Probing Many-Body Localization in a Disordered Quantum Magnet

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Outline

- Overview of the Ising Spin Liquid,

$$LiHo_{0.045}Y_{0.955}F_4$$

- Disorder, Nonlinear Response, and Coherence
- Tuning Emergent Magnetic Degrees of Freedom

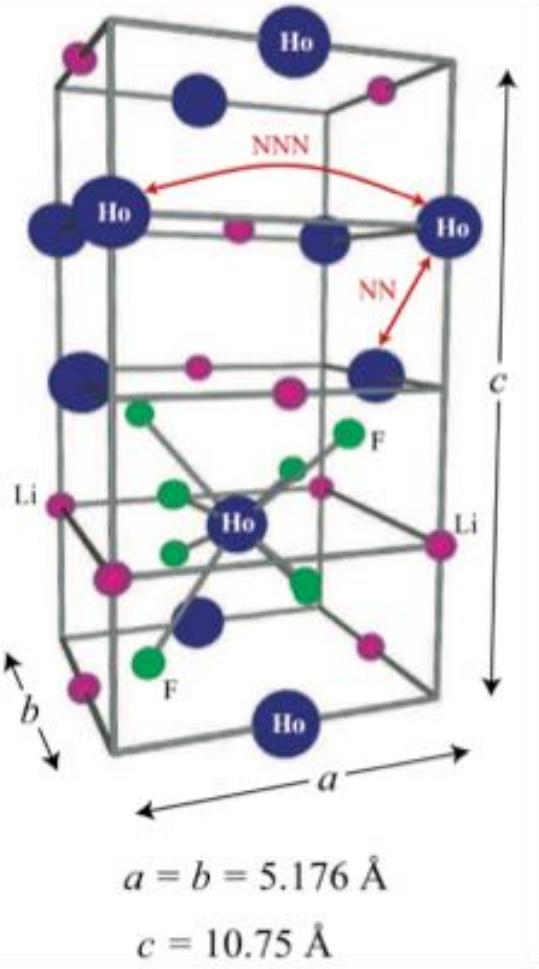
Many-Body Localization

$LiHo_xY_{1-x}F_4$

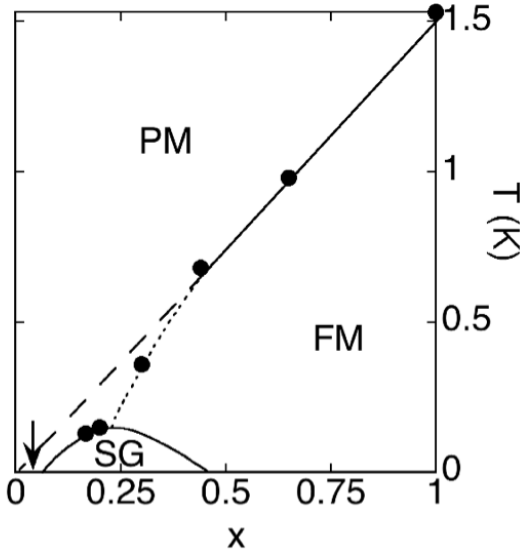
- **Parent compound $LiHoF_4$**
  - Dipolar Ferromagnet, T_c = 1.53 K

$$\hat{H} = -\sum_{i,j} J_{ij} S_i^z S_j^z - \Gamma \sum_i S_i^x$$

  - Transverse Field Ising Model
- Mix of random fields and quantum tunneling with Γ



