LARGE-SCALE QUANTUM PHENOMENA

COURSE

to be given at the

UNIVERSITY of INNSBRUCK

(June 2010)

universität innsbruck

PiTP

UBC

25 years cifar

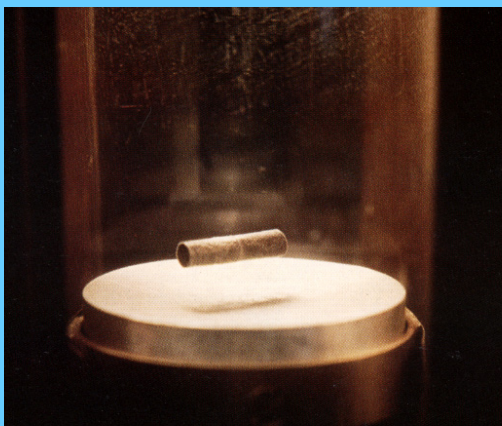
Canadian Institute for Advanced Research

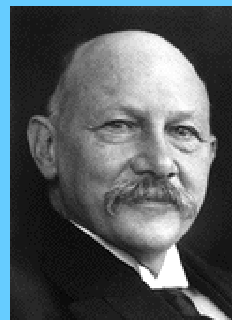
INTRODUCTION

1. BASIC PHENOMENA
2. EXPERIMENTAL OBSERVATIONS
3. THEORETICAL FRAMEWORK

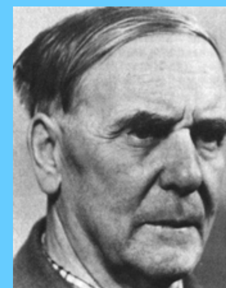
LARGE-SCALE QUANTUM PHENOMENA: Traditionally associated with superfluids & superconductors- superflow, the Meissner and Hess-Fairbank effects, the Josephson effects, etc.- and most dramatically, macroscopic quantum tunneling and coherence in SQUIDs.

But can one envisage large-scale quantum phenomena in any other system?





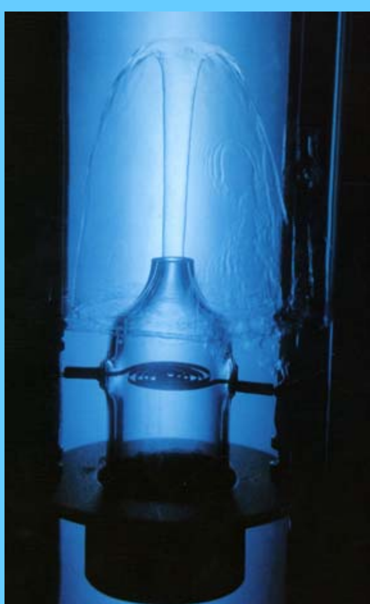
H K Onnes (1853-1926)



PL Kapitza (1894-1984)

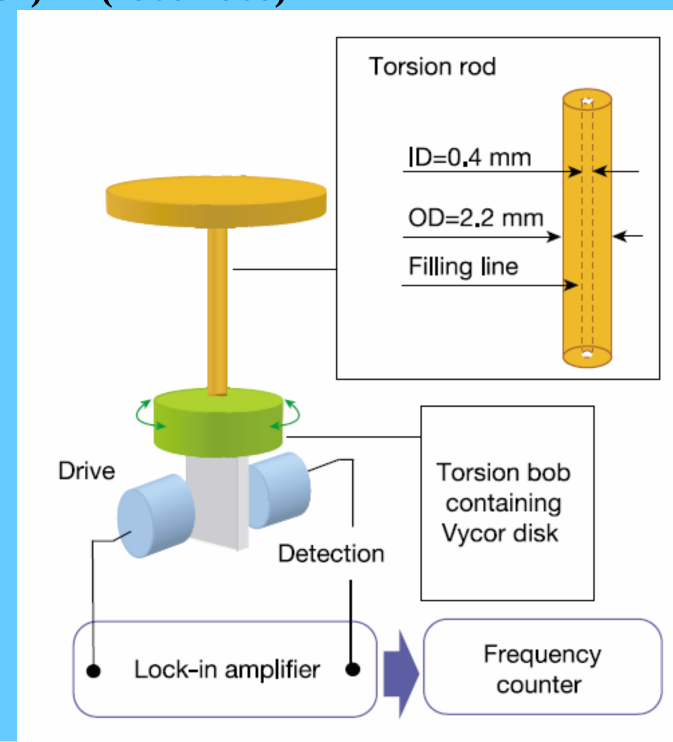
F London (1900-1954)

LD Landau (1908-1968)



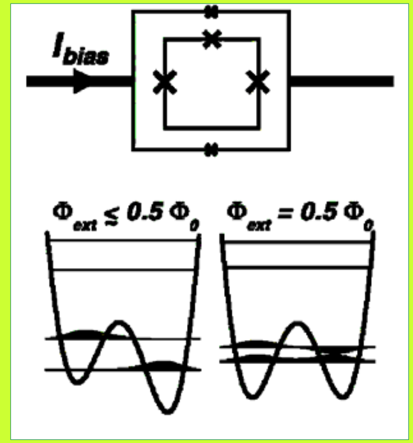
Some of the remarkable phenomena that depend on off-diagonal long-range order: persistent currents/Meissner & Hess-Fairbank effects; fountain effect.

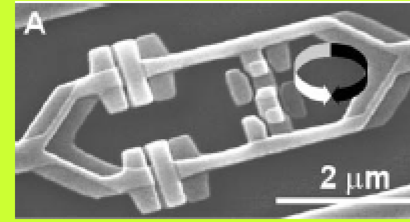
Last but not least, supersolidity (whose nature has yet to be really clarified), discovered in 2003 (M Chan et al.)

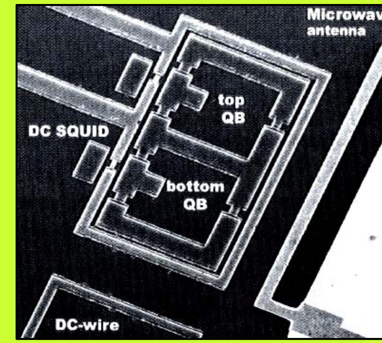


Large-Scale Q Phenomena in Solids: SOLID-STATE QUBITS

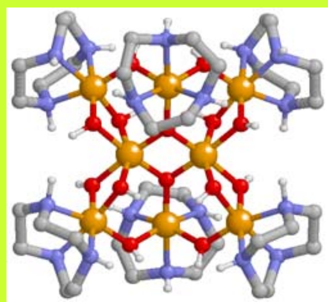
(1) Superconducting SQUID qubits (where qubit states are flux states); all parameters can be controlled.

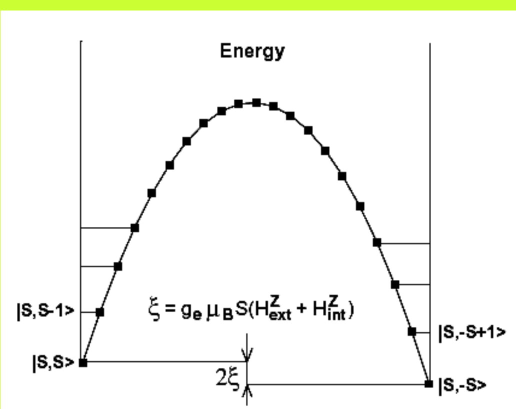


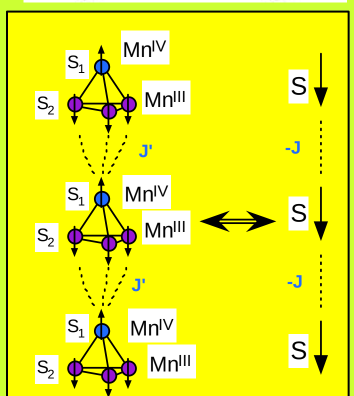




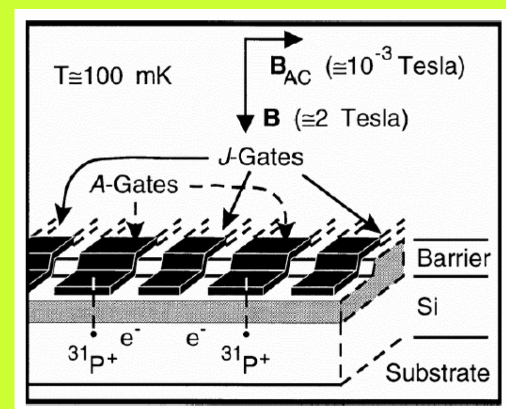
(2) Magnetic molecule qubits (where an easy axis anisotropy gives 2 low energy spin states, which communicate via tunneling, & couple via exchange or dipolar interactions. Control of individual qubit fields is easy in principle- interspin couplings less so...







