A 2-ions probe for anomalous heating

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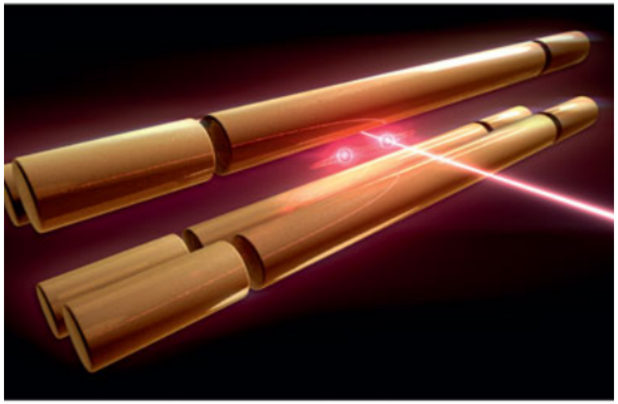
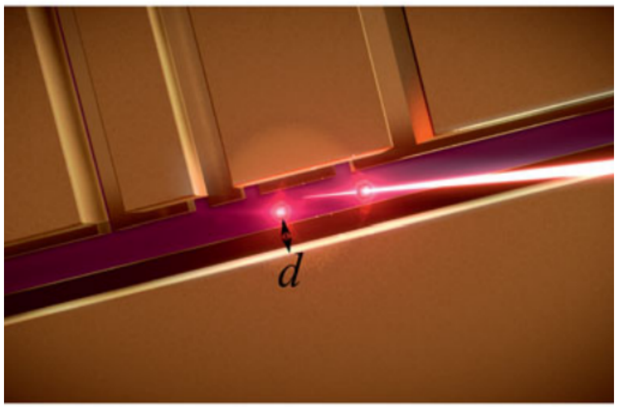
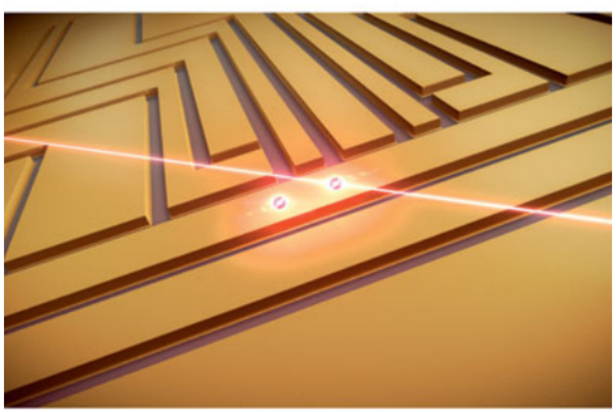
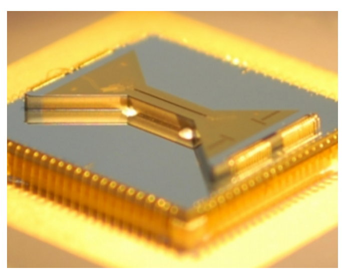
- Importance of anomalous heating
- Possible sources
- What is known?
- A 2-ion probe approach
- Results

Importance of anomalous heating









$$\Gamma_{\mathrm{h}} \simeq \frac{e^2}{4 m_{\mathrm{I}} \hbar \omega_{\mathrm{t}}} S_E(\omega_{\mathrm{t}})$$

- From 3D traps to 2D (surface electrode) traps, technical noise dominates heating.
- Once all of them removed, anomalous heating remains.
- Anomalous heating is adverse because of its scaling with ion-electrode distance ***d***

$$d^{-4}$$

- Faster quantum gate operations require smaller (µm-size) traps, so this becomes the fundamental, non-technical, hindrance.

Miniaturization-friendly, lithographic-ready 2D traps

Cool pictures taken from MRS Bull. **38**, 826. (2013).

Anomalous heating

Technical noise sources

A. Blackbody radiation
   1. Blackbody radiation in free space
   2. Blackbody radiation above surfaces

B. Electromagnetic interference

C. Electromagnetic pickup

D. Johnson-Nyquist noise
   1. Frequency-dependent resistance
   2. Characteristic distances
   3. Temperature scaling of Johnson noise
   4. Absolute values of Johnson noise
   5. Johnson noise in a filter network
   6. Johnson noise in an rf resonator
   7. Technical noise

E. Space charge

once removed

Microscopic noise sources

A. Patch-potential models
   1. Origin of patch potentials
   2. Electric-field noise from fluctuating patches
   3. Distance scaling for a planar trap
   4. Influence of the electrode geometry

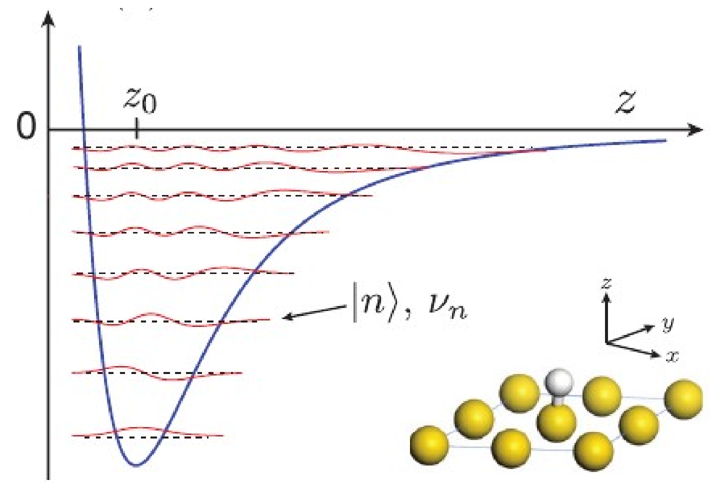
B. Two-level fluctuator models
   1. Electric-field noise from fluctuating dipoles
   2. Two-level fluctuators
   3. Thermally activated fluctuators
   4. Tunneling states
   5. Nonuniform distributions of activation energies