- **$LiHo_xY_{1-x}F_4$**
- From ferromagnet
  to spin glass
  to spin liquid



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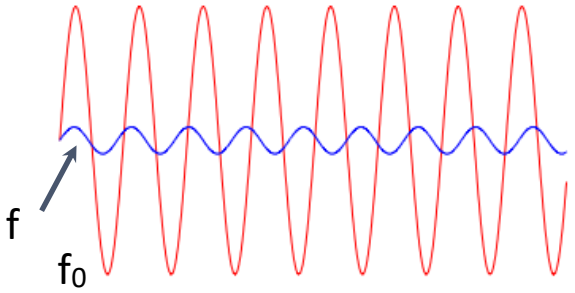
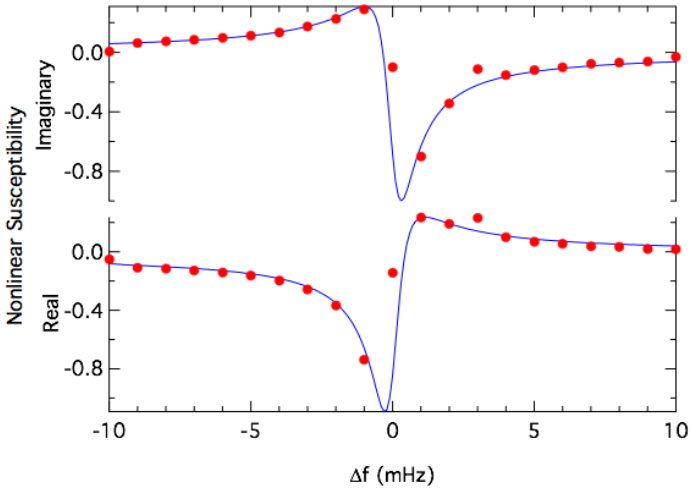
Magnetic pump-probe spectroscopy

- Drive system with two simultaneous ac magnetic fields
  - Large (~1 Oe) pump at f_o to excite nonlinear response
  - Small (~0.01 Oe) probe to measure response over range of frequencies



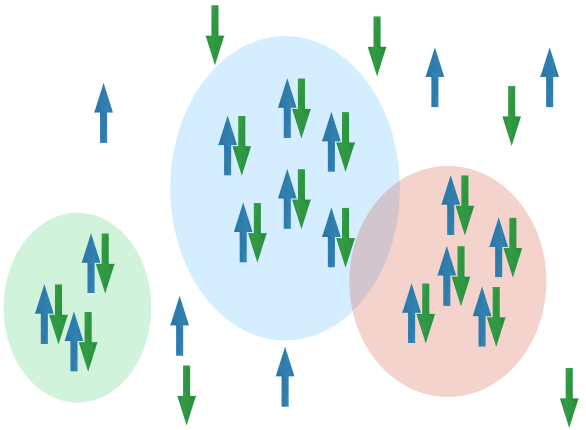
- High resolution probe shows Fano resonance around pump frequency
  - Coherent scattering between two-level system and continuum

