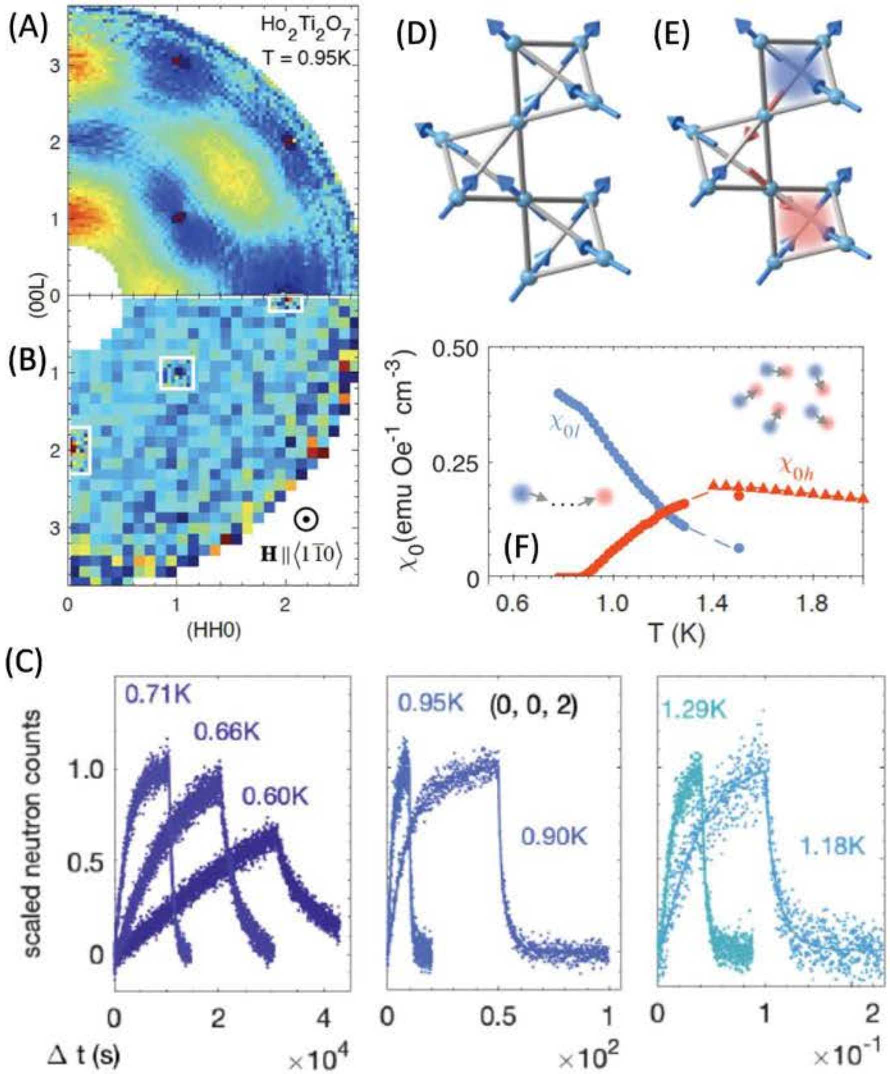
# Monopolar and dipolar relaxation in spin ice $Ho_2Ti_2O_7$




Yishu Wang, T. Reeder, Y. Karaki, J. Kindervater, T. Halloran, N. Maliszewskyj, Yiming Qiu, J. A. Rodriguez, S. Gladchenko, S. M. Koohpayeh, S. Nakatsuji , C. Broholm, Sci. Adv. 2021; **7**: eabg0908 (2021).