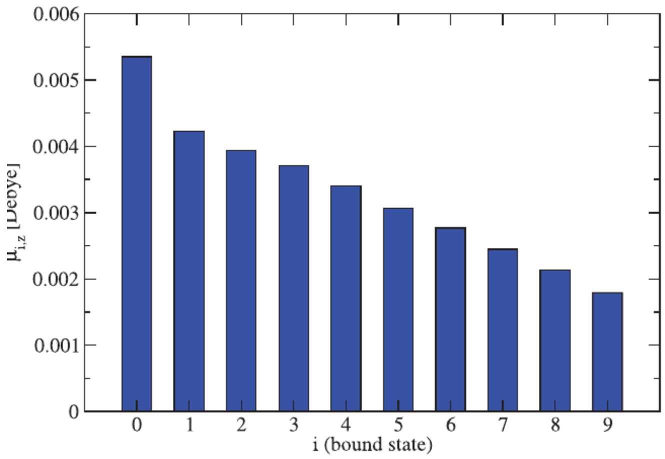
C. Adatom dipoles
   1. Adatoms
   2. Phonon-induced dipole fluctuations
   3. Noise spectrum

D. Adatom diffusion
   1. Adatom diffusion on surfaces
   2. Adatom-diffusion-induced noise
   3. Diffusion on smooth surfaces
   4. Diffusion on corrugated surfaces

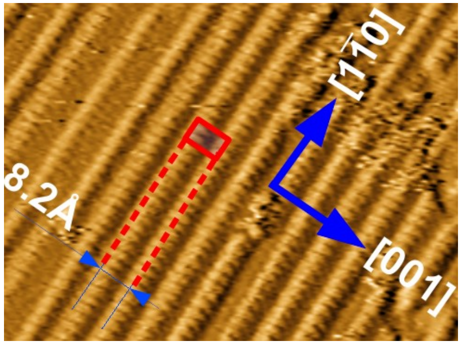
M. Brownnutt *et al.*, Rev. Mod. Phys. **87,** 1419 (2015)

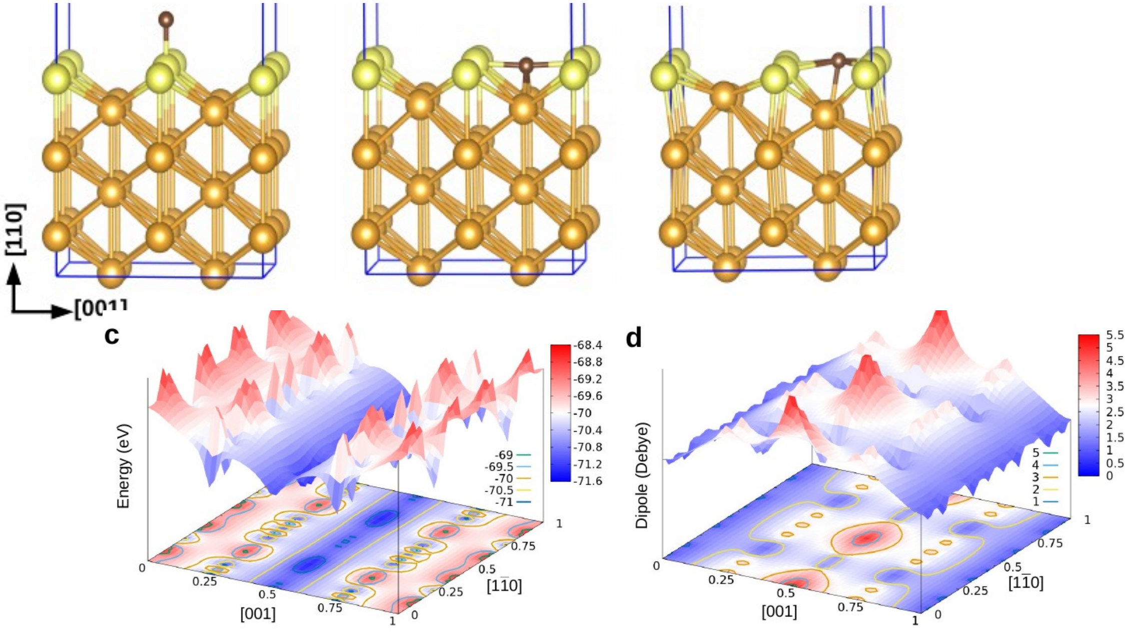
Adatoms at fixed position*





Adatoms diffusing**





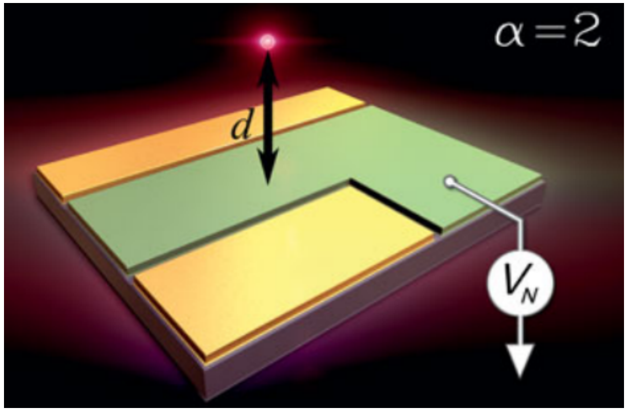
* Phys. Rev. A **84**, 023412 (2011)
** arXiv:1610.01079

What is known?

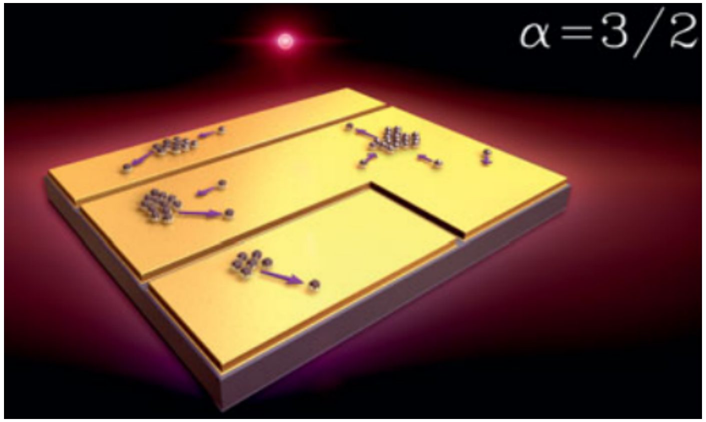
Heating rate of 1 trapped ion has been measured routinely and checked against the scaling *ansatz*

