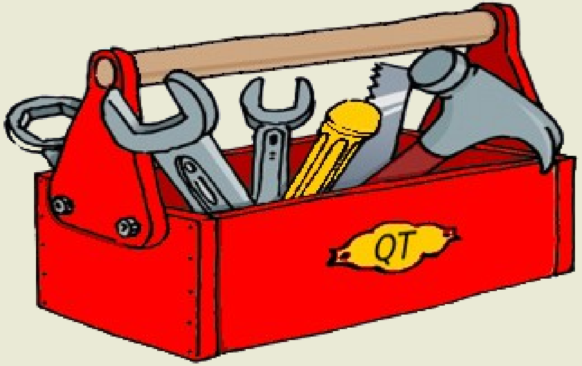
Department of Physics
Clarendon Laboratory

Quantum impurities as probes of complex quantum systems

Jordi Mur-Petit
Clarendon Laboratory
University of Oxford

Outline

- **Quantum gases and Quantum technologies**
- Quantum impurities
- Quantum Thermodynamics
- QFRs 4 GGEs



From Q. gases to Q. simulators…

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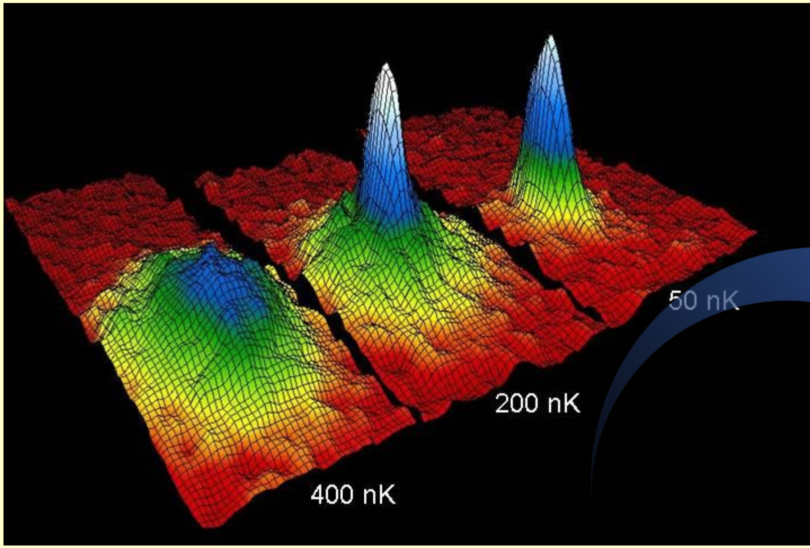
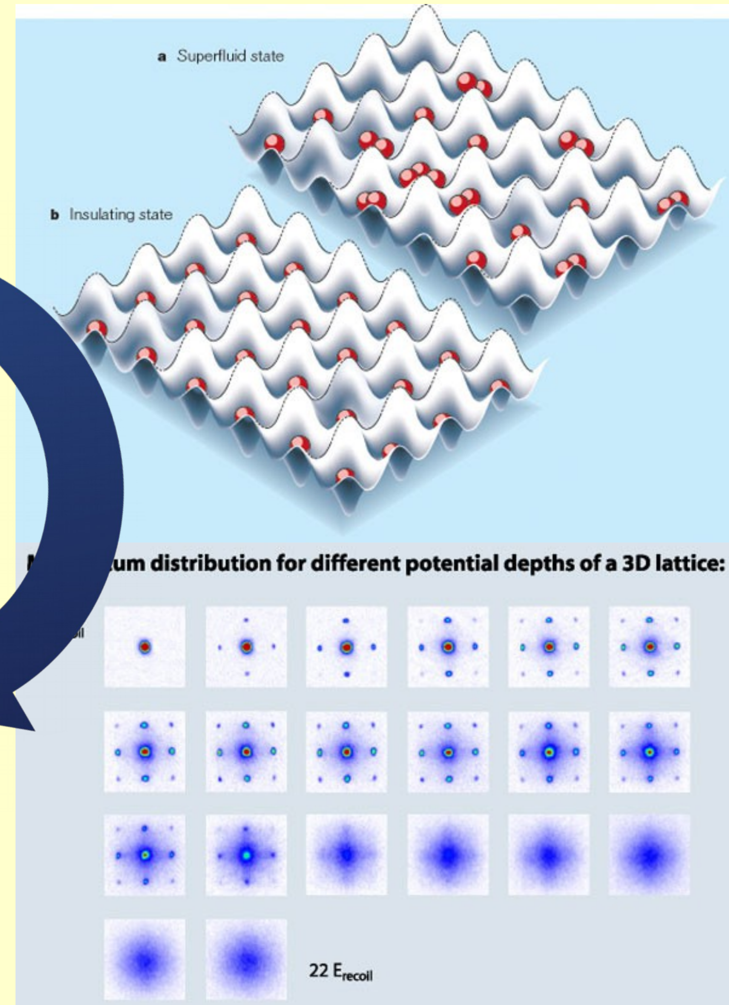
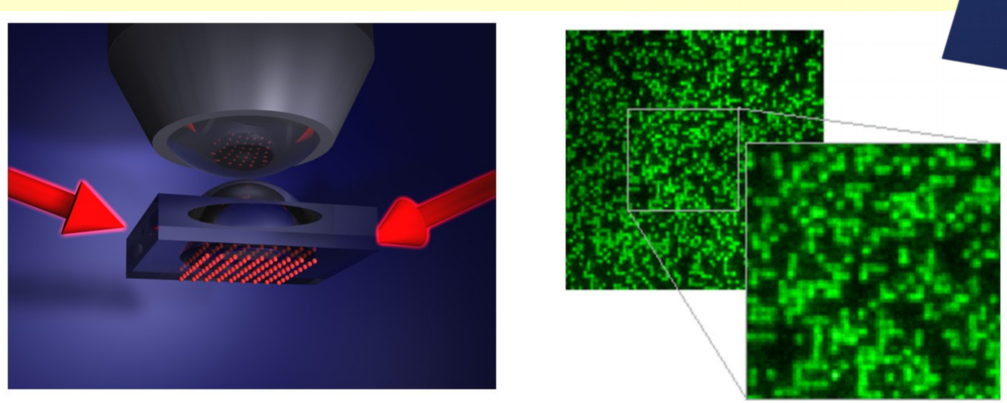
BEC, JILA 1995



SF-MI transition, Munich 2002



Q. gas microscope, MIT 2009



Quantum technologies

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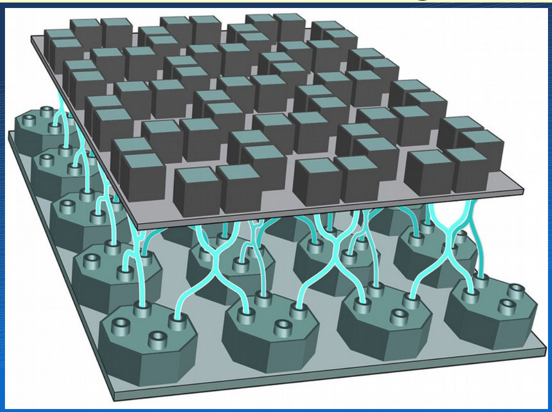
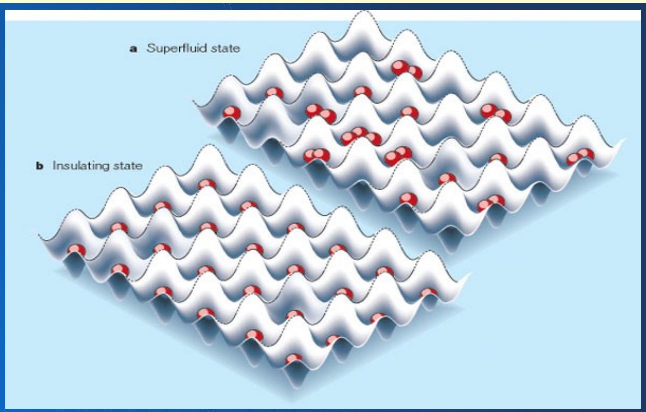
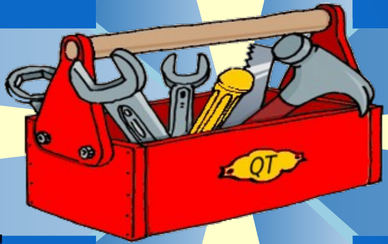
Q. computing

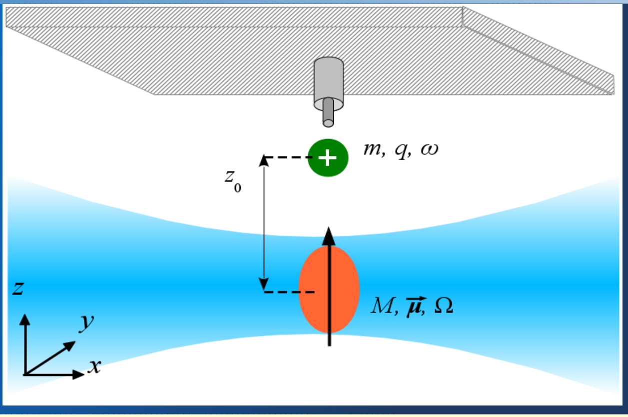


Q. simulation





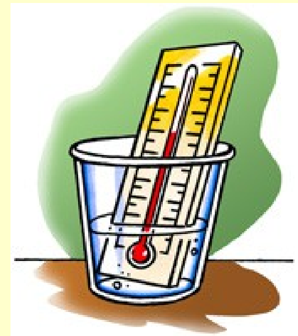
Q. communications



Q. sensing & metrology

Measuring the quantum way

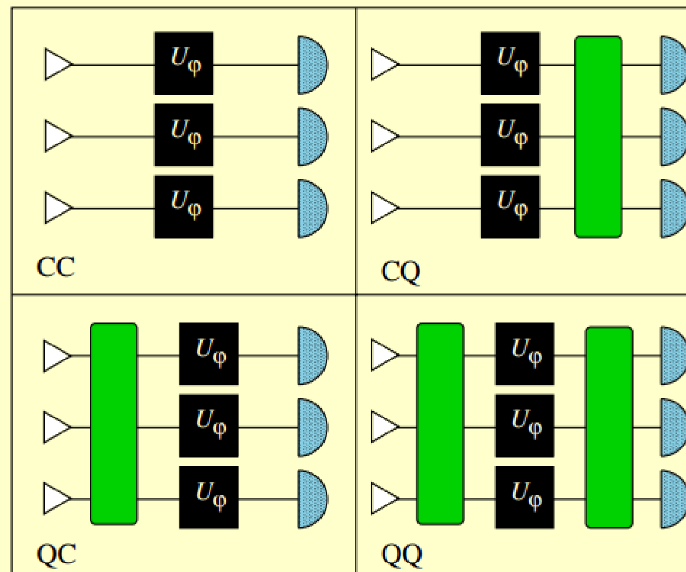
How do we measure something?



1. Prepare a probe
2. Probe to interact with system
3. Read probe

Quantum Metrology

- “quantum effects enable an increase in precision when estimating a parameter”
- Uncertainty scales with no. probes *N* as 1/*N* **[QC,QQ]** vs. 1/sqrt(*N*) **[CC,CQ]**
- Goal: ‘ultimate’ precision limit
- *Giovannetti et al., PRL 2006, Nat. Photon. 2011*



Measuring the quantum way

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How do we measure something?