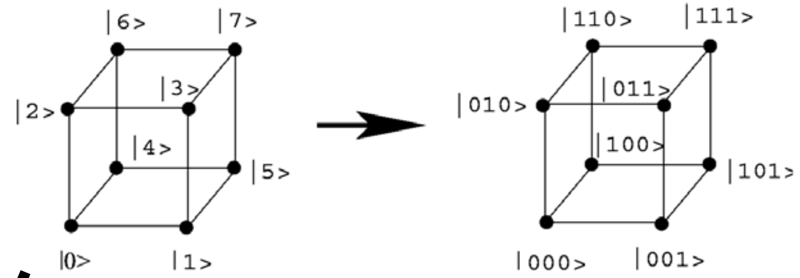
(3) Spins in semiconductors (or in Q Dots). Local fields can be partially controlled, & the exchange coupling is also controllable.

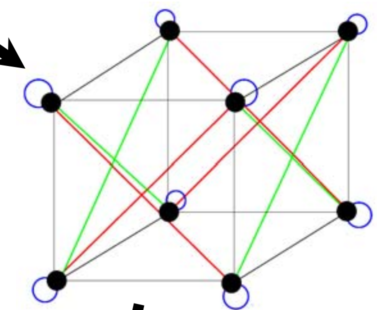


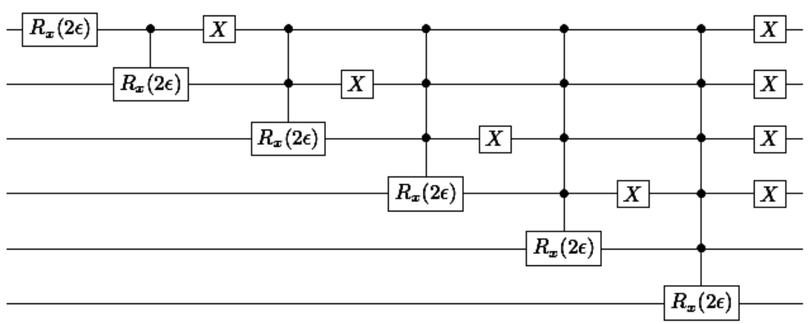
QUANTUM INFORMATION PROCESSING

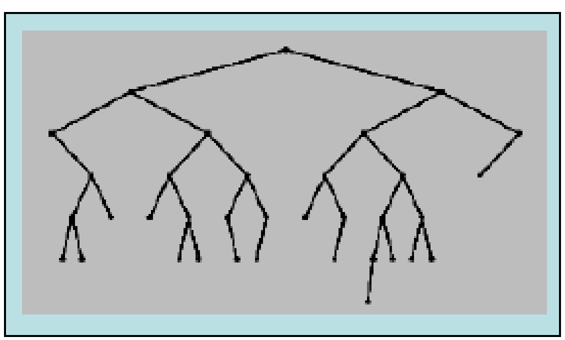
One of the great research enterprises of today is the effort to make systems with large-scale entanglement

We can map QIP processes involving qubits, etc., to a system of a particle hopping around a graph. Thus one can think of any quantum computing process as a quantum walk in quantum information space.

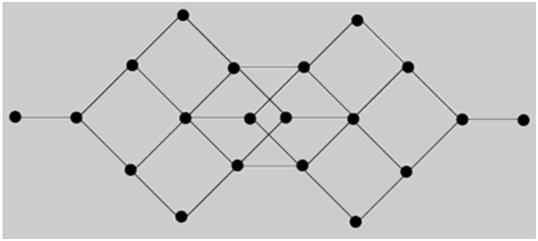






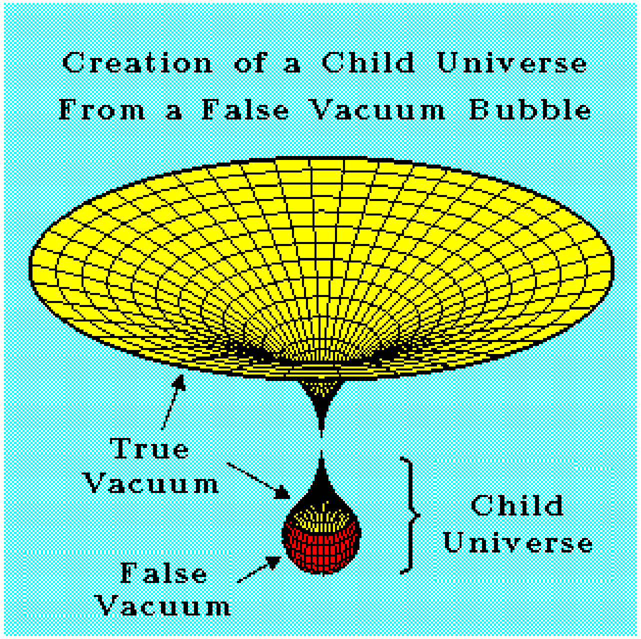


Large variety of different graphs on which the “walker” can undergo quantum diffusion.



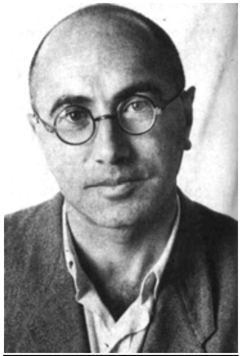
Q: How to implement this in the real world?

Really Large-Scale Quantum Phenomena

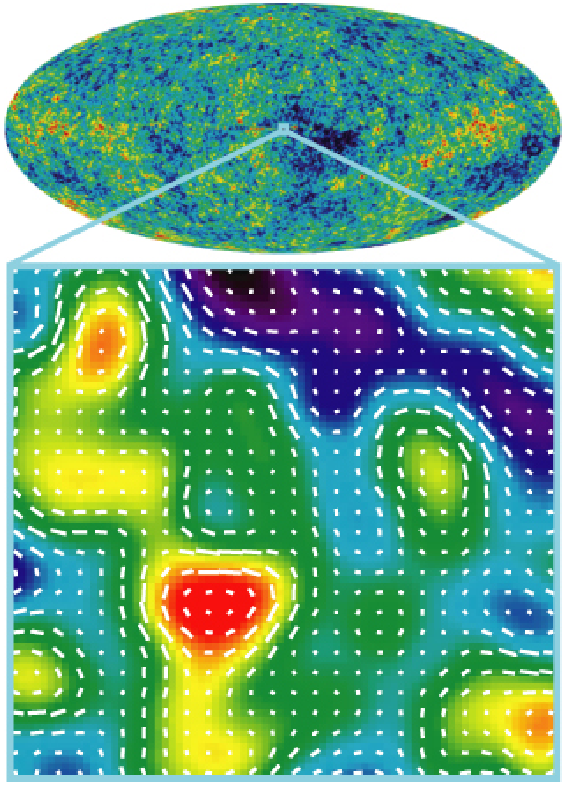


In the last few decades evidence has grown for the “inflationary universe” scenario of the formation of the universe. Support for it from measurements such as the WMAP results has given real confidence in this picture.


Alan Guth (1947-)


YB Zeldovich (1914-1984)

The idea that one can apply quantum mechanics
to the entire universe
Has become almost commonplace amongst theorists.



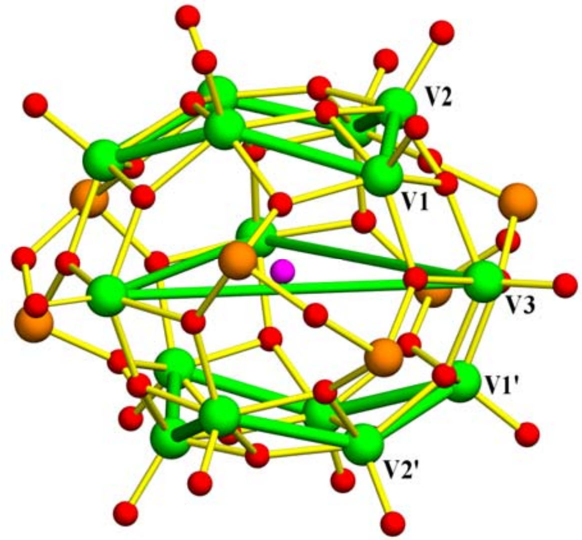
One can even go on to discuss ‘multiverses’ in this context.