## Scientific Achievement

**Two distinct magnetic relaxation processes were discovered in the spin-ice compound $Ho_2Ti_2O_7$. The cross-over in the relaxation dynamics is associated with spin fractionalization into monopoles.**

## Significance and Impact

**While dipolar relaxation dominates at higher T, a unique low T regime with exponentially activated Debye-like relaxation is associated with monopole motion through the spin-ice vacuum.**

## Research Details

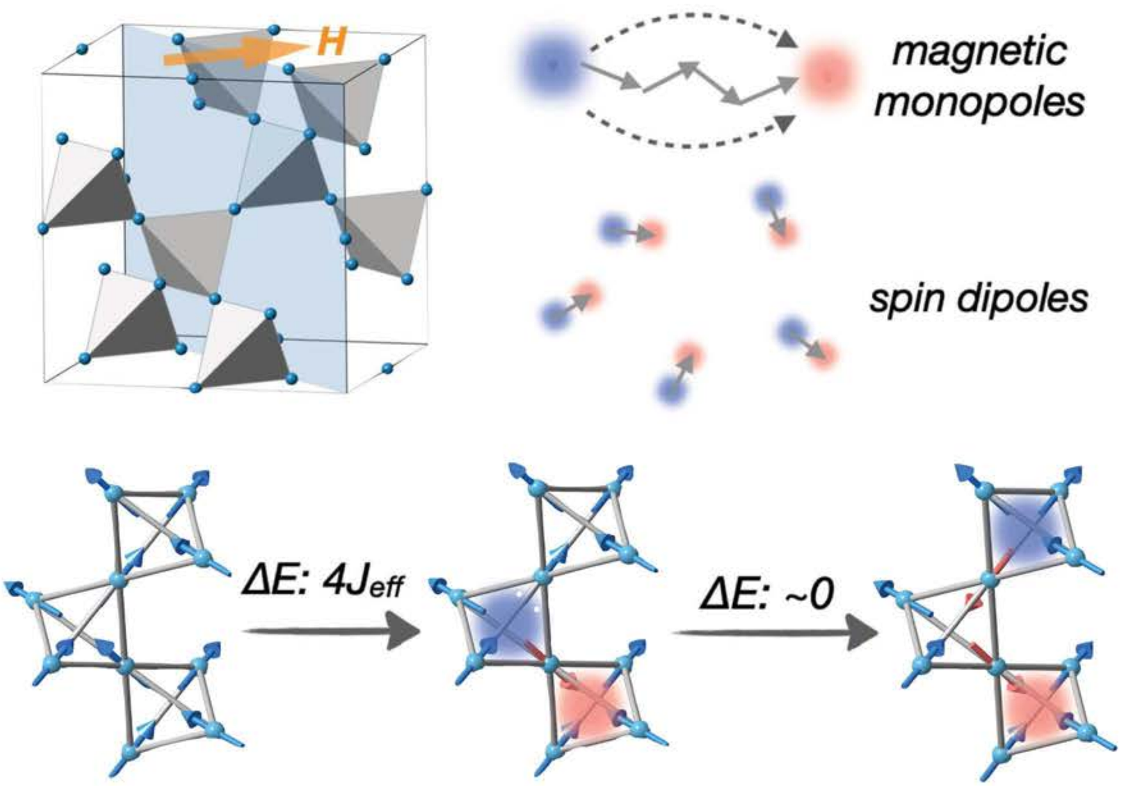
– A time resolved neutron scattering technique was developed to probe slow magnetic dynamics (ms to hours) with atomic scale spatial resolution