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Quantum Metrology

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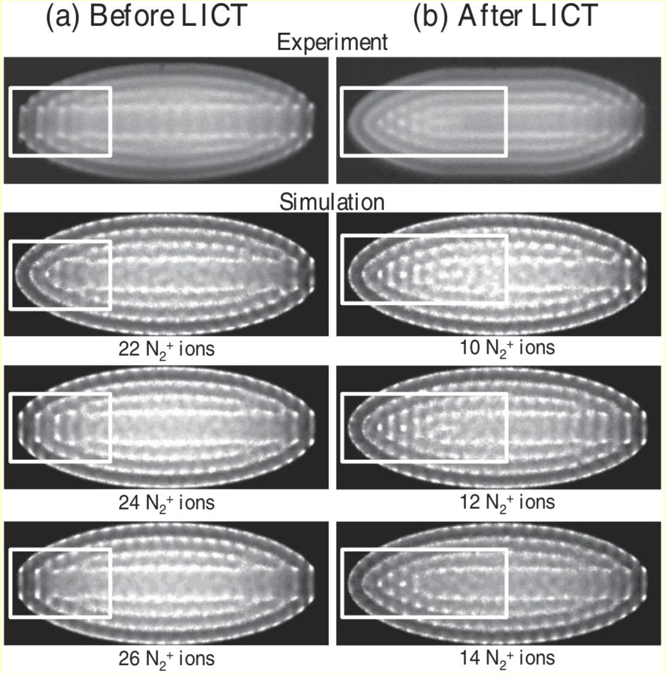
Quantum Sensing

- Quantum systems can be very sensitive to external fields
- Harness increased control & measurement capabilities on them to measure with enhanced accuracy
- Goal: improve precision

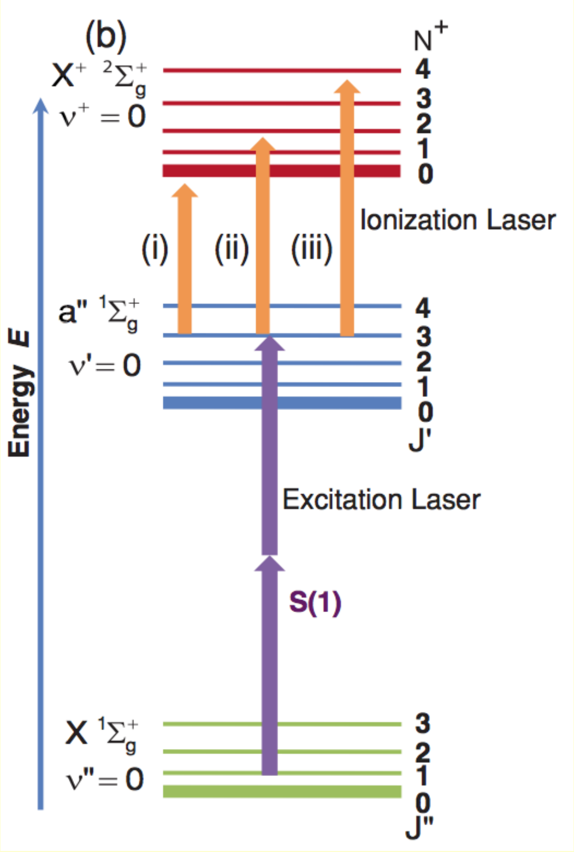
Q. logic molecular spectroscopy

The Challenge: Willitsch lab, 2010

- N2+ in ground vib-rot state, |*v=0,N*=0>
- State identification by LICT – ***destructive***



X. Tong et al., PRL (2010)



Q. logic molecular spectroscopy

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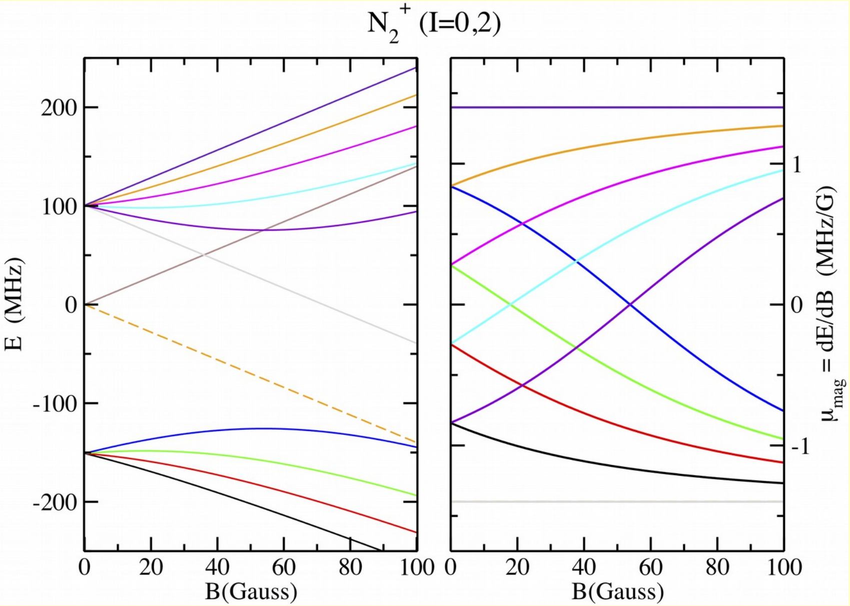
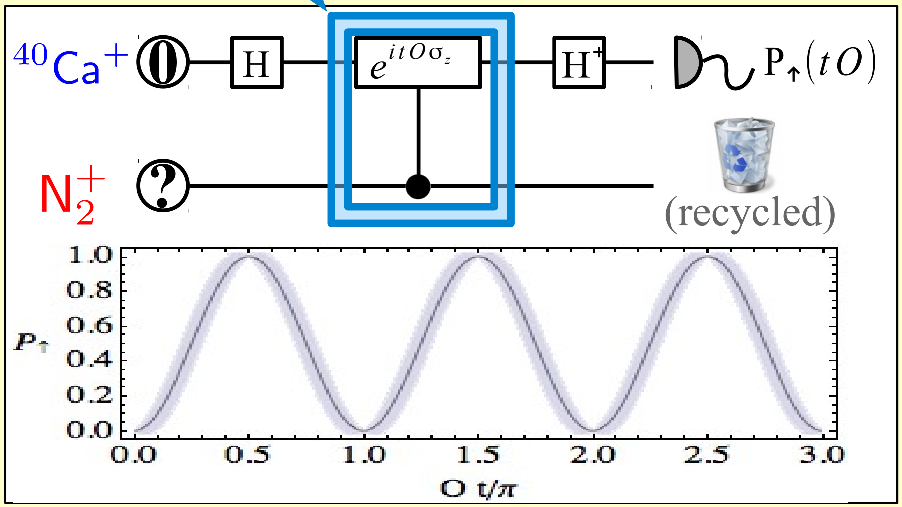
The Team: QI + Molec. Phys. + Basel:

- Molecular hf structure N_2^+
- Q. logic spectroscopy
- State-dependent forces & phase gates

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
Uni Basel
MARIE CURIE ACTIONS

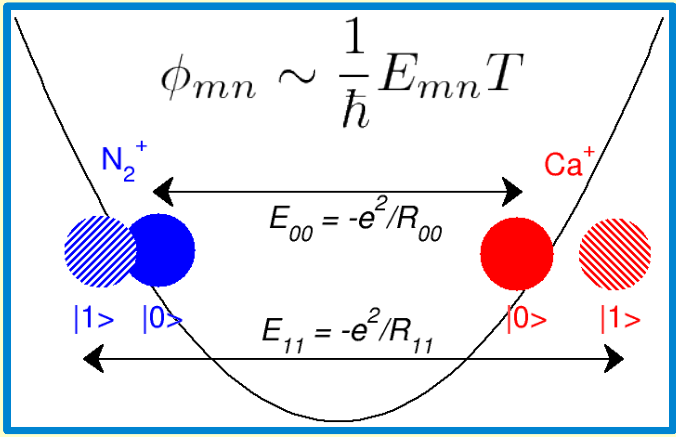




J. Mur-Petit et al., PRA 85, 022308 (2012)

A new spectroscopy protocol

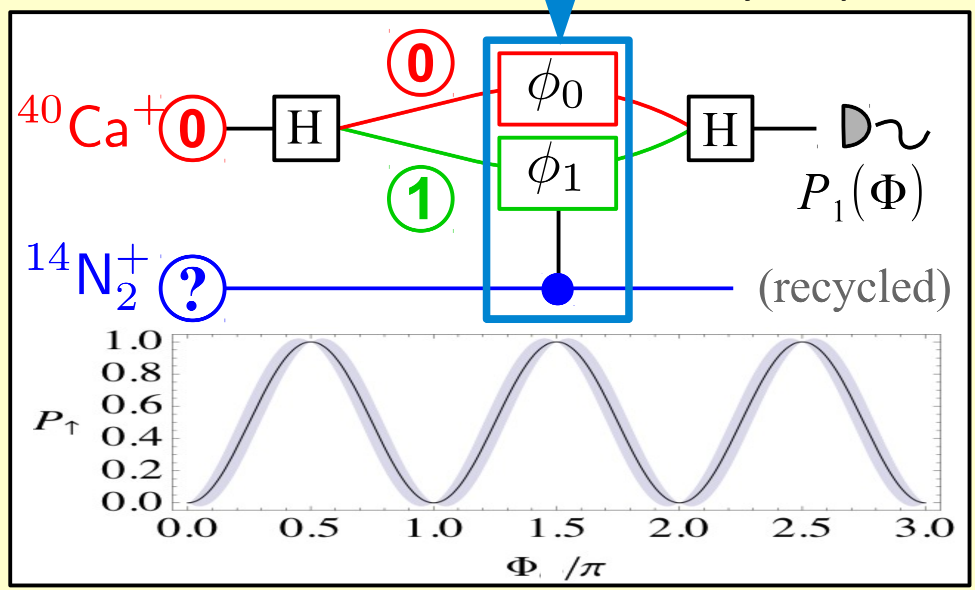
Q. Logic Spectroscopy + State-dependent forces
= a *non-destructive* measurement protocol