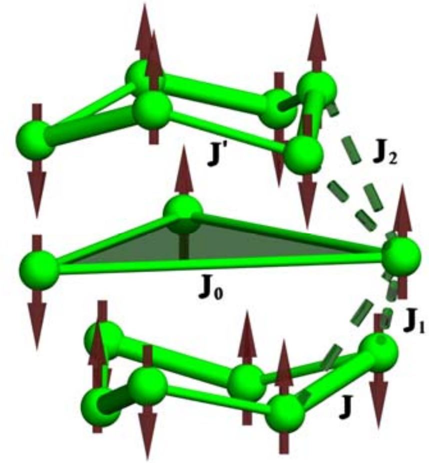
2. EXPERIMENTS

Coherence & Decoherence in LARGE-SPIN MAGNETIC MOLECULES

Large-spin magnetic molecules can tunnel between different spin orientations.

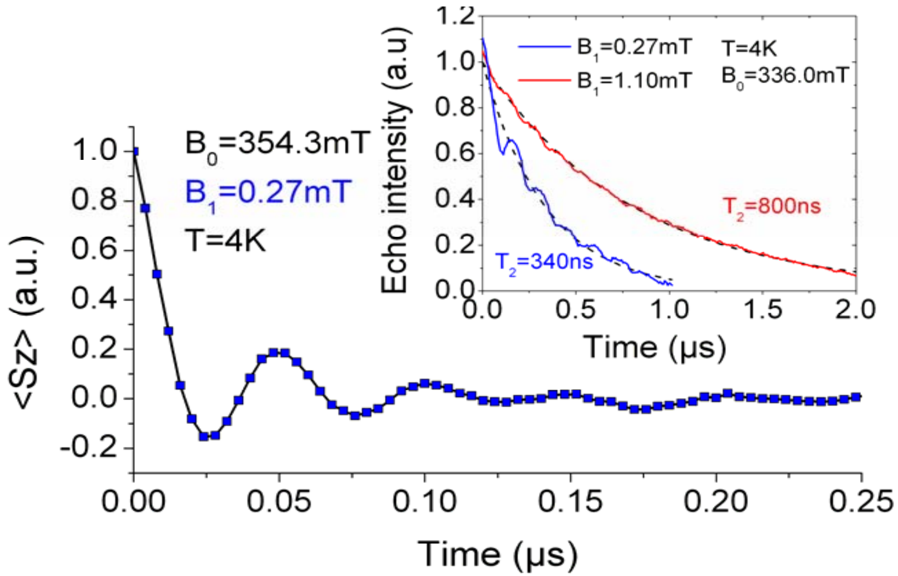
Very good agreement with theory was claimed for the V-15 system, by Bertaina et al. Nature 453, 203 (2008). The decoherence comes from nuclear spins, phonons, and dipolar Interactions between molecules.

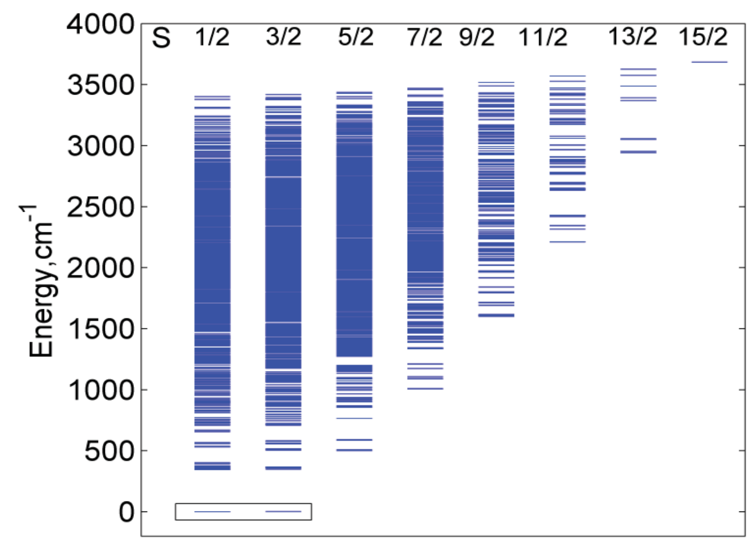




SPIN & Level structure of the molecule

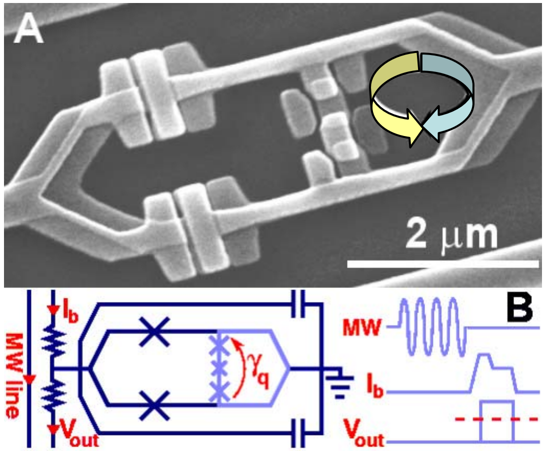
RABI Oscillations

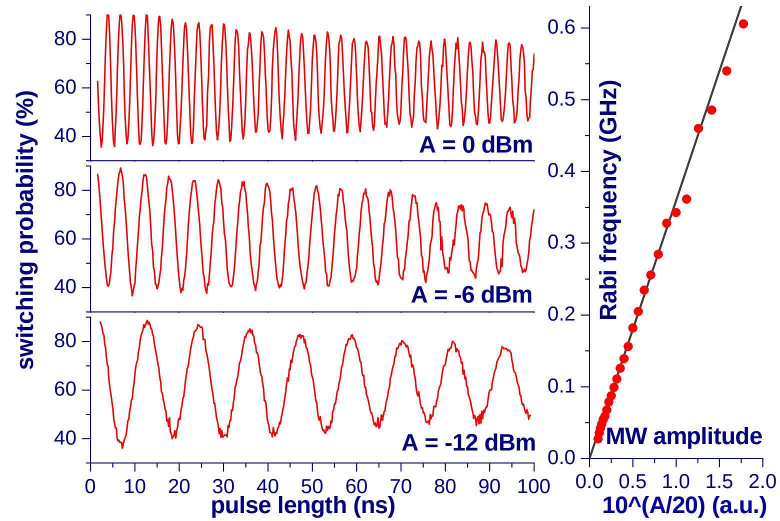




COHERENCE & DECOHERENCE in SUPERCONDUCTORS

The spectacular confirmation of the prediction (Leggett et al., 1984-87) of MQC in superconductors came in 2003

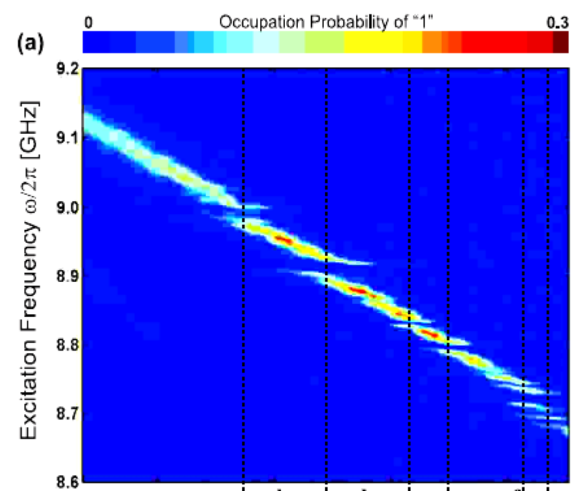




I Chiorescu et al., Science 299, 1869 (2003)

The first experiments by this group (C van der Wals et al., Science 2000) found a decoherence rate 10^6 times greater than the Caldeira-Leggett (oscillator bath) predictions.

That this was caused by the spin bath (in the form of defects in the junction) was confirmed in 2004, by the UCSB group.