$$\chi \propto \frac{((f - f_0) + (q\Gamma/2))^2}{(f - f_0)^2 + (\Gamma/2)^2}$$

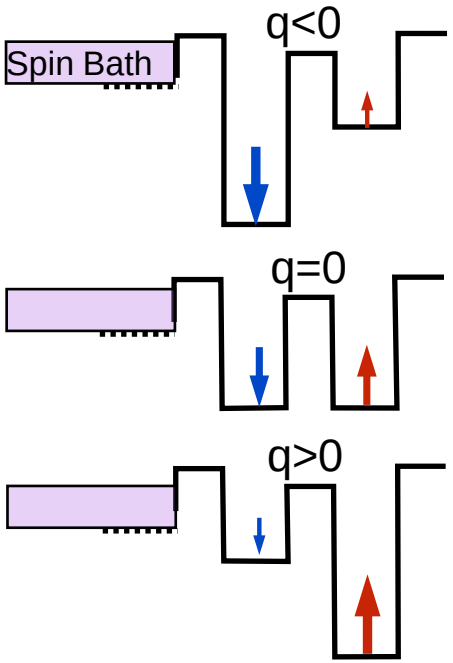


Fano Resonance probes interactions

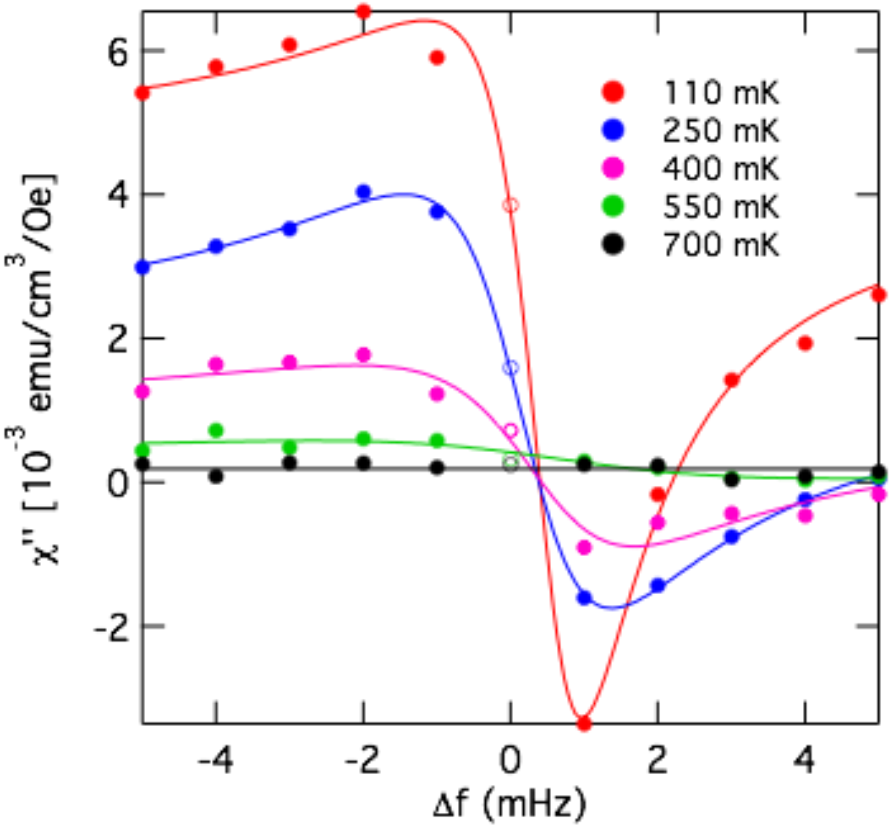
- Randomly-distributed spins form sets of clusters
  - Driven clusters oscillate coherently
  - Interactions between clusters and to diffuse bath of free spins



- External tuning parameter changes relative energy of cluster states
  - Use Fano resonance to probe energies, interaction with bath



