Quantum-classical: What can be done with large spins?

The experimental team

Roland Ketzmerick
Peter Schlagheck

Introduction

Emergence of chaos in many particle systems

observation of Poincaré-Birkhoff scenario

together with Roland Ketzmerick and Peter Schlagheck

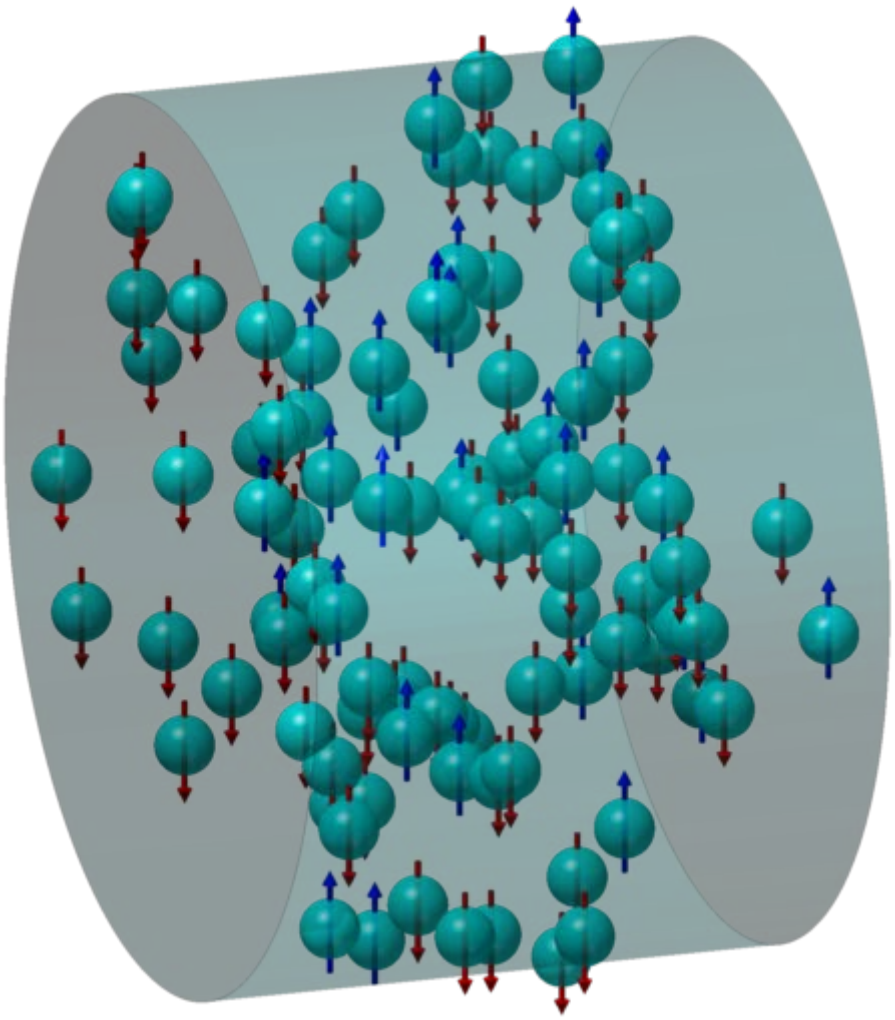
Unstable fix point: Generation of entanglement

Non gaussian states and Fisher information

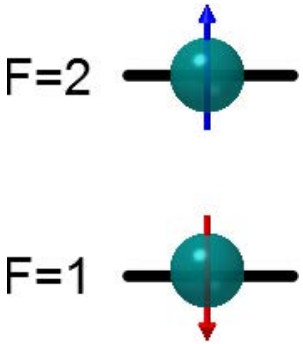
Kirchhoff Institut für Physik
University Heidelberg