$$S_E(\omega) \sim \omega^{-\alpha} d^{-\beta} T^{\gamma}$$

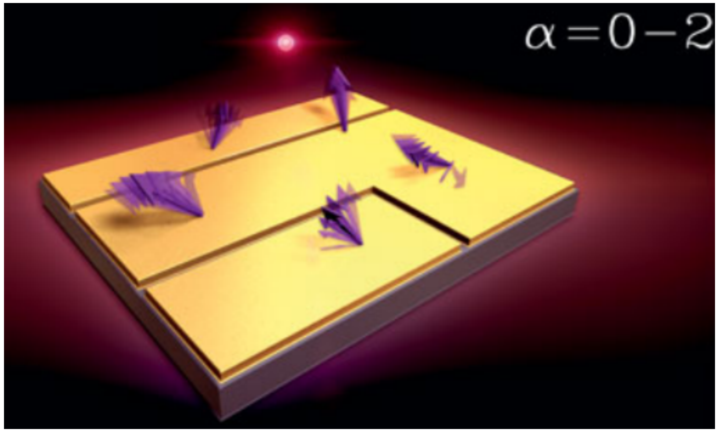
- A distance scaling exponent ~4 has been found almost always, consistent with independent (uncorrelated) point-like dipoles on the surface of electrodes. However, modifications of the exponent for miniature traps (when ***d*** is similar to dipole-dipole correlation distances) is predicted for patch models *.
- Different noise models yield different frequency scalings, e.g.:



Johnson-Nyquist noise



Adatom diffusion-induced dipole fluctuations



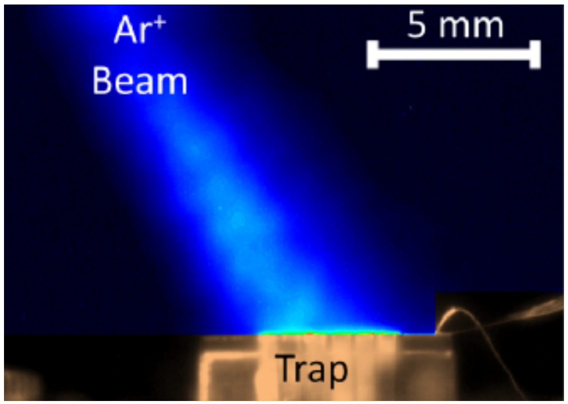
Adatom phonon-induced fluctuations

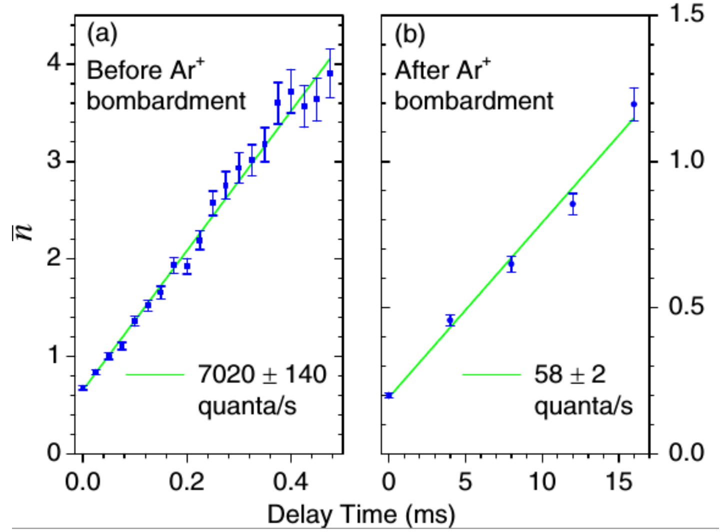
* Phys. Rev. A 80, 031402 (R) (2009)

What is known?

Recent results point at adatoms being the microscopic source:

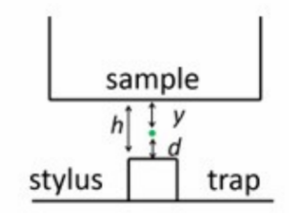
- 100-fold reduction in heating after Argon$^+$ bombardment [D. A. Hite et al., PRL. **109**, 103001 (2012)]





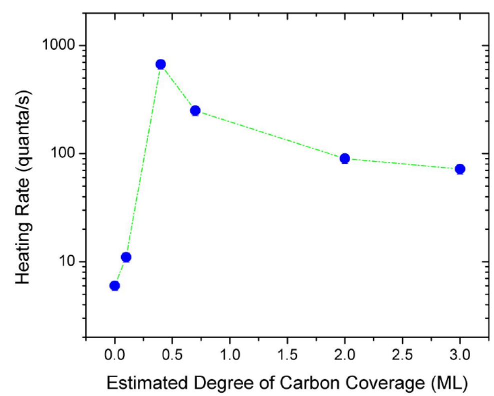
Results from this year [D. A. Hite et al., MRS Advances, **1**, (2017)] point at:

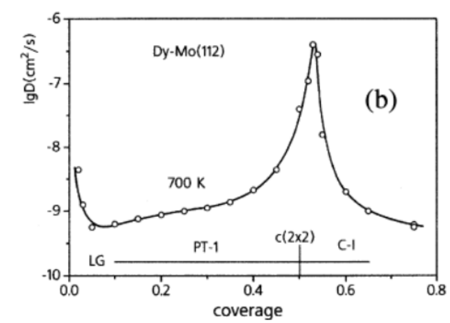
- RF-grounded electrodes as the only sources