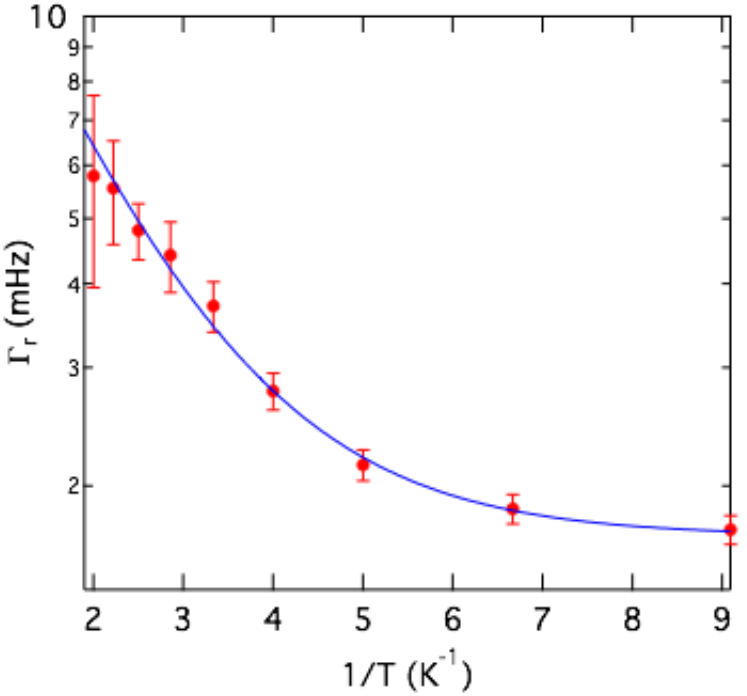
Temperature Evolution of Resonance



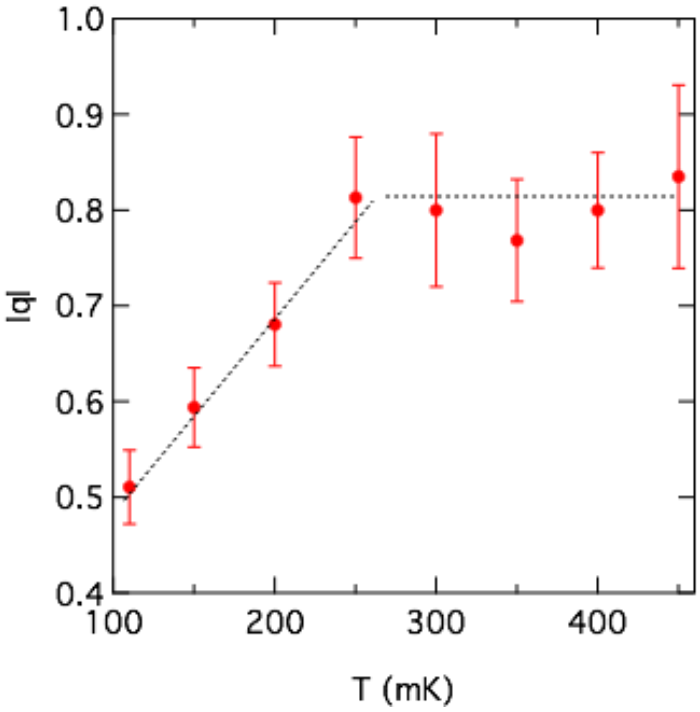
- Driven Clusters effectively melt by 700 mK