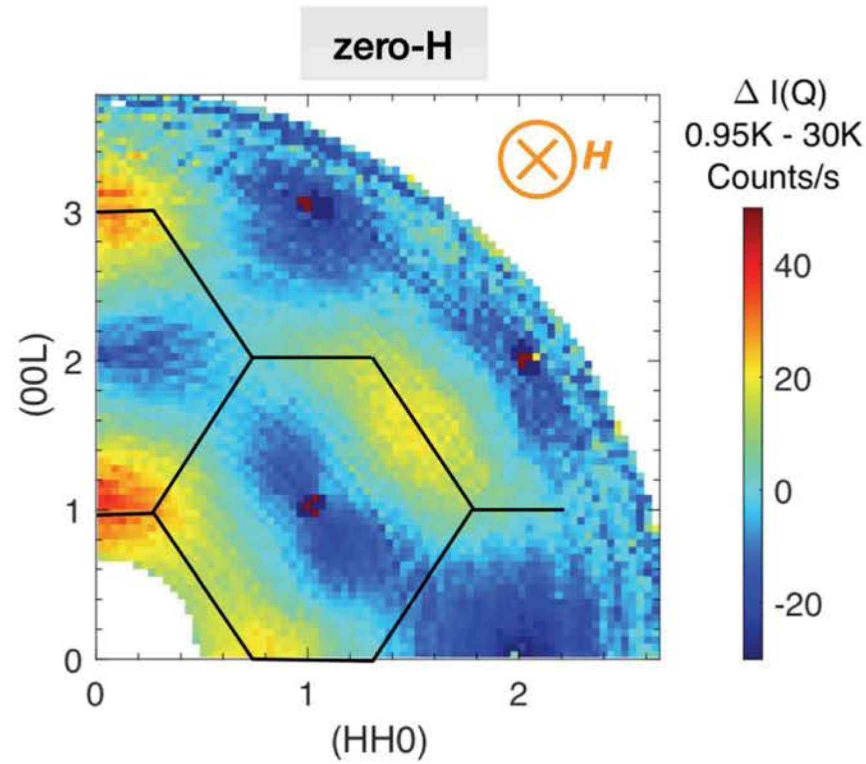
– A new class of ultra-pure $Ho_2Ti_2O_7$ crystals grown by a travelling solvent floating zone method was needed to manifest individual monopole dynamics

– Observing this regime in $Ho_2Ti_2O_7$ is encouraging for the prospects of coherent quantum dynamics of monopoles in quantum siblings such as $Ce_2Zr_2O_7$

# Spin ice and magnetic monopoles at zero magnetic field

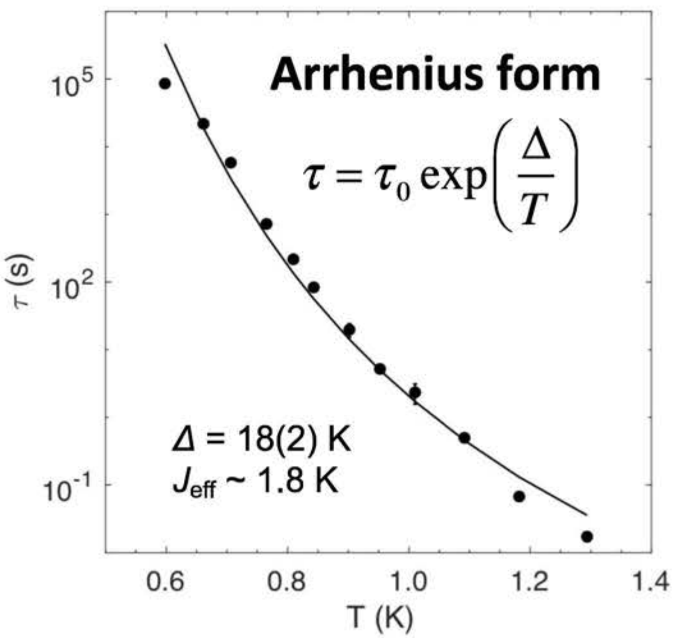
- Spin ice: ferromagnetic Ising spins + pyrochlore lattice → 2-in-2-out
- Zero-field neutron scattering reveals absent diffraction at Brillouin zone centers and diffuse intensity at zone boundaries.
- Successive spin-flips via quantum tunneling should fractionalize a spin dipole into a pair of magnetic monopoles.