RW Simmonds et al., PRL 93, 077003 (2004)

DECOHERENCE
&
QUANTUM PHASE TRANSITIONS

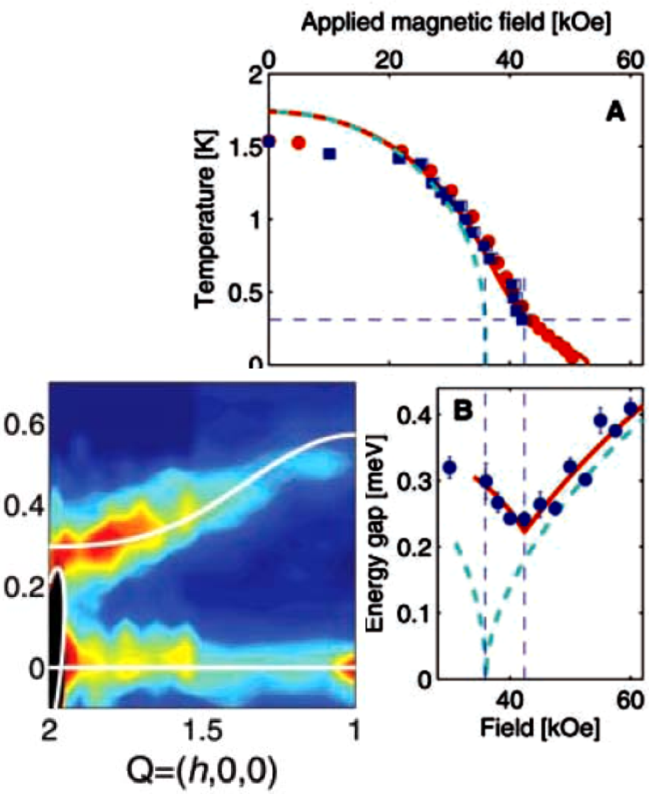
The hyperfine coupling to the nuclear spin bath has a profound effect on a Q Phase transition

M Schechter, PCE Stamp, PRL **95**, 267208 (2005))

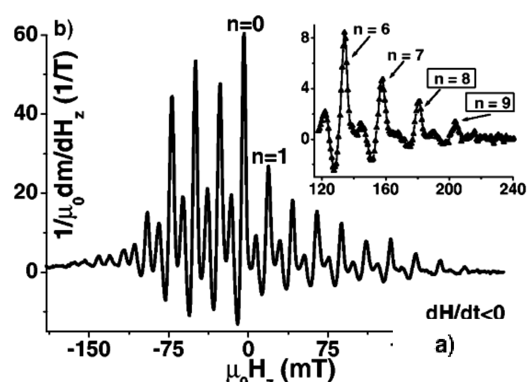
Quantum Phase Transition of a Magnet in a Spin Bath

H. M. Rønnow,[1,2,3]* R. Parthasarathy,[2] J. Jensen,[4] G. Aeppli,[5]
T. F. Rosenbaum,[2] D. F. McMorrow[3,4,6]

The excitation spectrum of a model magnetic system, $LiHoF_4$, was studied with the use of neutron spectroscopy as the system was tuned to its quantum critical point by an applied magnetic field. The electronic mode softening expected for a quantum phase transition was forestalled by hyperfine coupling to the nuclear spins. We found that interactions with the nuclear spin bath controlled the length scale over which the excitations could be entangled. This generic result places a limit on our ability to observe intrinsic electronic quantum criticality.

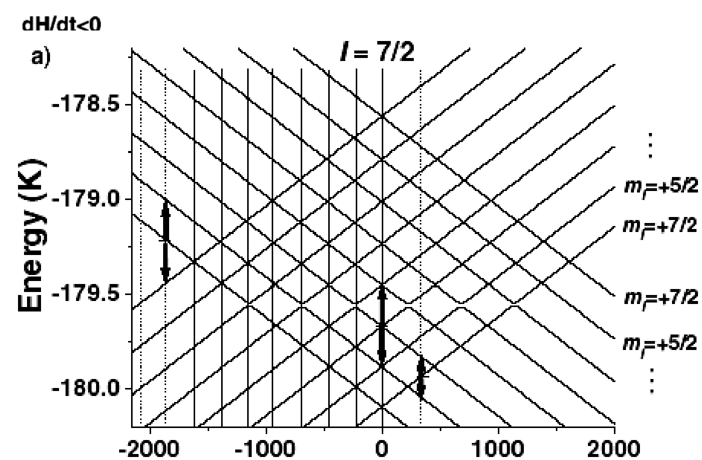


H.M. Ronnow et al., Science 308, 389 (2005)



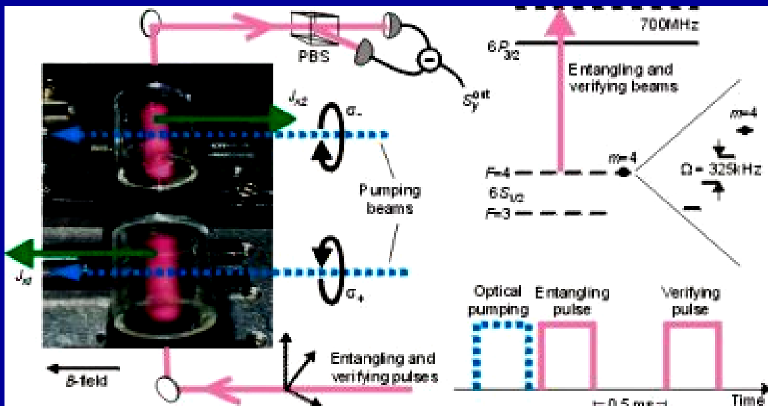
See also:

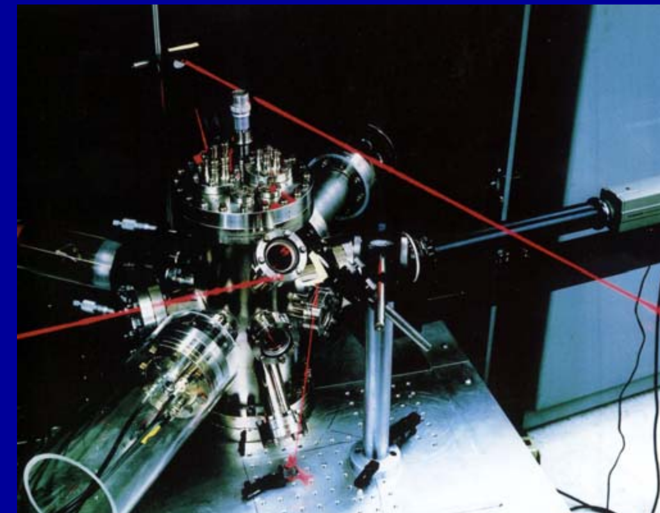
R. Giraud et al., PRL 87, 057203 (2001)
" PRL 91, 257204 (2003)



LARGE-SCALE COHERENCE with PHOTONS

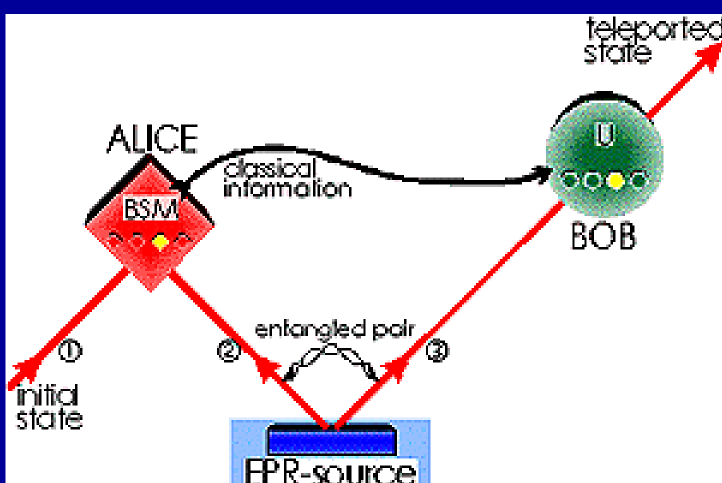
The 1st tests of quantum theory for entangled photons were done in the 1960's. The results indicated the validity of QM, but communication between the 2 polarisers was not eliminated.





Experiments have now been done in which the quantities measured on 2 separated but entangled systems, are varied separately & randomly- so quickly that no signal can pass between the 2 systems . The results rule out ANY such theory in favour of QM.

An experiment (above) has also entangled 10^{12} atomic spins in 2 separate gas cylinders.