State-dependent forces lead to state-dependent phases ϕ_{mn}

$\phi_{mn}(f_{Ca}, f_N)$

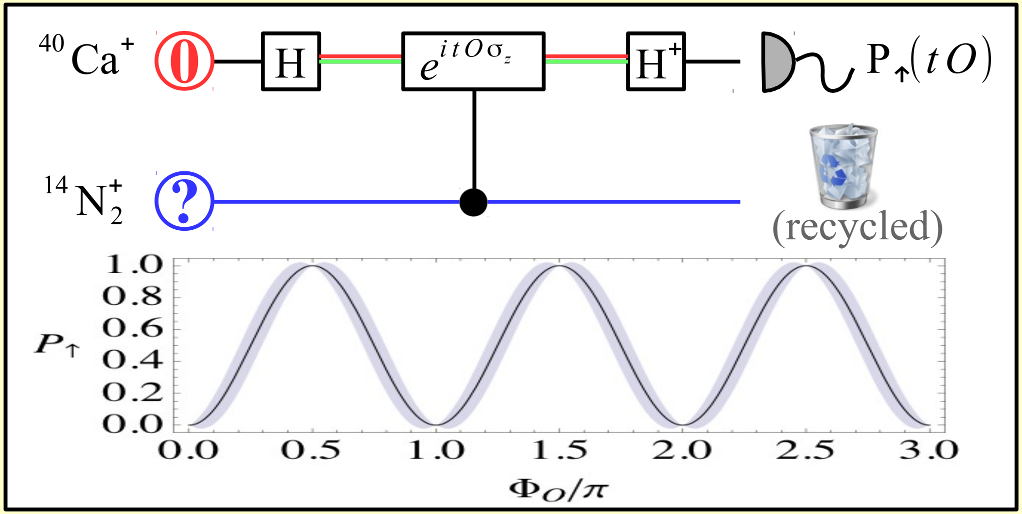
Ramsey sequence



J. Mur-Petit et al., PRA 85, 022308 (2012)

How-to: Zeeman spectroscopy

Spectroscopy protocol + Structure calculations



Measure $P_\uparrow$

$O=\mu$

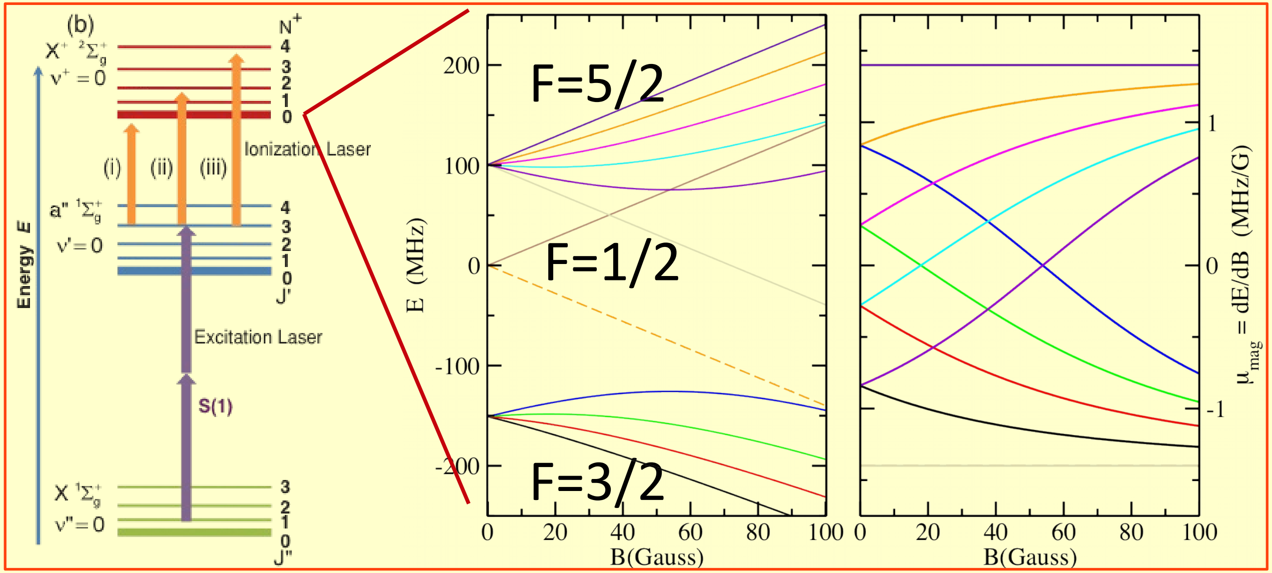
Obtain phase Φ_O

$\Phi_O=\Phi_O(f1,f2)$

Deduce μ_{mag}

Structure calcs.

Know your quantum state



PRA **85** 022308 (2012)

Q. logic molecular spectroscopy

LETTERS
PUBLISHED ONLINE: 21 SEPTEMBER 2014 | DOI: 10.1038/NPHYS3085
nature physics

Observation of electric-dipole-forbidden infrared transitions in cold molecular ions

Matthias Germann[1], Xin Tong[1,2] and Stefan Willitsch[1*]

doi:10.1038/nature16513

Non-destructive state detection for quantum logic spectroscopy of molecular ions

Fabian Wolf[1], Yong Wan[1†], Jan C. Heip[1], Florian Gebert[1], Chunyan Shi[1] & Piet O. Schmidt[1,2]

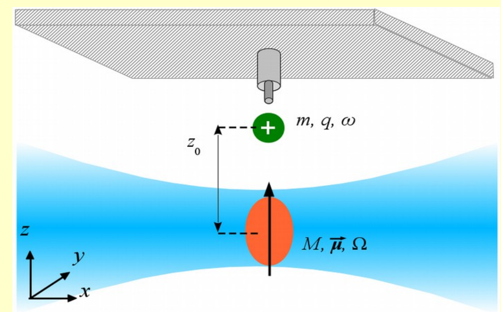
Q. sensing protocol extended:

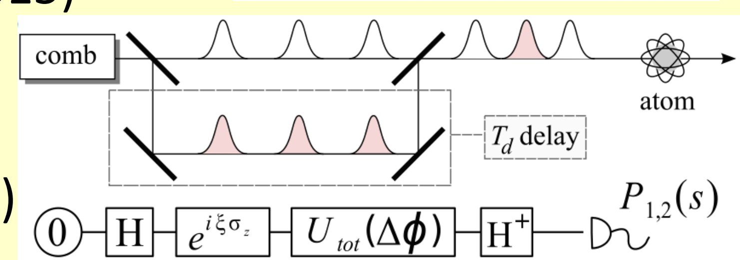
- molecular EDMs

  JMP & JJ Garcia-Ripoll, APB (2014), PRA (2015)

- frequency comb CEP stabilization

  A. Cadarso, JMP, JJ Garcia-Ripoll, PRL (2014)





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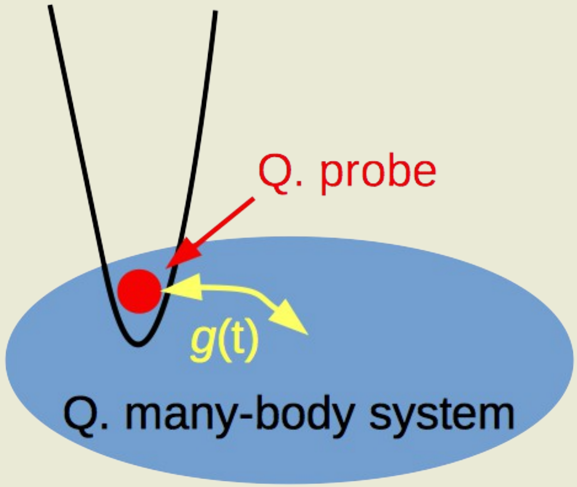
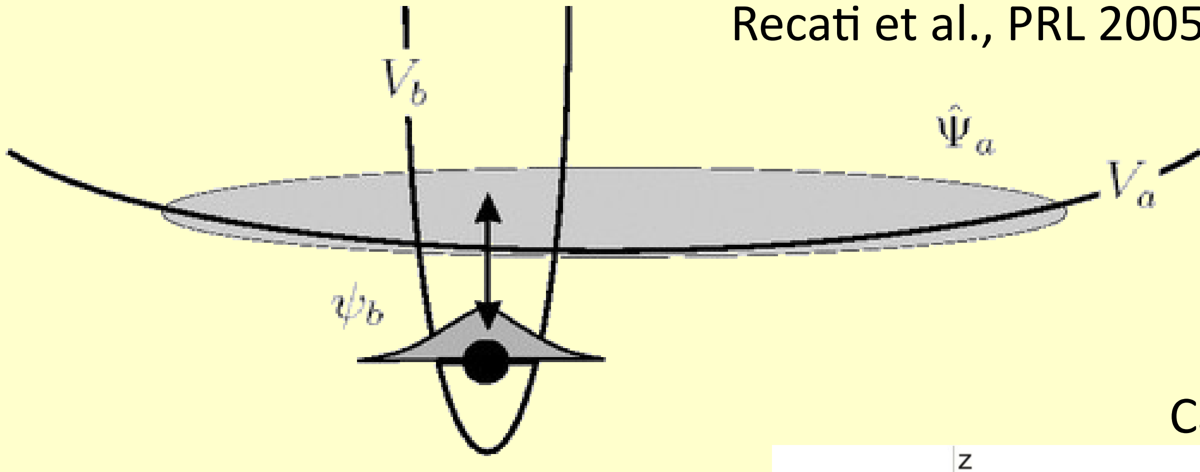
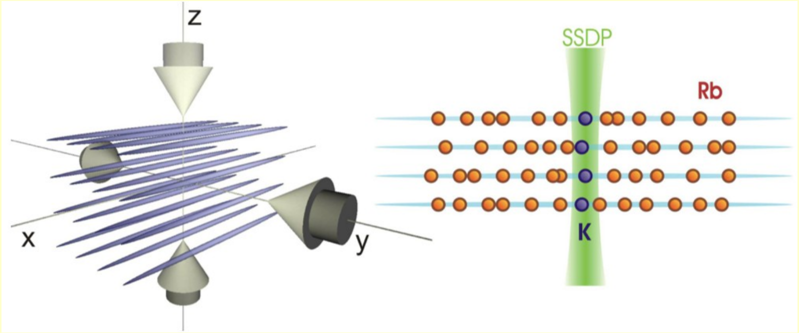