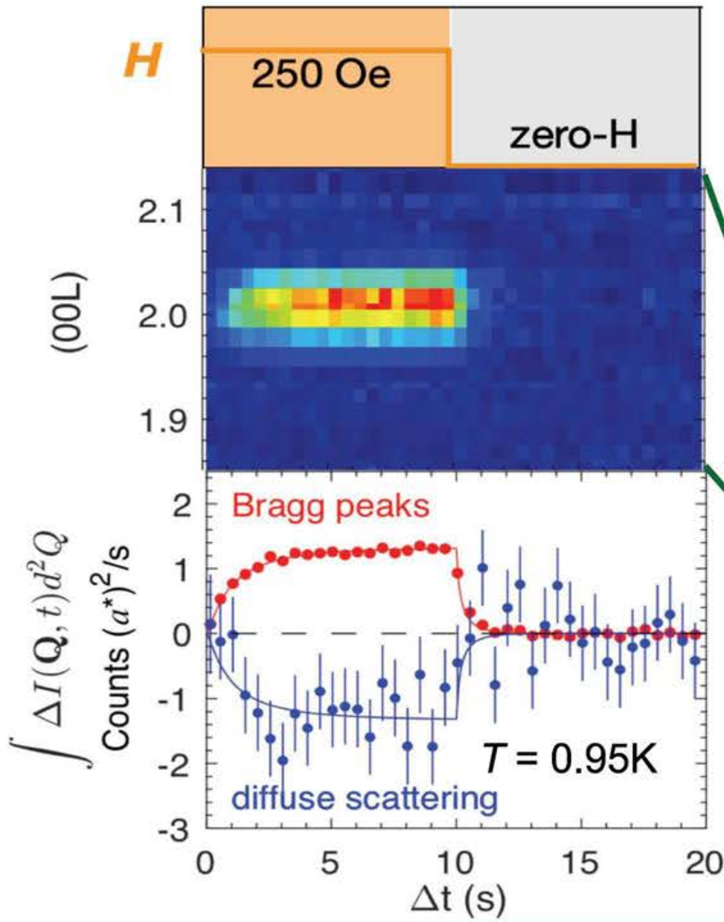


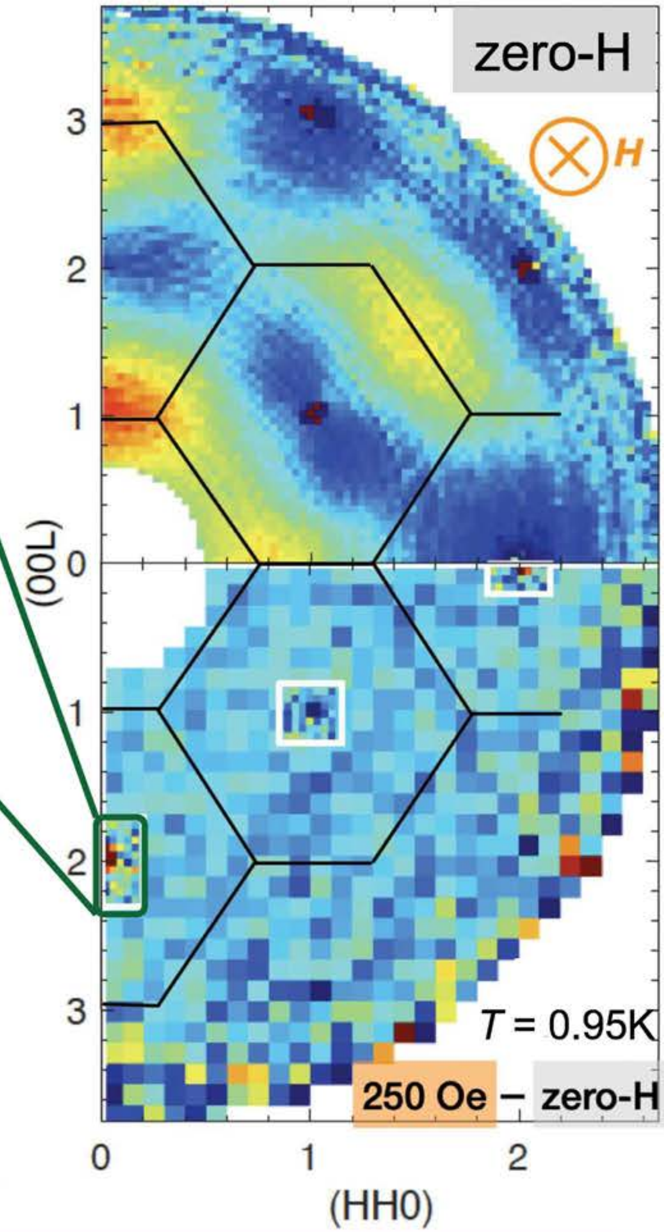



# Time-resolved neutron scattering under a small field

- Spin ice ground state is unperturbed. ($\mu H << k_B T$, $J_{eff}$)
- Spins aligned along the field direction give rise to magnetic scattering at the zone centers.
- The magnetization process relies on the thermal excitation.