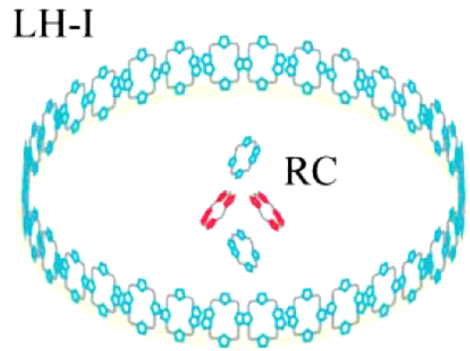


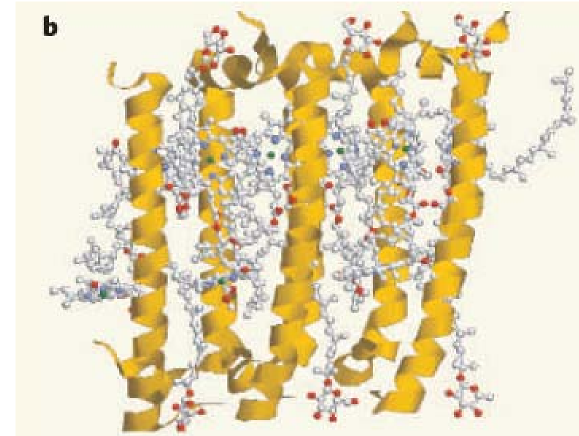
In **QUANTUM TELEPORTATION** a pair of photons or spins is prepared in an UNKNOWN entangled state, and one of each is sent to Bob & Alice. Neither observes their spin- instead, each of them lets it interact with another one of their own. Then Alice measures the state of her new pair (thereby destroying it), & sends the result to Bob (this is classical information). Bob can then manipulate his pair, based on this info, to exactly recreate the original entangled state.

COHERENCE in BIOLOGICAL RINGS: LIGHT-HARVESTING MOLECULES

These molecules have coherent exciton propagation around large protein ring structures

It is quite astonishing to see coherence at such large length scales at ROOM TEMPERATURE

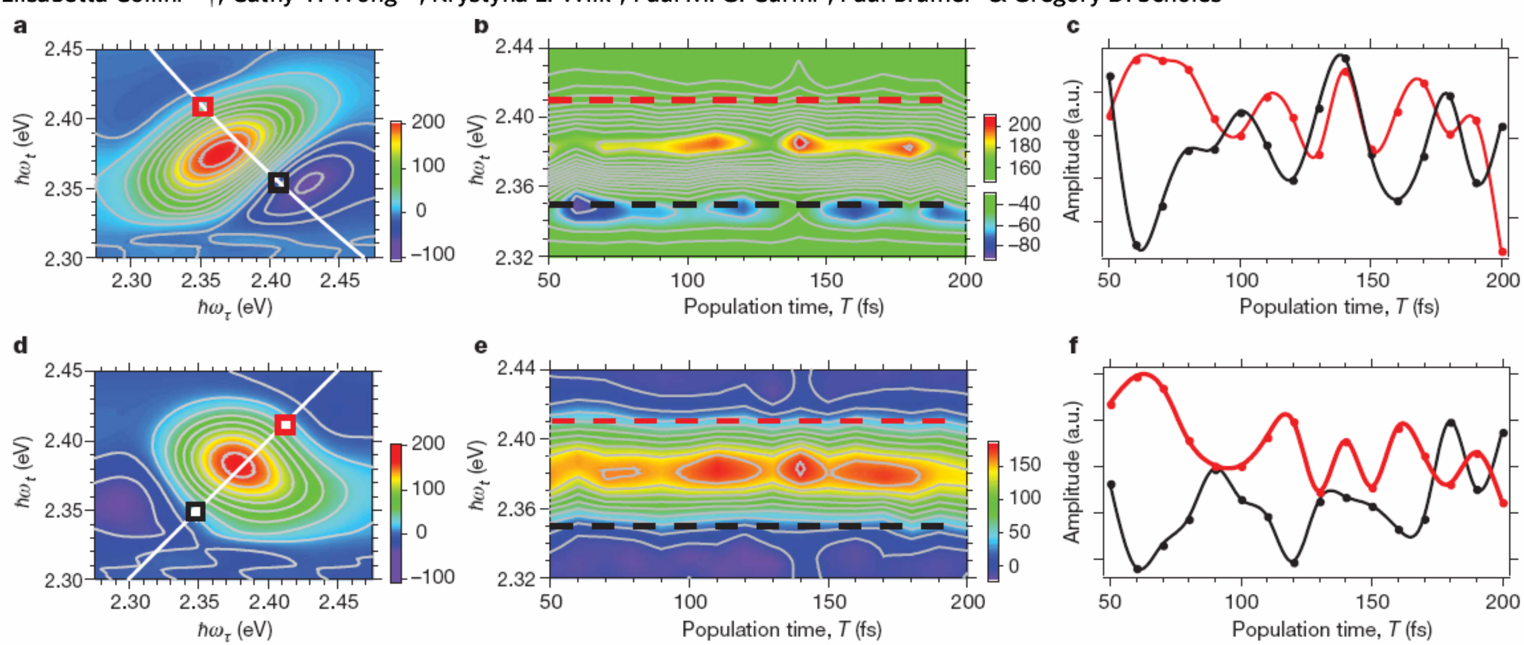




Coherently wired light-harvesting in photosynthetic marine algae at ambient temperature

E Collini et al., Nature 463, 644 (2010)

Elisabetta Collini[1]*†, Cathy Y. Wong[1]*, Krystyna E. Wilk[2], Paul M. G. Curmi[2], Paul Brumer[1] & Gregory D. Scholes[1]



DECOHERENCE in the EARLY UNIVERSE

Consider, eg., inflationary universe, in a simplified model eqtn of motion:

$$\left(H_0 + \sum_n H_n(a,\phi,x_n)\right)\psi_0(a,\phi)\prod_n \psi_n(a,\phi,x_n) = 0$$

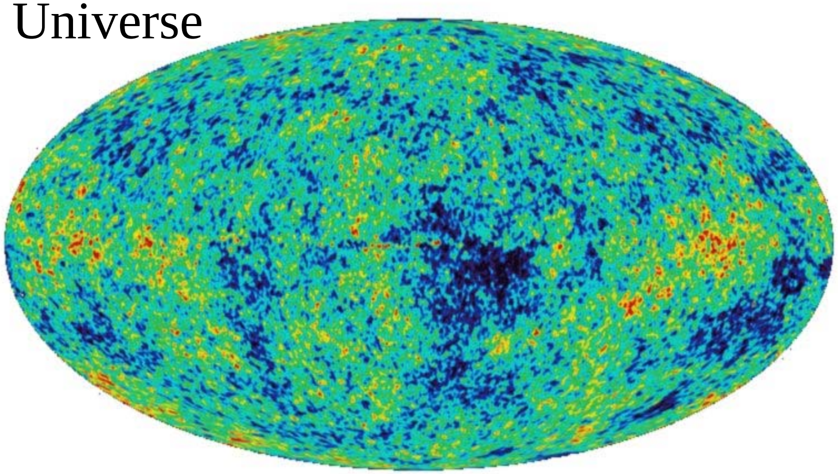
In semiclassical approximation: $\psi_0 \approx C\exp(\mathrm{i}S_0/\hbar)$

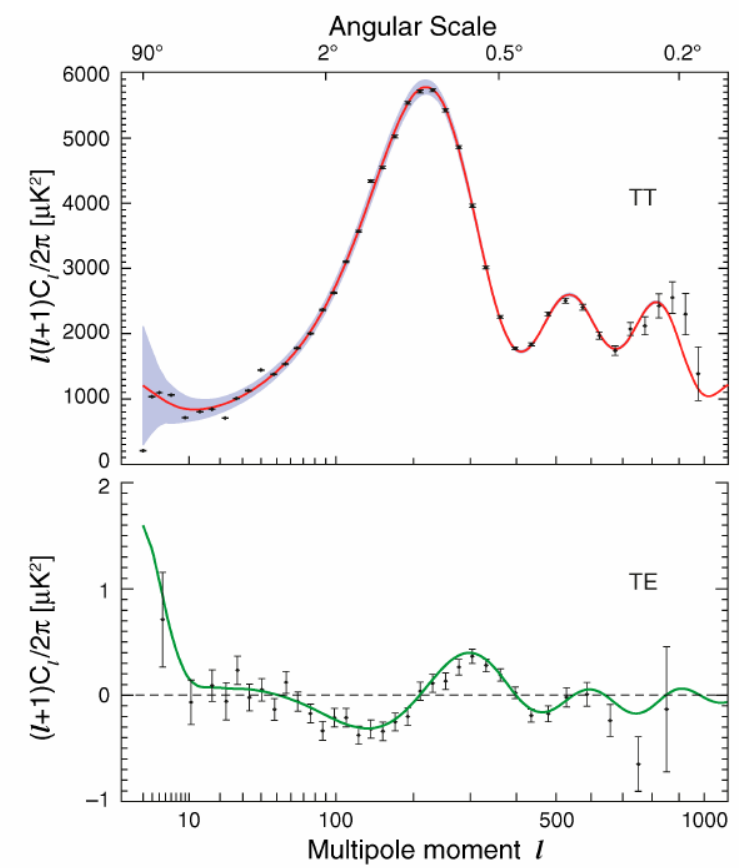
and multipole fluctuations satisfy: $\mathrm{i}\hbar\frac{\partial\psi_n}{\partial t} \approx H_n\psi_n$

where: $\frac{\partial}{\partial t} \equiv \nabla S_0 \cdot \nabla$ (WKB time)