www.matterwave.de

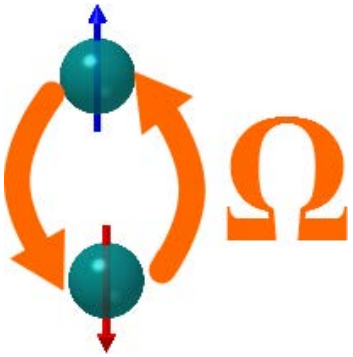
N Bosons in two internal states



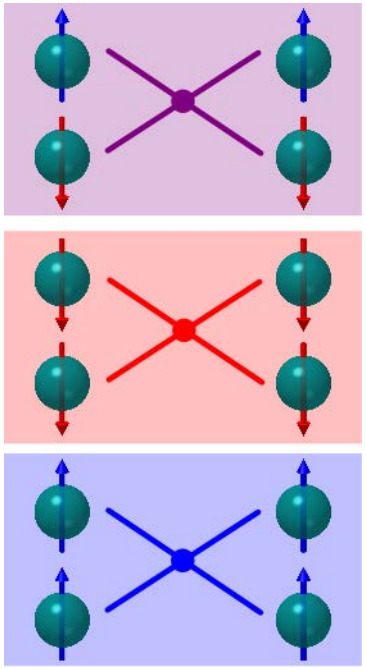
Rubidium – pseudo spin ½

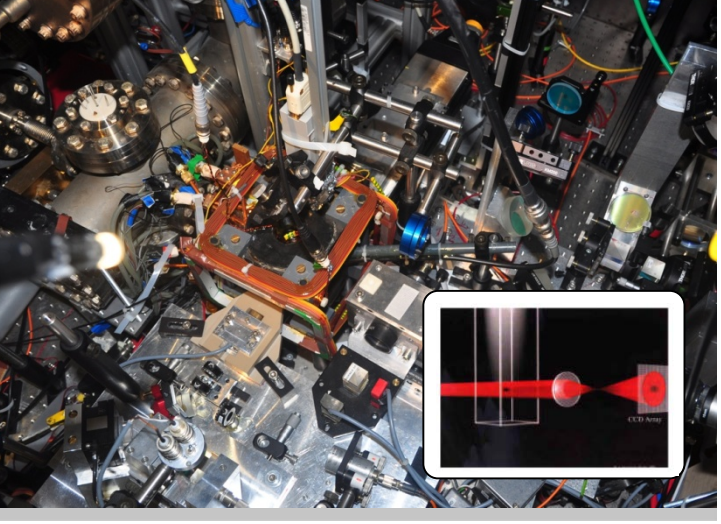


linear coupling

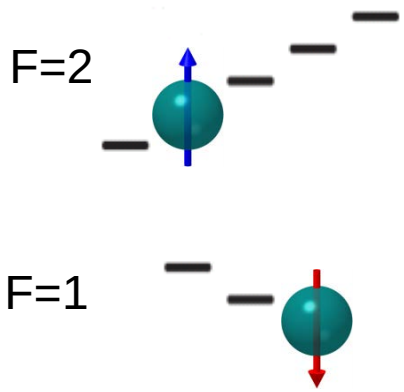


contact interaction

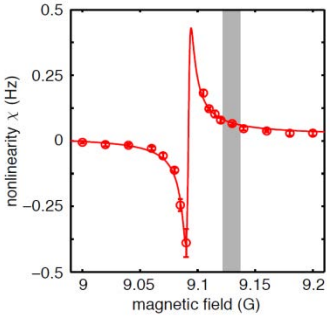




Rubidium BEC

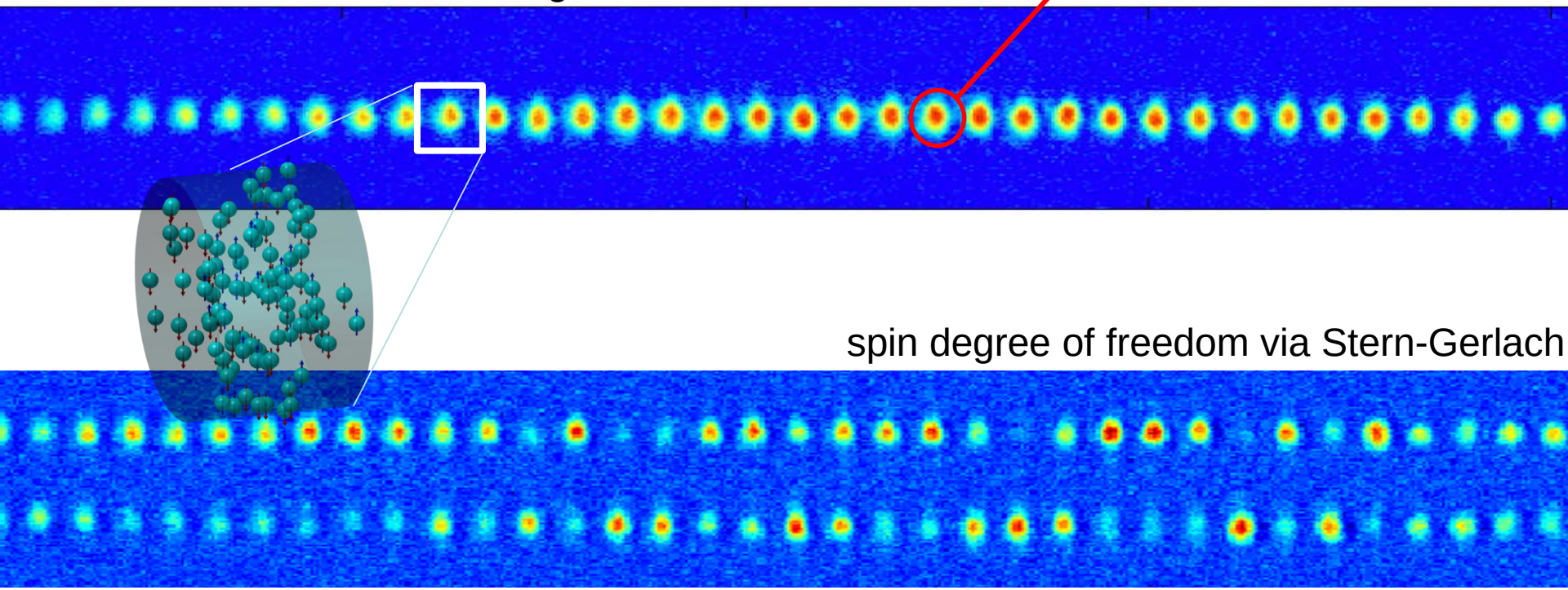


Feshbach resonance



36 x 0-dim transverse field Ising model

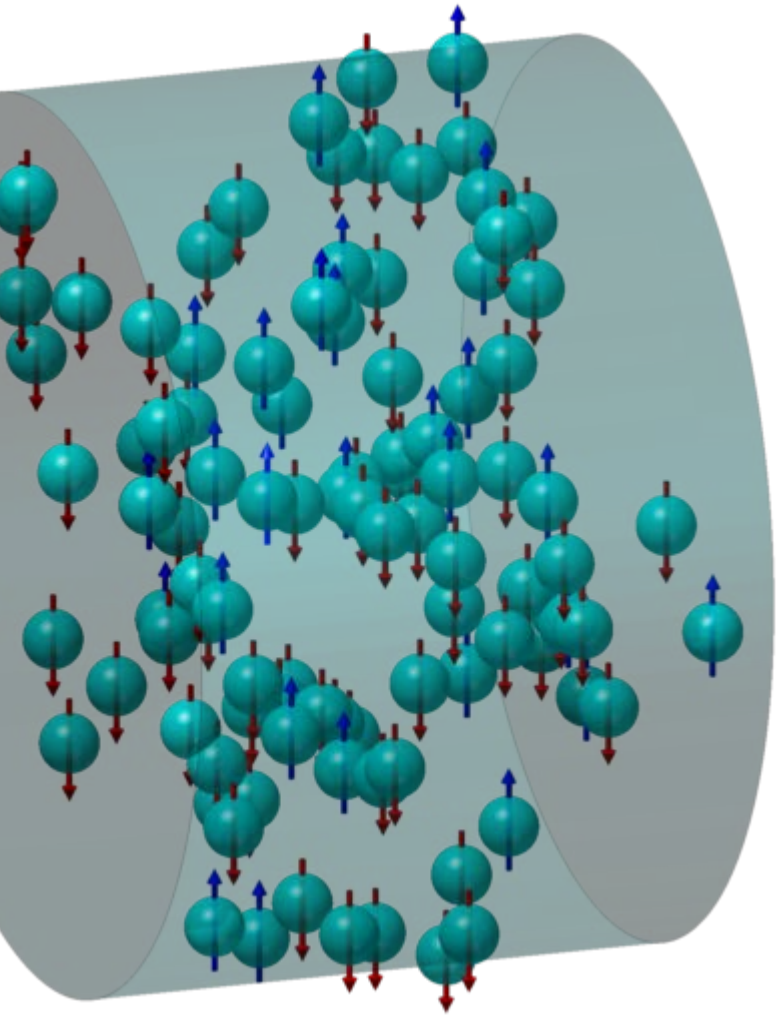
~ 500 ± 4 atoms

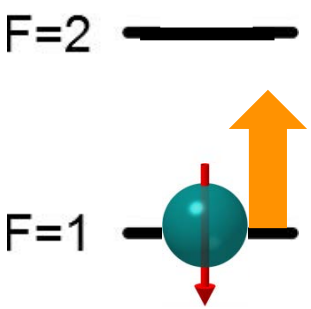


spin degree of freedom via Stern-Gerlach

Fully connected transverse Ising

the system

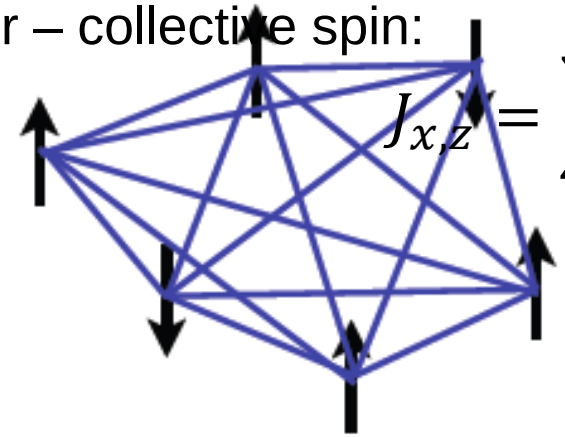




$$H = -\Omega \sum_i^N S_x^i - \delta \sum_i^N S_z^i$$

linear coupling

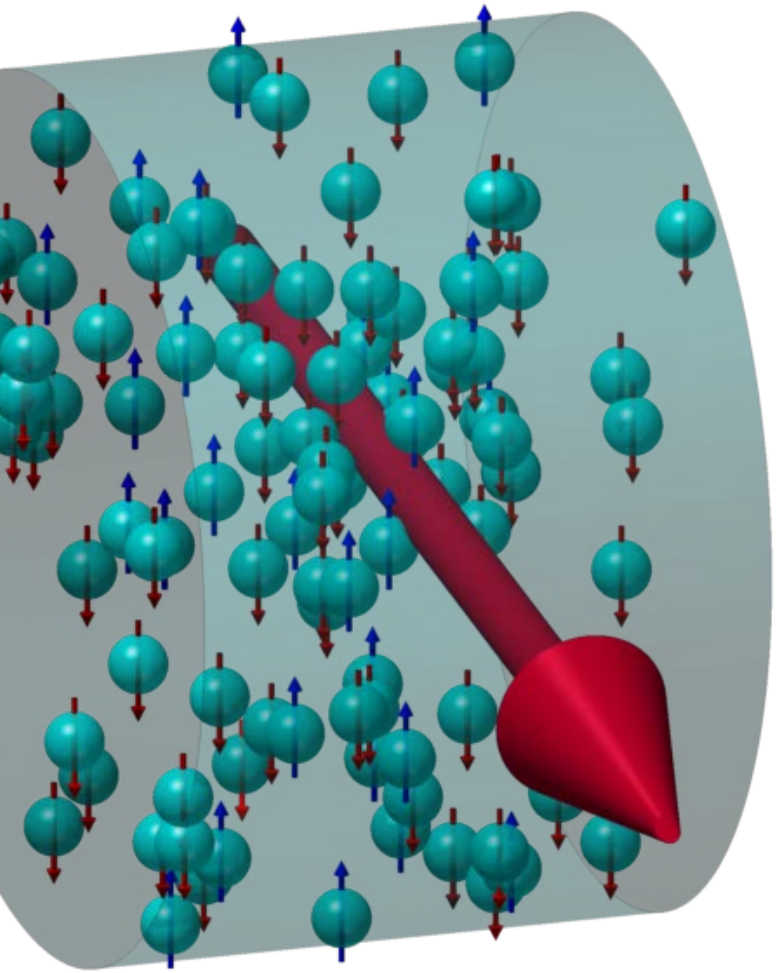
Schwinger – collective spin:



$$J_{x,z} = \sum_i^N S_{x,z}^i$$

Fully connected transverse Ising

the 0-D system



$$H = \chi \sum_{i \neq j}^{N} S_z^i S_z^j - \Omega \sum_{i}^{N} S_x^i - \delta \sum_{i}^{N} S_z^i$$

interaction

linear coupling

Schwinger – collective spin:

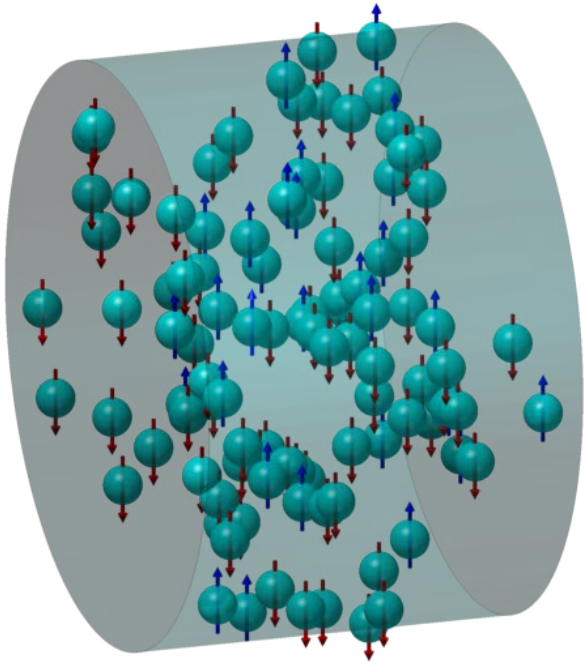
$$J_{x,z} = \sum_{i}^{N} S_{x,z}^i$$

$$H = \chi J_z^2 - \Omega J_x + \delta J_z$$

Bifurcation

Classical trajectories

$$H = \chi J_z^2 - \Omega J_x \quad \xrightarrow{\text{classical}} \quad H = \frac{\Lambda}{2}\Delta n^2 - \sqrt{1-\Delta n^2}\cos\varphi$$



$$\hat{a}^+ = \sqrt{n_a}\, e^{i\varphi_a}$$

$$\hat{J}_x = \frac{1}{2}\left(\hat{a}^+\hat{b} + \hat{b}^+\hat{a}\right)$$

$$\hat{J}_y = \frac{1}{2i}\left(\hat{a}^+\hat{b} - \hat{b}^+\hat{a}\right)$$

$$\hat{J}_z = \frac{1}{2}\left(\hat{a}^+\hat{a} - \hat{b}^+\hat{b}\right)$$

Schwinger spin

$$\hat{J}_x \cong \sqrt{n_a n_b}\cos\varphi$$

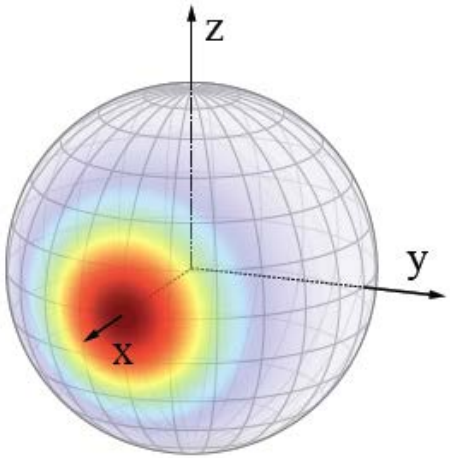
$$\hat{J}_y \cong \sqrt{n_a n_b}\sin\varphi$$