Quantum impurities

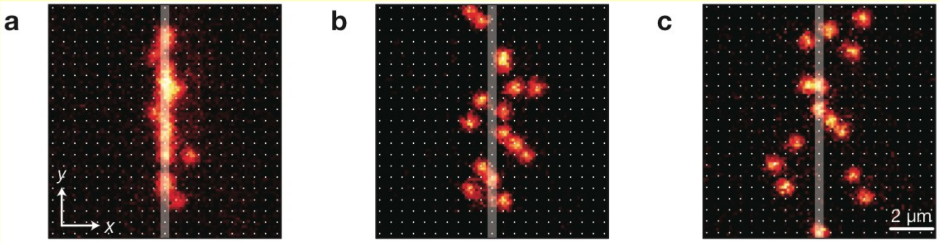


Recati et al., PRL 2005

Catani et al., 2012



Fukuhara et al., 2013



Impurity in quantum system

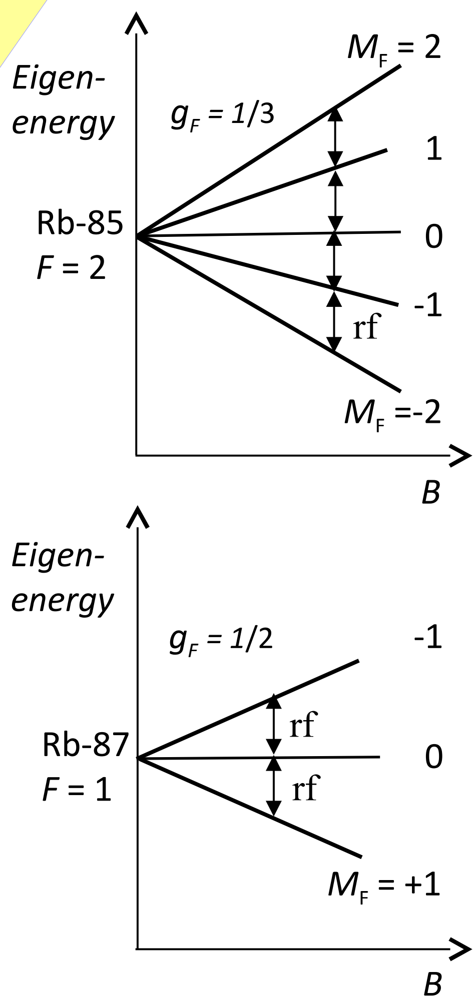
- Spin-boson model

- Polaron problem

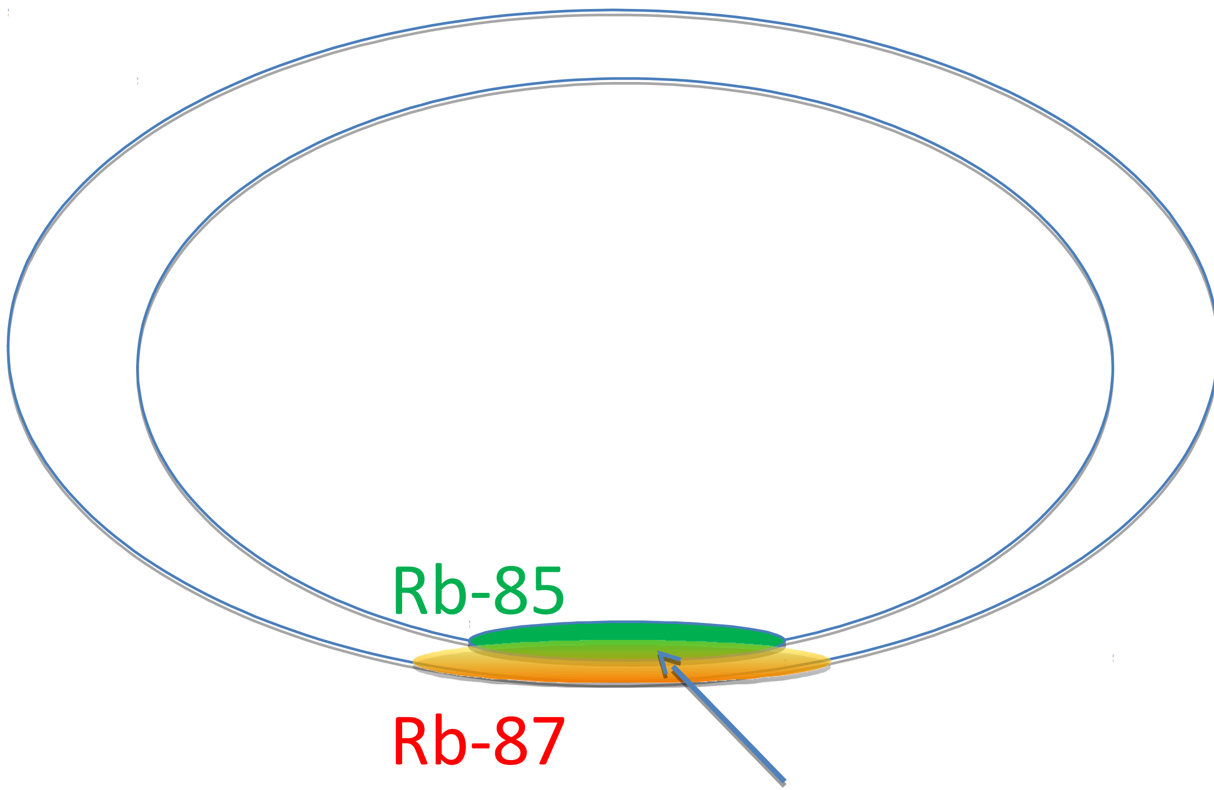
- ...

Species-specific trapping

Slide courtesy of Chris Foot



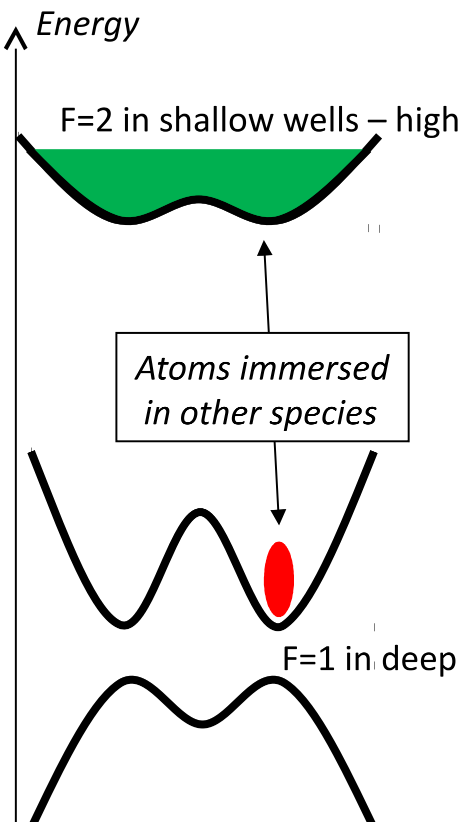
Two isotopes Rb-87 and Rb-85



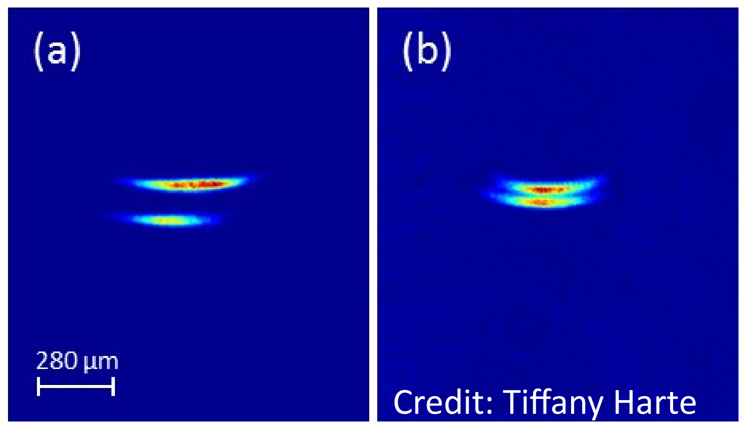
Control overlap of the clouds

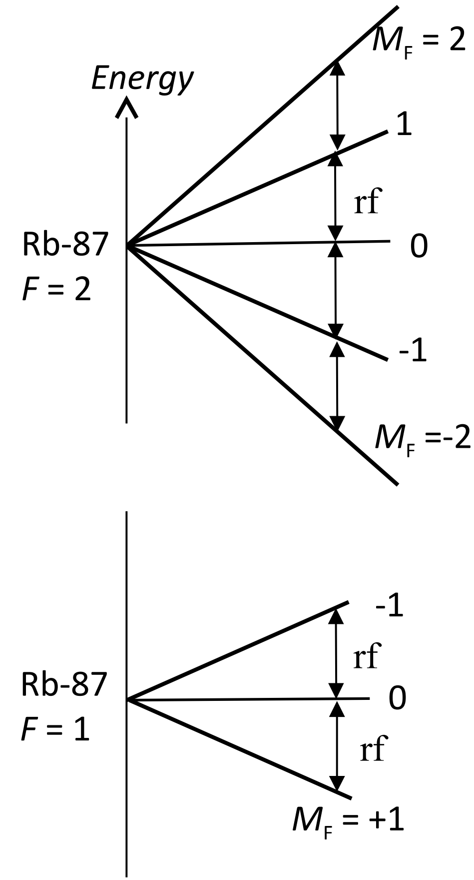
Slide courtesy of Chris Foot

Expts with Rb-87 only



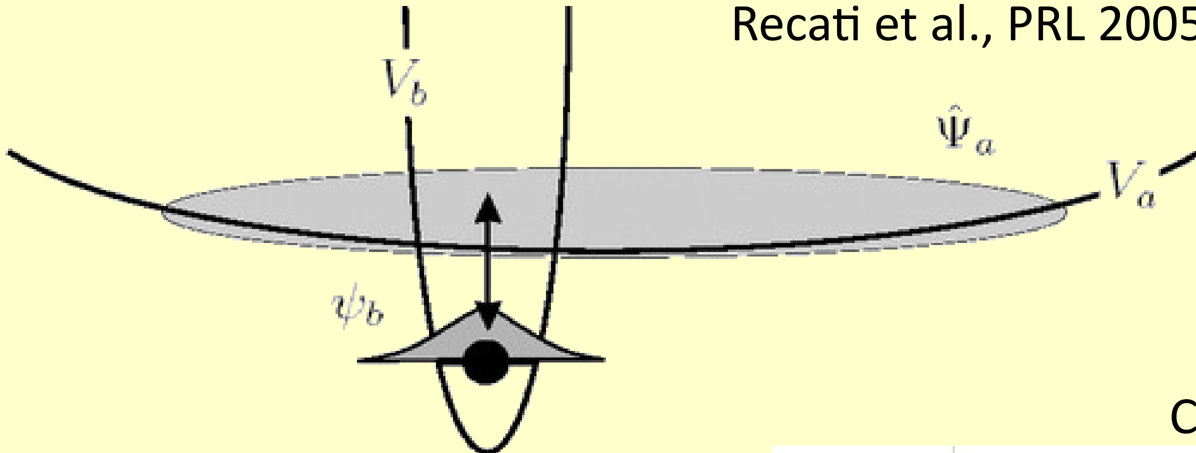
Double well potential formed by the dressed-atom Adiabatic Potential





Eigenenergies of a Rb-87 atom

Quantum impurities



Recati et al., PRL 2005

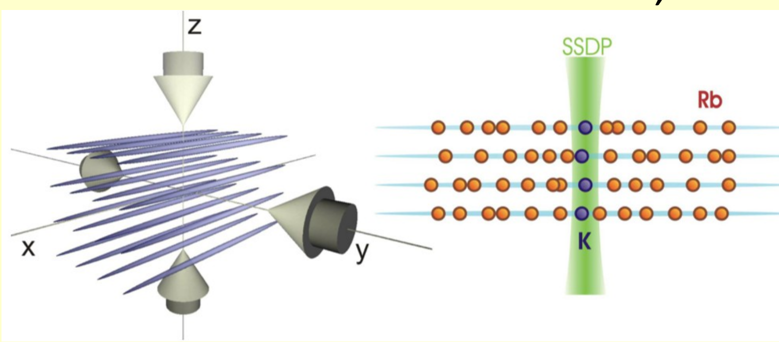
Impurity in quantum system

- Spin-boson model

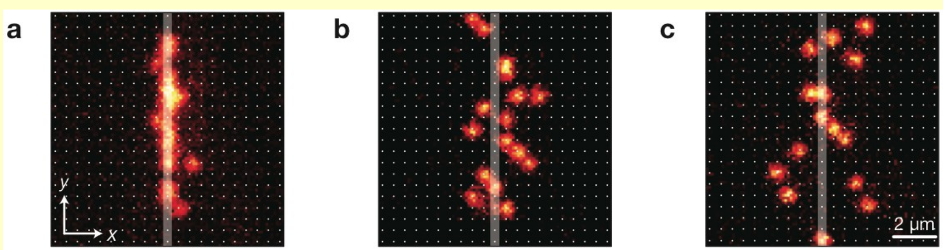
- 'Polaron' problem

- Quantum probe

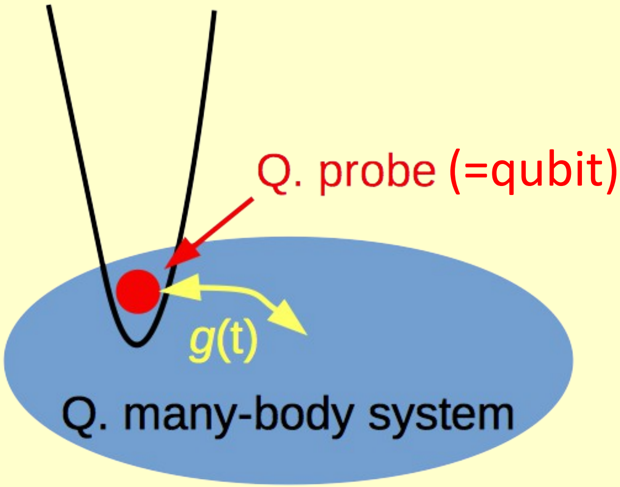
Catani et al., 2012

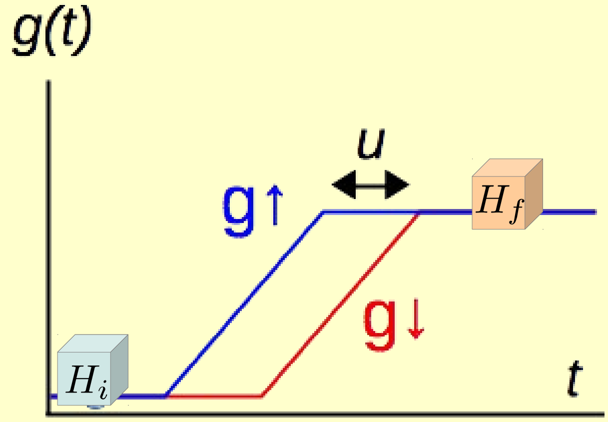


Fukuhara et al., 2013



Q. Probing 1: Work statistics





$$H_{int} = (g_{\uparrow}(t)|\uparrow\rangle\langle\uparrow| + g_{\downarrow}(t)|\downarrow\rangle\langle\downarrow|) \otimes V$$

$$\rho(t=0) = |q\rangle\langle q| \otimes \rho_{\beta}\,, \quad \rho_{\beta} = e^{-\beta H}/Z$$

