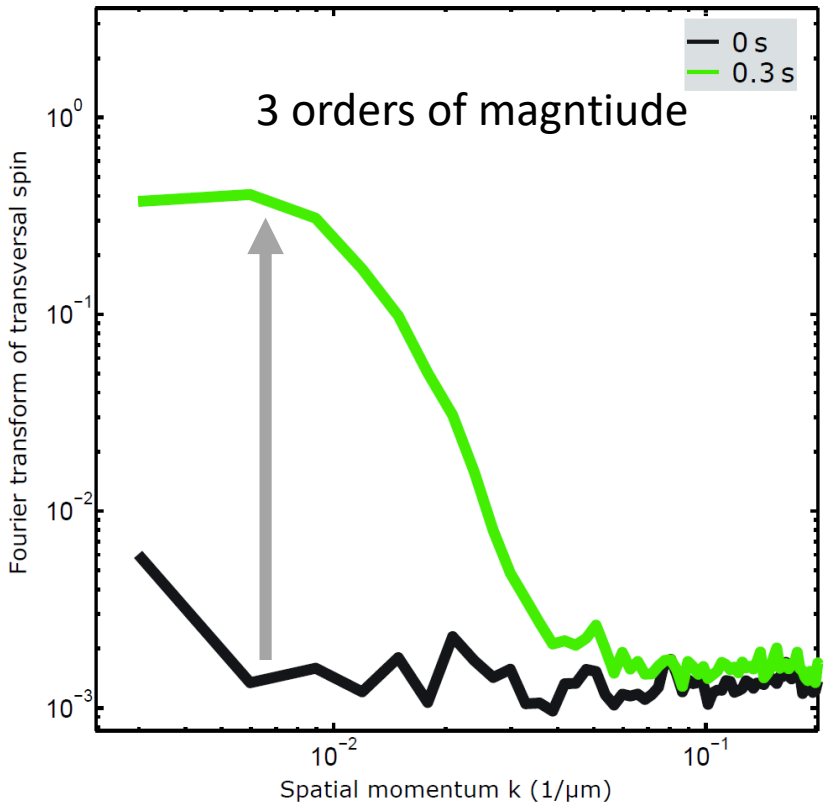


Going extreme

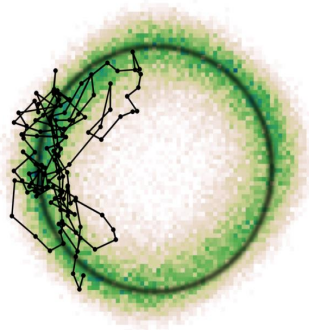


Structure factor $f_\theta(k)$

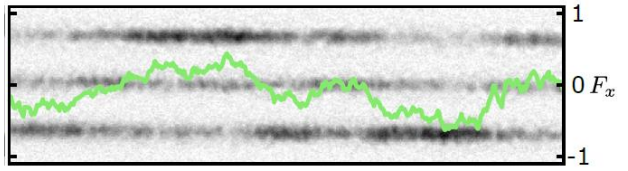


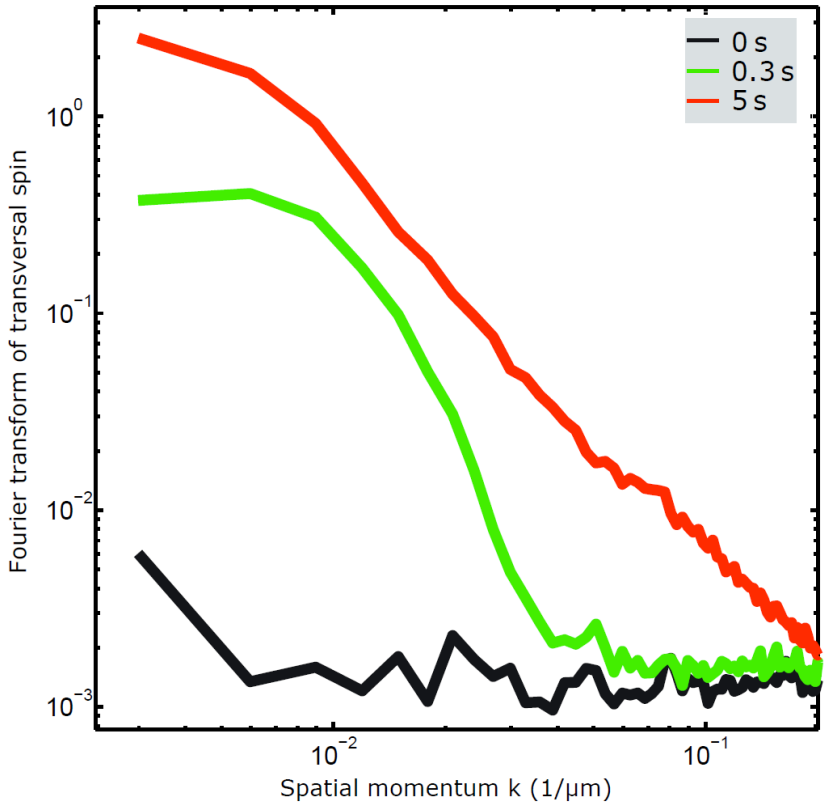


Going extreme

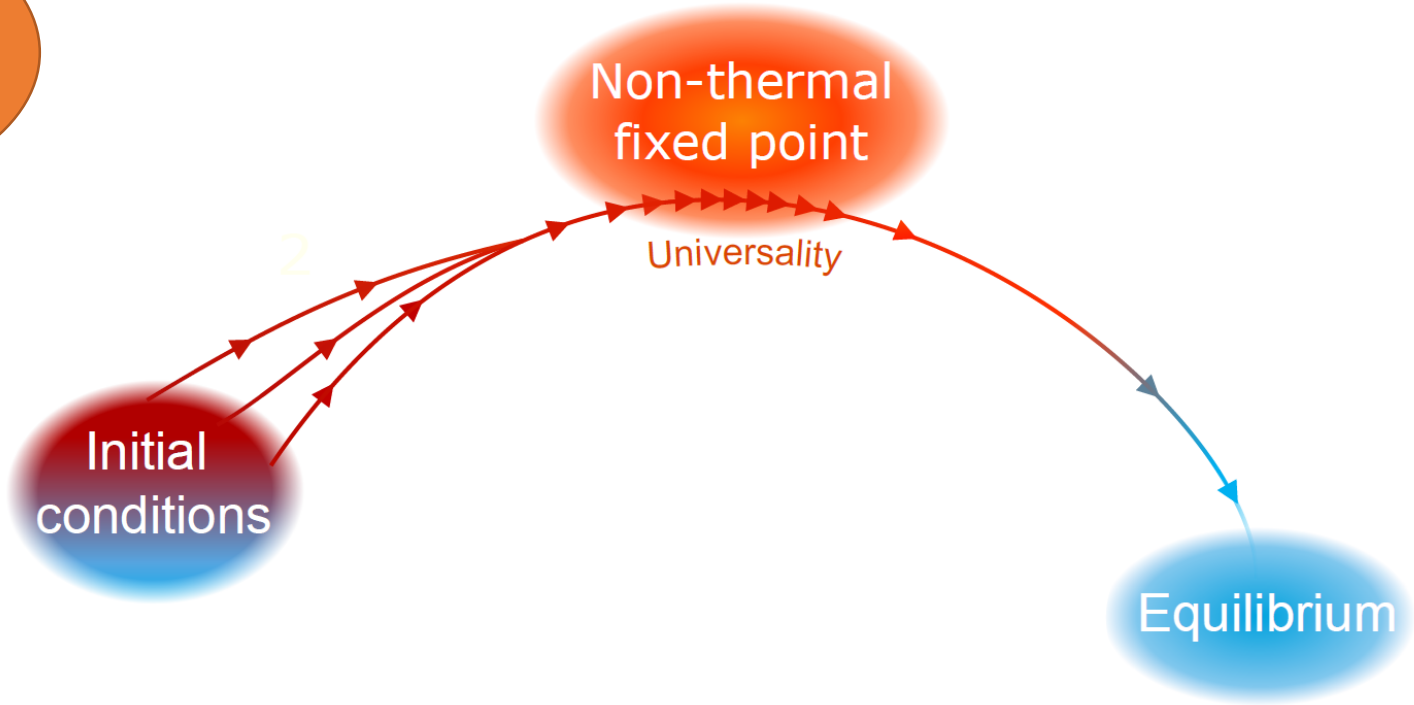


Structure factor $f_\theta(k)$



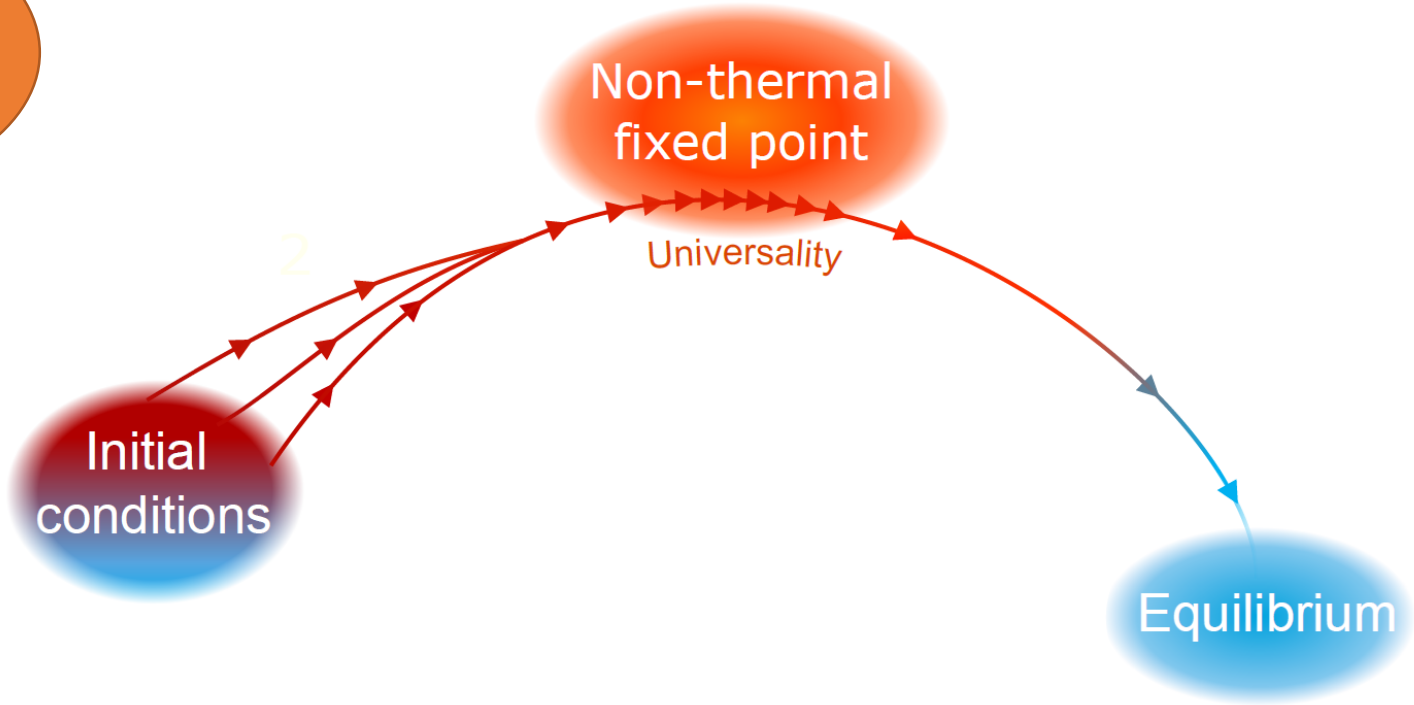


Isolated many-body quantum sytems out of equilibrium



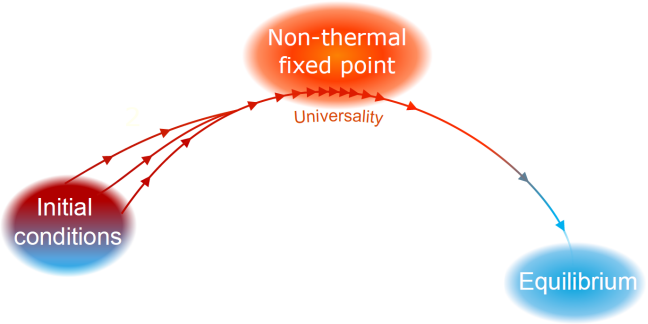
Prüfer, M. et al., Nature **563**, 217-220(2018)

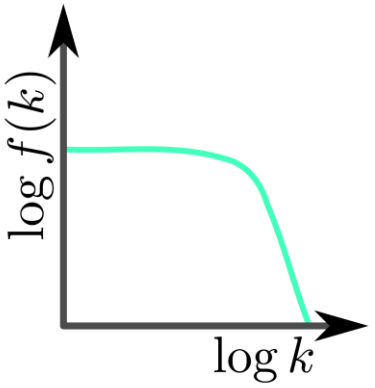