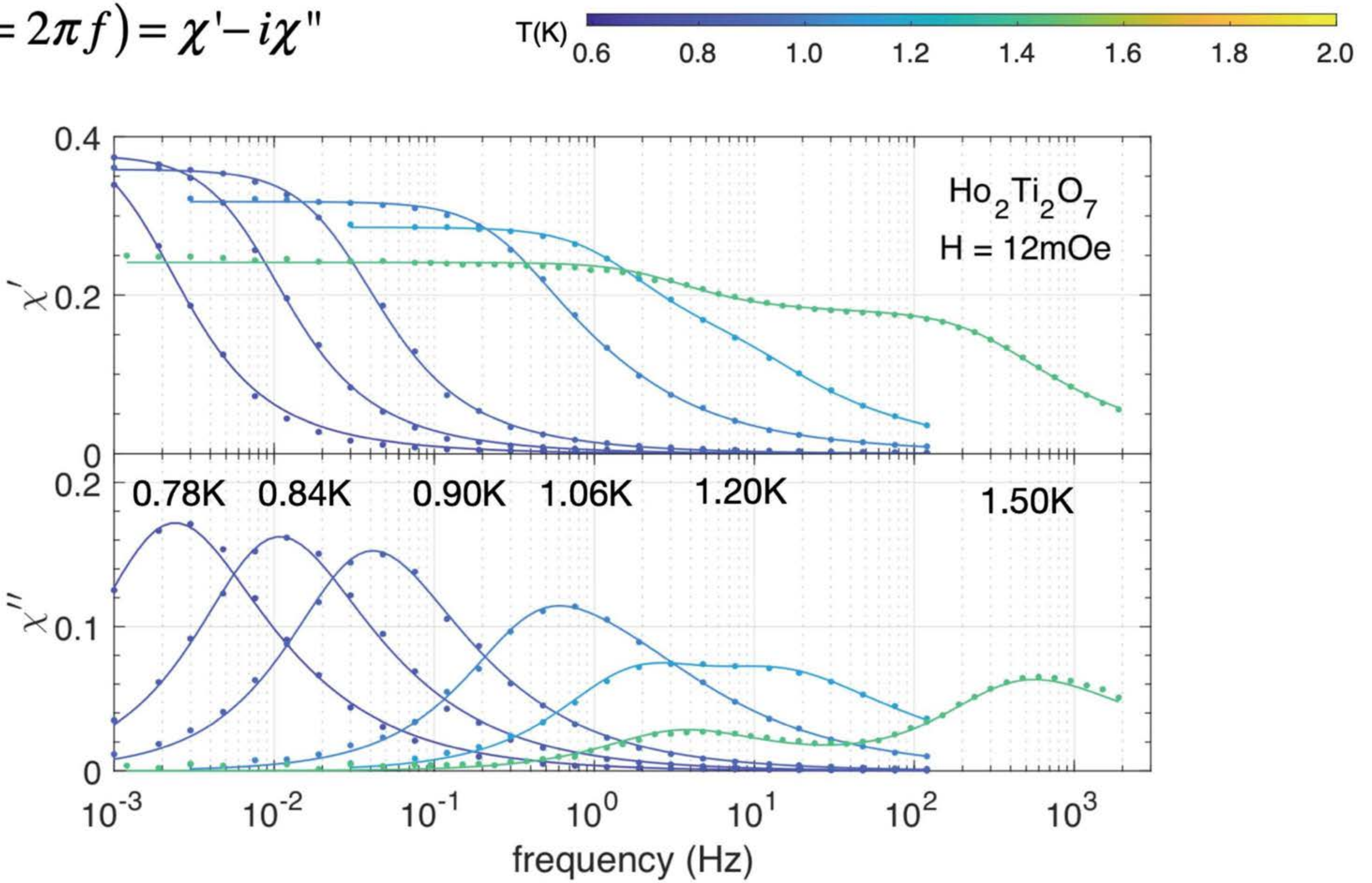


# AC susceptibility in a broad range of *T* and frequency

$$\chi(\omega = 2\pi f) = \chi' - i\chi''$$



# Thermal crossover revealed by AC susceptibility

$$\chi(\omega = 2\pi f) = \chi_l + \chi_h = \frac{\chi_{0l}}{(1+i\omega\tau_l)^{\beta_l}} + \frac{\chi_{0h}}{(1+i\omega\tau_h)^{\beta_h}}$$