Dorner *et al.*, PRL 110, 230601 (2013); Mazzola *et al.*, *ibid.* 230602 (2013)

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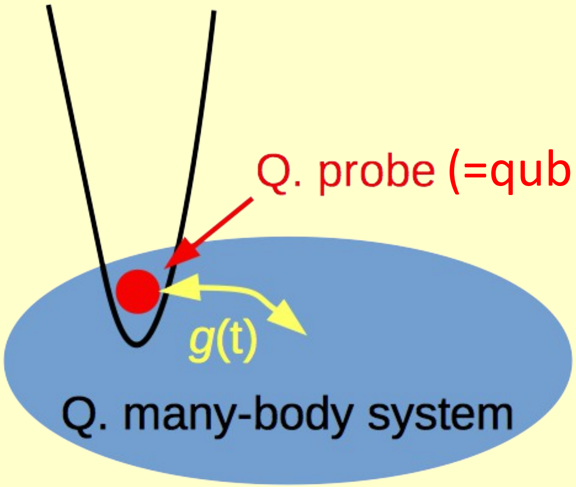
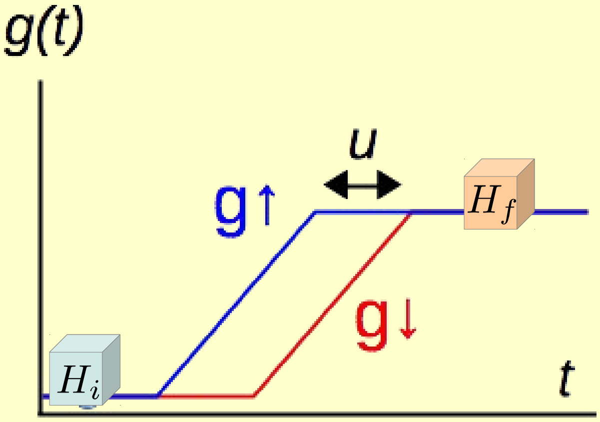




$$H_{int} = (g_{\uparrow}(t)|\uparrow\rangle\langle\uparrow| + g_{\downarrow}(t)|\downarrow\rangle\langle\downarrow|) \otimes V$$

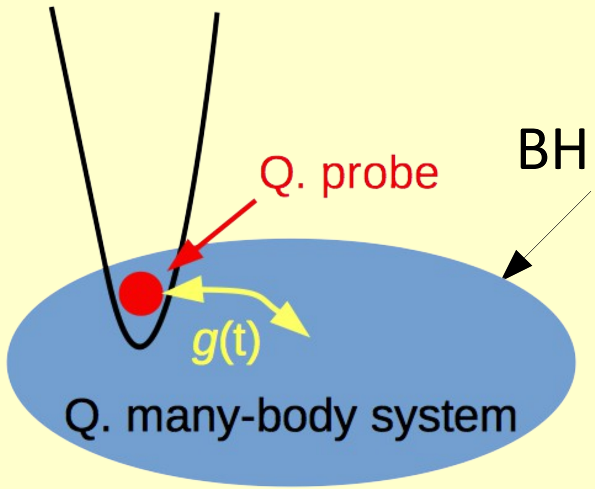
$$\rho(t=0) = |q\rangle\langle q| \otimes \rho_\beta\,, \quad \rho_\beta = e^{-\beta H}/Z$$

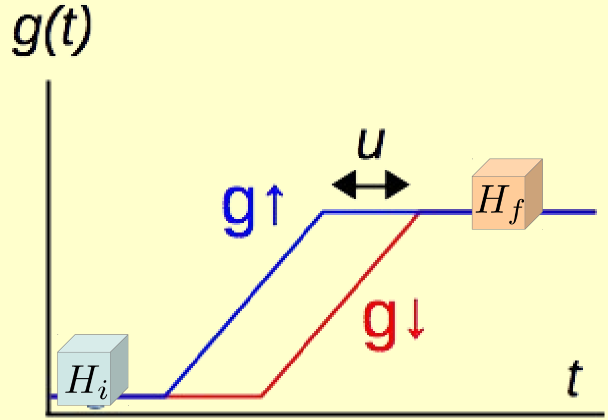
$$\langle\uparrow|\rho_q(t=t_f)|\downarrow\rangle \propto \mathcal{F}[P(w|\beta)]$$

$$P(w|\beta) := PDF[w = \text{work done to system}|\beta]$$

Dorner *et al.*, PRL 110, 230601 (2013); Mazzola *et al.*, *ibid.* 230602 (2013)

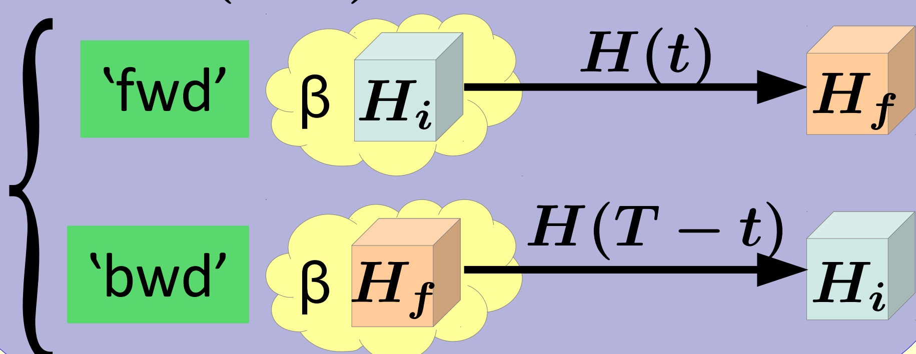
Q. Probing 2: Thermometry

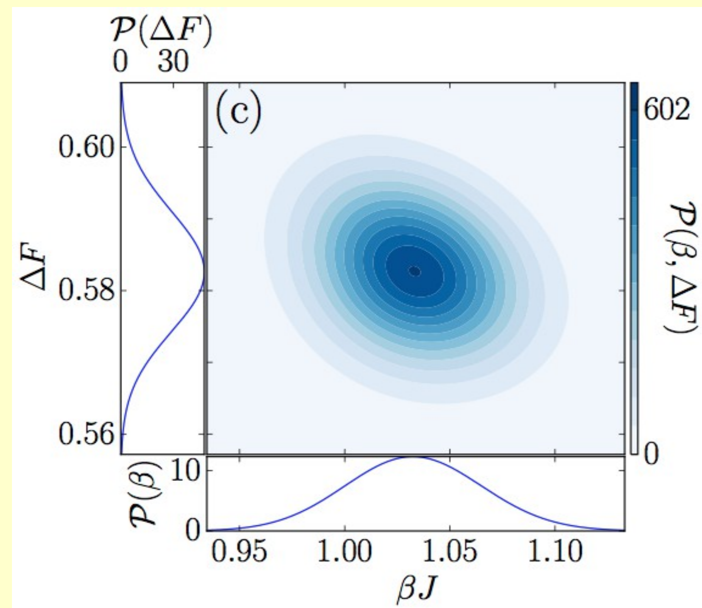




Tasaki-Crooks relation (TCR)

$$\frac{P_f(w)}{P_b(-w)} = e^{\beta(w-\Delta F)}$$

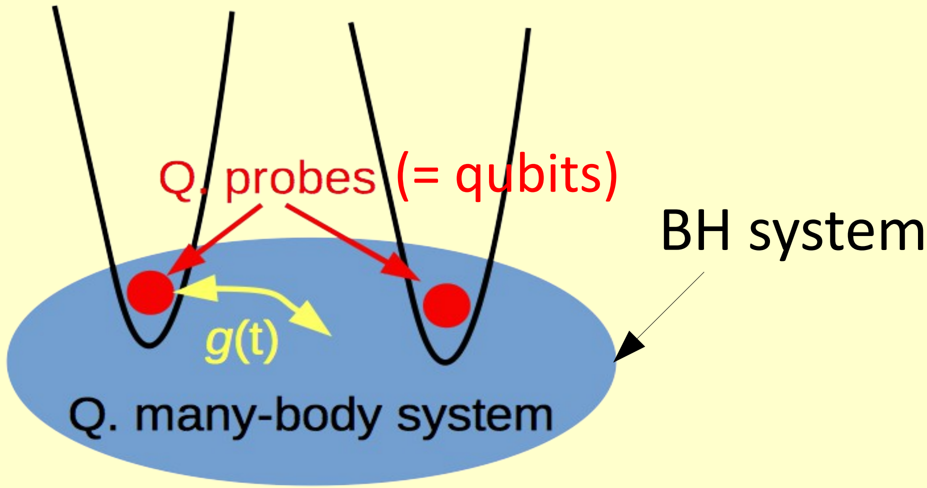


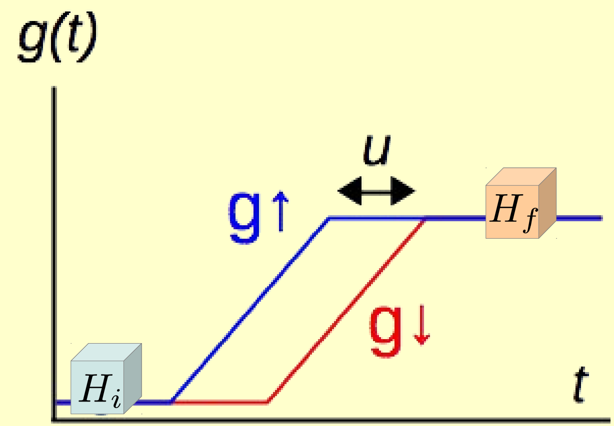


TH Johnson et al., PRA (2016)

Q. Probing 3: Correlations

M. Streif, D. Jaksch, JMP, in preparation





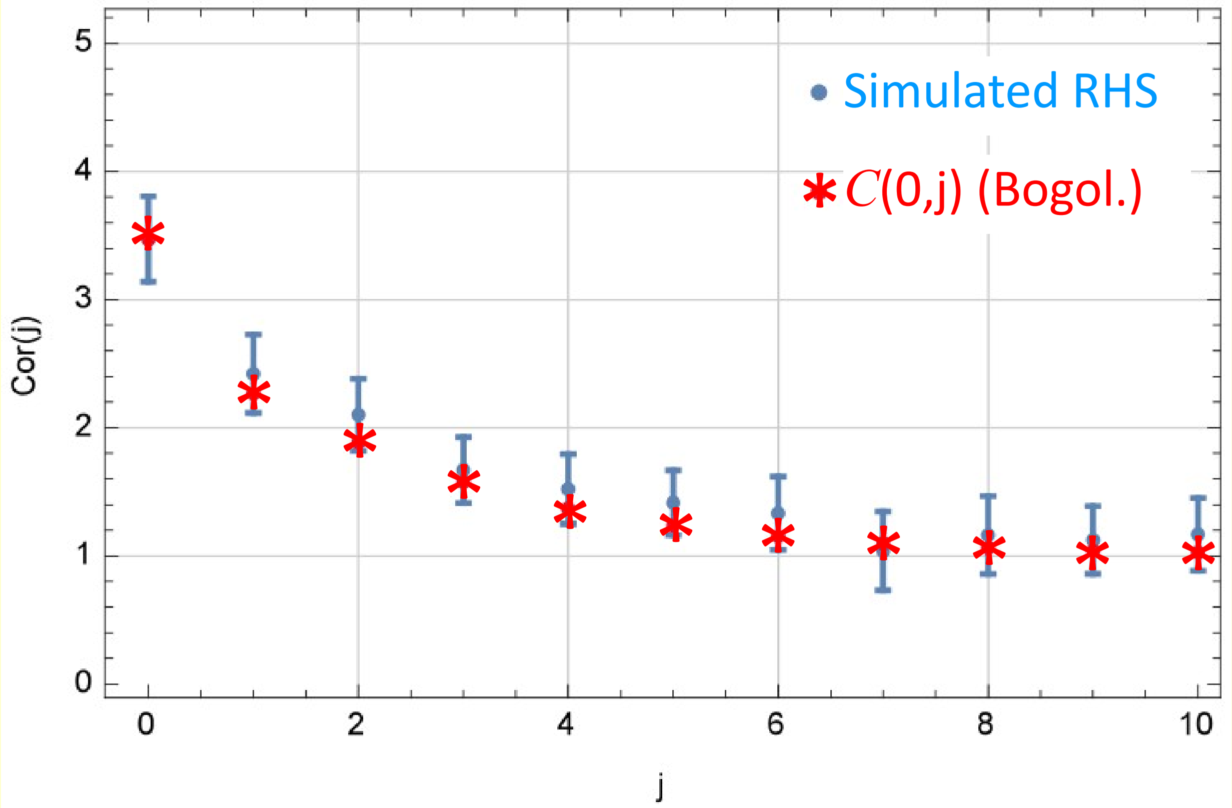
$$\rho(t=0) = |\Psi_+\rangle\langle\Psi_+| \otimes \rho_\beta$$

$$C(i,j) := \langle n(ia) n(ja) \rangle \qquad \chi(u) \equiv \langle \uparrow\uparrow | \rho_{2q} | \downarrow\downarrow \rangle$$

$$C(0,j) \equiv \frac{2}{g_1 + g_2} \left[\left. \frac{d^2 \chi(u;j)}{du^2} \right|_{u=0} - \left. \frac{d^2 \chi(u;0)}{du^2} \right|_{u=0} \right]$$