No difference in noise between treated and untreated samples

- Diffusion model more probable





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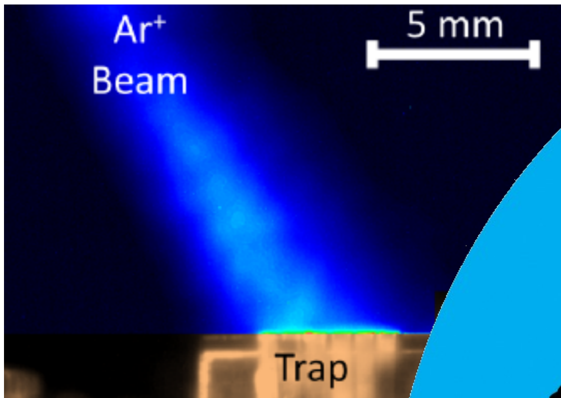
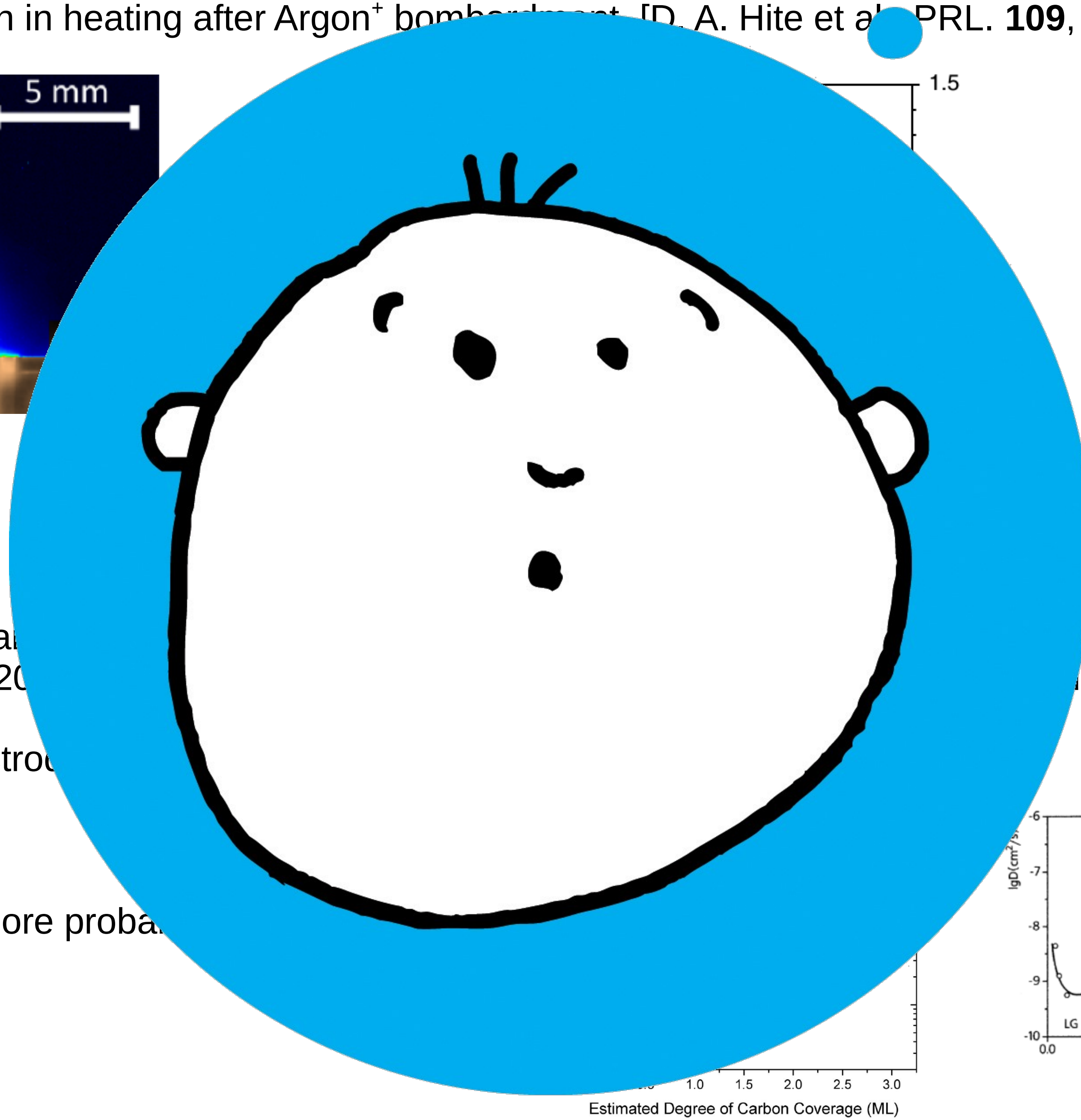
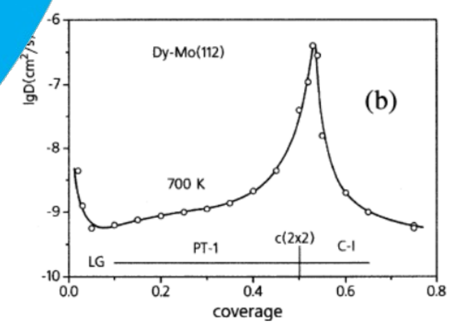