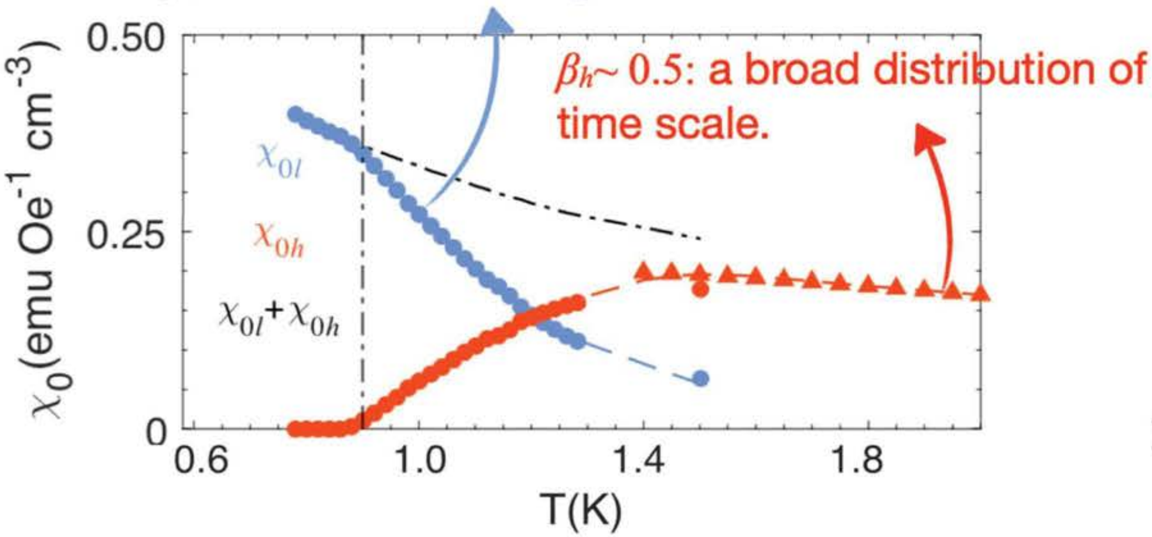
**Cole-Davidson form**

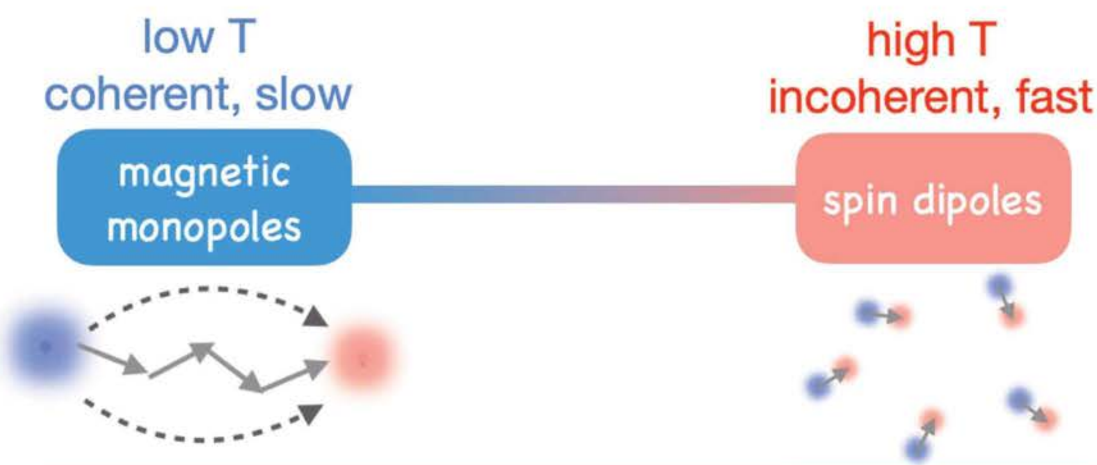
$\chi_0$ — static susceptibility

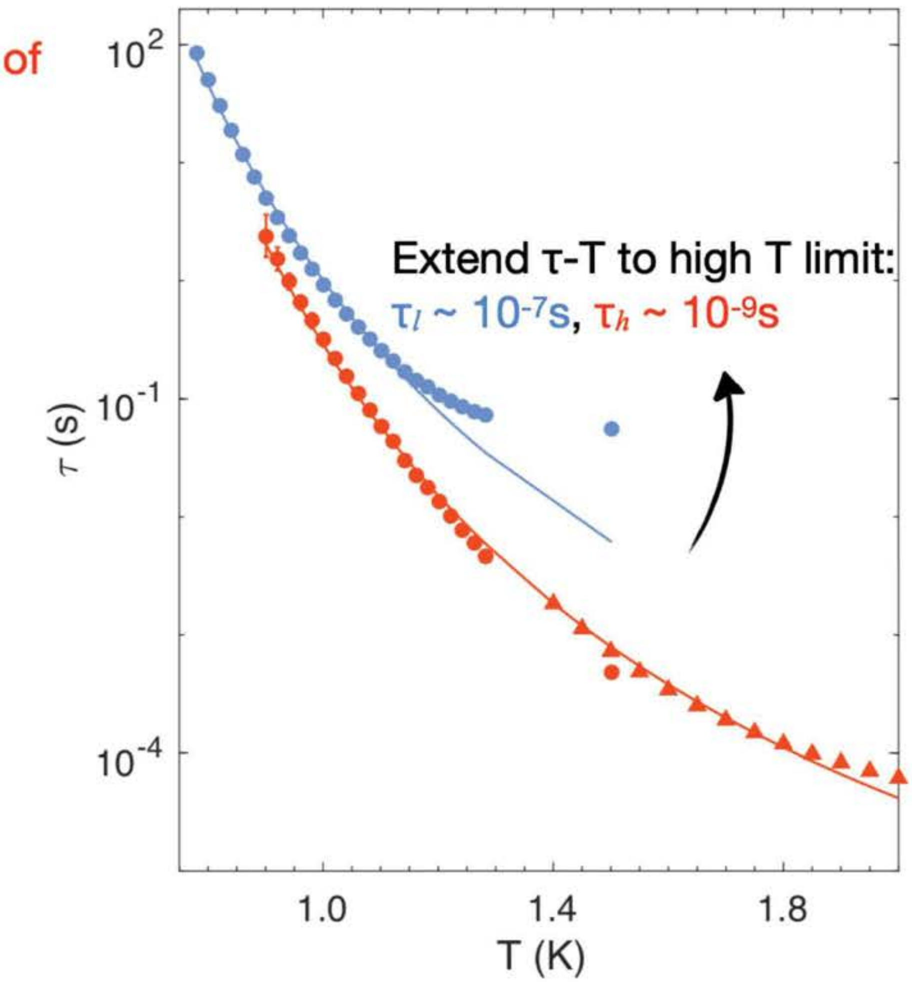
$\tau$ — time scale

$0<\beta<1$ — distribution of time scale

$\beta_l \sim 0.8$: close to a single time scale.





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# Sensitivity to disorder

- Reduced disorder slows dynamics, making two time-scales experimentally distinguishable
- Debye relaxation is approached at low-$T$ in the pure crystal.