Correlations: Numerical results

M. Streif, D. Jaksch, JMP, in preparation



U/J=0.1

N=M=1000

*g*1=*g*2=0.5

β J=1

sims=100/j

$$C(0,j) \equiv \frac{2}{g_1+g_2}\left[\frac{d^2\chi(u;j)}{du^2}\bigg|_{u=0} - \frac{d^2\chi(u;0)}{du^2}\bigg|_{u=0}\right]$$

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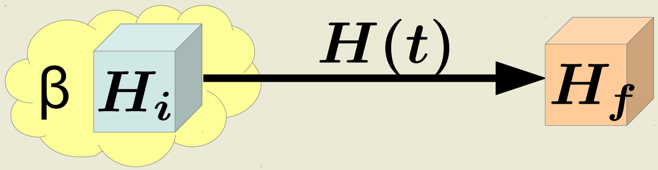


Q. Fluctuation Relations (QFRs)

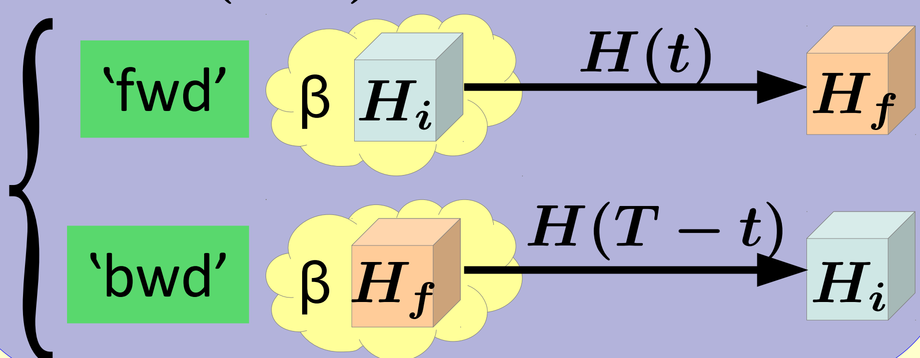
– Strict equalities vs. 'thermodynamic laws', e.g., $w \geq \Delta F$

– Derivation assumes initial state = canonical

$$\rho_\beta = \frac{e^{-\beta H}}{Z}$$

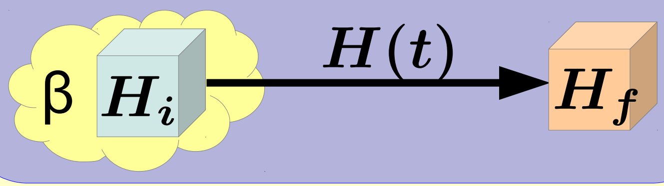
TCR: Tasaki-Crooks relation

$$\frac{P_f(w)}{P_b(-w)} = e^{\beta(w - \Delta F)}$$



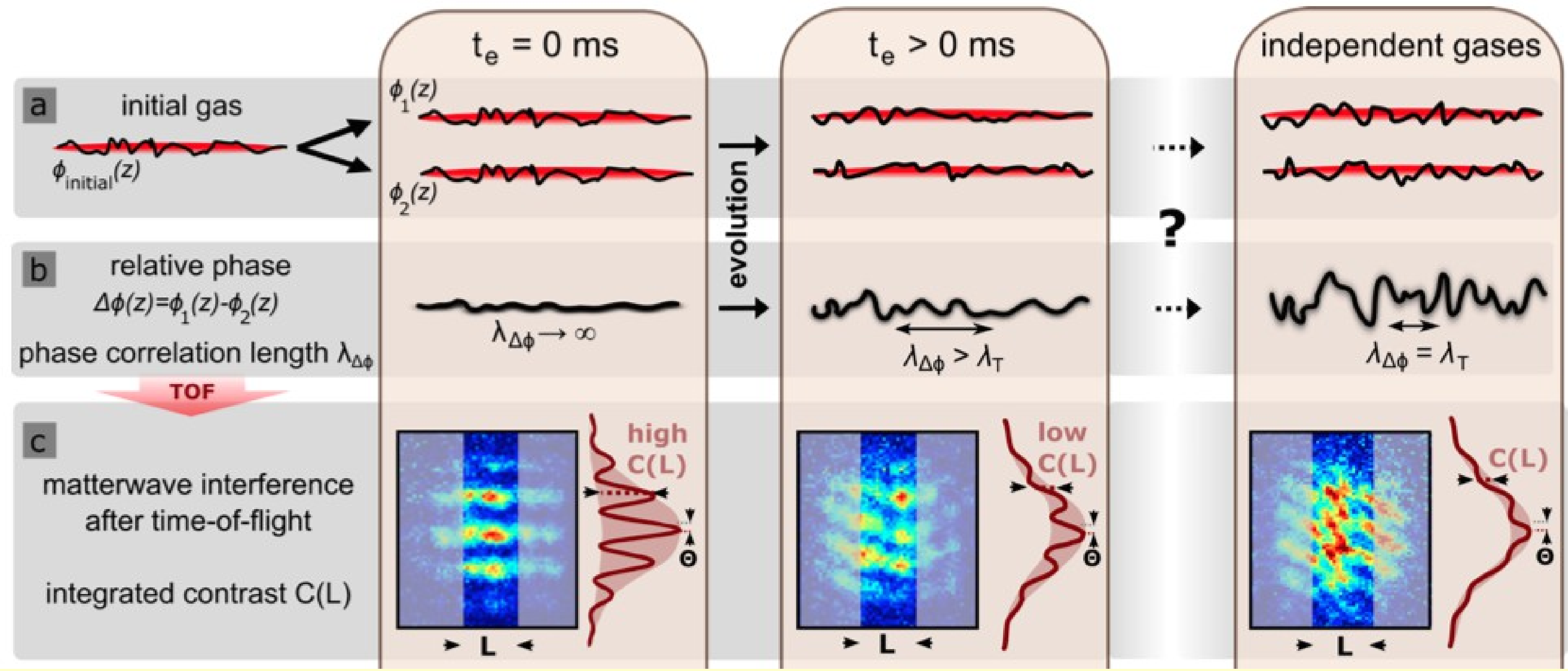
Q. Jarzynski equality

$$\langle e^{-\beta w} \rangle = e^{-\beta \Delta F}$$



A quench in 1D

Split a 1D gas quasi-adiabatically *[Schmiedmayer/Vienna, 2012]*



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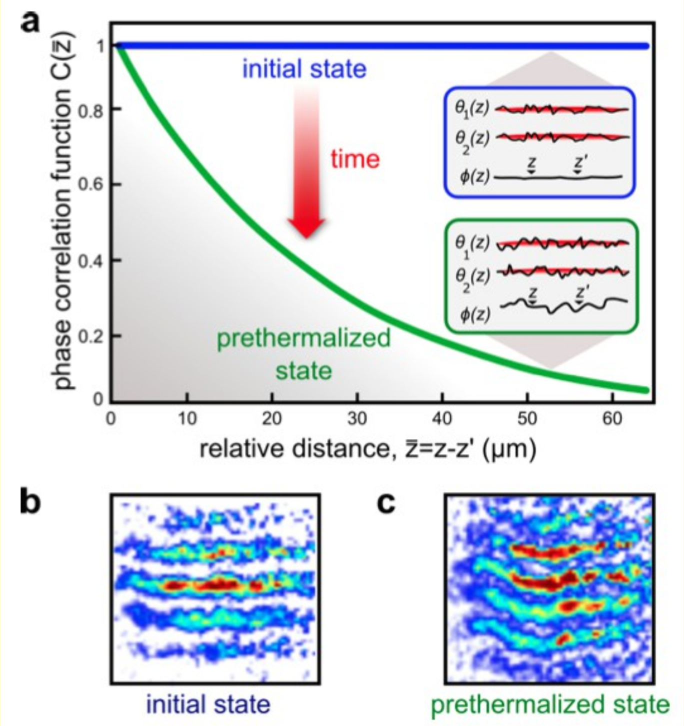
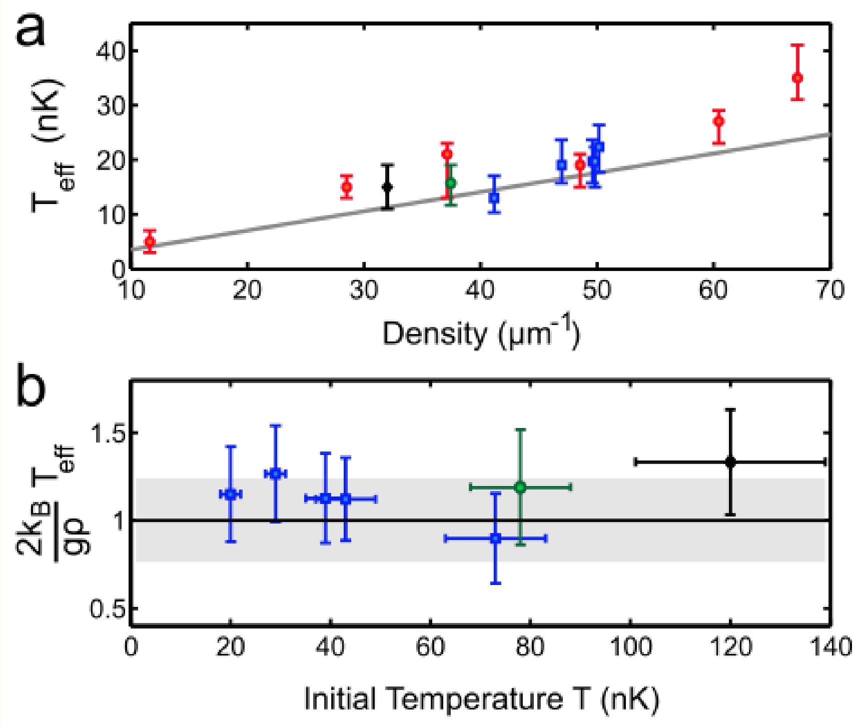




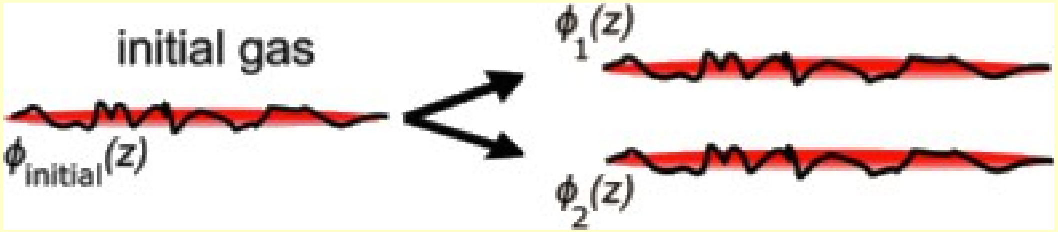
* Fit 2-point correlation functions -> Extract *T*eff
* Apparent thermalization with *T*eff independent of initial *T*!