Isolated many-body quantum sytems out of equilibrium



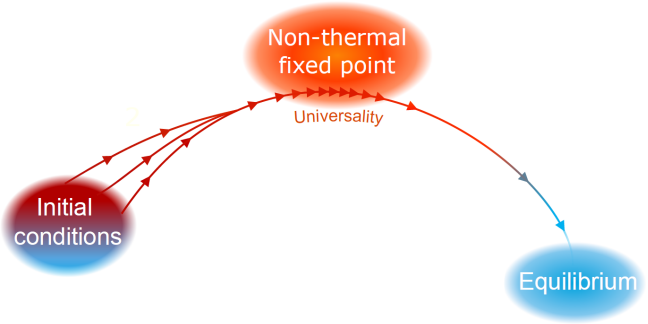
Similar results: Erne, S. et al., Nature **563**, 225-229 (2018)

Universal dynamics



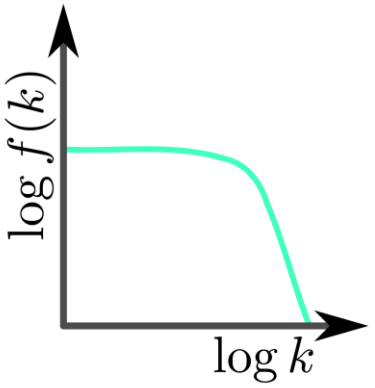


Universal dynamics

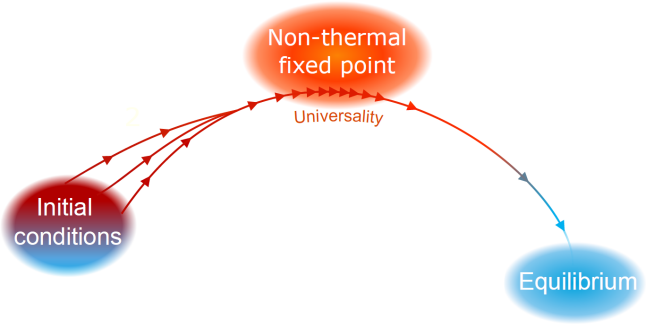


Dynamics is described by:

1. Scaling function f_S
2. Scaling exponents α, β

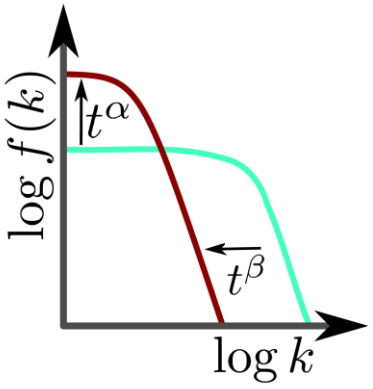


Universal dynamics



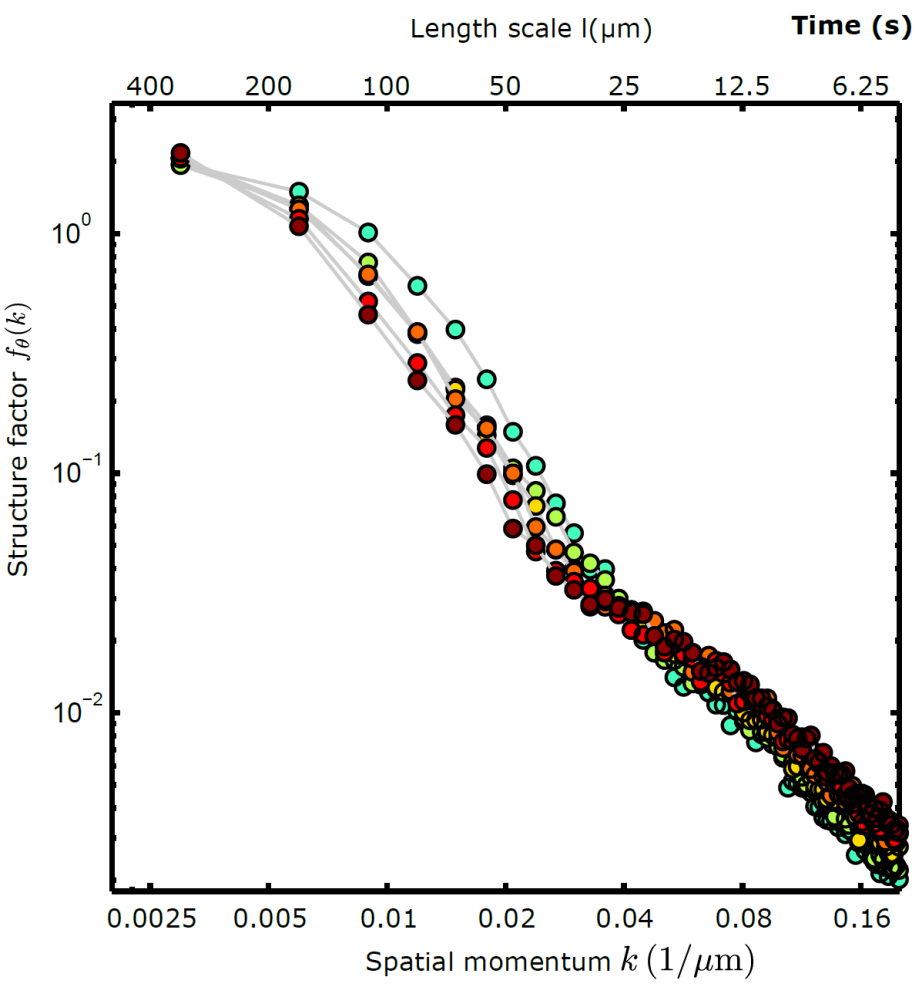
Dynamics is described by:

1. Scaling function f_S
2. Scaling exponents $\alpha,\ \beta$

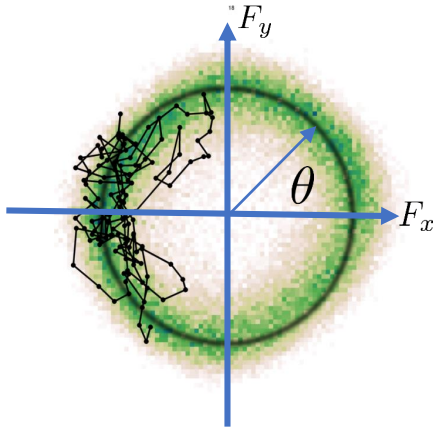


$$f_\theta(k,t) = t^\alpha f_S(t^\beta k)$$

Rescaling

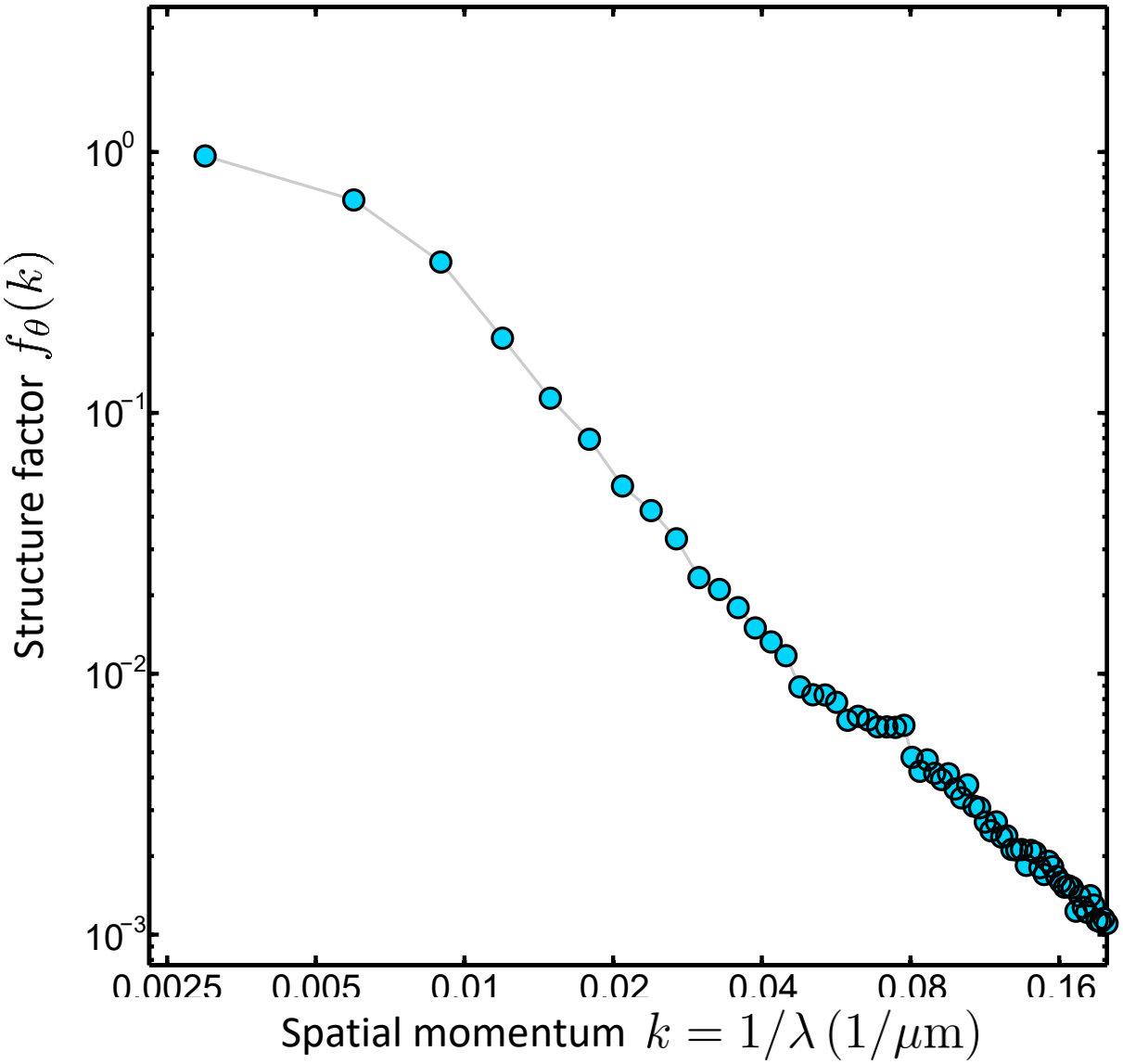


Structure factor $f_\theta(k)$

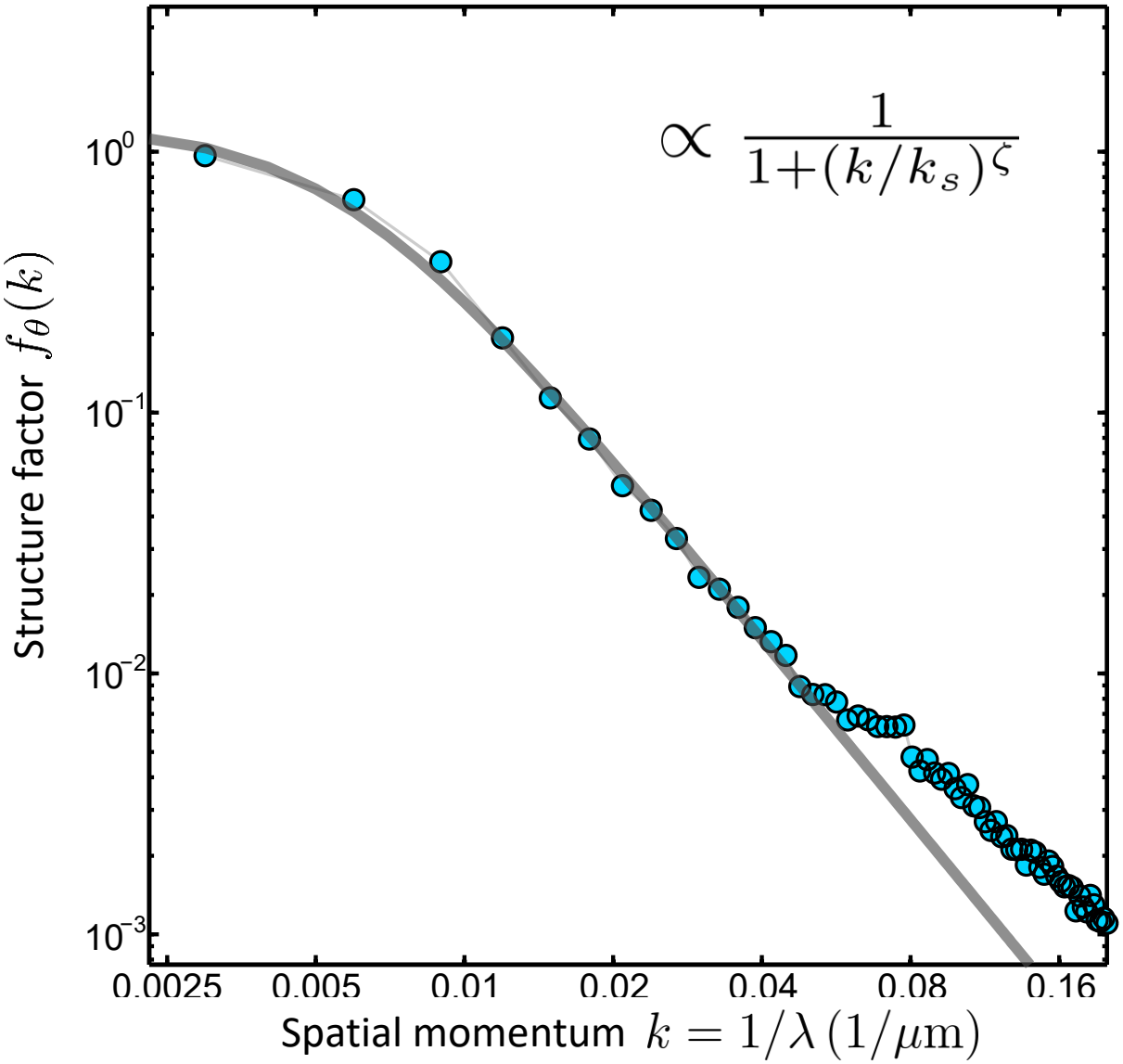


Prüfer, M. et al., Nature **563**, 217-220 (2018)