Temperature Evolution of Resonance

- Linewidth: Arrhenius + low-T cutoff



Fano parameter *q* evolves continuously for T < 250 mK



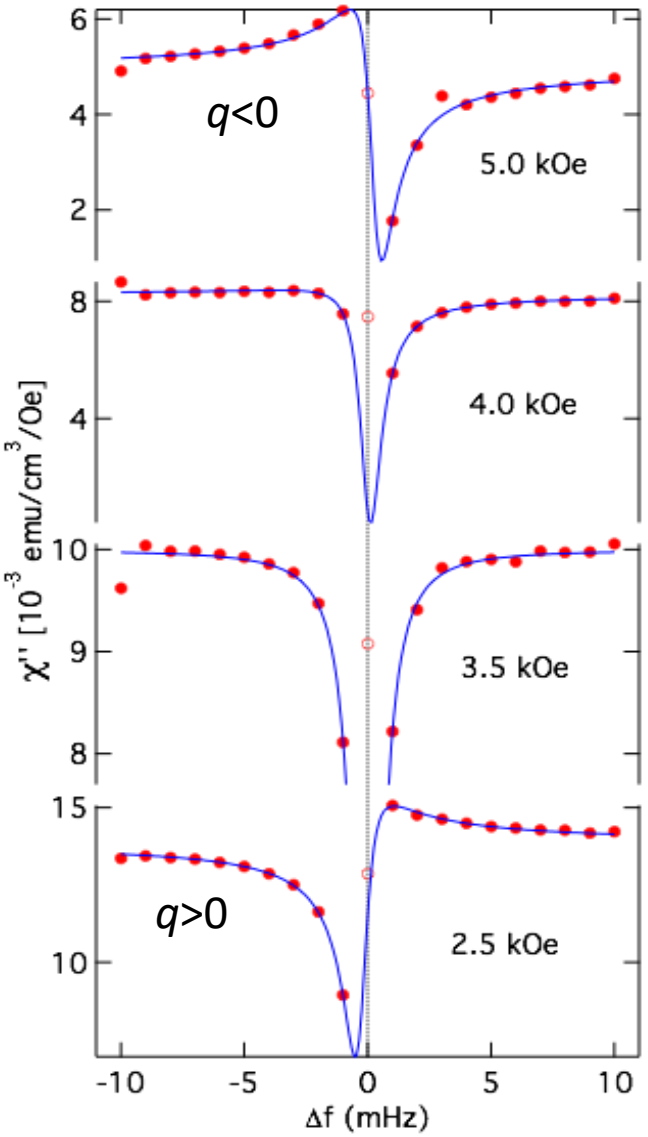
Tuning resonance with transverse field

- Tune rate of quantum tunneling by applying transverse field

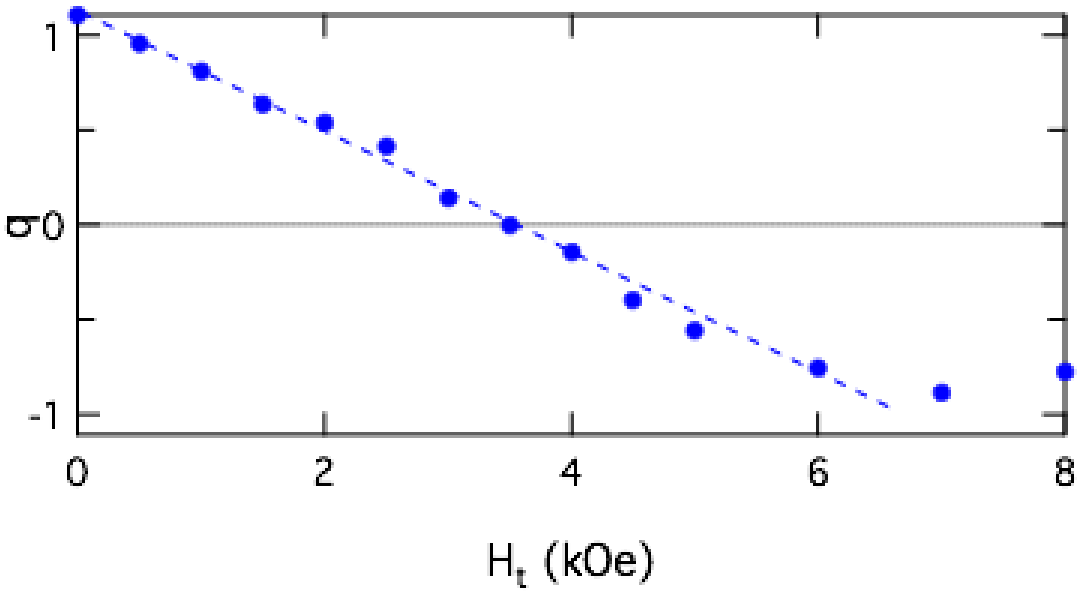
$$\hat{H} = -\sum_{i,j} J_{ij} S_i^z S_j^z - \Gamma \sum_i S_i^x$$