Results from this yea… between
MRS Advances, **1**, (20… samples

- RF-grounded electro…
  sources

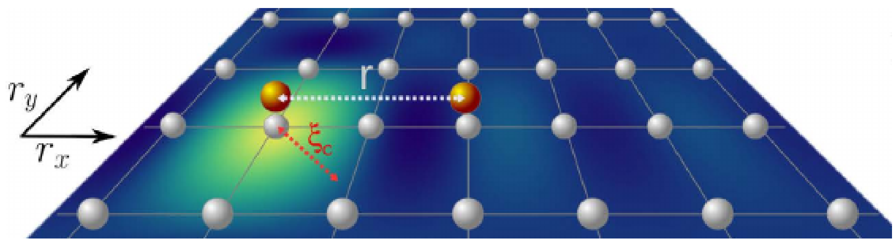
- Diffusion model more proba…

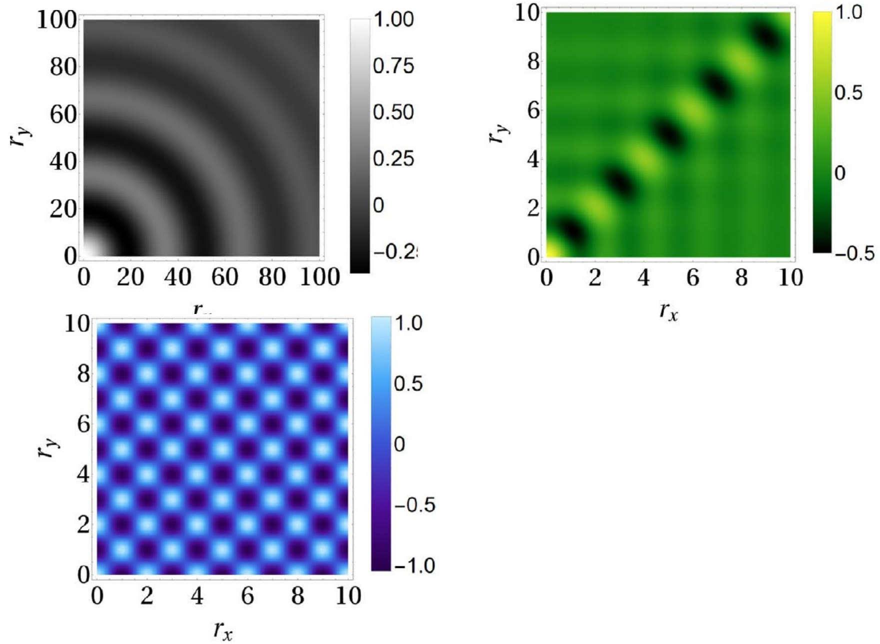


2-ions probe

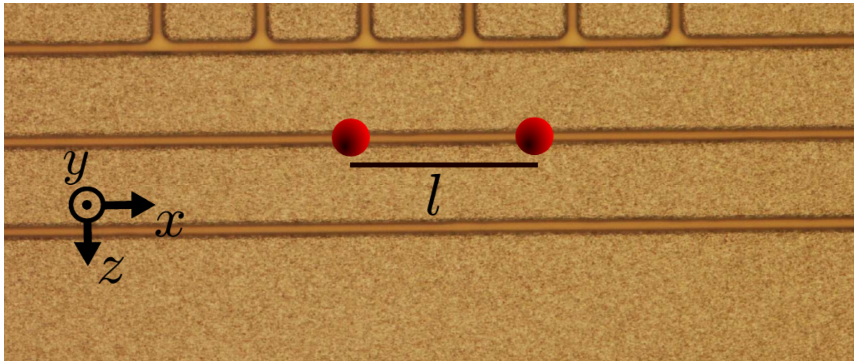
Idea: Can we learn about spatial-like features of this noise when we use a spatial probe?

- In Sci. Reps **7**, 42050 (2017) we showed that you can learn about crystal symmetry, anisotropy of dispersion relations, etc. of translational invariant, structured substrates, by studying heating rates.





In segmented surface-electrode Paul traps, 2 ions can be moved along its center axis.



arXiv:1703.09657

- Normal modes coordinates $x_\pm = (x_1 \pm x_2)/\sqrt{2}$

have heating rates $\Gamma_\pm = \frac{e^2}{4m\hbar\Omega_\pm} S_\pm$ $S_\pm = 2\int_{-\infty}^{\infty} \mathrm{d}\tau e^{-\mathrm{i}\Omega_\pm \tau} \langle E_x^{(\pm)}(\tau) E_x^{(\pm)}(0) \rangle$

(equivalently for ion's motion along other directions *y, z*)

- The modes see noise densities $S_\pm = S_{\mathrm{self}} \pm S_{\mathrm{cross}}$ which are a combination of the noise densities seen by the individual ions (self) and a *cross*-damping term.
- In the literature, the case of common-bath (CB), where center of mass (+) dissipates but relative motion does not, corresponds to $S_{\mathrm{cross}} = S_{\mathrm{self}}$
- Separate baths case (SB), where both modes dissipate, corresponds to $S_{\mathrm{cross}} = 0$
- The case where only relative motion (-) dissipates also occurs in the presence of dipole sources, when $S_{\mathrm{cross}} = -S_{\mathrm{self}}$

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- Defining $s_{i,j}(\tau) := \langle E_x^{(i)}(\tau) E_x^{(j)}(0)\rangle$ we can write $S_\pm = \int_{-\infty}^{\infty} \mathrm{d}\tau e^{-\mathrm{i}\Omega_\pm \tau}[s_{1,1} + s_{2,2} \pm (s_{1,2} + s_{2,1})](\tau)$

using $E_x(\vec{r},t) = -\partial_x \phi(\vec{r}) = \sum_i (1/4\pi\epsilon_0)\mu_i(t) g_x(\vec{r},\vec{r}_i)$

we get $s_{i,j}(\tau) = \sum_{l,k} \frac{\langle \mu_l(t)\mu_k(0)\rangle}{(4\pi\epsilon_0)^2} g_x(\vec{r}_i,\vec{r}_l) g_x(\vec{r}_j,\vec{r}_k)$

- For uncorrelated dipole sources, we have $s_{i,j}(\tau) = \sum_{l} \frac{\langle \mu_l(\tau)\mu_l(0)\rangle}{(4\pi\epsilon_0)^2} g_x(\vec{r}_i,\vec{r}_l) g_x(\vec{r}_j,\vec{r}_l)$ and we can assume homogeneous dipole fluctuations on the electrode $\langle \mu_l(\tau)\mu_l(0)\rangle \simeq \langle \mu(\tau)\mu(0)\rangle \hat{=} s_\mu(\tau)$
- So the normal mode noise densities are given basically by the combination of the spatial functions $g_n(\vec{r}_i,\vec{r}_l)$ and the Fourier transform of $s_\mu(\tau)$
- For correlated sources we will later assume a spatially-decaying correlation function

$$\langle \mu_l(\tau)\mu_k(0)\rangle \simeq s_\mu(\tau)\exp(-|\vec{r}_l - \vec{r}_k|/\xi)$$

Let us first explore the case of uncorrelated dipole sources

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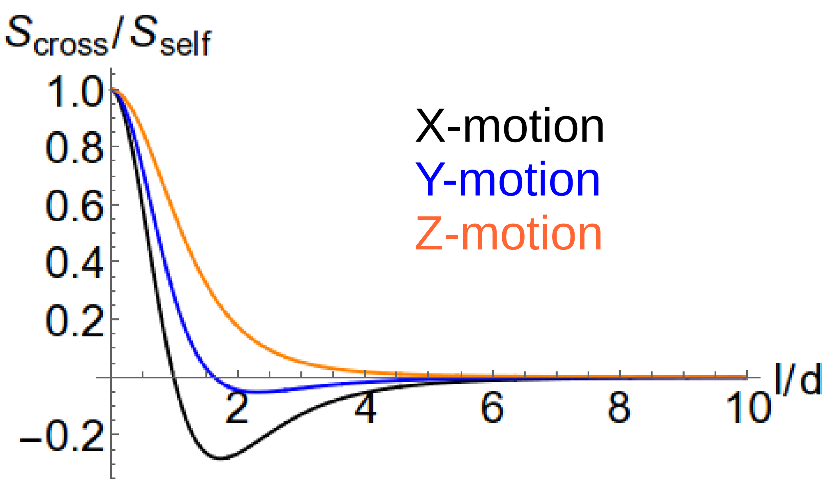
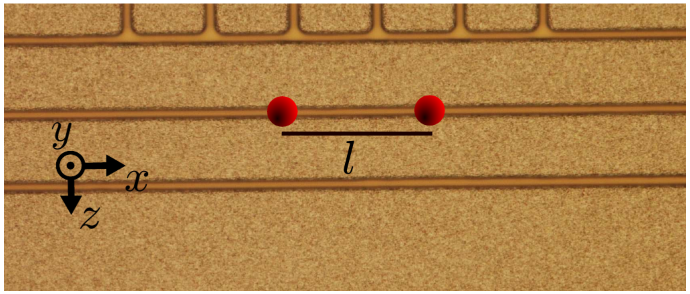
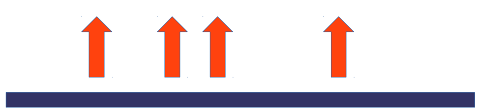
UNCORRELATED DIPOLES