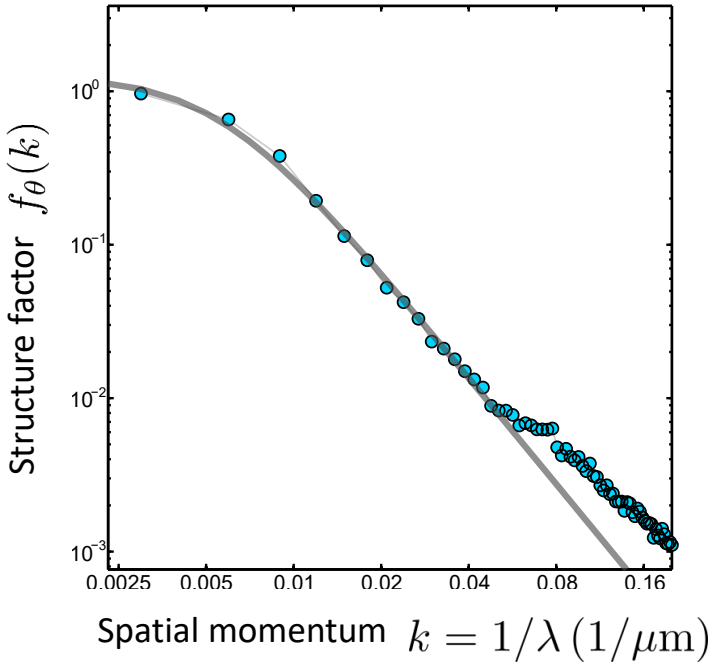
Scaling function

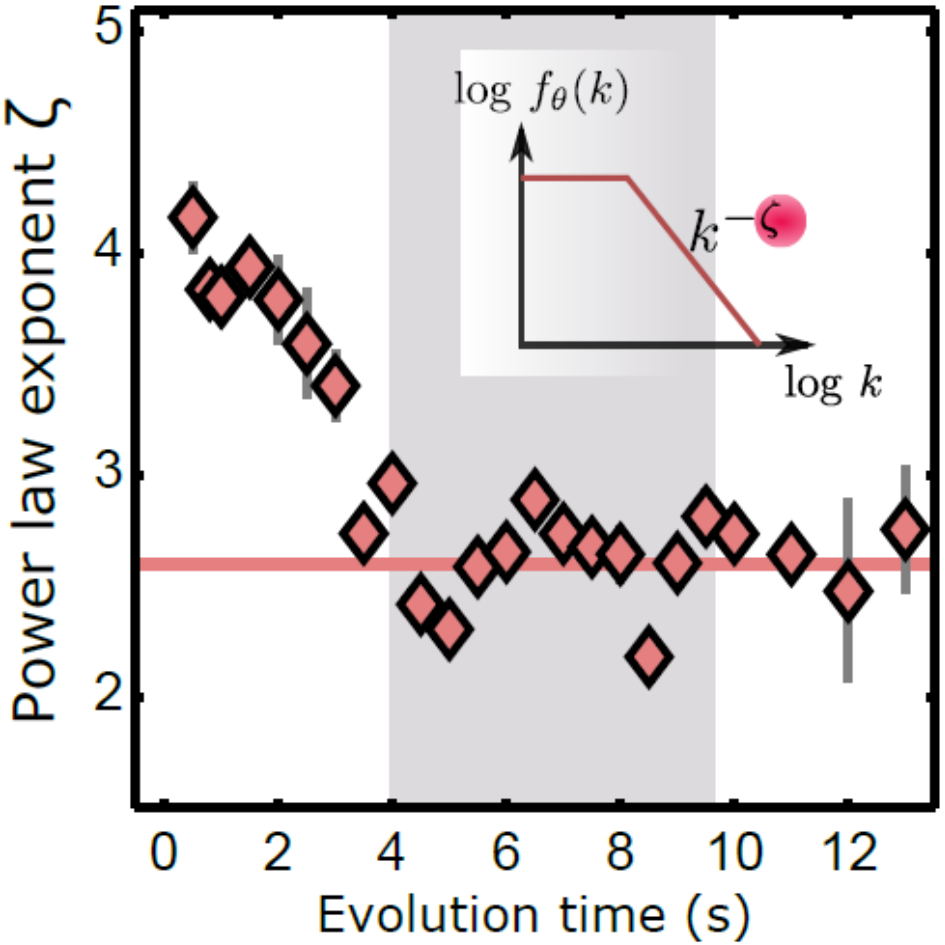


Scaling function

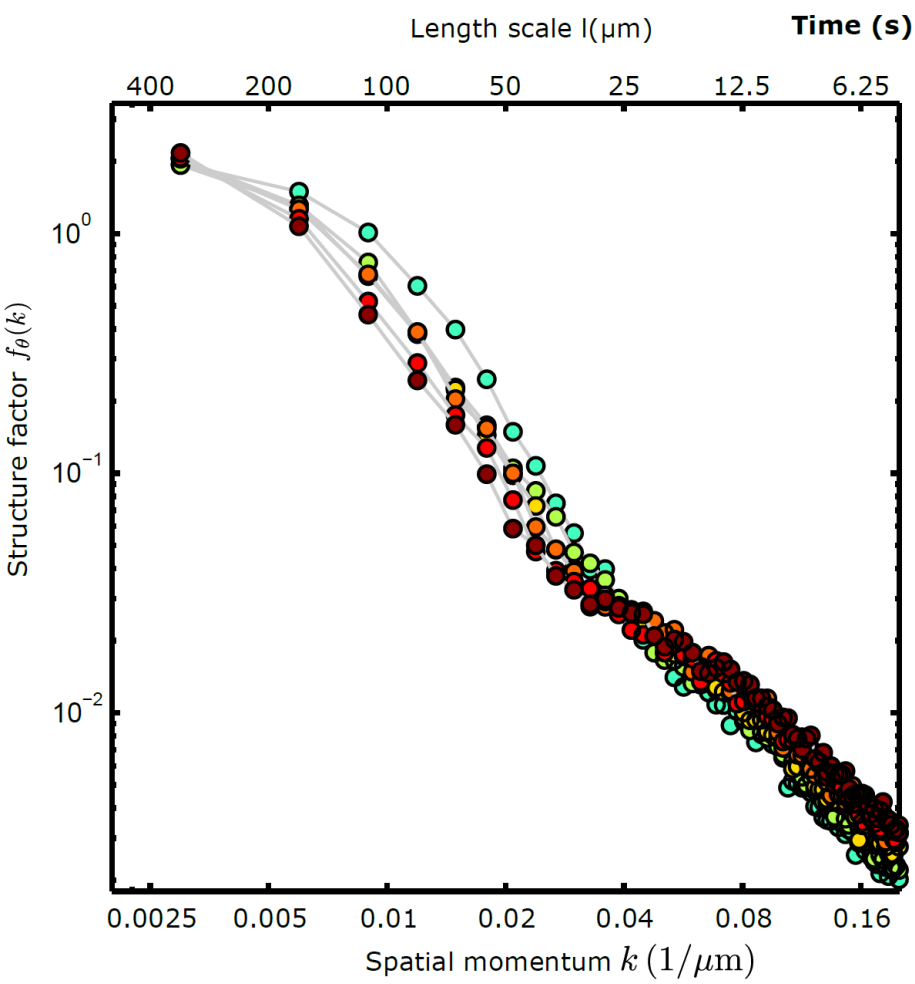


Scaling function

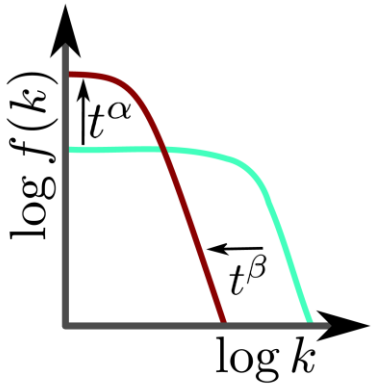




Rescaling



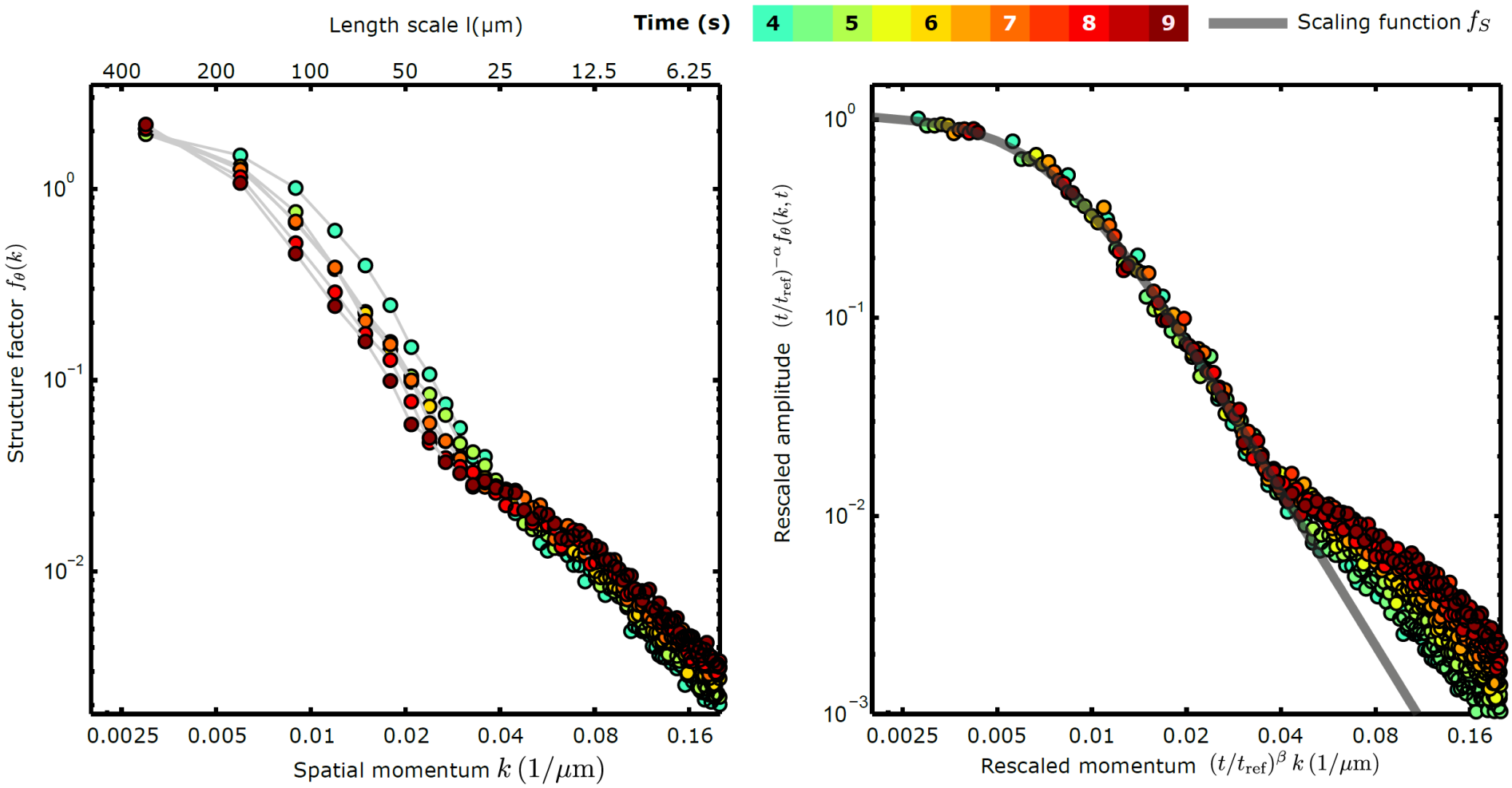
Structure factor $f_\theta(k)$



$$f_\theta(k,t) = t^\alpha f_S(t^\beta k)$$

Prüfer, M. et al., Nature **563**, 217-220 (2018)