This is probed in observations of the microwave background

Ψ_{Universe}





3. THEORETICAL FRAMEWORK

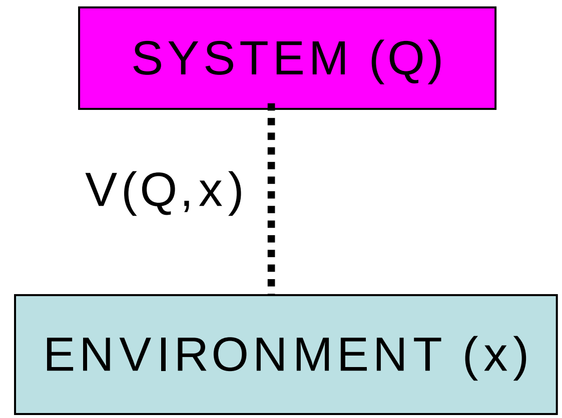
HOW DO WE MODEL a QUANTUM ENVIRONMENT in PHYSICS?

Orthodix discussions of decoherence and relaxation use models where the system of interest couples to an environment of some kind.

The effective Hamiltonian is

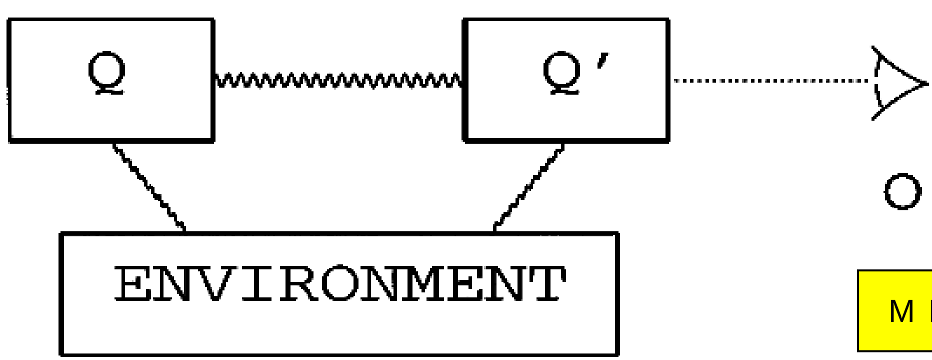
$$\mathcal{H} = H_o(Q) + V(Q,x) + H_{env}(x)$$

where the environmental variables range over the rest of the universe.



We 'integrate out' (ie., average over) environmental variables → the statistical behaviour (reduced density matrix) of the system. If the dynamics of system and environment are entangled, this produces decoherence in the system dynamics (even without dissipation).

RP Feynman, FL Vernon, Ann Phys 24, 118 (1963)



We can do the same analysis for the dynamics of a system plus measuring apparatus

M Dube, PCE Stamp, Chem Phys 268, 257 (2001)

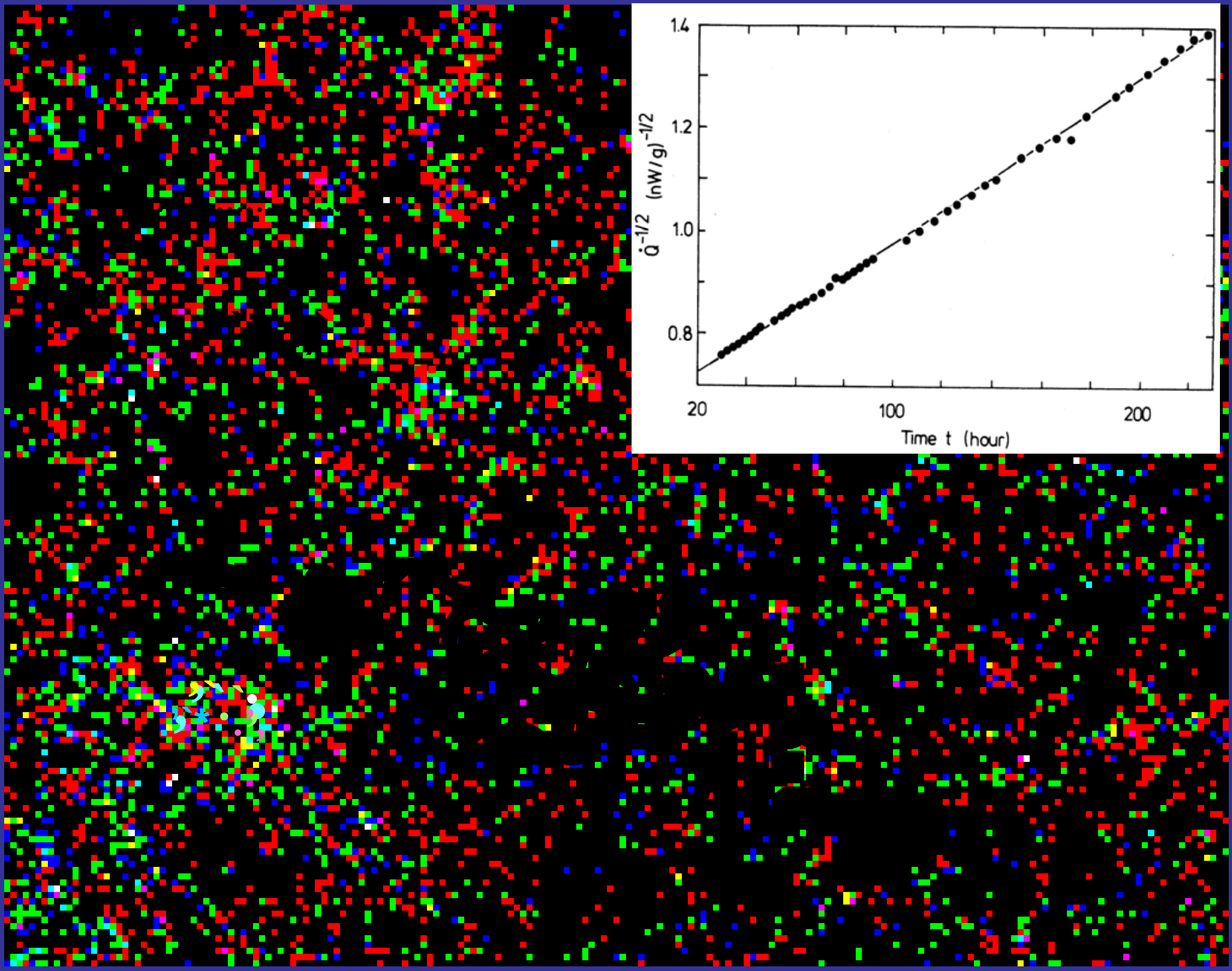
WHAT ARE THE LOW-ENERGY EXCITATIONS IN A SOLID ?

DELOCALISED

Phonons, photons, magnons, electrons, ………

LOCALISED

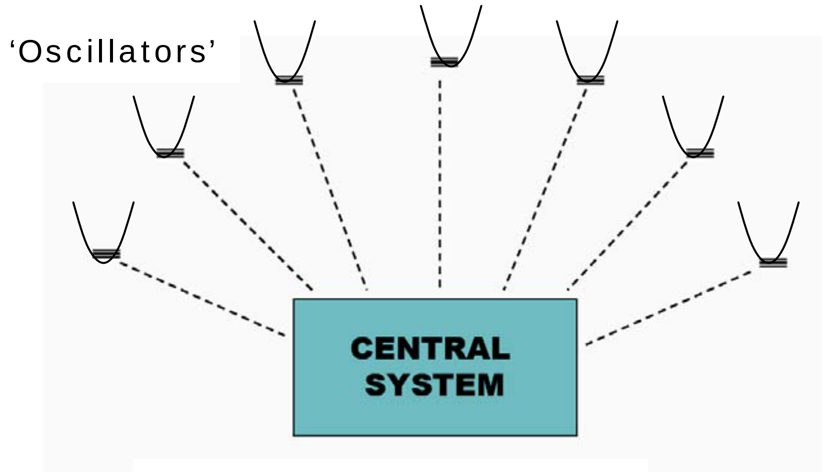
Defects,
Dislocations,
Paramagnetic impurities,
Nuclear Spins,
…….



At right- artist's view of energy distribution at low T in a solid- at low T most energy is in localised states.