$$\hat{J}_z \cong \frac{n_a - n_b}{2}$$

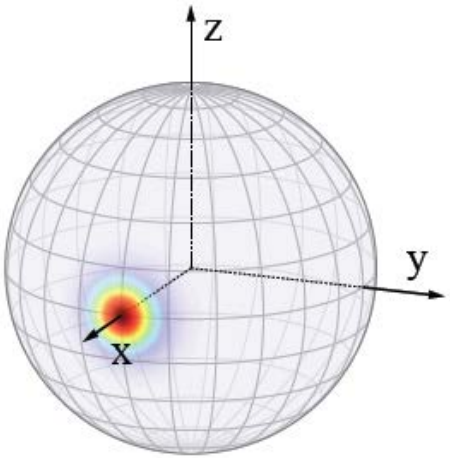
Classical description

effective Planck's constant

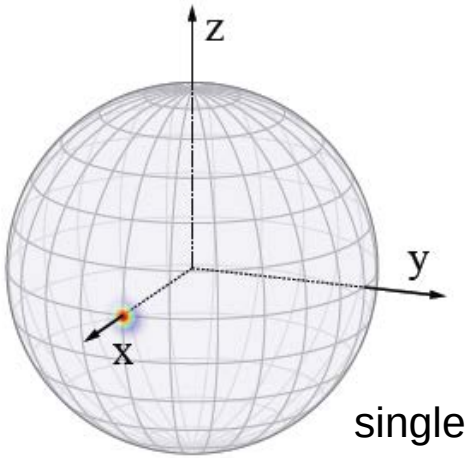
minimal uncertainty state



N=10



N=100

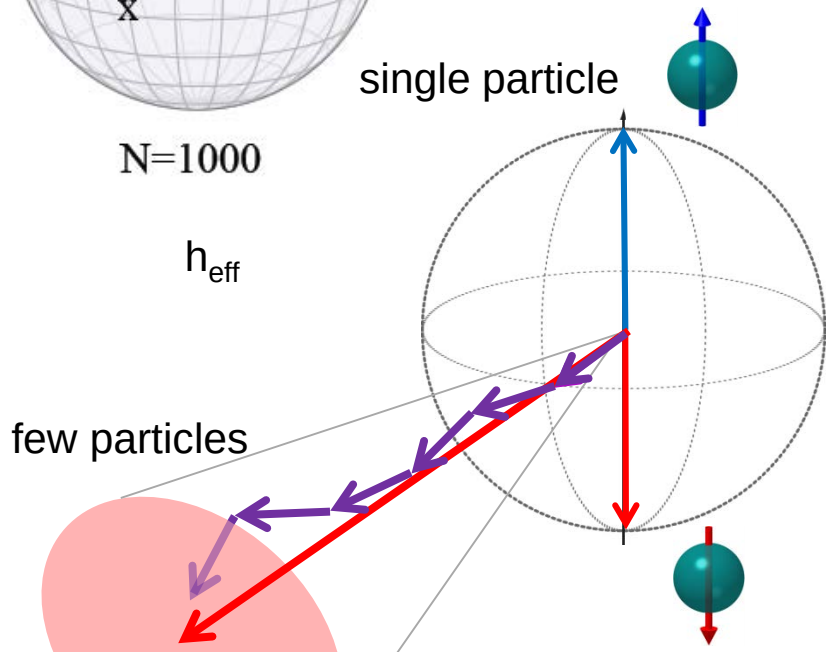


N=1000

h_{eff}

h_{eff}

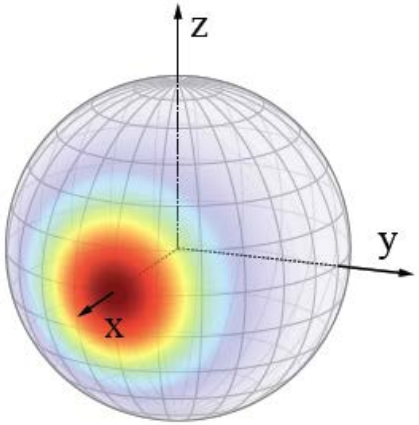
h_{eff}



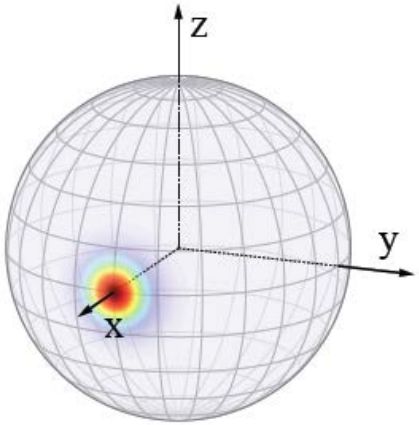
$$[\Delta n/N, \varphi] = i\frac{2}{N} \quad \Leftarrow \quad [J_y, J_z] = iJ_x$$

Quantum - Semiclassical – Classical

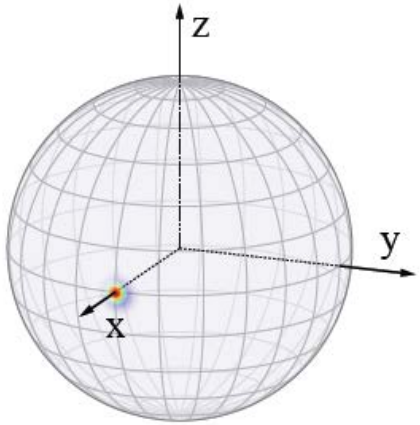
PRL **111**, 253001 (2013) Physics



N=10



N=100

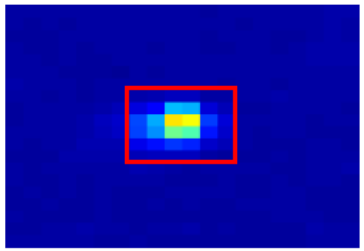


N=1000

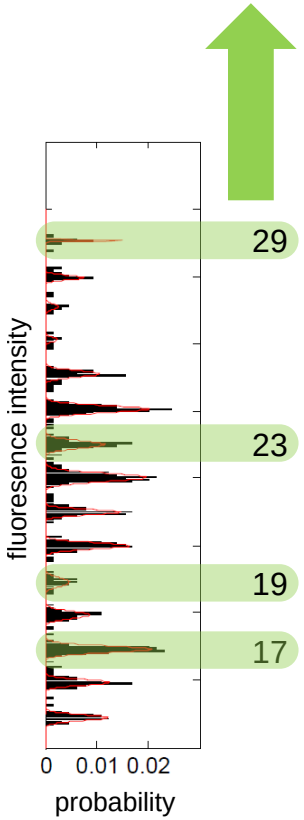
h_{eff}

h_{eff}

h_{eff}



up to 1000 !!



Bifurcation

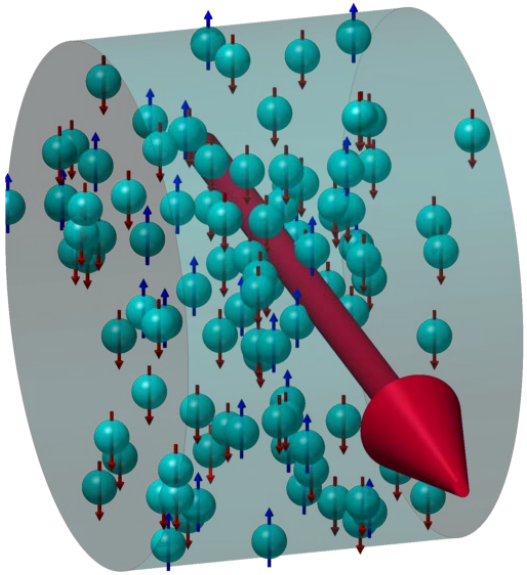
Classical trajectories

$$H = \chi J_z^2 - \Omega J_x$$

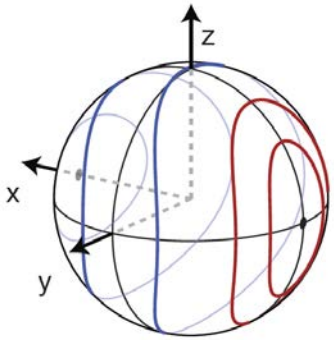
classical

$N \to \infty$

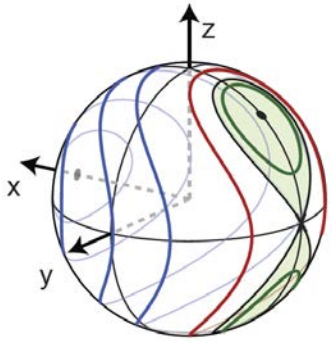
$$H = \frac{\Lambda}{2}\Delta n^2 - \sqrt{1-\Delta n^2}\cos\varphi$$