Rescaling



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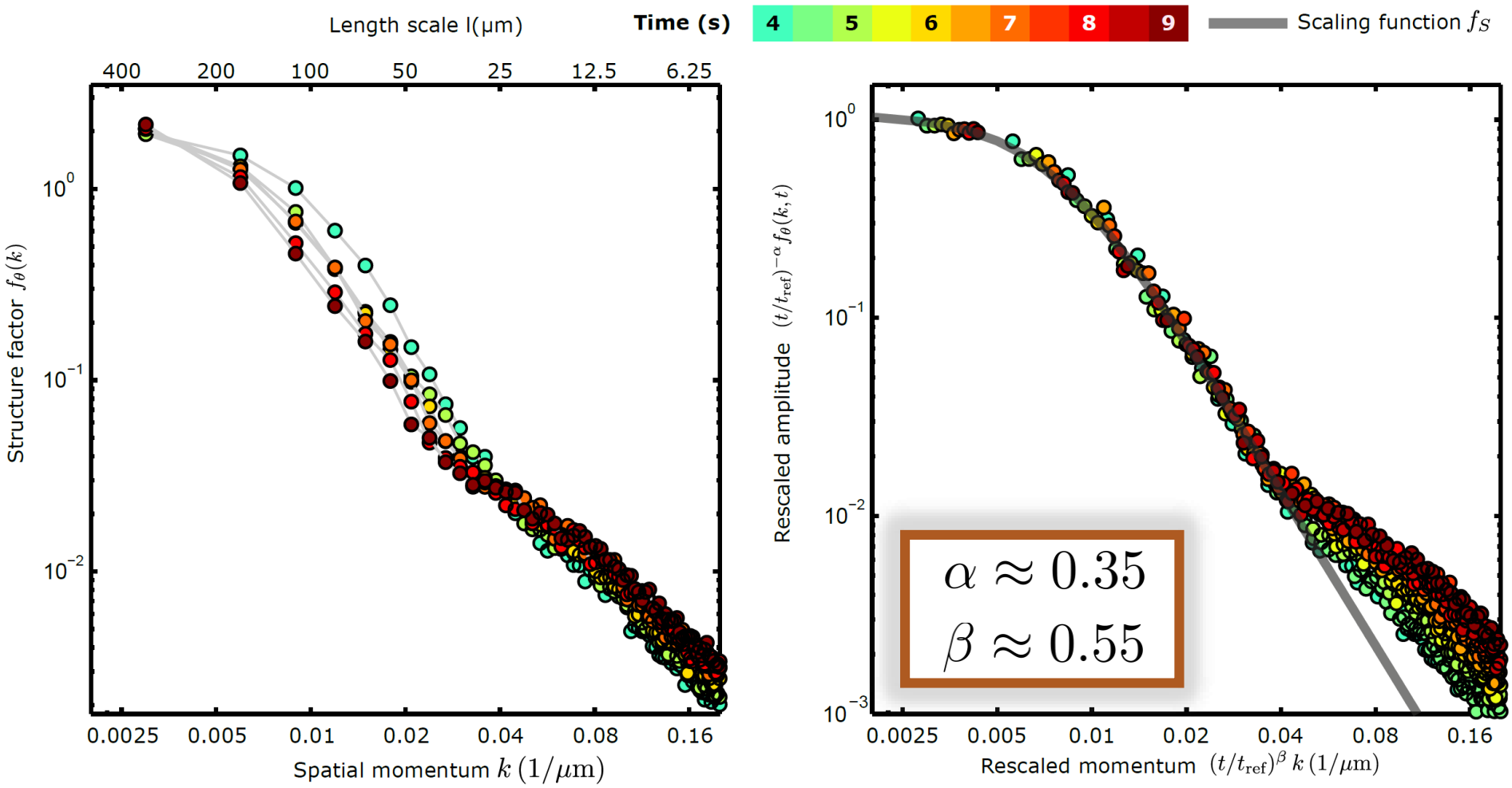
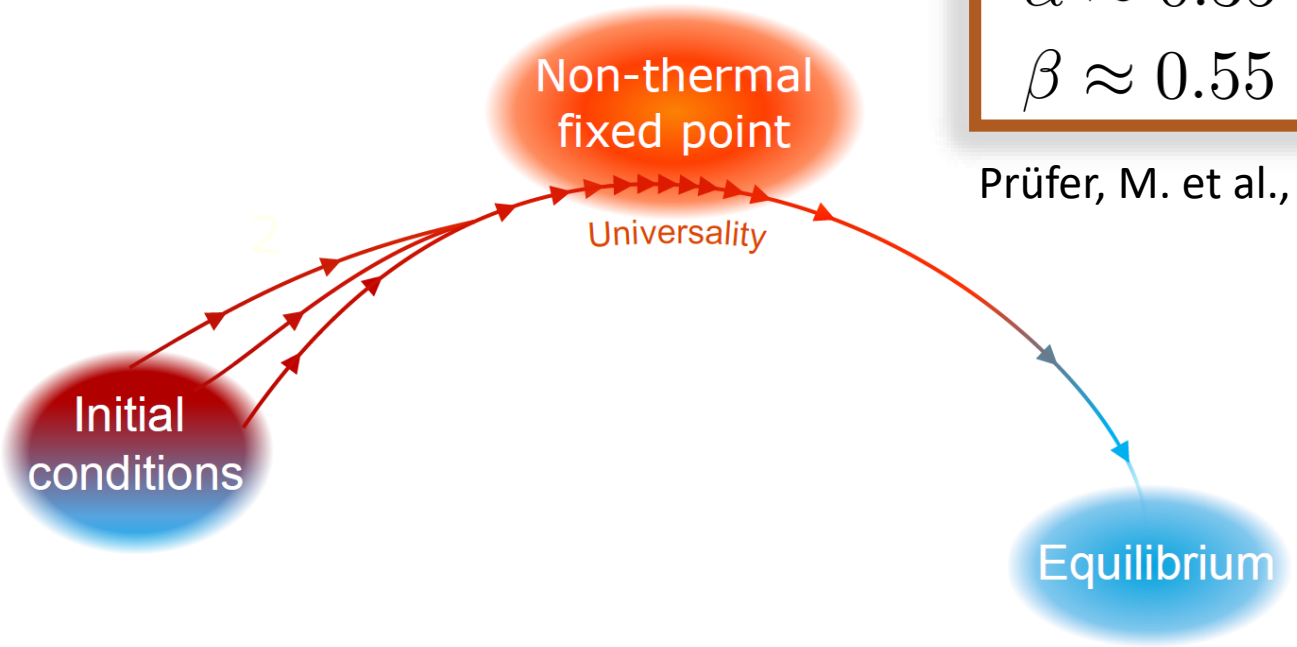
Rescaling



Prüfer, M. et al., Nature **563**, 217-220 (2018)

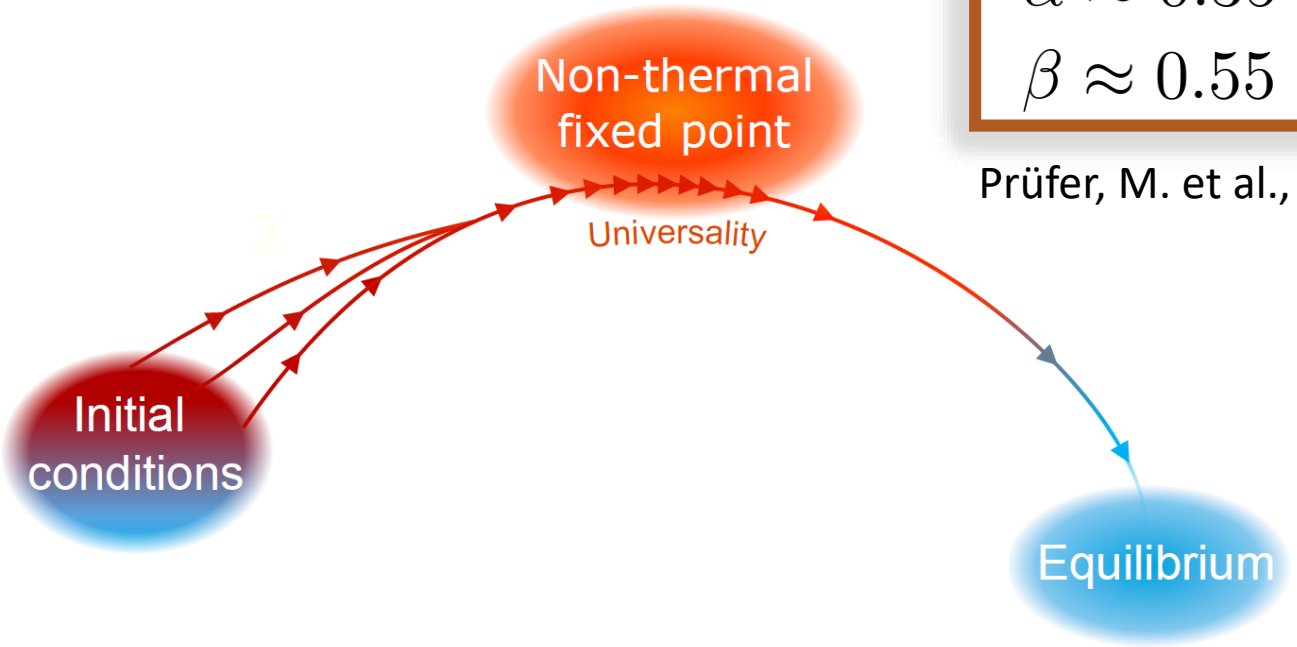
Robustness



$$\alpha \approx 0.35$$
$$\beta \approx 0.55$$

Prüfer, M. et al., Nature **563**, 217-220 (2018)