$$\Gamma \propto H_t^2$$

- Shift energetics & coupling of spin clusters w/o thermal broadening



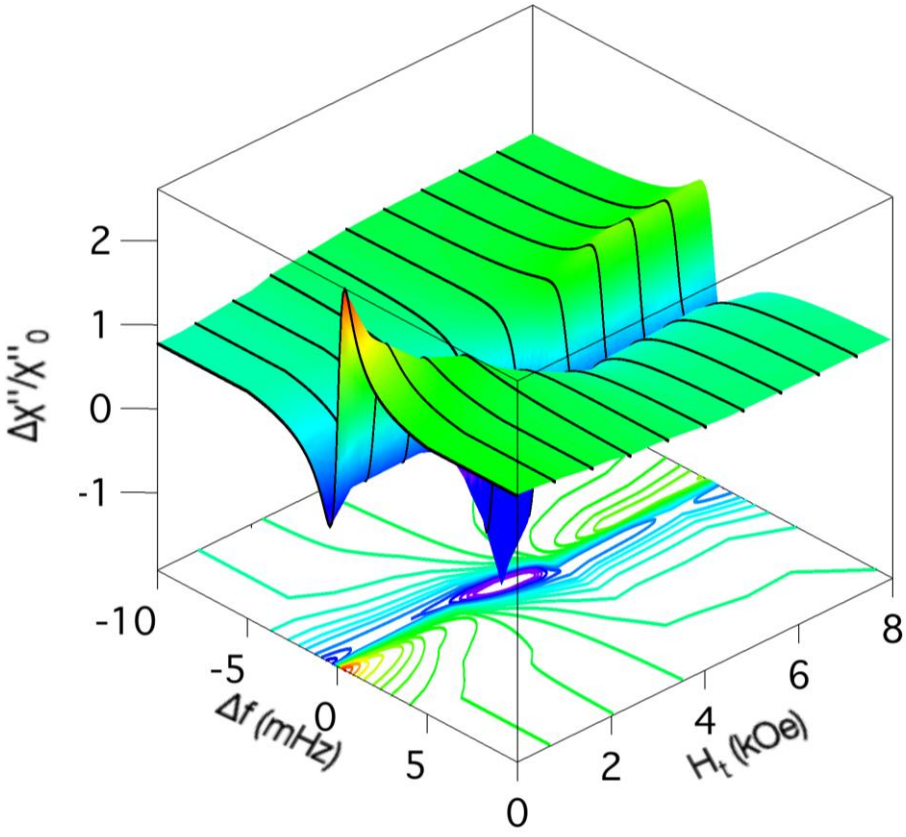
Tuning resonance with transverse field



- *q* crosses 0 at H_t = 3.5 kOe!