$$\Lambda = \frac{N\chi}{\Omega} < 1$$



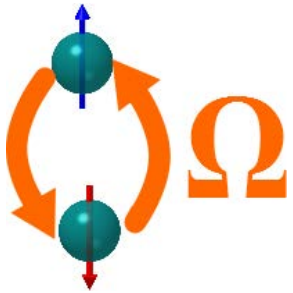
$$\Lambda > 1$$

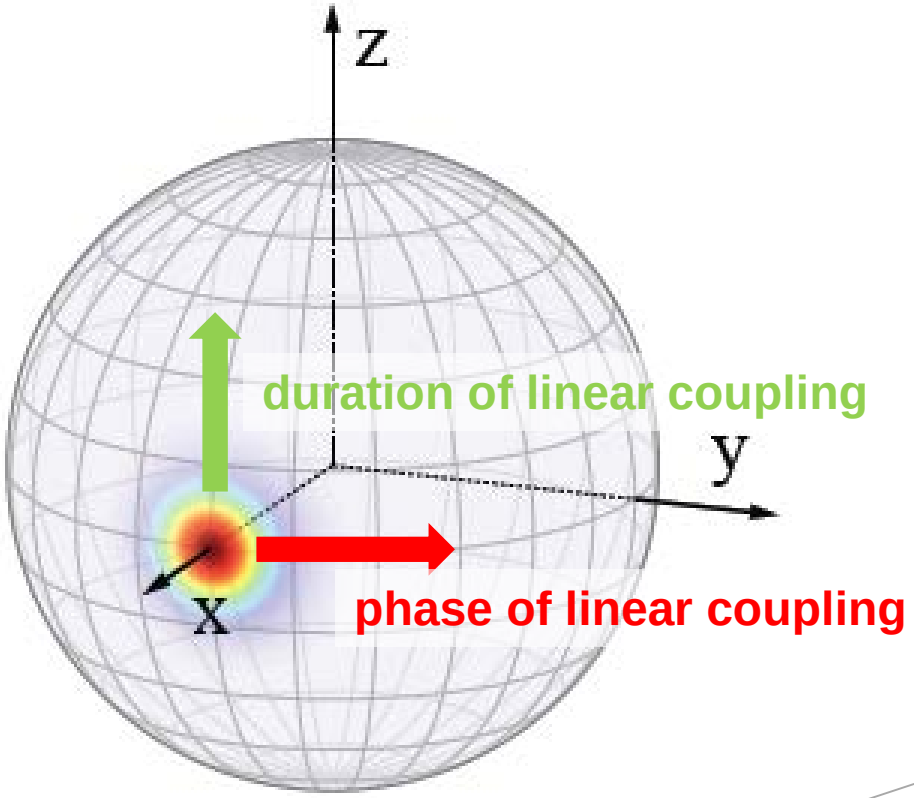


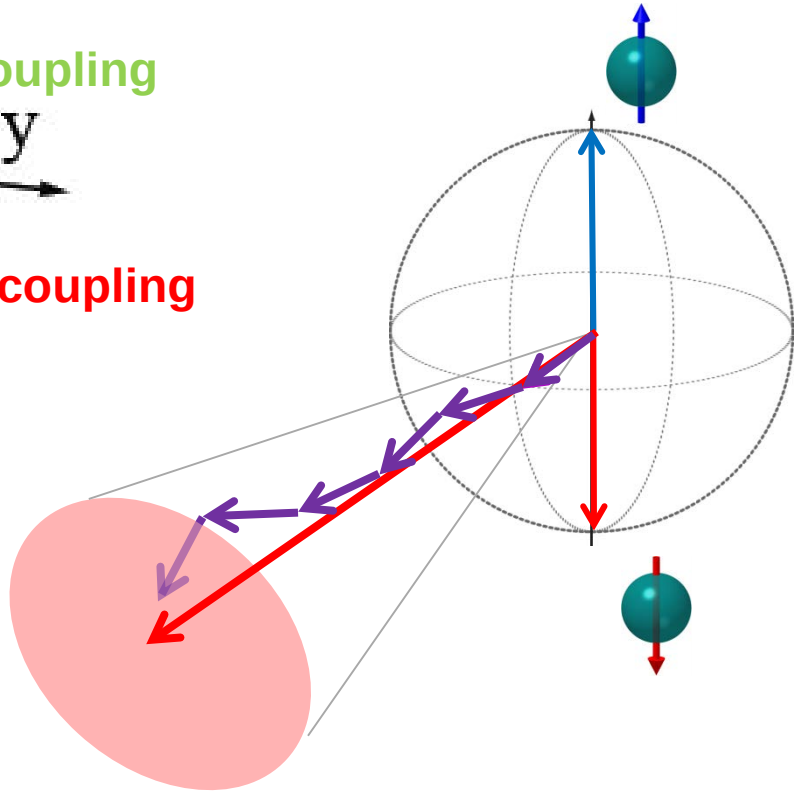
increasing interactions

Experimental observation: Zibold et al. PRL 105, 204101 (2010)

Single particle Rabi coupling



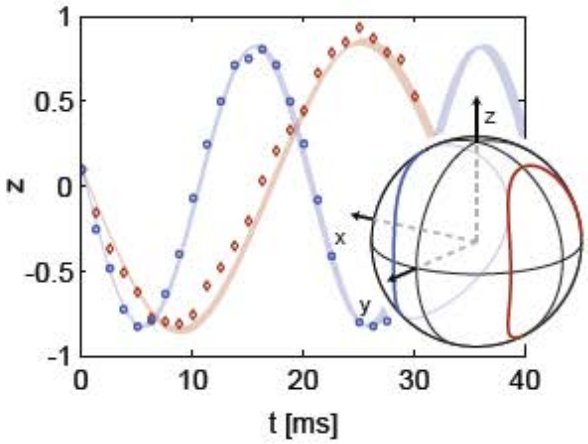


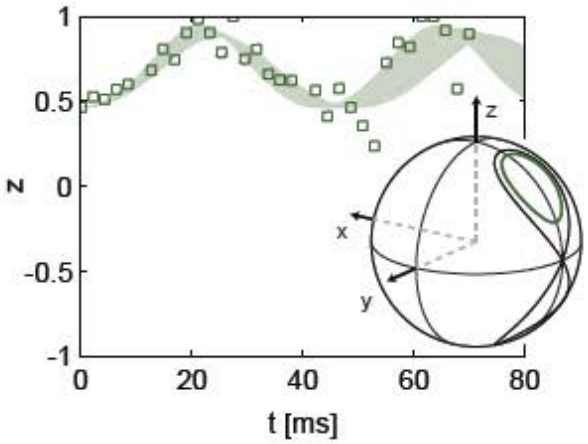


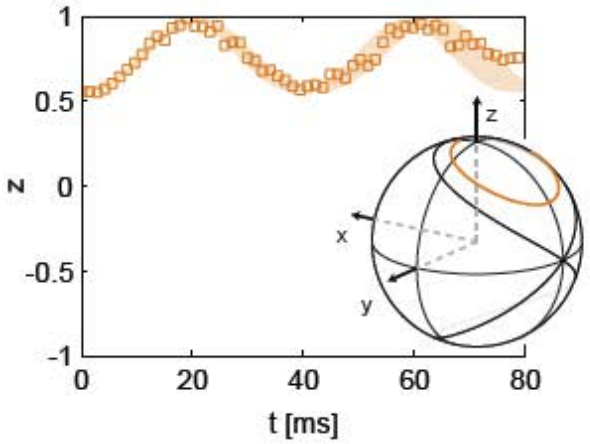
PRL 105, 204101 (2010)

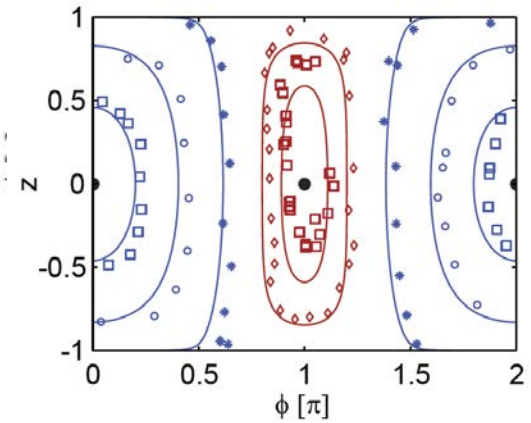
Dynamics

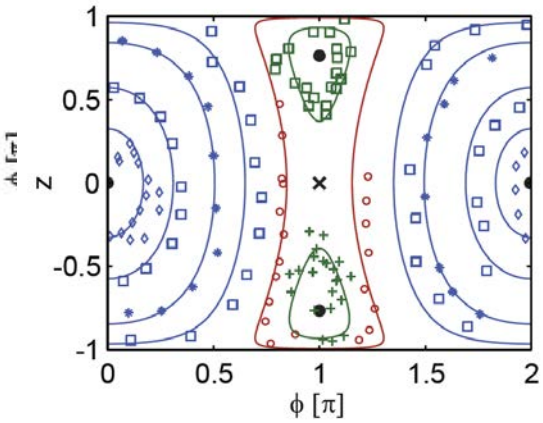
see ‚also': Steinhauer group

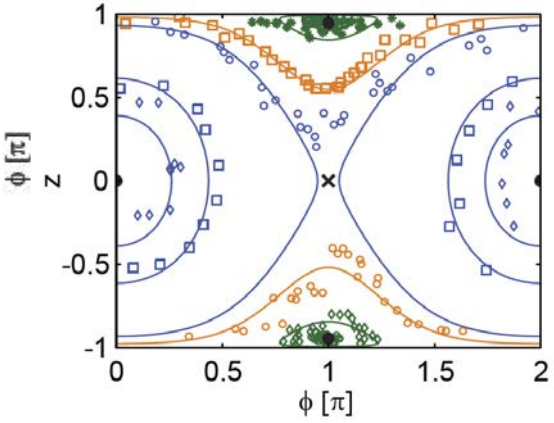










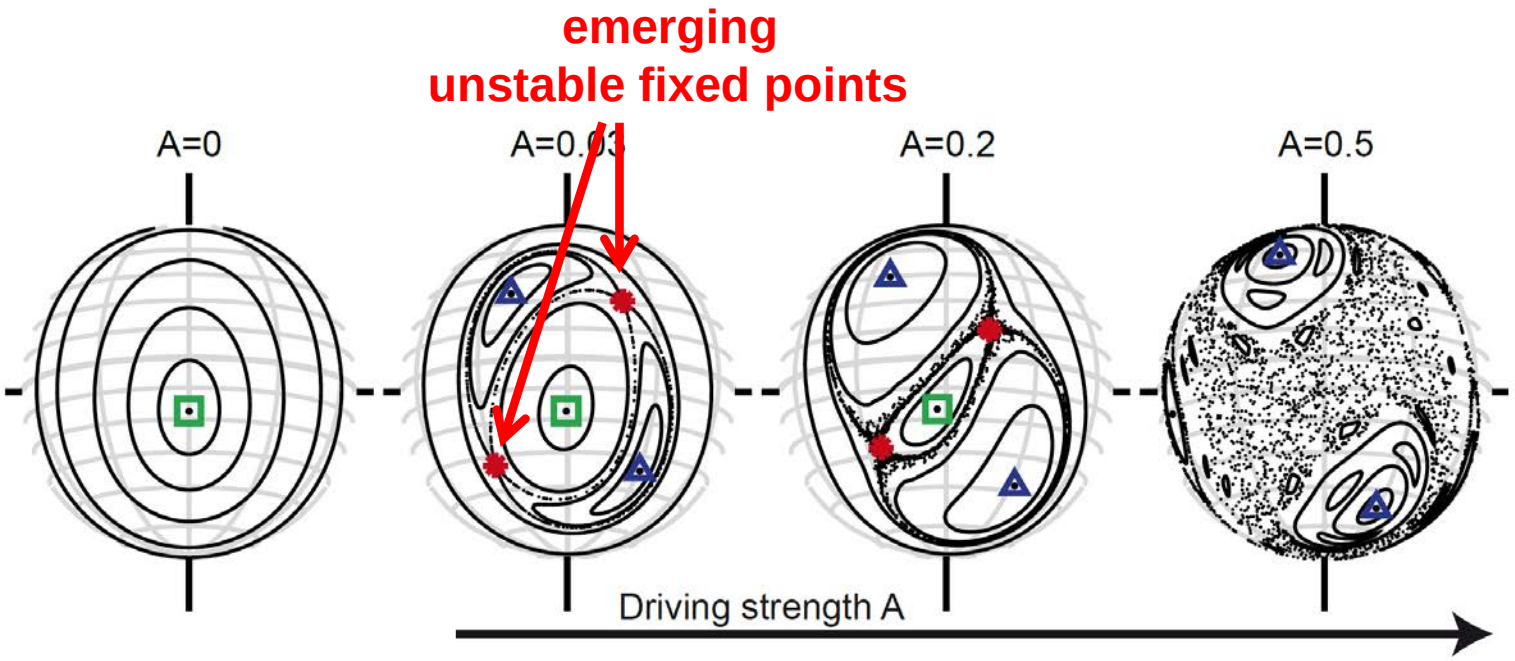


increasing interactions

Driven quantum dimer

$$1 + A\sin(\omega_d t + \phi_d)$$

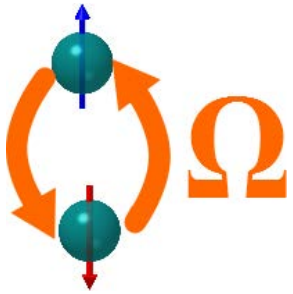
$$H = \frac{\Lambda}{2}\Delta n^2 - \sqrt{1-\Delta n^2}\cos\varphi$$