Pre-thermalization

$$\rho = \exp\left(-\beta_{\text{eff}} E\right)/Z$$

Another quench of the 1D screw

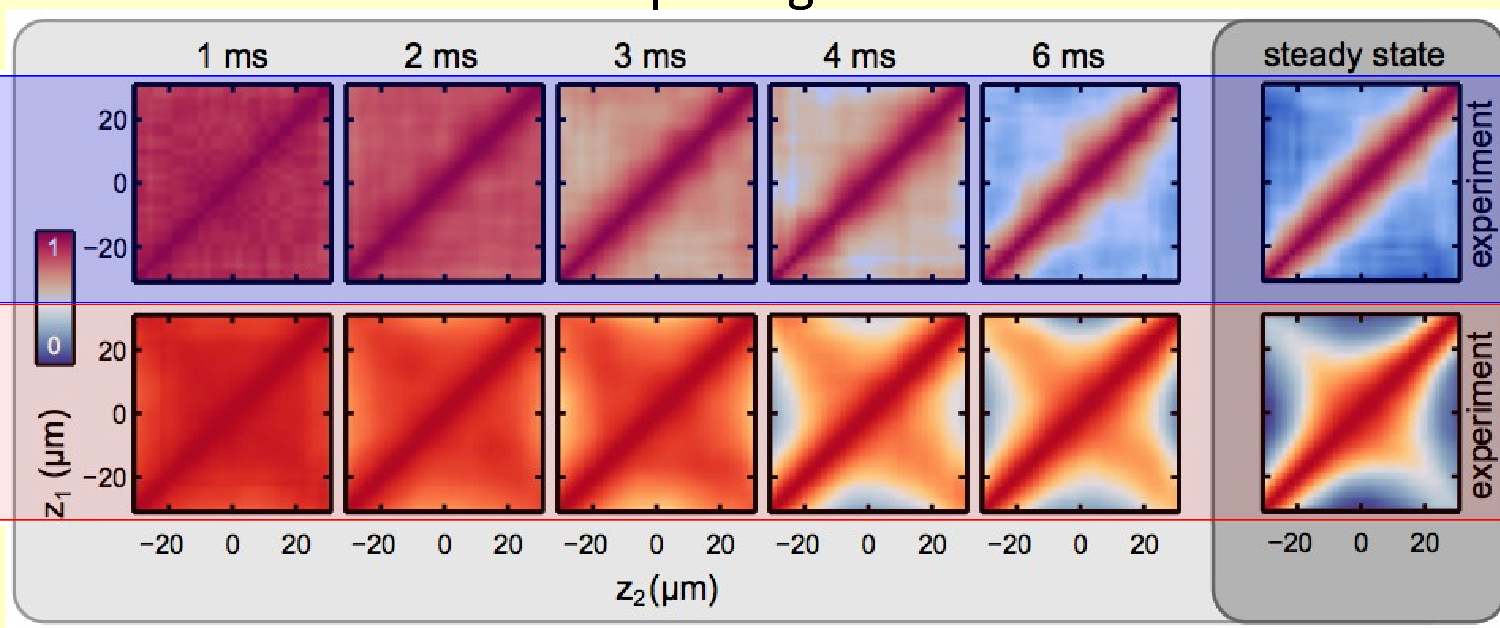
Split a 1D gas **non-**adiabatically *[Schmiedmayer/Vienna, **2015**]*



Two-point correlation function vs. splitting rate:

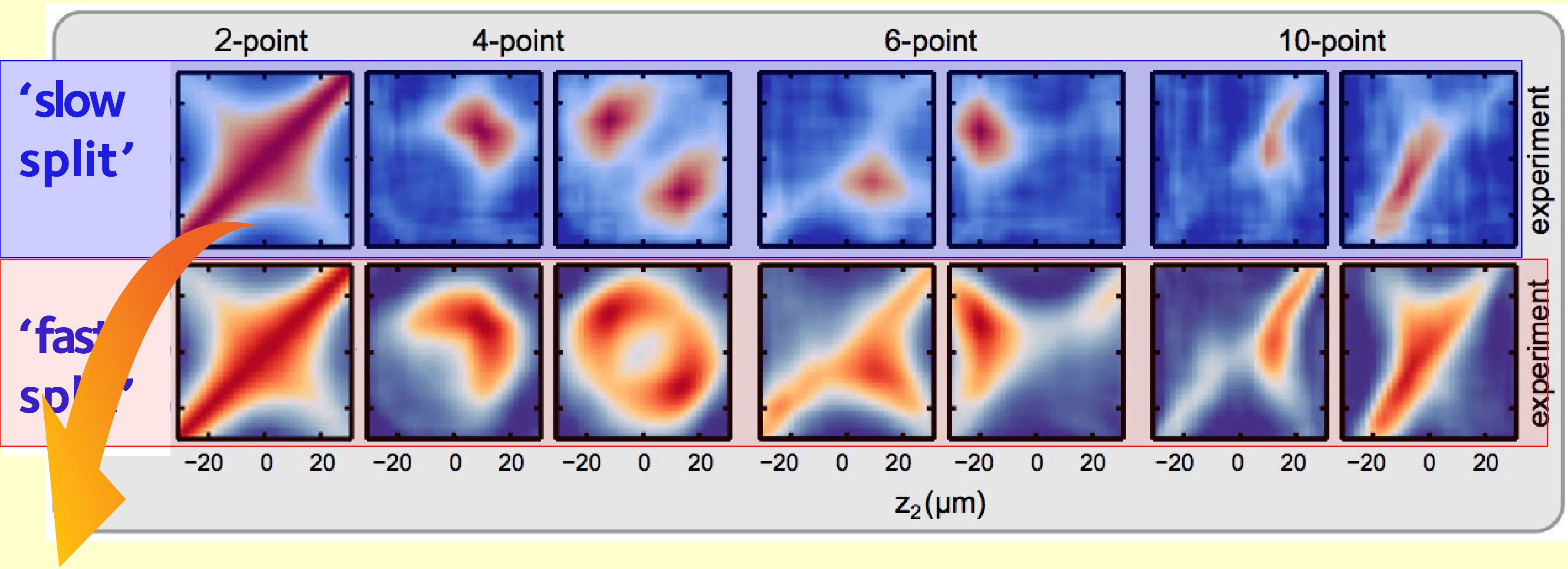
‘slow split’

‘fast split’



Another quench of the 1D screw

$$C(z_1, \ldots, z_N) = \langle \Psi_1(z_1)\Psi_2^\dagger(z_1)\Psi_1^\dagger(z_N)\Psi_2(z_N)\rangle$$



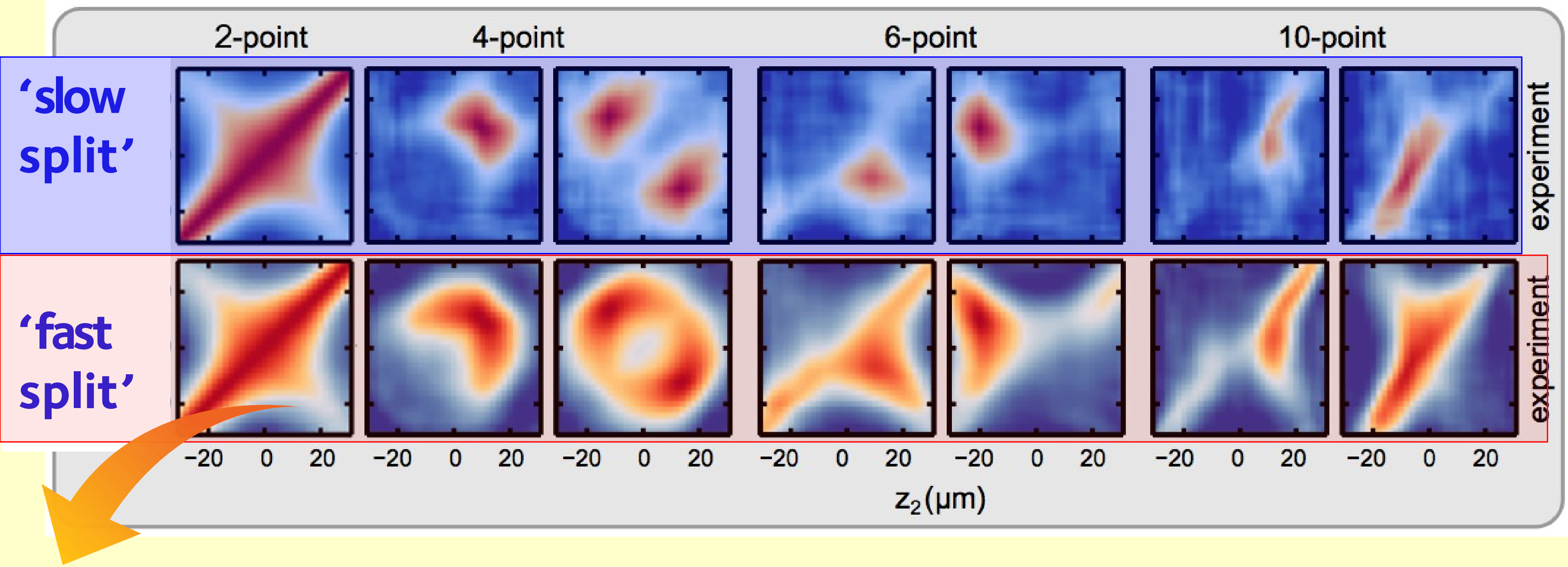
Slow split: Correlations well described with Gibbs distribution with... T_{eff} independent of initial T: Pre-thermalization

$$\rho = \exp\left(-\beta_{\text{eff}} H\right)/Z$$

Gring et al., Science 2012; Langen et al., Science 2015

Another quench of the 1D screw

$$C(z_1,\ldots,z_N) = \langle \Psi_1(z_1)\Psi_2^\dagger(z_1)\Psi_1^\dagger(z_N)\Psi_2(z_N)\rangle$$



Fast split: Need up to 10 different 'temperatures' to fit!