INSET: heat relaxation in bulk Cu at low T

MODELS of QUANTUM ENVIRONMENTS



$$H_{\rm eff}^{\rm osc} = H_0 + H_{\rm int} + H_{\rm env}^{\rm osc}$$

Bath: $$H_{osc} = \sum_{q=1}^{N_o} \left(\frac{p_q^2}{m_q} + m_q \omega_q^2 x_q^2\right)$$

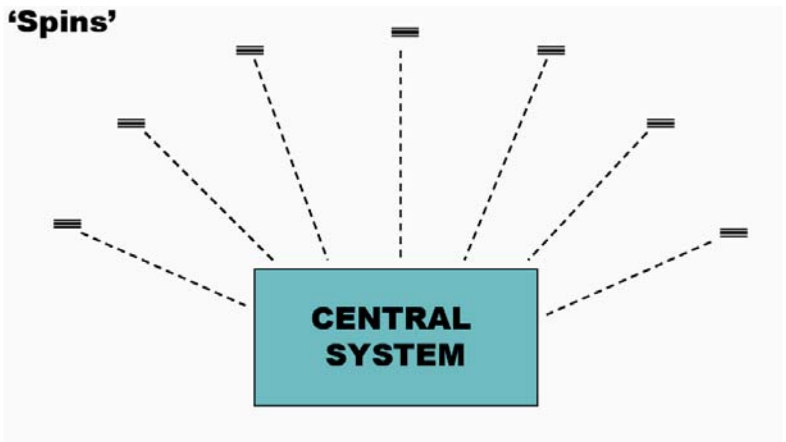
Int: $$H_{\rm int}^{\rm osc} = \sum_{q=1}^{N} [F_q(Q) x_q + G_q(P) p_q]$$

Phonons, photons, magnons, spinons,
Holons, Electron-hole pairs, gravitons,..

Feynman & Vernon, Ann. Phys. 24, 118 (1963)

Caldeira & Leggett, Ann. Phys. 149, 374 (1983)
AJ Leggett et al, Rev Mod Phys 59, 1 (1987

DELOCALIZED BATH MODES
↓
OSCILLATOR BATH



$$H_{\rm eff}^{\rm sp}(\Omega_0) = H_0 + H_{\rm int}^{\rm sp} + H_{\rm env}^{\rm sp}$$

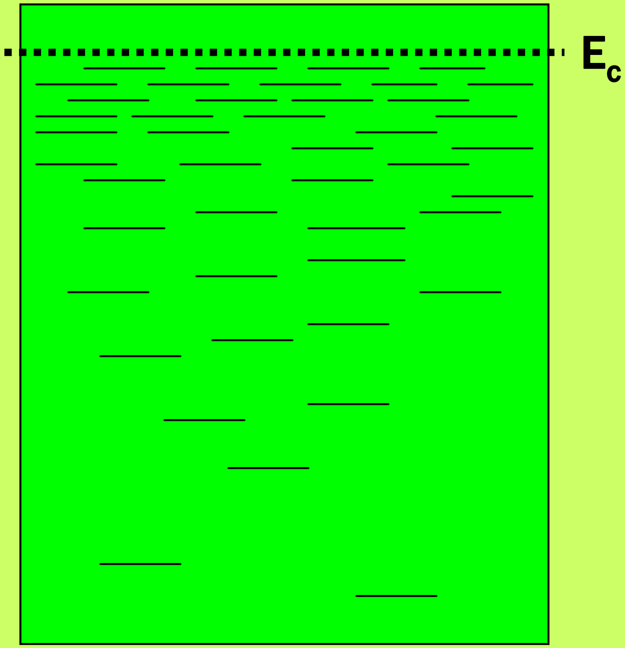
Bath: $$H_{\rm env}^{\rm sp} = \sum_{k}^{N_s} \mathbf{h}_k \cdot \boldsymbol{\sigma}_k + \sum_{k,k'}^{N_s} V_{kk'}^{\alpha\beta} \sigma_k^\alpha \sigma_{k'}^\beta$$

Interaction: $$H_{\rm int}^{\rm sp} = \sum_{k}^{N_s} \boldsymbol{F}_k(P,Q) \cdot \boldsymbol{\sigma}_k$$

Defects, dislocation modes, vibrons,
Localized electrons, spin impurities,
nuclear spins, ...

LOCALIZED BATH MODES
↓
SPIN BATH

(1) P.C.E. Stamp, PRL 61, 2905 (1988)
(2) NV Prokof'ev, PCE Stamp, J Phys CM5, L663 (1993)
(3) NV Prokof'ev, PCE Stamp, Rep Prog Phys 63, 669 (2000)

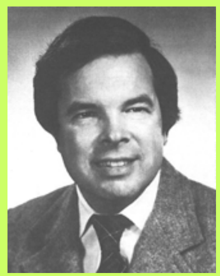


DERIVING THE $\mathcal{H}_{eff}$

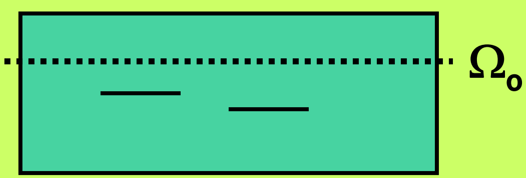
This done using perturbation theory, adiabatic expansions, semiclassical expansions, etc.

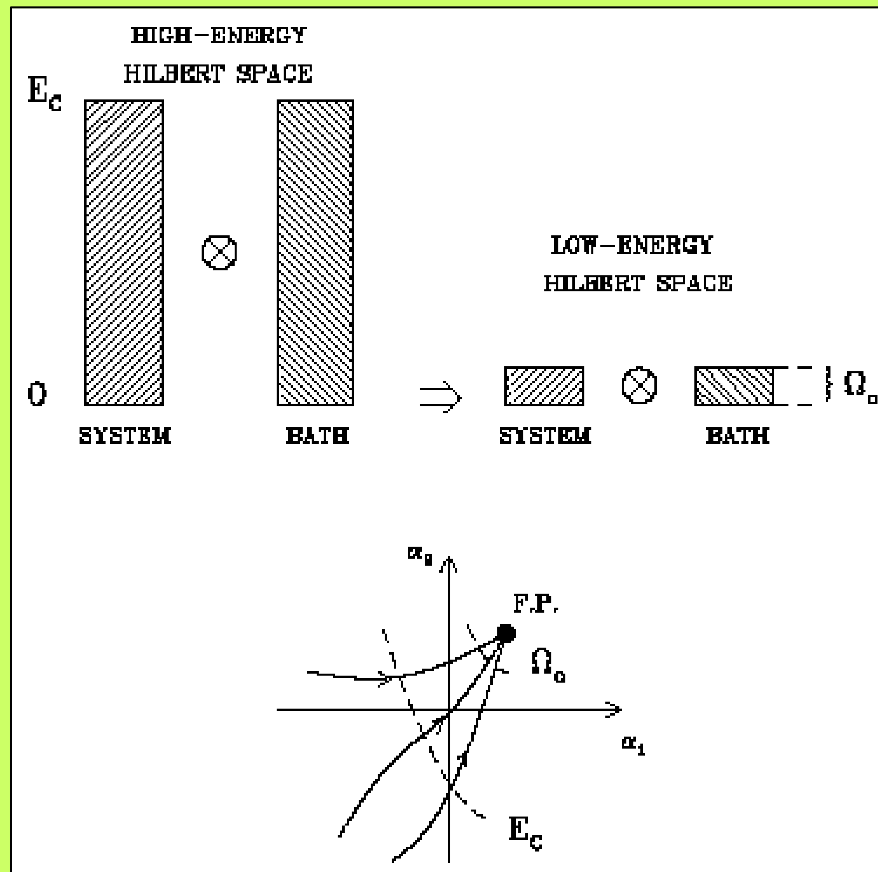
Behind this lies: *The RG mantra*:

RG flow & fixed points
low-energy $\mathcal{H}_{eff}$
universality classes



Scale out High-E modes





$$\mathcal{H}_{eff}(E_c) \rightarrow \mathcal{H}_{eff}(\Omega_o)$$

$$|\psi_i\rangle \; H_{ij}(E_c) \; \langle\psi_j| \quad \rightarrow \quad |\phi_\alpha\rangle \; \mathcal{H}_{\alpha\beta}(\Omega_o) \; \langle\phi_\beta|$$

Flow of Hamiltonian & Hilbert space with UV cutoff

DYNAMICS: FORMAL NATURE of the PROBLEM

Density matrix propagator: $K(Q_2, Q_2'; Q_1, Q_1'; t, t') = \int_{Q_1}^{Q_2} \mathcal{D}q \int_{Q_1'}^{Q_2'} \mathcal{D}q' \, e^{-i/\hbar(S_0[q]-S_0[q'])} \mathcal{F}[q, q'],$

with $\mathcal{F}[Q, Q'] = \prod \langle \hat{U}_k(Q, t) \hat{U}_k^\dagger(Q', t) \rangle$

Here the unitary operator $\hat{U}_k(Q, t)$ describes the evolution of the kth environmental mode, given that the central system follows the path $Q(t)$ on its 'outward' voyage, and $Q'(t)$ on its 'return' voyage; and $\mathcal{F}[Q, Q']$ acts as a weighting function, over different possible paths $(Q(t), Q'(t'))$.