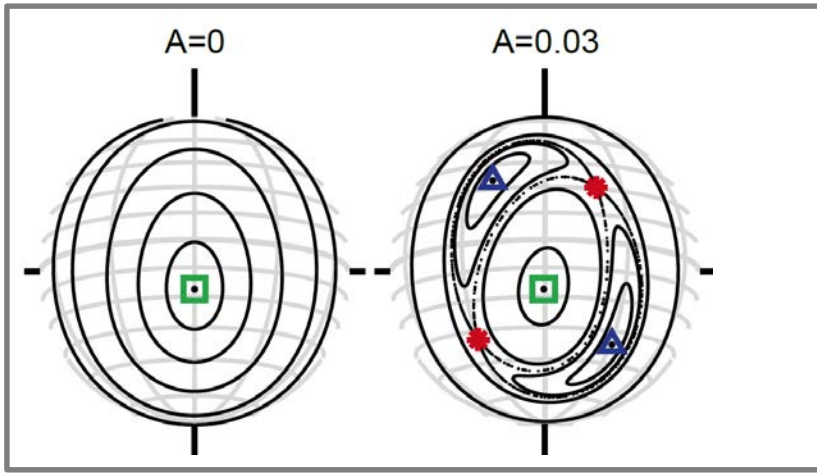


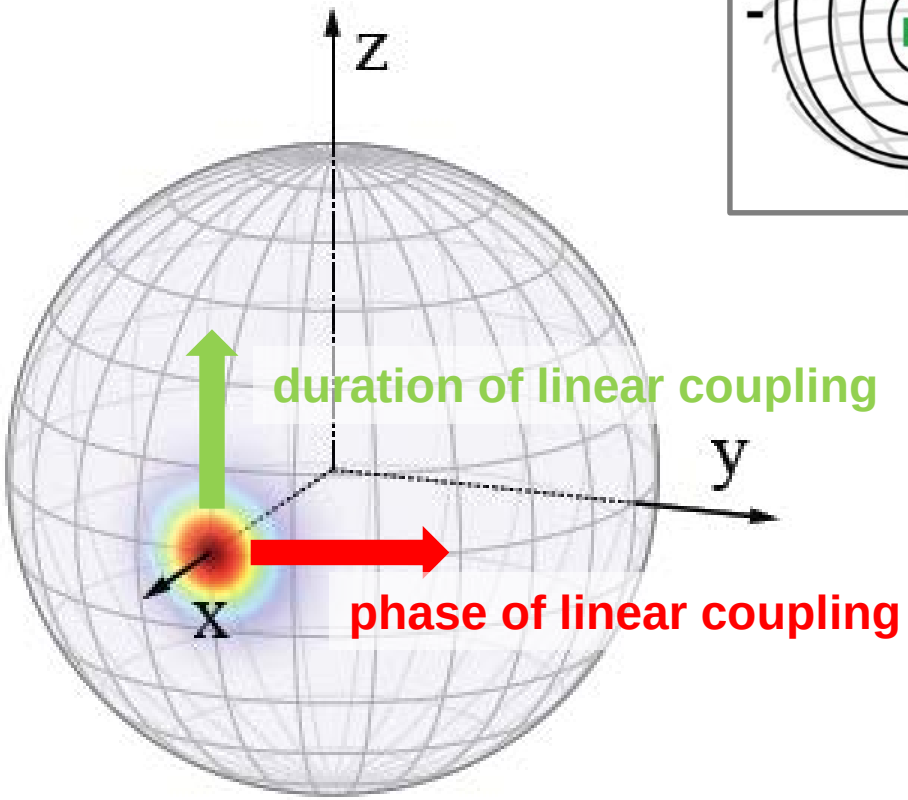
Poincaré-Birkhoff theorem

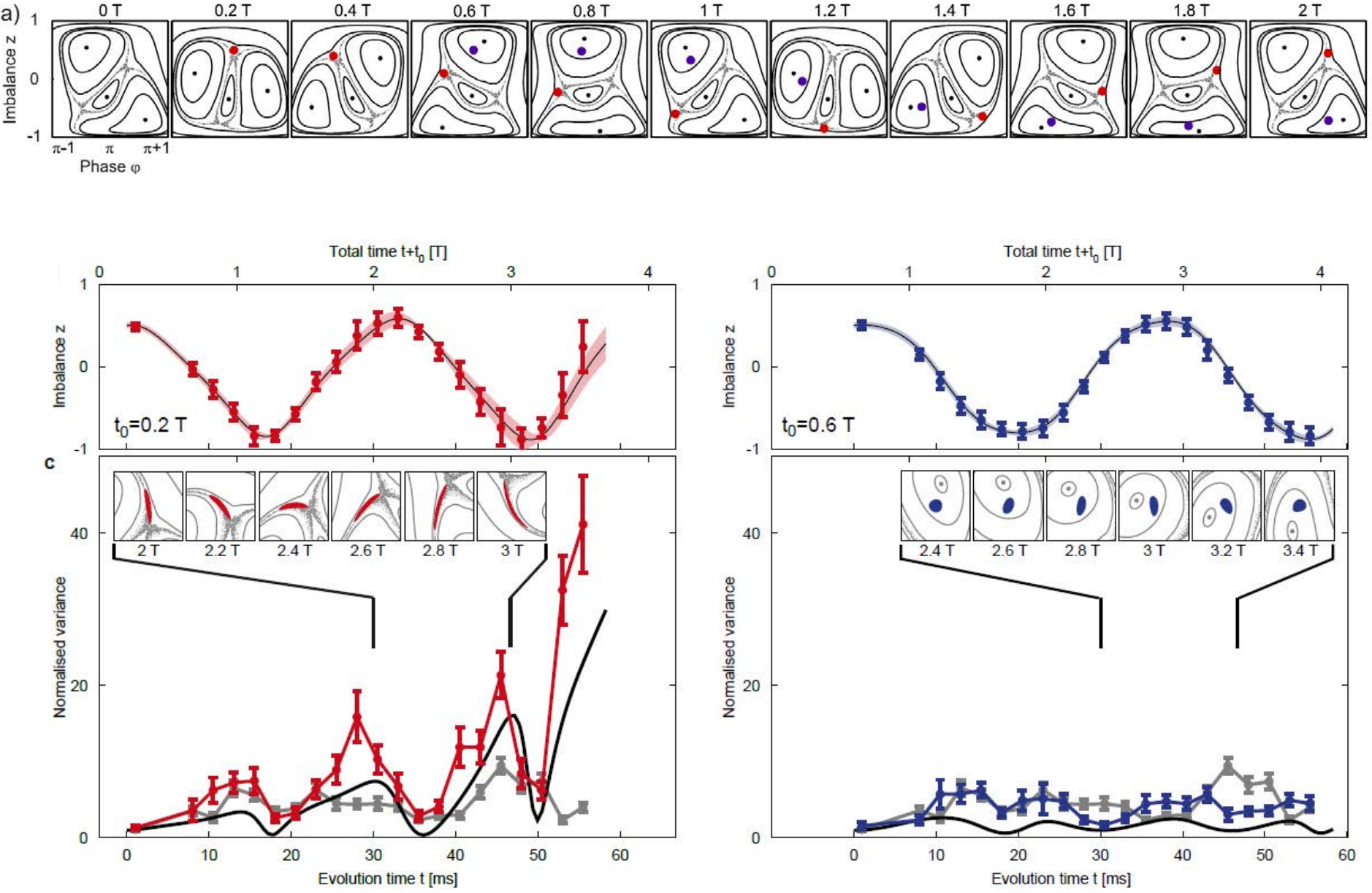
Single particle Rabi coupling

preparation



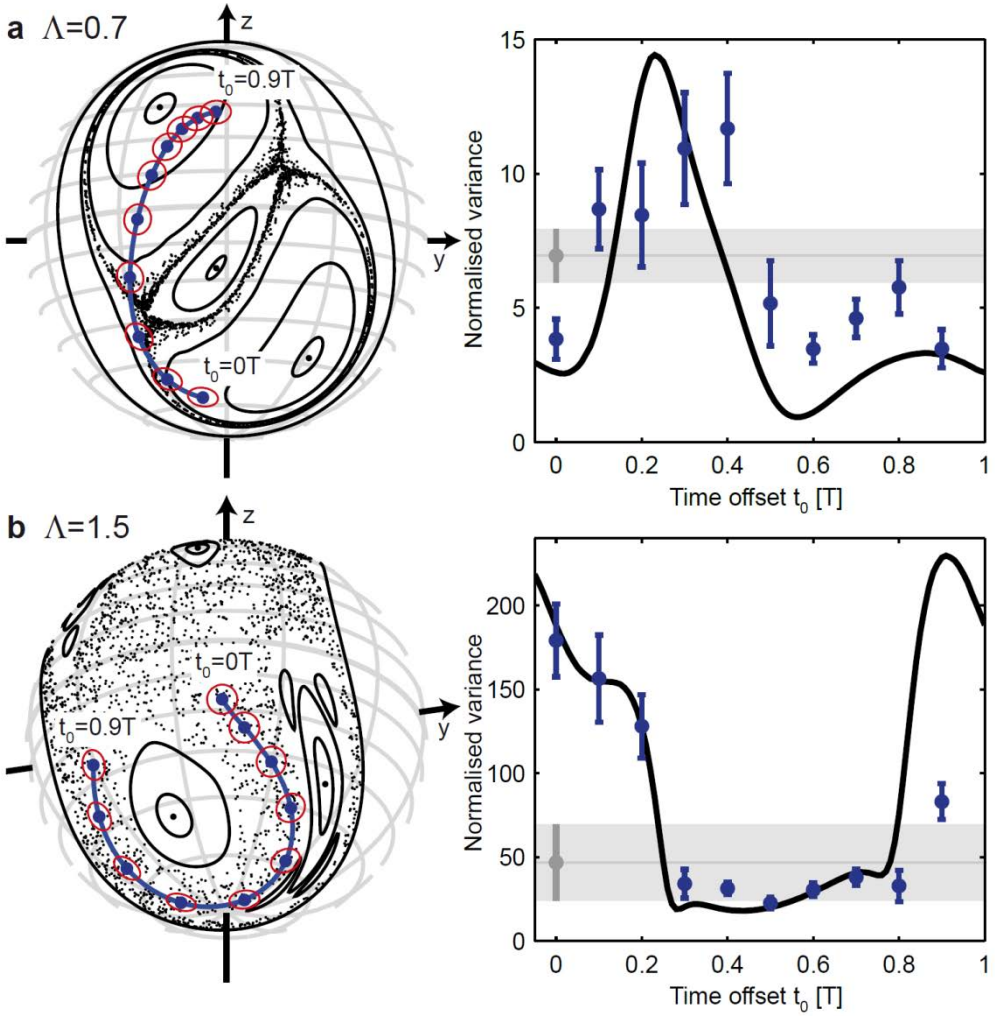





a)
0 T
0.2 T
0.4 T
0.6 T
0.8 T
1 T
1.2 T
1.4 T
1.6 T
1.8 T
2 T
Imbalance z
1
0
-1
π-1
π
π+1
Phase φ
Total time t+t0 [T]
Imbalance z
t0=0.2 T
c
2 T
2.2 T
2.4 T
2.6 T
2.8 T
3 T
Normalised variance
Evolution time t [ms]
Total time t+t0 [T]
Imbalance z
t0=0.6 T
2.4 T
2.6 T
2.8 T
3 T
3.2 T
3.4 T
Normalised variance
Evolution time t [ms]