Robustness



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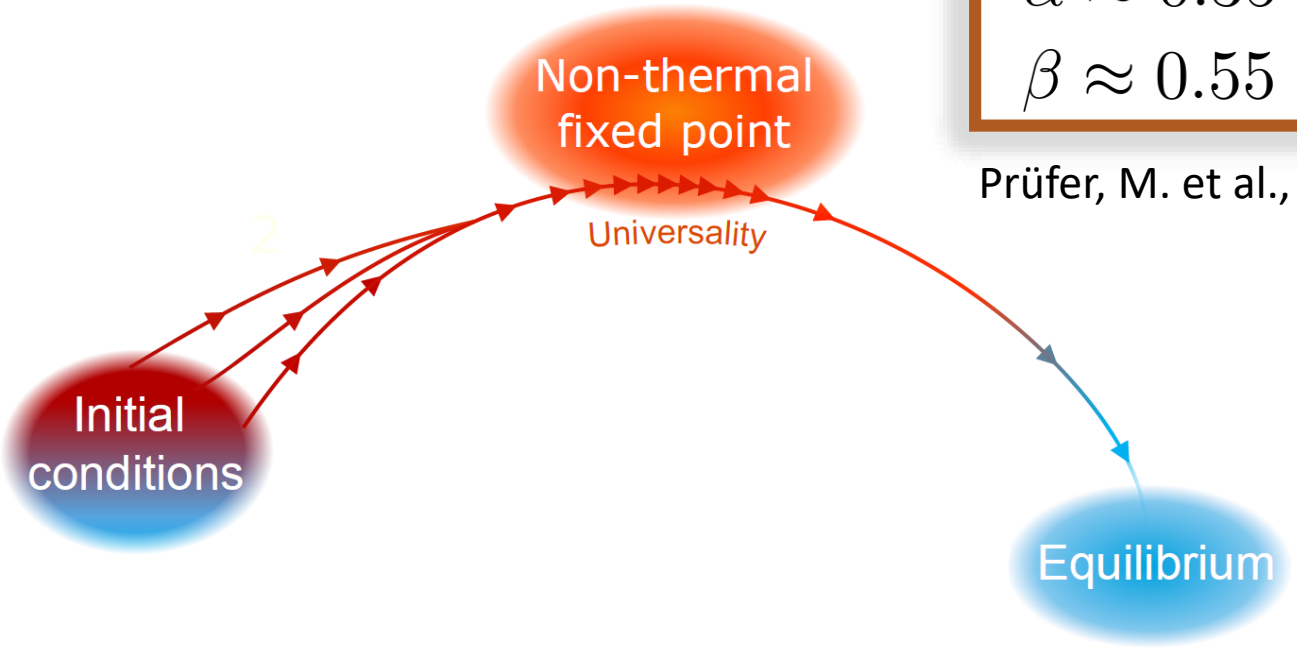
Prüfer, M. et al., Nature **563**, 217-220 (2018)

$$\alpha \approx 0.1$$
$$\beta \approx 0.1$$

Erne, S. et al., Nature **563**, 225-229 (2018)

Robustness



$$\alpha \approx 0.35$$
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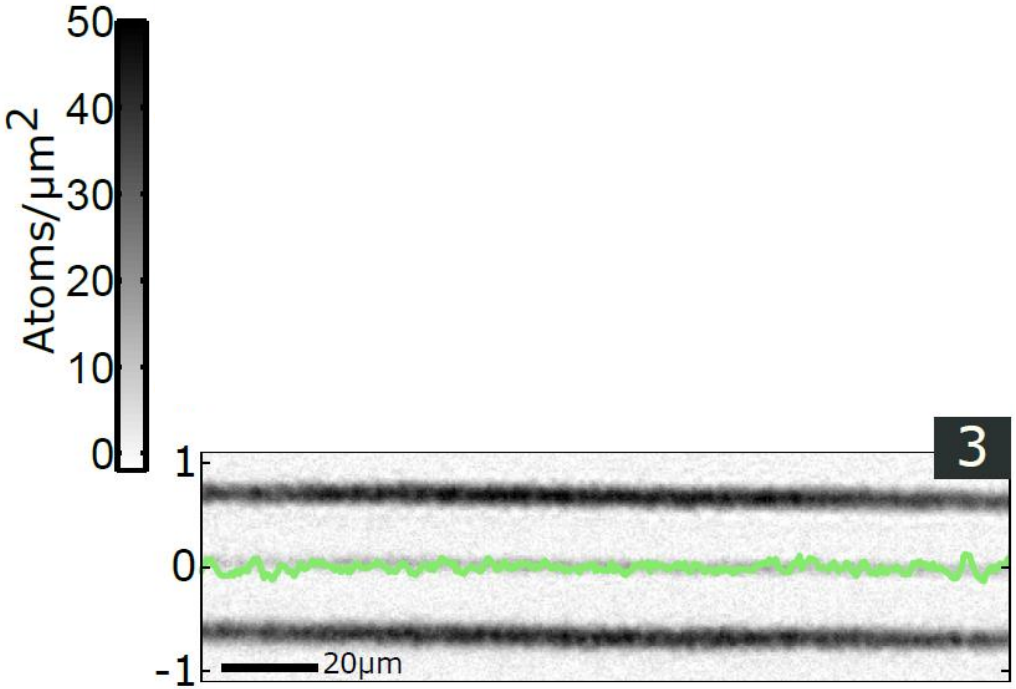
Prüfer, M. et al., Nature **563**, 217-220 (2018)

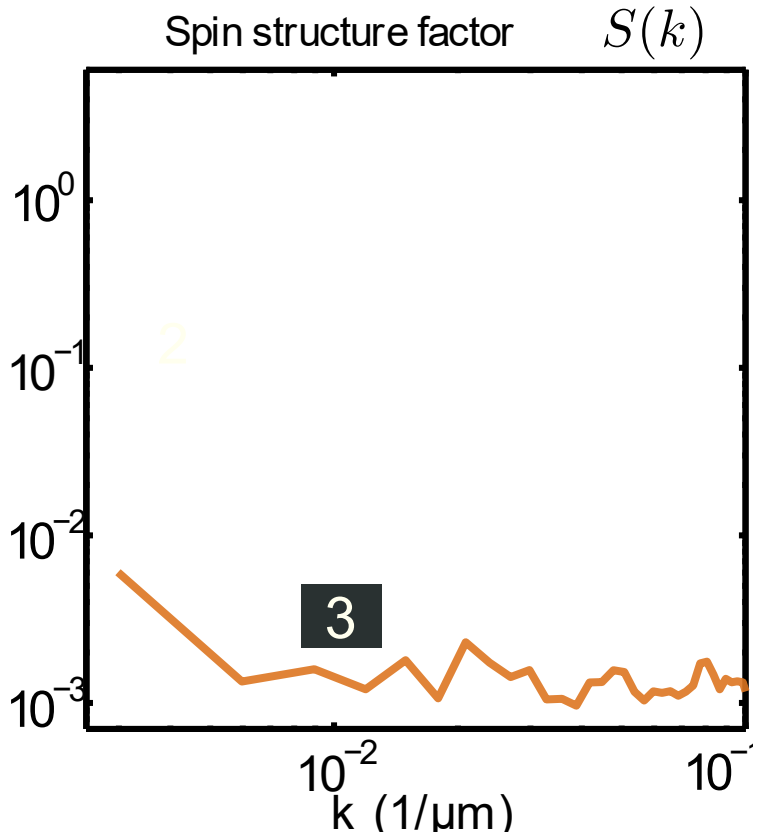
How can we test the robustness?

$$\alpha \approx 0.1$$
$$\beta \approx 0.1$$

Erne, S. et al., Nature **563**, 225-229 (2018)

Robustness





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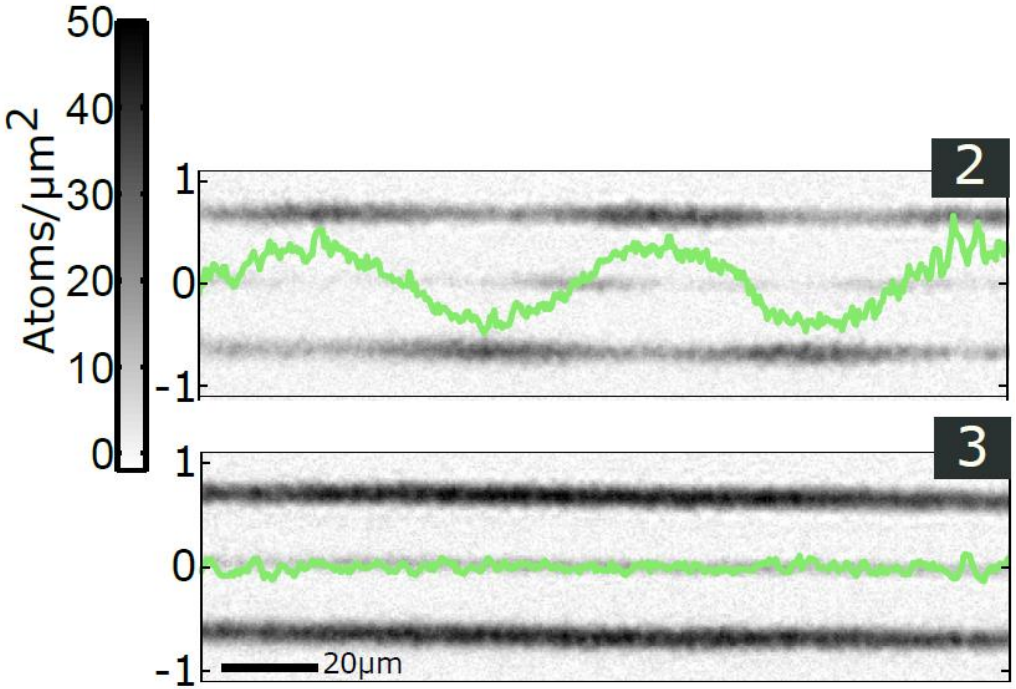
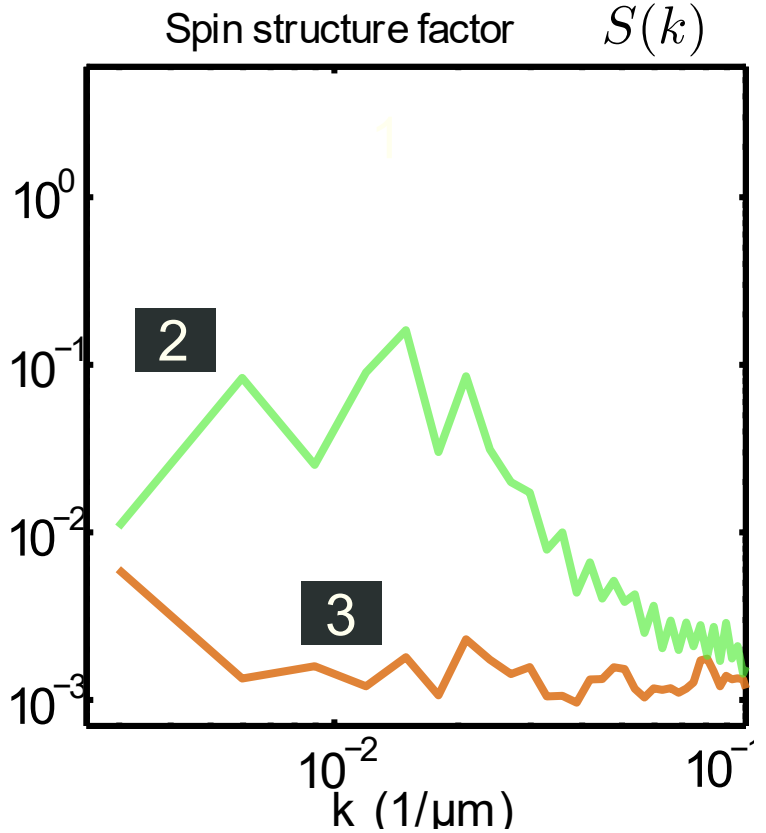
Robustness