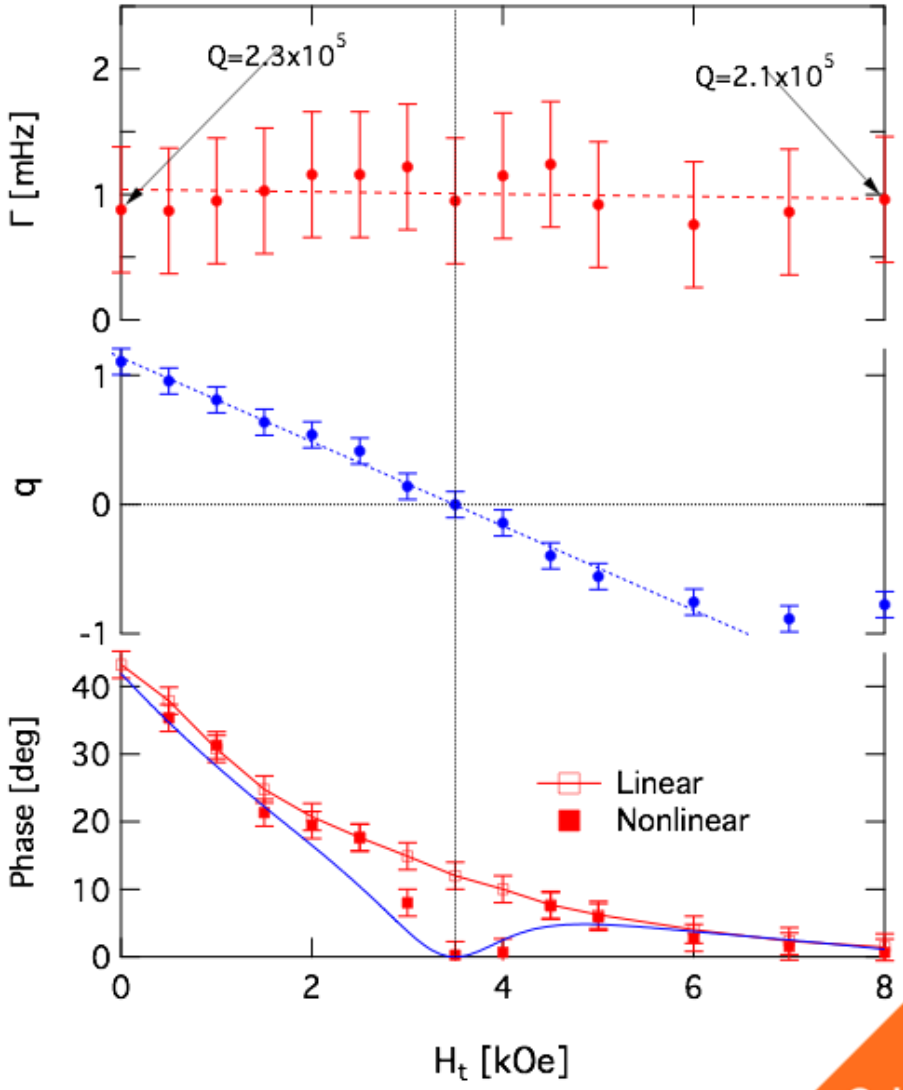
Tuning resonance with transverse field

- Linewidth stays constant as H_t (quantum tunneling rate) increases
- Long lifetime
  - Strongly localized excitations
  - Weak coupling to environment
- Tune *q* to zero: No interference between scattering pathways
  - Dissipation should be minimized when *q*=0



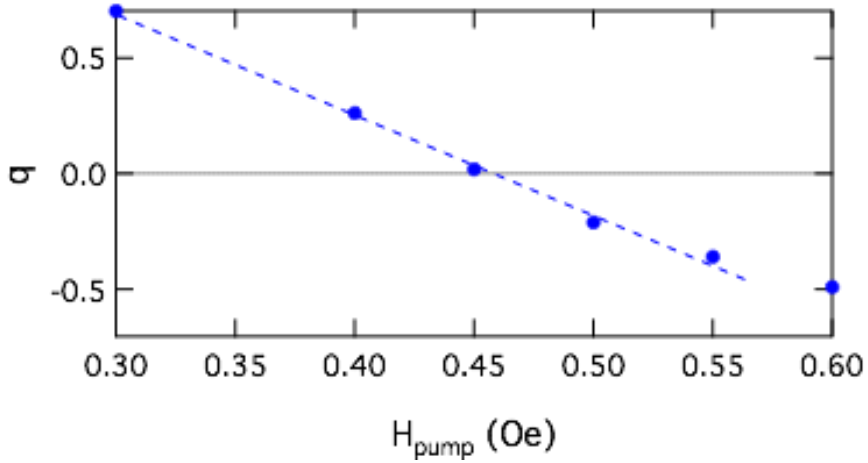
Tuning to zero dissipation

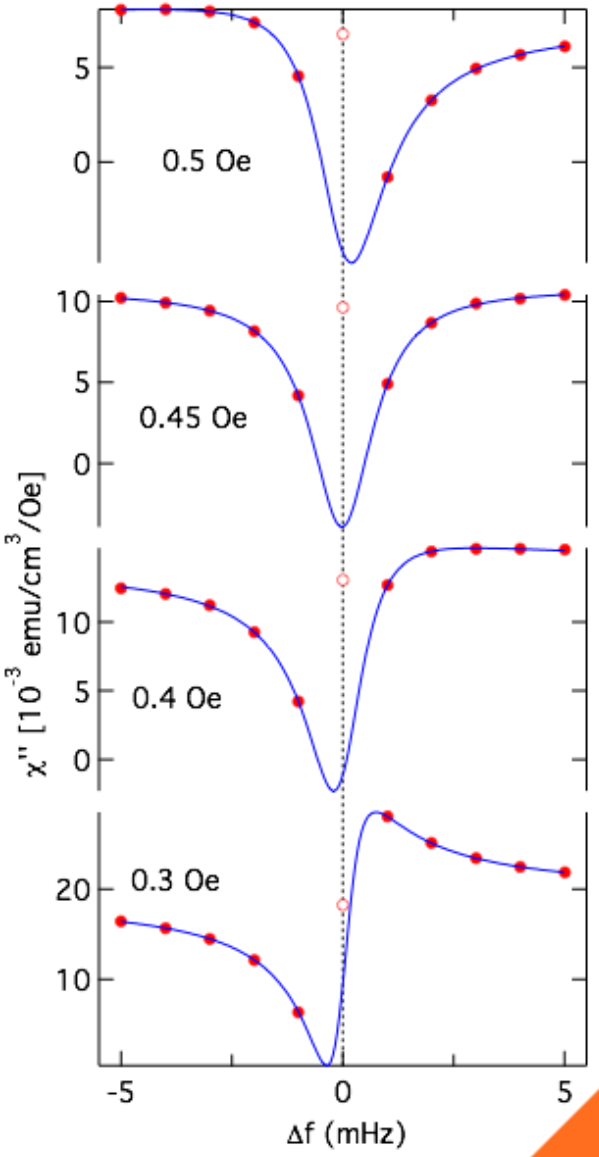
- Dissipation → Phase φ of complex susceptibility
- Nonlinear response: φ goes to zero when q changes sign
  - Vanishing dissipation as clusters decouple from the drive field
  - ***Many-body localized states that can be tuned***