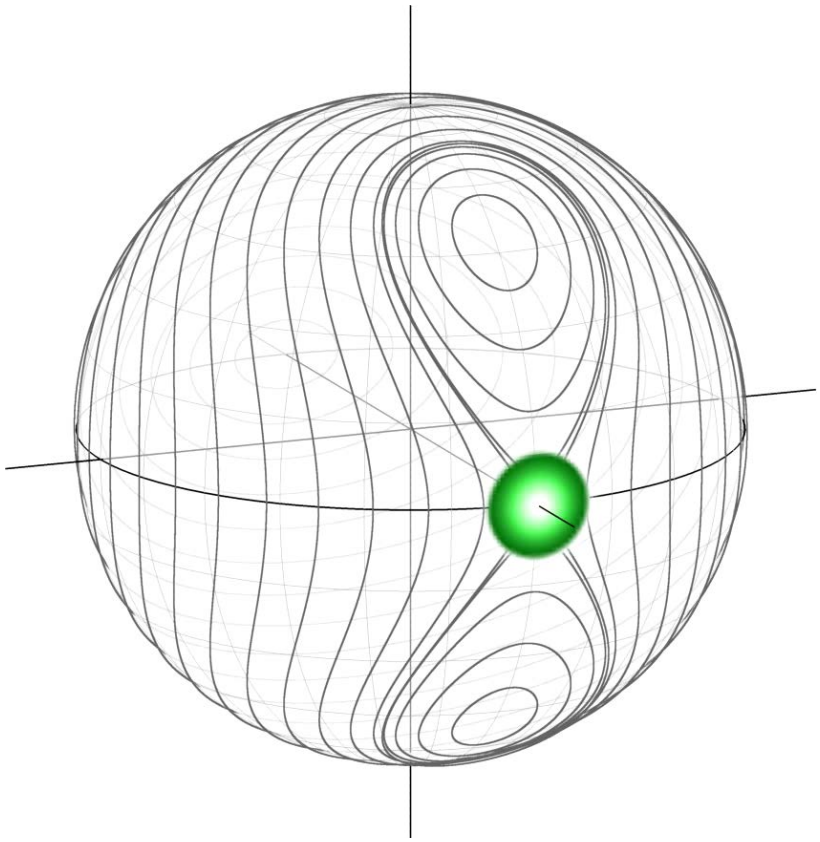
Probing ‚chaotic' phase space

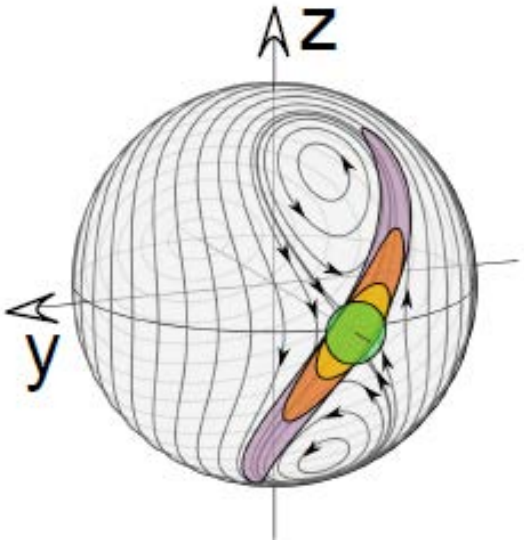
Mixed phase space



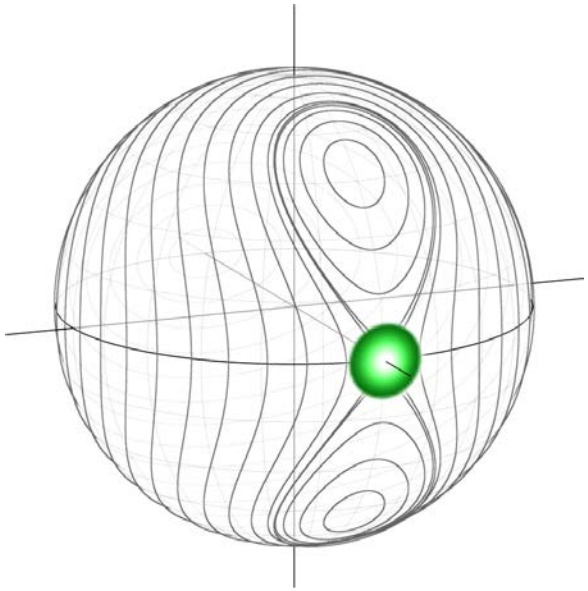
kicked rotor experiments: Raizen, Phillips, Jessen, Summy, Wilson, …