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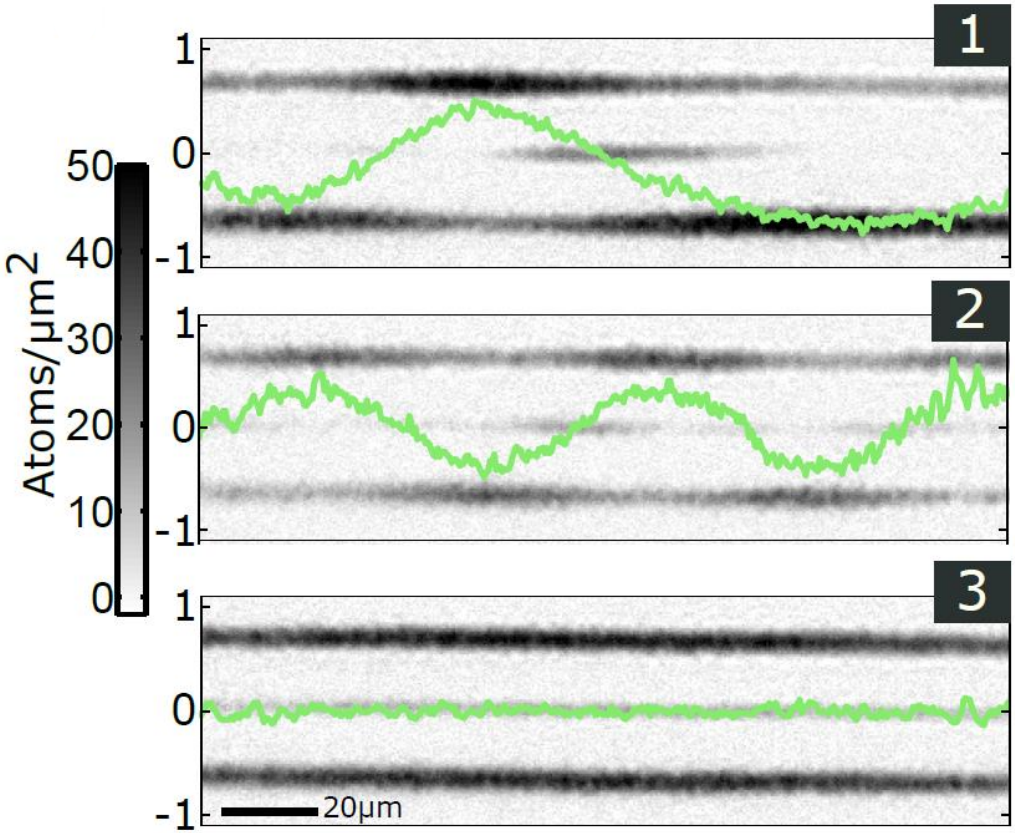

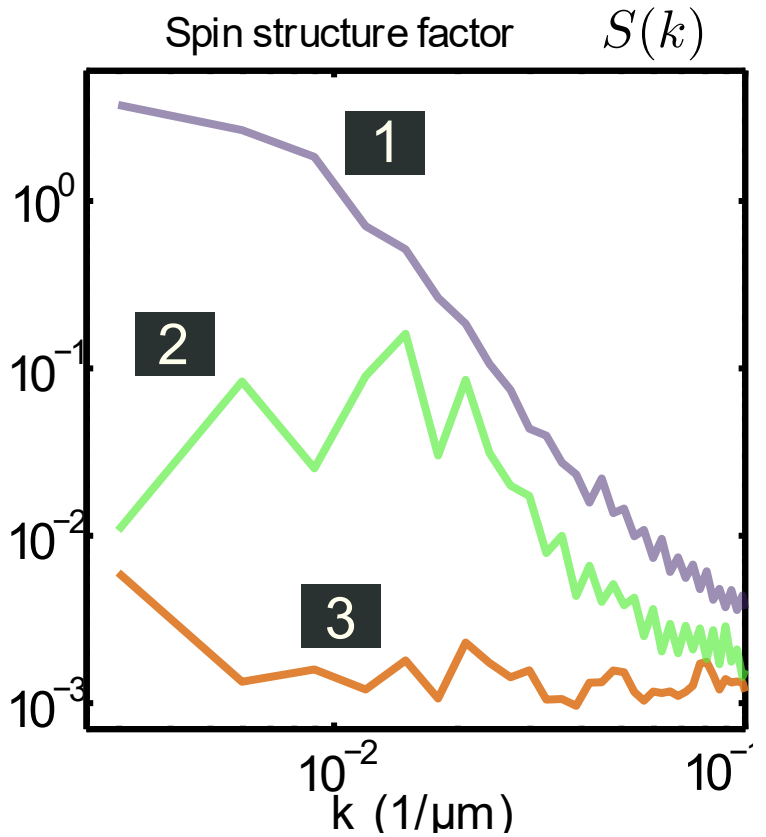

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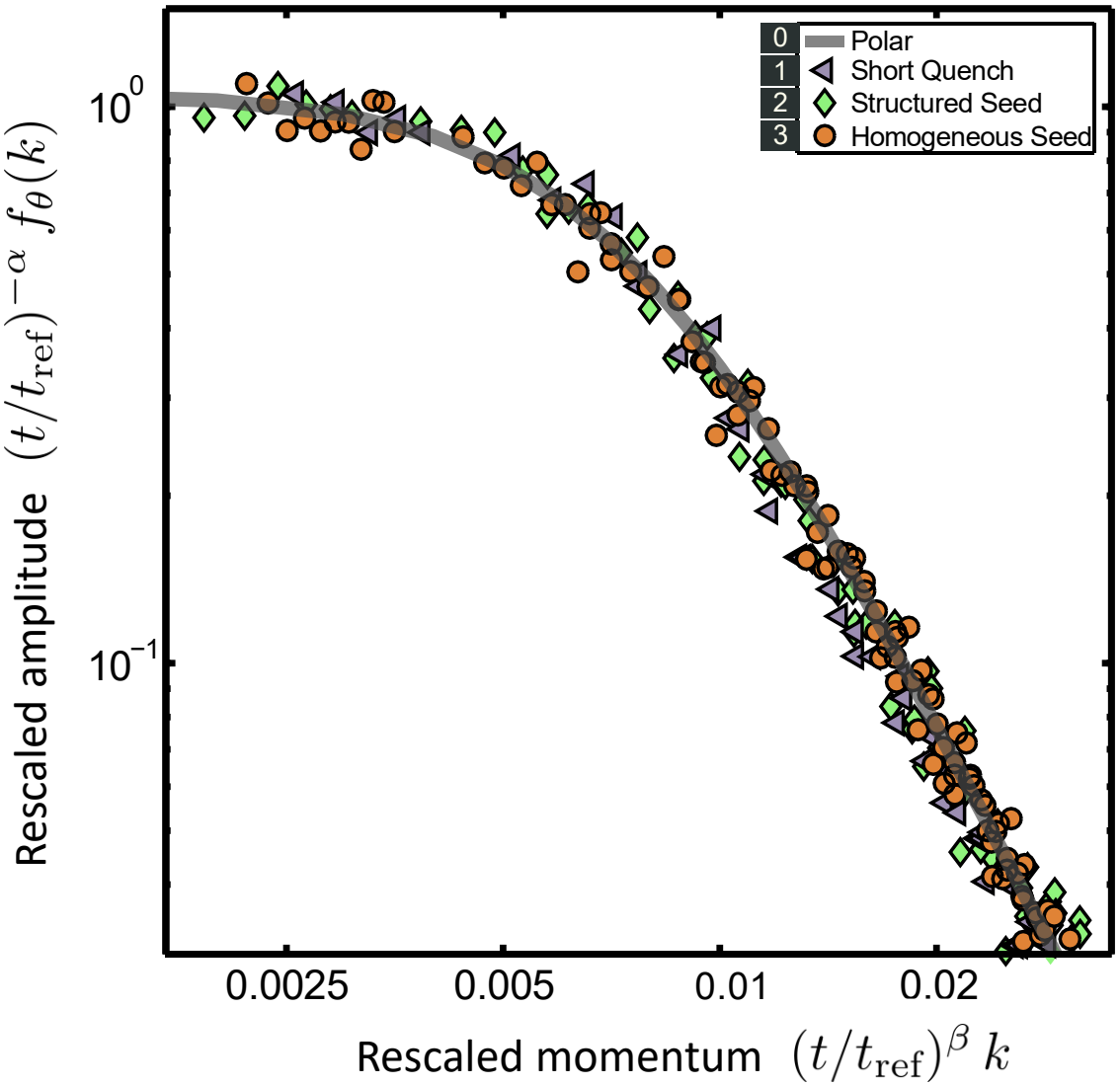
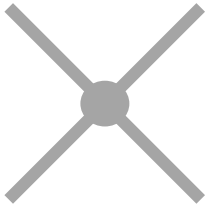
Robustness