- Immediate consequence of the geometric functions *g(·)* : the existence of a 0 for the cross-noise at specific ion-ion and ion-electrodes distances!







Dipoles pointing perpendicular to surface electrode

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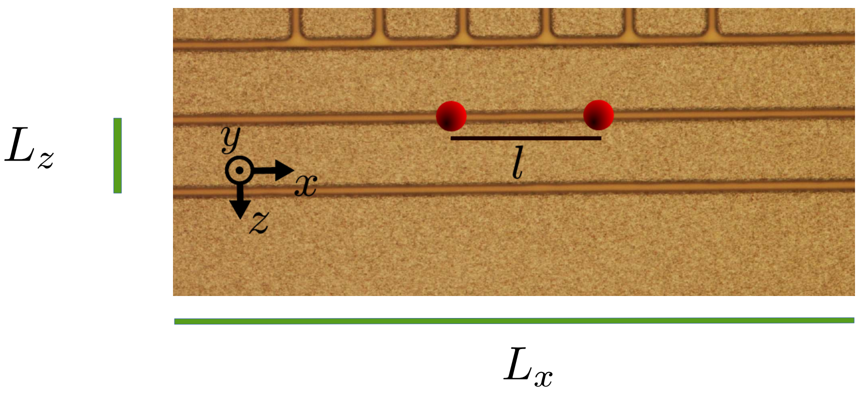
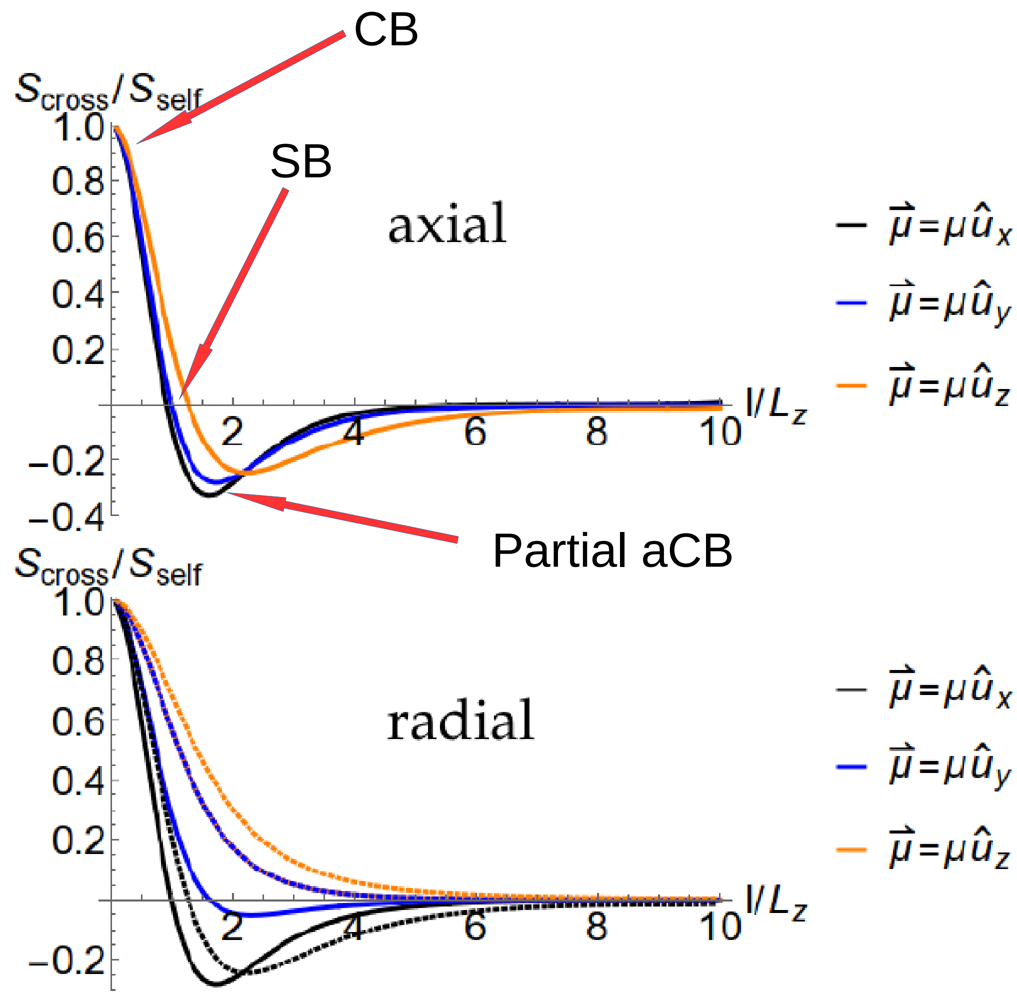
UNCORRELATED DIPOLES

- Take $d \simeq L_z$ as experimentally realistic ions-electrode distance





- The existence of this cross-over depends on the net orientation of dipoles

- A table of existence of crossover for *radial* motional degrees of freedom can tell me what the net orientation is