oversqueezing

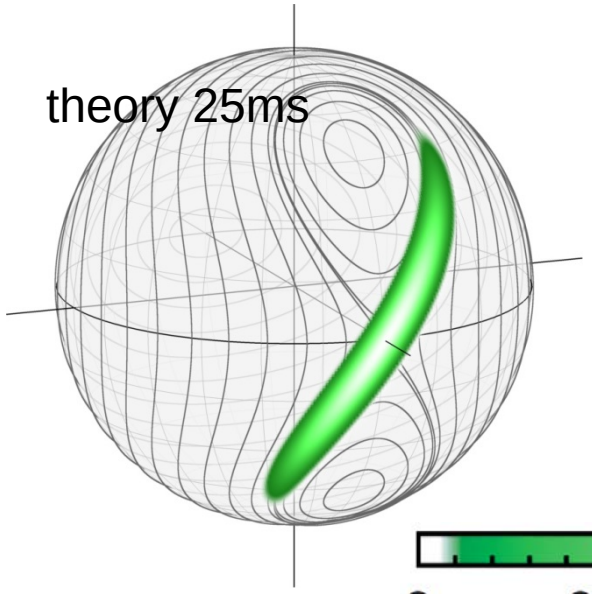


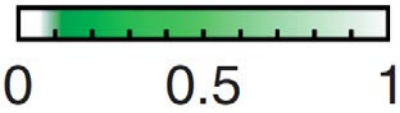


oversqueezing

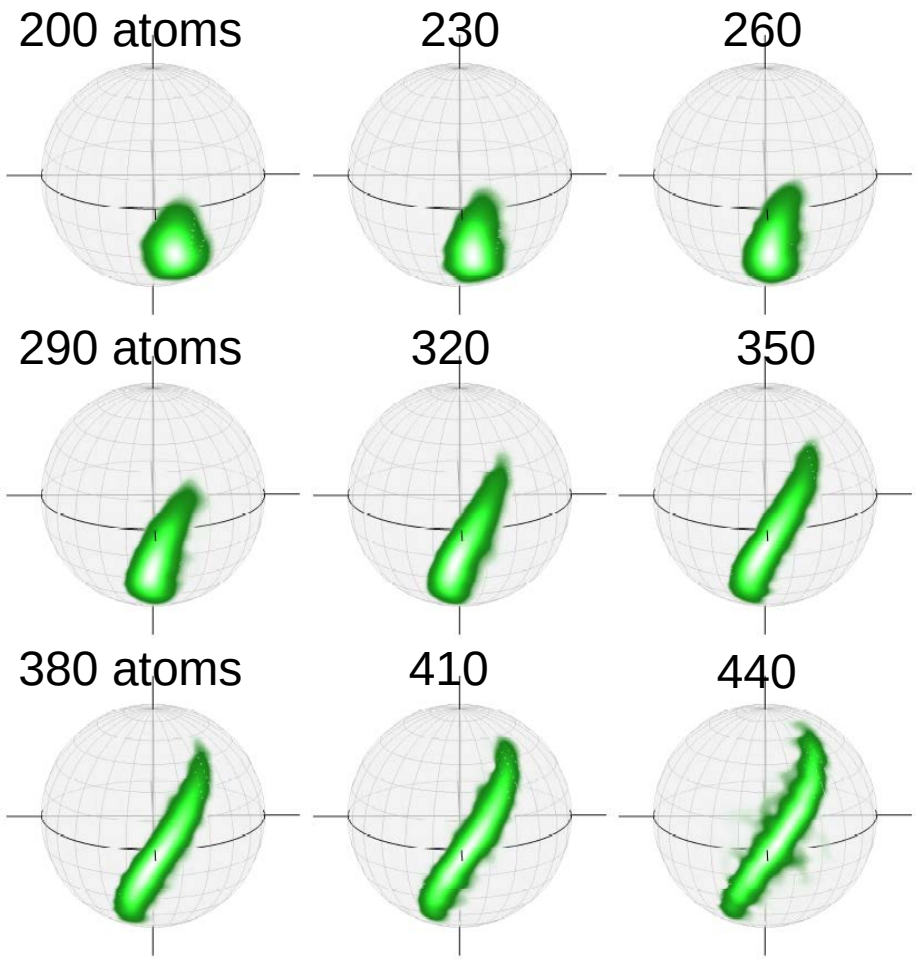


theory 25ms



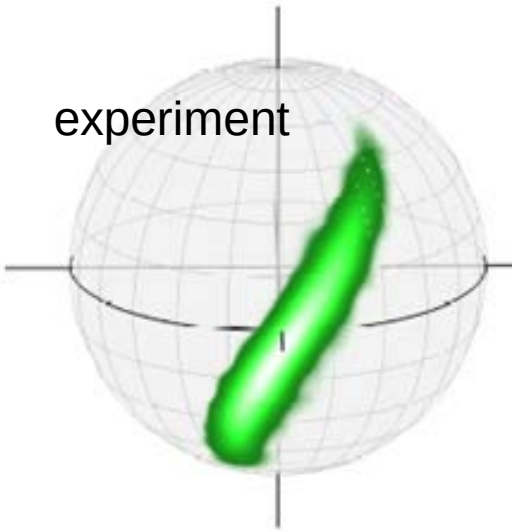


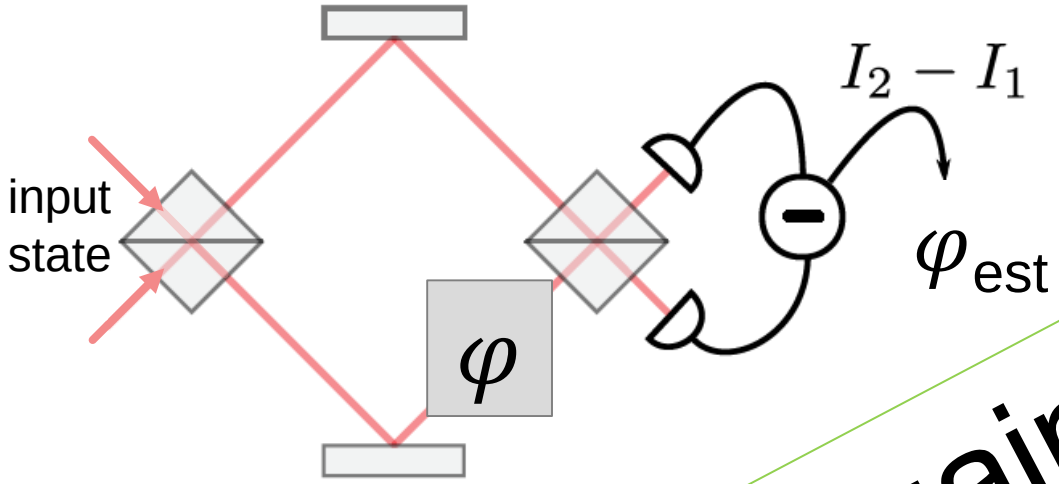
reconstructed Husimi distribution



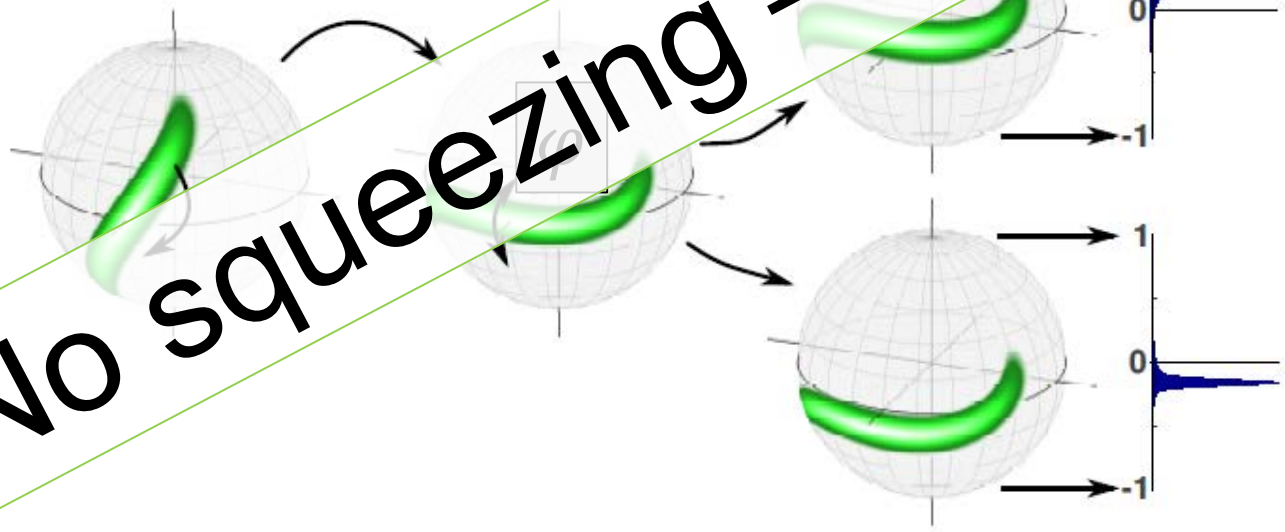
parameter estimation

interferometry beyond squeezing



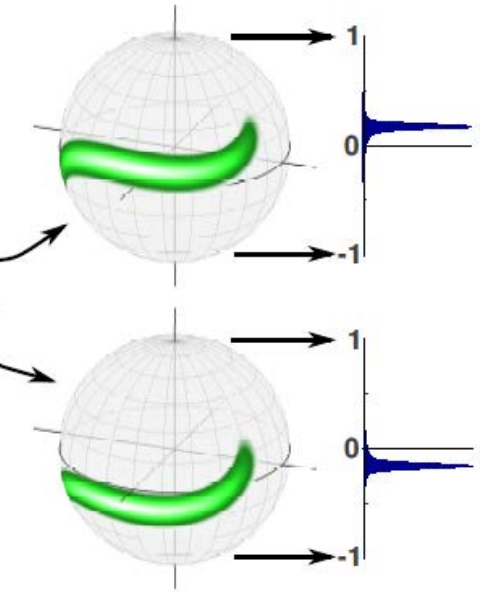


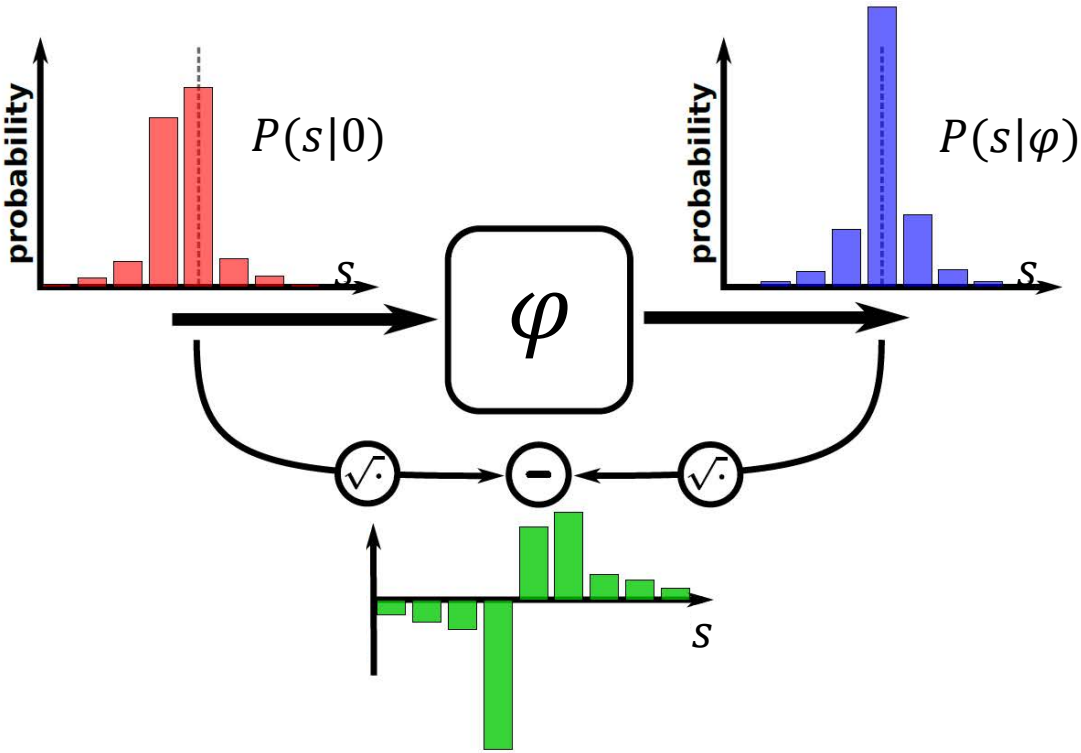
No squeezing – no gain



Hellinger distance

Luca Pezzè, Augusto Smerzi



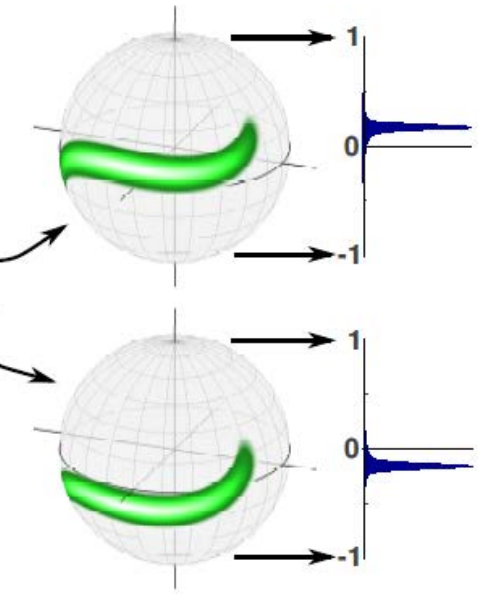


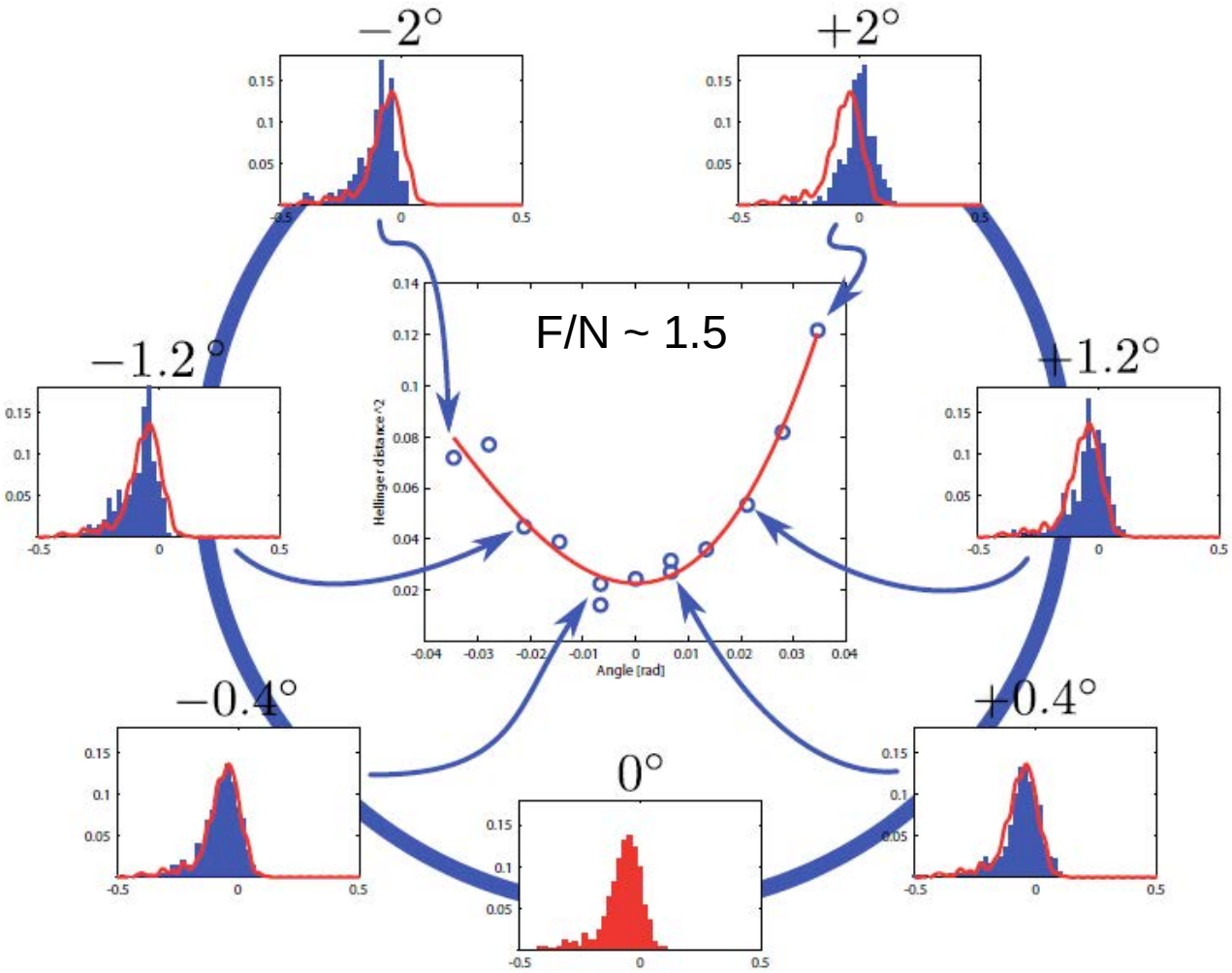
Hellinger distance

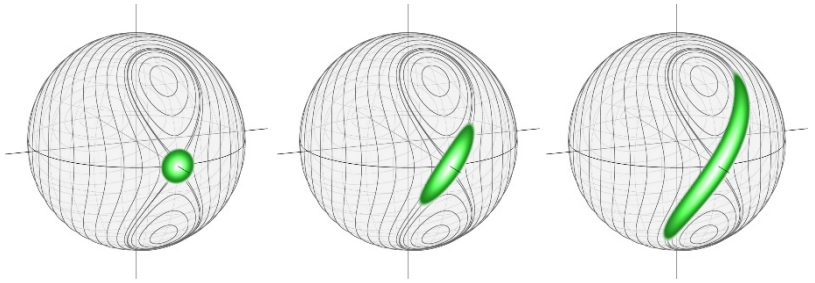
$$d_H^2 = \frac{1}{2}\sum_s \left(\sqrt{P(s|\varphi)} - \sqrt{P(s|0)}\right)^2$$

parameter estimation