0 Polar
1 Short Quench
2 Structured Seed
3 Homogeneous Seed
10^0
10^{-1}
Rescaled amplitude $(t/t_{\mathrm{ref}})^{-\alpha}\ f_\theta(k)$
0.0025
0.005
0.01
0.02
Rescaled momentum $(t/t_{\mathrm{ref}})^{\beta}\ k$

Outlook

- Higher order correlation functions $\langle\theta(y)\theta(y')\theta(y'')\theta(y''')\rangle$

  Extract couplings of effective field theory describing the system



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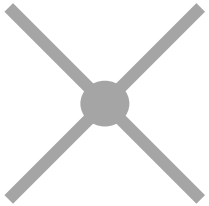
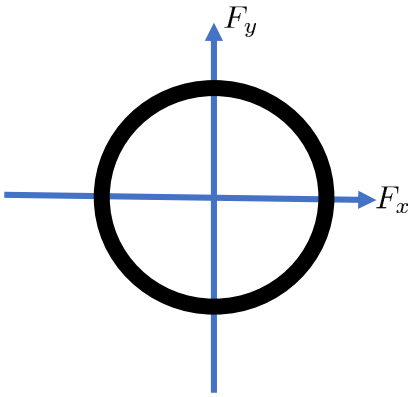


- Role of defects for universal dynamics



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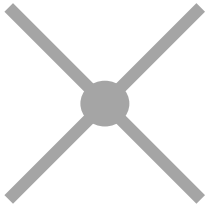

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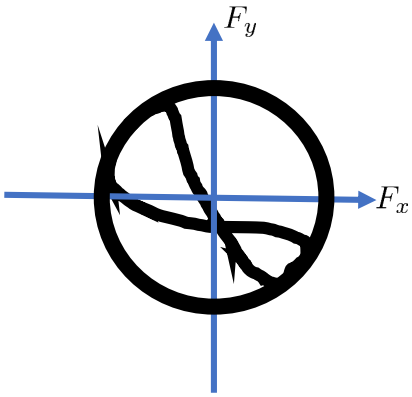

Outlook

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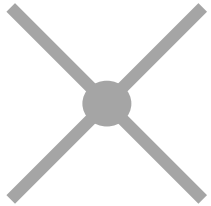
  Extract couplings of effective field theory describing the system



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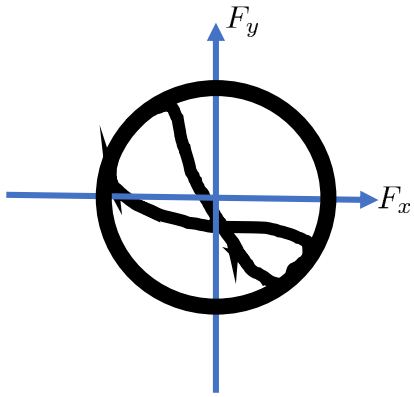
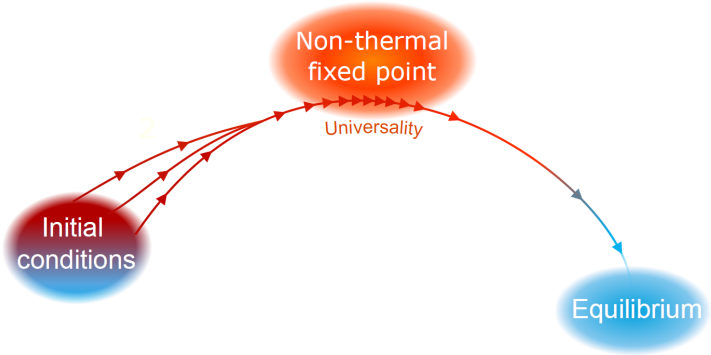
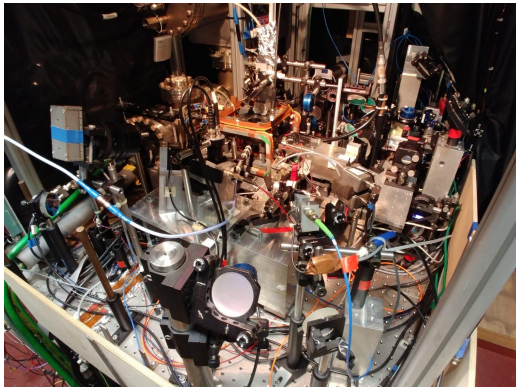
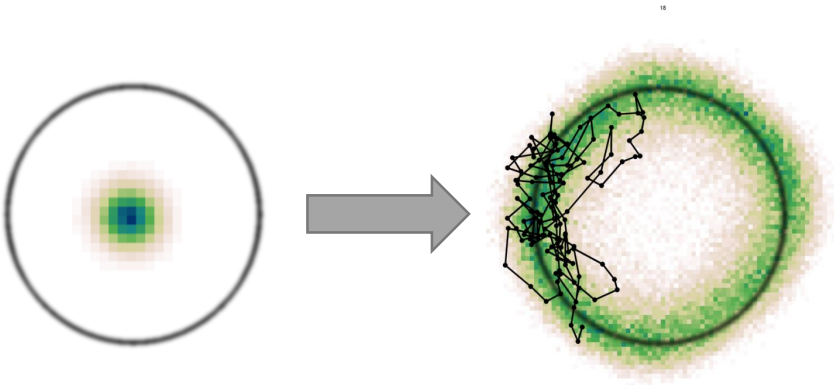


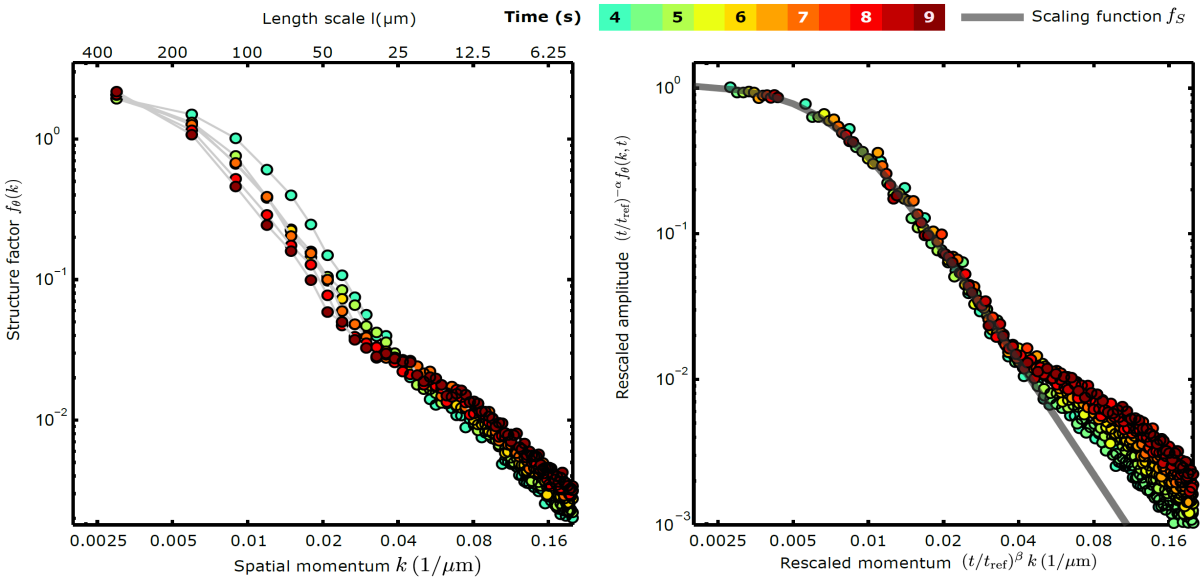
- Thermalisation of spinor gases as isolated quantum systems

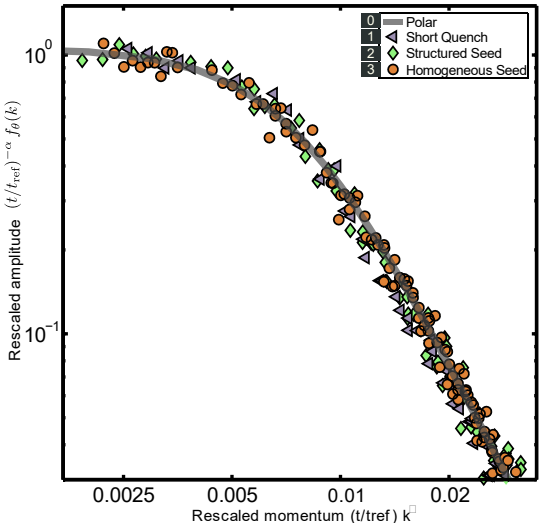


Summary









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Maximilian Prüfer