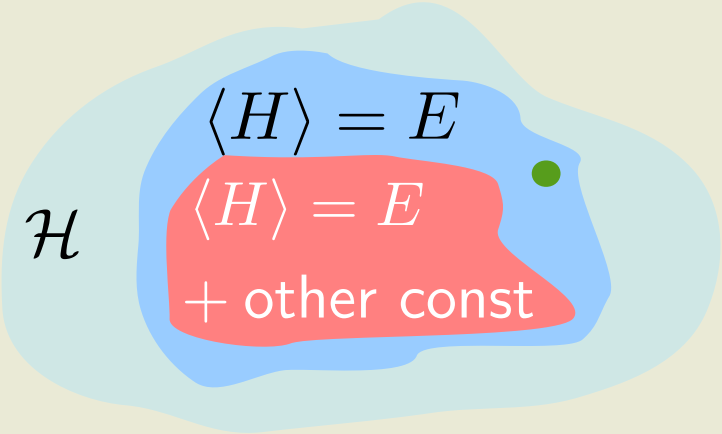
=> Memory of conserved quantities: generalized Gibbs ensemble

$$\rho_{\mathrm{GGE}} = \exp\left(-\sum \beta_k Q_k\right)/Z$$

Langen et al., Science 2015

Outline

- Quantum gases and Quantum technologies
- Quantum impurities
- Quantum Thermodynamics
- **QFRs 4 GGEs**



Recall Q. Fluctuation Relations

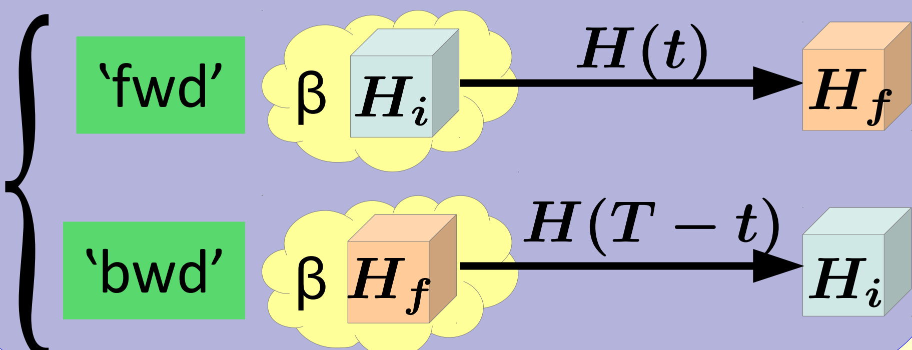
– Strict equalities vs. ‘thermodynamic laws’ [e.g., $w \geq \Delta F$]

– Derivation assumes initial state = canonical

$$\rho_\beta = \frac{e^{-\beta H}}{Z}$$

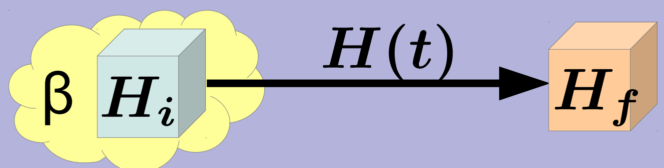
TCR: Tasaki-Crooks relation

$$\frac{P_f(w)}{P_b(-w)} = e^{\beta(w-\Delta F)}$$



Q. Jarzynski equality

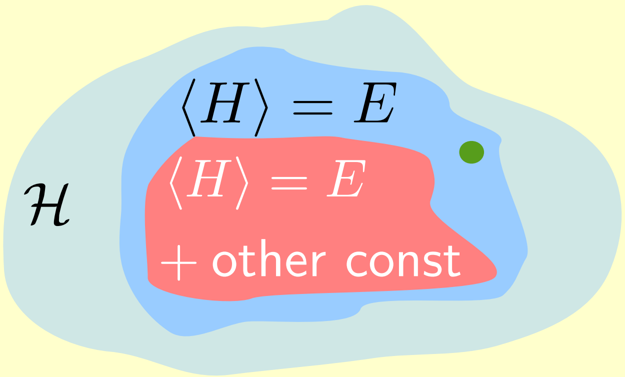
$$\langle e^{-\beta w} \rangle = e^{-\beta \Delta F}$$



QFRs for GGEs

– Can we derive q. fluctuation relations if initial state = GGE?

$$\rho_\beta = \frac{e^{-\beta H}}{Z} \to \rho_{\text{GGE}} = \frac{e^{-\beta H - \sum_k \beta_k Q_k}}{Z}, \quad [Q_k, H] = 0 \ \forall k$$



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Generalized Q. Jarzynski equality

$$\langle e^{-\beta W} \rangle = e^{-\beta \Delta F}$$

$$\beta W := \beta(\langle H' \rangle_f - \langle H \rangle_i) + \sum \beta_k(\langle Q'_k \rangle_f - \langle Q_k \rangle_i)$$

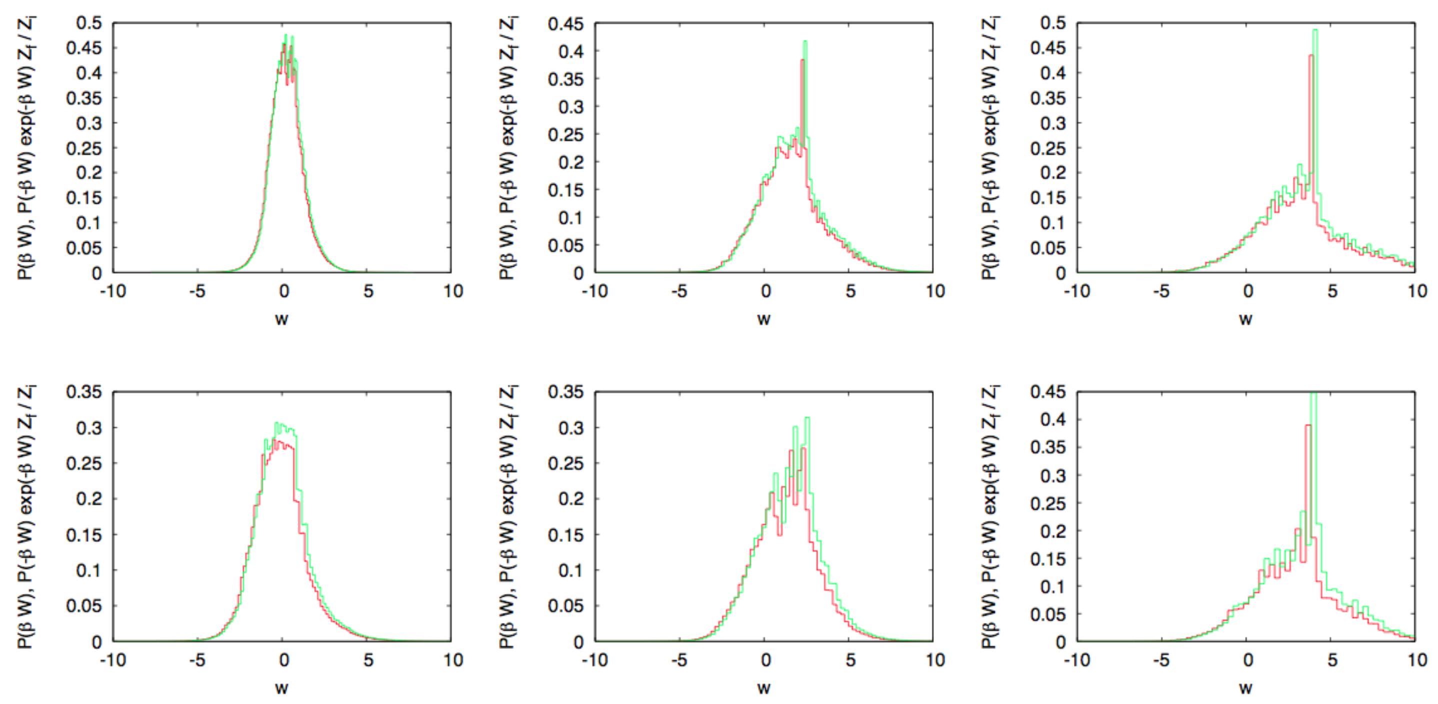
Generalized Tasaki-Crooks relation(s)

$$e^{-\beta \Delta \mathcal{F}} = e^{-\beta W} \frac{\mathcal{P}_f(W)}{\mathcal{P}_b(-W)} = e^{-\beta w} \frac{P_f(w)}{P_b(-w)} = e^{-\beta_k w_k} \frac{P_f^{(k)}(w_k)}{P_b^{(k)}(-w_k)}$$

*Equil. Q. Thermo with conserved quant's: Guryanova et al., & Halpern et al., arXiv:1512**

QFRs for GGEs

Dicke model: fwd and bwd *P*(W) after quenches - *preliminary*



Generalized Tasaki-Crooks relation(s)

$$e^{-\beta\Delta\mathcal{F}} = e^{-\beta W}\frac{\mathcal{P}_f(W)}{\mathcal{P}_b(-W)} = e^{-\beta w}\frac{P_f(w)}{P_b(-w)} = e^{-\beta_k w_k}\frac{P_f^{(k)}(w_k)}{P_b^{(k)}(-w_k)}$$

QFRs for GGEs: Outlook

Can we derive q. fluctuation relations if initial state = GGE?

$$\rho_\beta = \frac{e^{-\beta H}}{Z} \rightarrow \rho_{\mathsf{GGE}} = \frac{e^{-\beta H - \sum_k \beta_k Q_k}}{Z}, \quad [Q_k, H] = 0 \ \forall k$$

– Dynamics of relaxation with conserved quantities

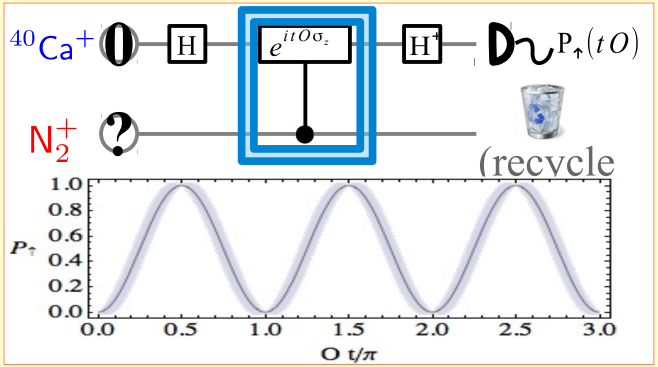
– Extract 'generalized' work?

– Probing with new QFRs? How to couple to conserved quantities?

Summary

✔ Quantum sensing

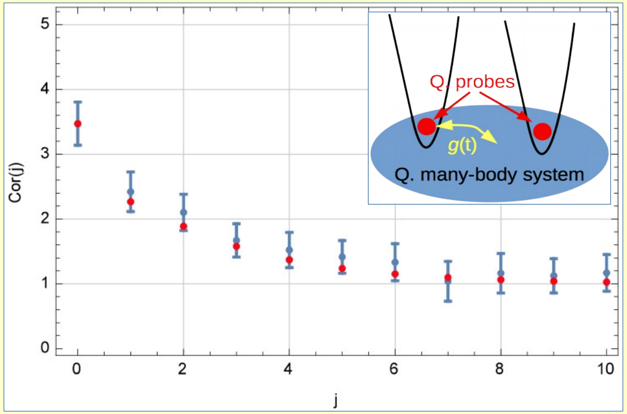
  ✔ Molecular spectroscopy



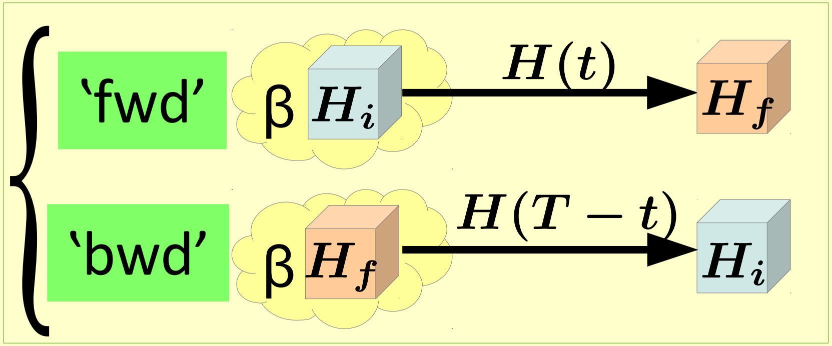
✔ Quantum probing

  ✔ Thermometry

  ✔ Correlations



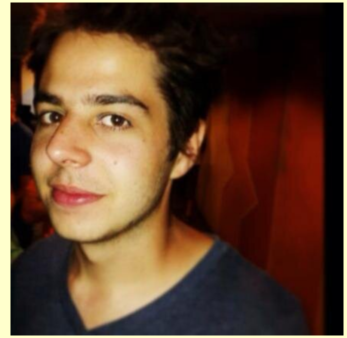
➢ QFRs for GGEs



Thank you!

Michael Streif (Freiburg/Oxf)

Dieter Jaksch



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