Crossover y-motion	Crossover z-motion	Dipole orientation
✓	✓	μ_x
✓	✗	μ_y
✗	✗	μ_z

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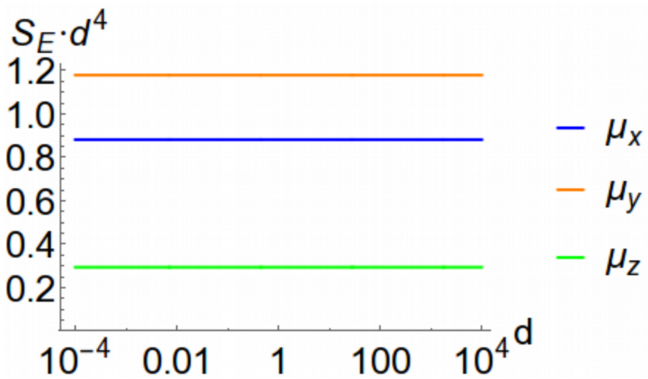
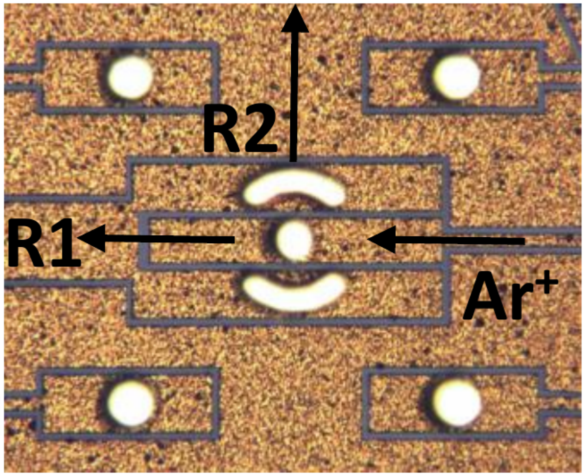
UNCORRELATED DIPOLES

- The level of noise for **1 ion** is also sensitive to dipole orientations, which might be behing recently measured noise levels in a stylus trap at NIST [D. A. Hite et al., MRS Advances, **1**, (2017) and private communications with D. Hite]





Measured noise in R1 ~5 times higher than in R2

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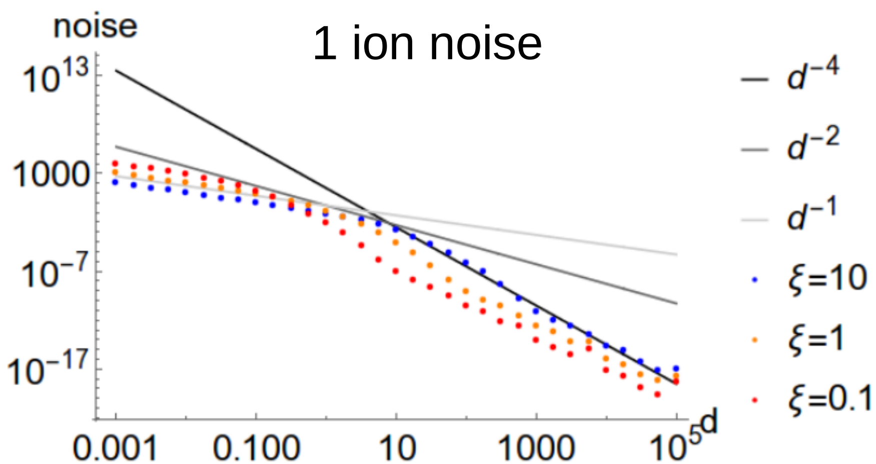
CORRELATED DIPOLES

What is the dipole-dipole correlation length of the proposed microscopic models in the literature?

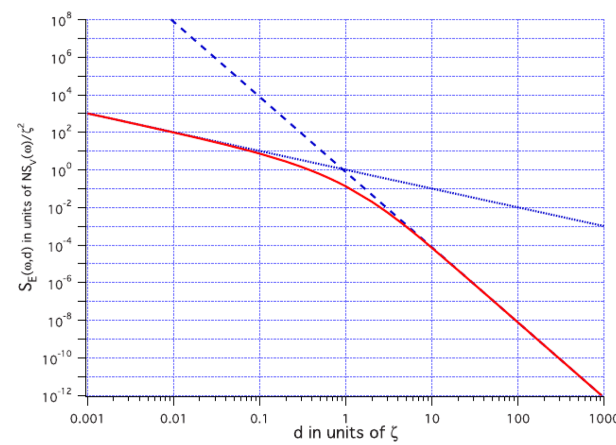
- Patch models: corr.length ~ patch size, has been measured by Kelvin probes: [10nm,10µm]
- Adatoms' dipole fluctuating due to vibrational noise in the electrode: [10nm, 0.1µm] (Neon on Gold, Hydrocarbons on Gold, respectively)
- Adatoms diffusing on the electrode's surface: ~1nm for ions motion in the Mhz regime

Can we measure it?



Can be derived from a mean-field dipole model

Formerly obtained for patch models by Dubessy,* T. Coudreau, and L. Guidoni PRA 80, 031402(R)(2009)