Tuning with pump amplitude

- Change relative occupancy of cluster states
- Continuous evolution of *q*, sign change at 0.45 Oe
  - Energy tuning mixed with thermal broadening (heating from increased pump)





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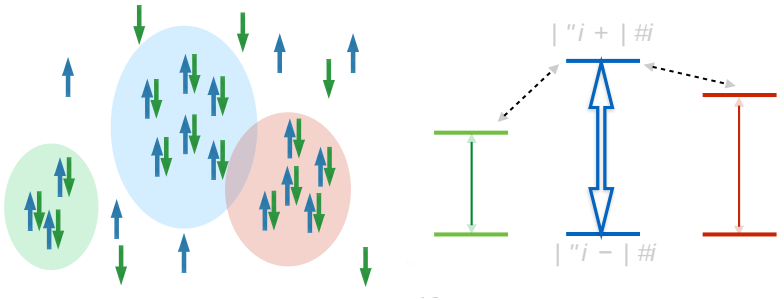
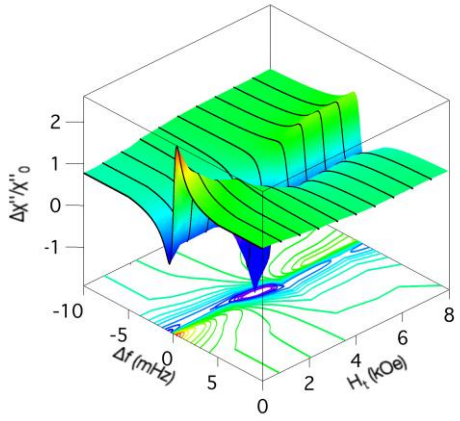
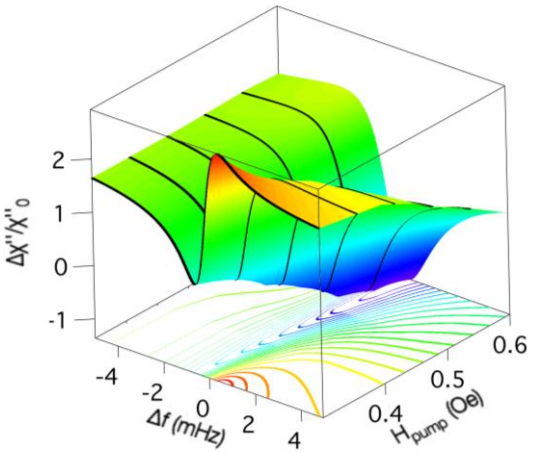
Summary

- Coherent spin clusters in $LiHo_{0.045}Y_{0.955}F_4$ studied with pump-probe magnetic spectroscopy
- Fano resonances probe interactions between clusters coupling to the spin bath
- Interactions tunable
  - Static transverse field
  - Also pump amplitude
- Clusters decouple from bath (zero dissipation), form localized states at critical value of ”quantum knob” Γ







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