interferometry beyond squeezing



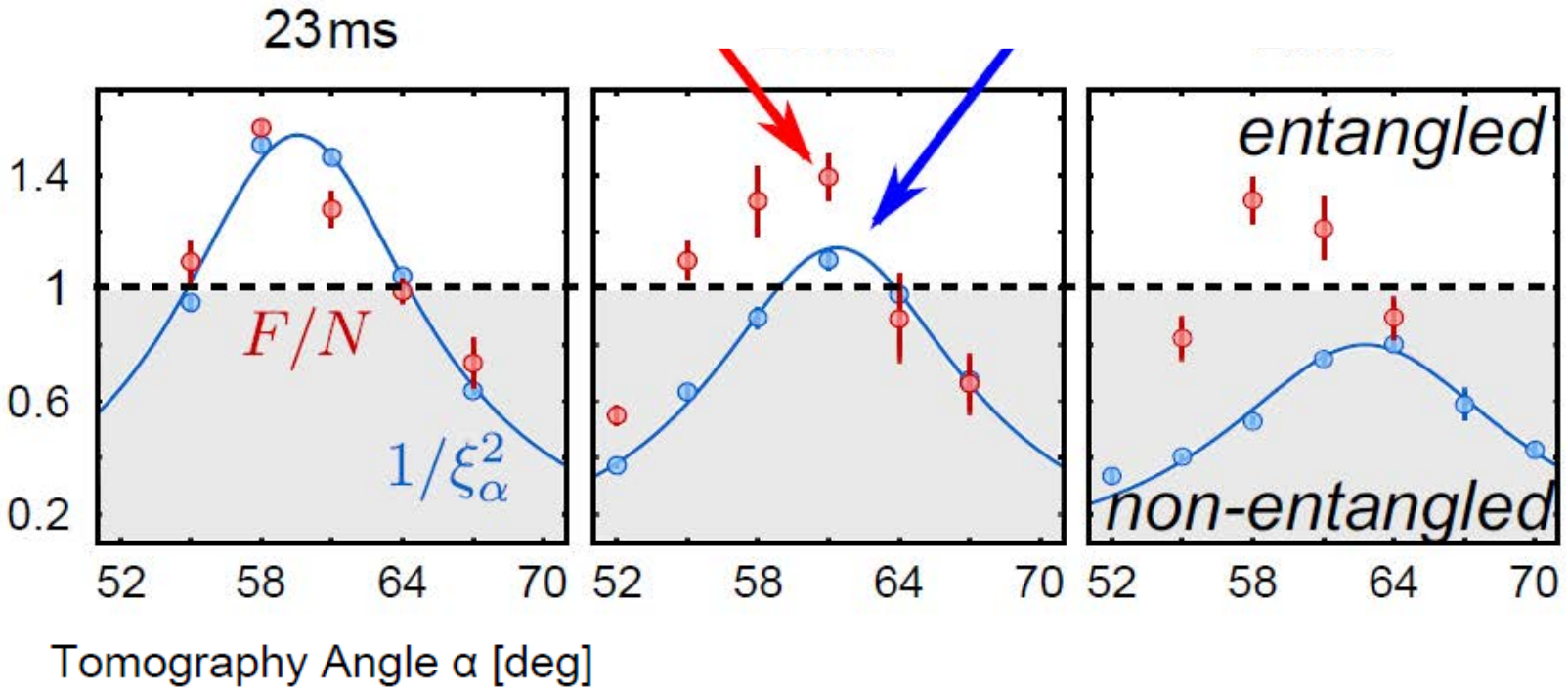




entanglement beyond squeezing

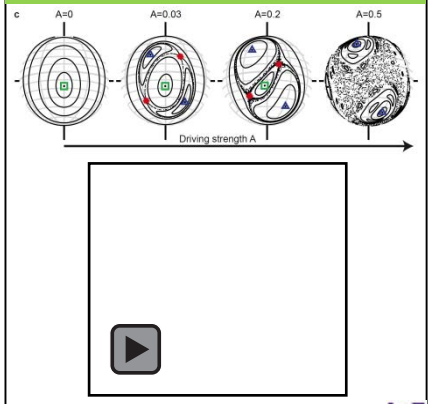
Science, 345, 424-427, (2014)

Fisher information is a more general entanglement witness than squeezing



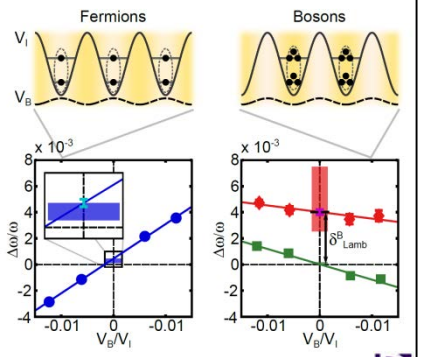
conclusion

Emergence of chaos



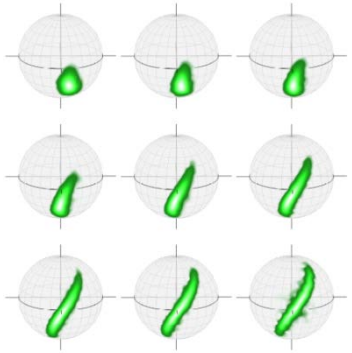
PRA **95**, 011602(R) (2017)

Phononic Lamb shift



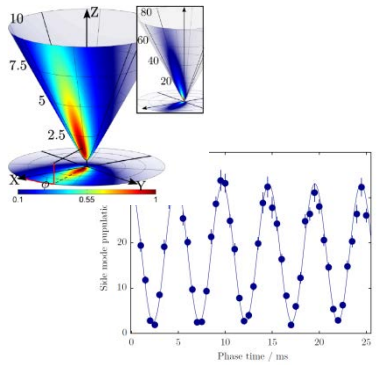
PRX **6**, 041041 (2016)

Non-gaussian states



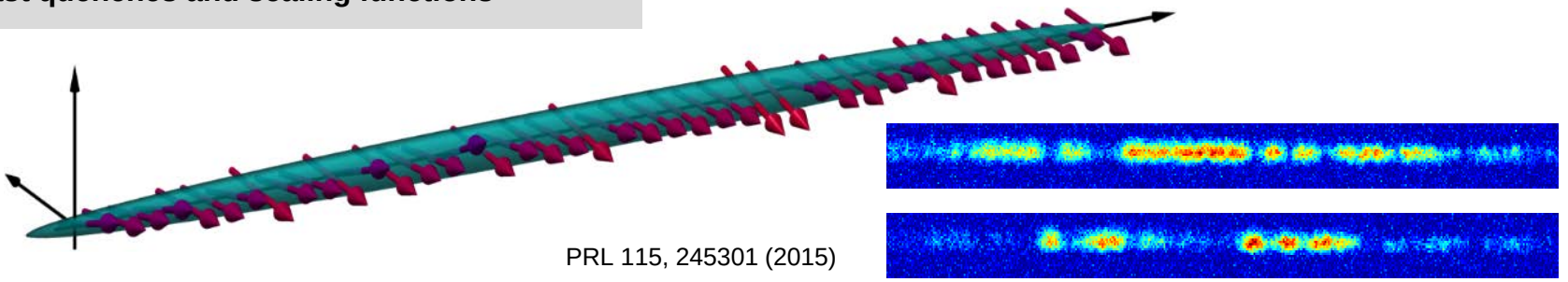
Science **345**, 424 (2014)
PRA **92**, 023603 (2015)

Nonlinear time-reversal



PRL **117**, 013001 (2016)

Fast quenches and scaling functions



PRL 115, 245301 (2015)

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