Easy for oscillator baths (it is how Feynman set up quantum field theory); we integrate out a set of driven harmonic oscillators

Each has the Lagrangian: $L = \frac{M}{2}\dot{x}^2 - \frac{M\omega^2}{2}x^2 - \gamma(t)x$

Thus:

$$\mathcal{F}[Q, Q'] = \prod_q^{N_o} \int \mathcal{D}x_q(\tau) \int \mathcal{D}x_q(\tau') \exp\left[\frac{i}{\hbar}\int d\tau \frac{m_q}{2}[\dot{x}_q^2 - \dot{x}_q'^2 + \omega_q^2(x_q^2 - x_q'^2)] + [F_q(Q)x_q - F_q(Q')x_q']\right]$$

Bilinear coupling →

$$F[q, q'] = \exp\left[-\frac{1}{\hbar}\int_{t_o}^{t} d\tau_1 \int_{t_o}^{\tau_1} d\tau_2 [q(\tau_1) - q'(\tau_2)][\mathcal{D}(\tau_1 - \tau_2)q(\tau_2) - \mathcal{D}^*((\tau_1 - \tau_2)q'(\tau_2)]\right]$$

Bath propagator

For spin baths it is more subtle:

$$\mathcal{F}[Q, Q'] = \prod_k^{N_s} \int \mathcal{D}\boldsymbol{\sigma}_k(\tau) \int \mathcal{D}\boldsymbol{\sigma}_k(\tau') \exp\left[\frac{i}{\hbar}(S_{int}[Q, \boldsymbol{\sigma}_k] - S_{int}[Q', \boldsymbol{\sigma}_k'] + S_E[\boldsymbol{\sigma}_k] - S_E[\boldsymbol{\sigma}_k'])\right]$$

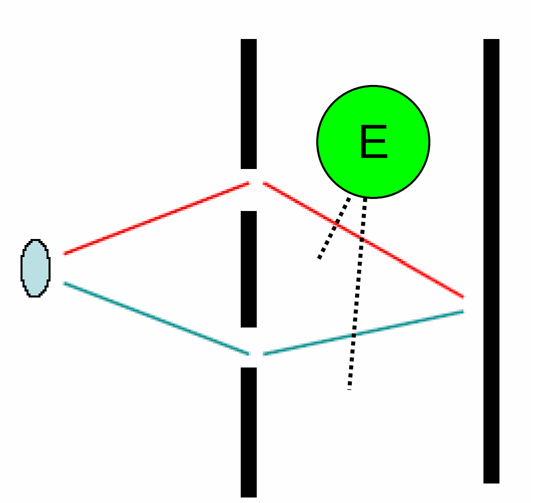
$$S_{int}^{sp}(Q, \boldsymbol{\sigma}_k) = -\int d\tau \sum_k^{N_s} \boldsymbol{F}_k(P, Q) \cdot \boldsymbol{\sigma}_k$$

$$S_{env}^{sp} = \int d\tau \left[\sum_k^{N_s} (\mathcal{A}_k \cdot \frac{d\boldsymbol{\sigma}_k}{dt} - \mathbf{h}_k \cdot \boldsymbol{\sigma}_k) - \sum_{k,k'}^{N_s} V_{kk'}^{\alpha\beta} \sigma_k^\alpha \sigma_{k'}^\beta\right]$$

Vector coupling

Berry phase coupling

ENVIRONMENTAL DECOHERENCE



When some quantum system with coordinate Q interacts with any other system (with coordinate x) , the result is typically that they form a combined state in which there is some entanglement between the two systems.

Example: **In a 2-slit expt., the particle coordinate Q couples to photon coordinates, so that we have the following possibility:**

$$\Psi_o(Q) \ \Pi_q \phi_q^{in} \ \rightarrow \ [a_1 \Psi_1(Q) \Pi_q \phi_q^{(1)} \ + \ a_2 \Psi_2(Q) \Pi_q \phi_q^{(2)}]$$

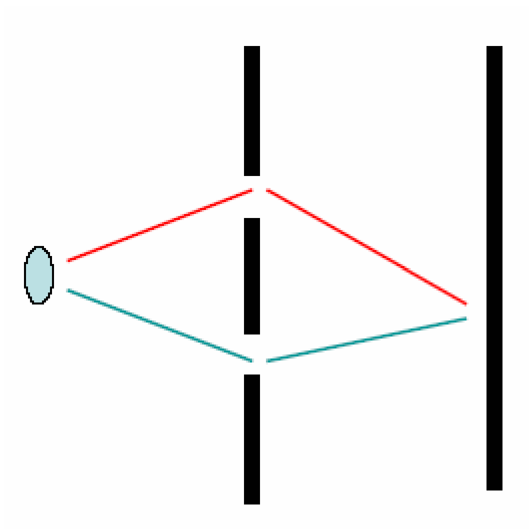
But now suppose we do not have any knowledge of, or control over, the photon states- we must then average over these states, in a way consistent with the experimental constraints. In the extreme case this means that we lose all information about the PHASES of the coefficients a_1 & a_2 (and in particular the relative phase between them). This process is called DECOHERENCE

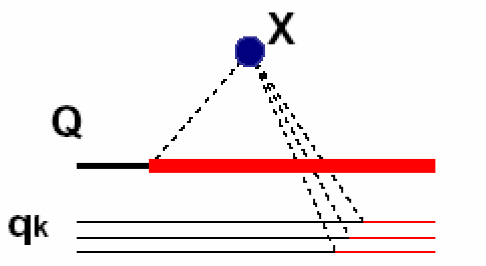
NB 1: In this interaction between the system and its "Environment" E (which is in effect performing a measurement on the particle state), there is no requirement for energy to be exchanged between the system and the environment- only a communication of phase information.

NB 2: Nor is it the case that the destruction of the phase interference between the 2 paths must be associated with a noise coming from the environment- what matters is that the state of the environment be CHANGED according to the what is the state of the system.

Question: How do we describe this for a 'COMPLEX' SYSTEM ?

OTHER KINDS of DECOHERENCE





(1) 3rd PARTY DECOHERENCE:

decoherence in the dynamics of a system A (coordinate **Q**) caused by *indirect* entanglement with an environment E- the entanglement is achieved via a 3rd party B (coordinate **X**).

Ex: Buckyball decoherence

Consider the 2-slit expt with buckyballs. The COM coordinate Q of the buckyball does not couple directly to the vibrational modes {qk } of the buckyball - by definition. However BOTH couple to the slits in the system, in a distinguishable way.

Note: the state of the 2 slits, described by a coordinate X, is irrelevant- it does not need to change at all. We can think of it as a scattering potential, caused by a system with infinite mass. It is a PASSIVE 3rd party. We can also have ACTIVE 3rd parties

PCE Stamp, Stud. Hist Phil Mod Phys **37**, 467 (2006)

See also PCE Stamp, WG Unruh, to be published

(2) INTRINSIC DECOHERENCE:

This is a hypothetical decoherence in Nature that has nothing to do with environments at all – IT AMOUNTS TO A BREAKDOWN OF QUANTUM MECHANICS. 2 examples are

(i) decoherence arising from spacetime distortion (gravitational decoherence)
(ii) decoherence suggested by the holographic principle, arising in all objects.

L Diosi, Phys Rev A40, 1165 (1989)
R Penrose, "Shadows of the Mind" (OUP, 1994)

Gravitational interaction energy:

$$E_{i,j} = -G \int\int \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2 \frac{\rho_i(\vec{r}_1)\rho_j(\vec{r}_2)}{|\vec{r}_1 - \vec{r}_2|}$$

Uncertainty:

$$\Delta E = 2E_{1,2} - E_{1,1} - E_{2,2}$$

Towards Quantum Superpositions of a Mirror
W. Marshall, C. Simon, R. Penrose, D. Bouwmeester: PRL 91, 130401 (2003).