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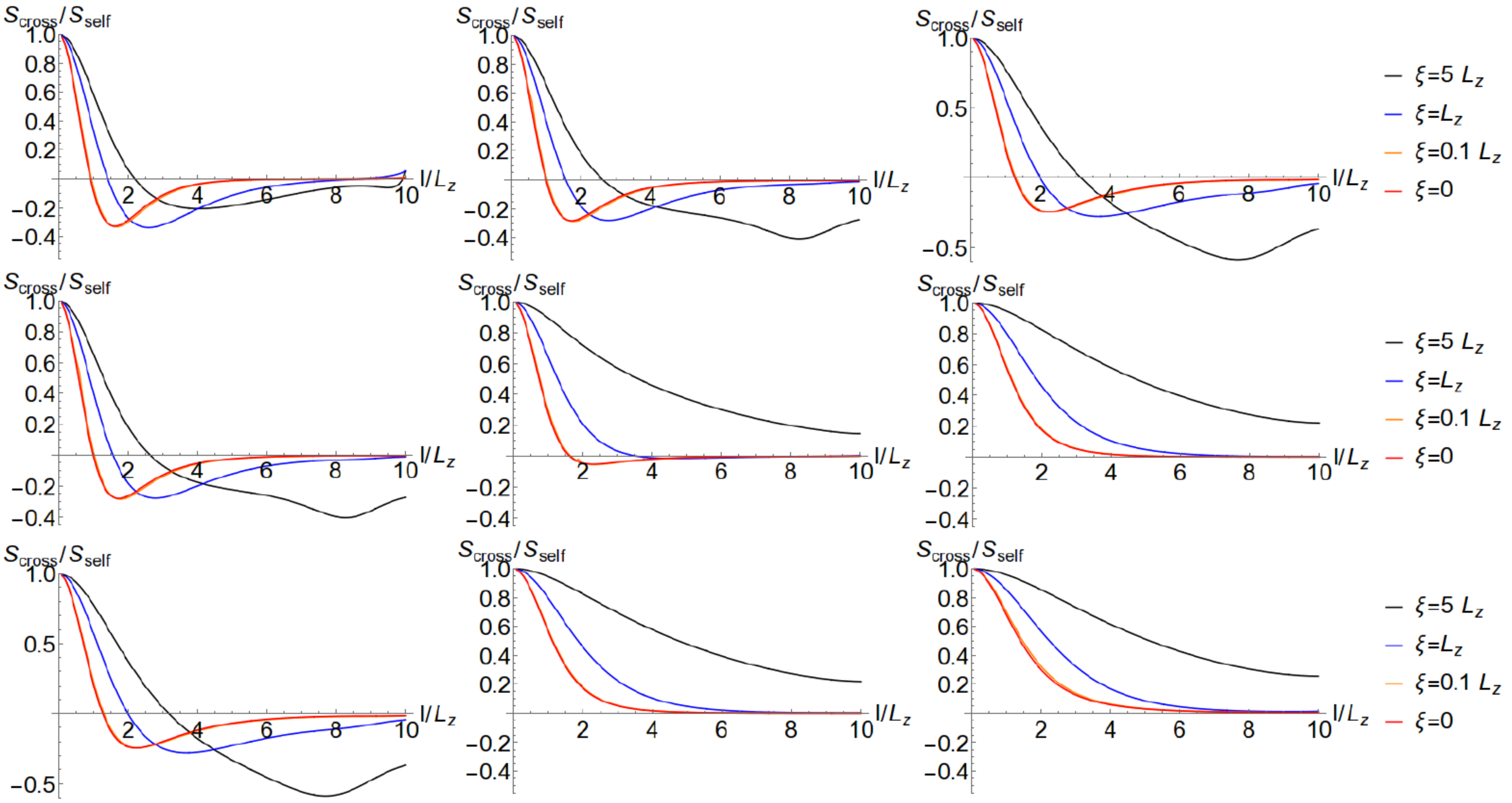
CORRELATED DIPOLES

With 2 ions : cross-over distance is changed (we take $d = L_z$)



Both for 1 ion and 2 ions probing, correlation length effects are only observed when

$$\xi \gtrsim d$$

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EXPERIMENTAL SETUP

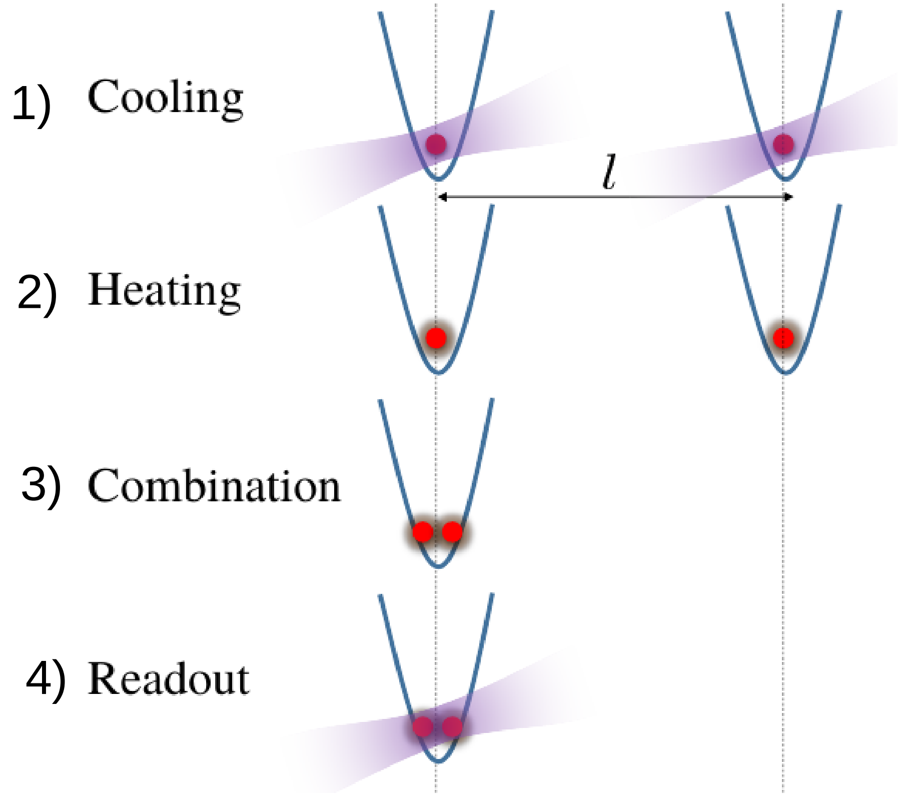
- We can measure the heating rates of normal modes to obtain

$$S_{\rm self} = (S_+ + S_-)/2 \text{ and } S_{\rm cross} = (S_+ - S_-)/2$$

- Radial (*x*, *z*) modes are used so as to be immune to step 3 (ion shuttling)
- With heating rate relative errors ε~5% we can achieve absolute uncertainty ~0.1

$$\delta S_{\rm ratio} = \epsilon\sqrt{1+S^2_{\rm ratio}}\frac{\sqrt{\Gamma_+^2+\Gamma_-^2}}{\Gamma_+ + \Gamma_-} \leq \epsilon\sqrt{2}$$

for the ratio $S_{\rm cross}/S_{\rm self}$ and thus resolve the crossover for both radial modes.



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Conclusions

- We predict a novel noise cross-over of anomalous heating in ion traps
- Taking seriously the possibility of net non-perpendicular dipole orientations we find: 1 ion sees different noise levels, 2 ions can qualitatively determine the direction of net dipole orientation (2 eyes see more than 1)
- Presence of dipole-dipole correlations translate into: modified distance scaling for 1ion, modified cross-over distance for 2 ions, although smaller traps would be required
- These effects can be put into practice with current technology with our proposed setup.

THANK YOU

for your attention