MANY BODY PHYSICS

45 YEARS OF NUCLEAR THEORY at STONY BROOK

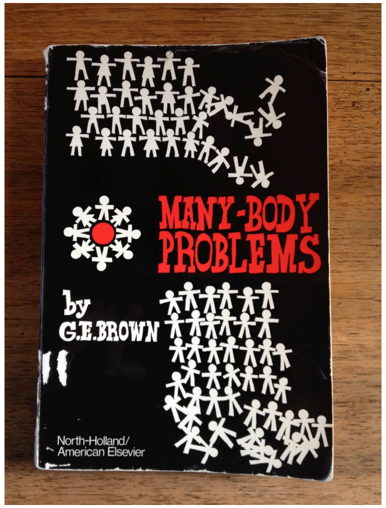
A Tribute To Gerald E. Brown
Stony Brook
November 25, 2013

European
Research
Council

Jean-Paul Blaizot, IPhT- Saclay

IPhT
SACLAY

MANY BODY PHYSICS



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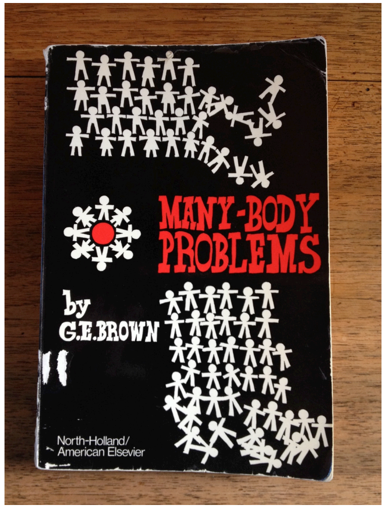

Collective fermionic excitations
in the **quark-gluon plasma**
and **cold atom** systems

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THE QUARK-GLUON PLASMA AS A MANY-BODY SYSTEM

- Ideal playground for application, and development, of many-body and quantum field theoretical techniques (and so are cold atom systems)

- Here we focus on high temperature ($T \gg \Lambda_{QCD}$), weak interactions (small gauge coupling). [Leave aside issues related to the so-called strongly coupled QGP, AdS/CFT, etc]

- Basic degrees of freedom are quarks and gluons (quasiparticles), interacting with strength g (long range interactions)

- Various collective phenomena

HIERACHY OF SCALES (AND PHENOMENA) AT WEAK COUPLING

T plasma 'particles' (***hard***)

gT collective excitations, screening, Landau damping (***soft***)

g^2T 'magnetic scale', hydrodynamical modes (***ultra-soft***)

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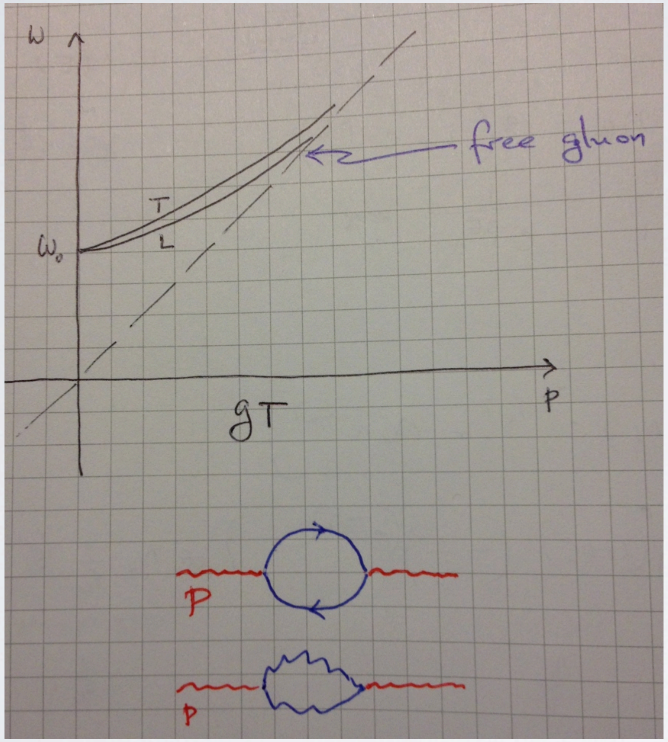
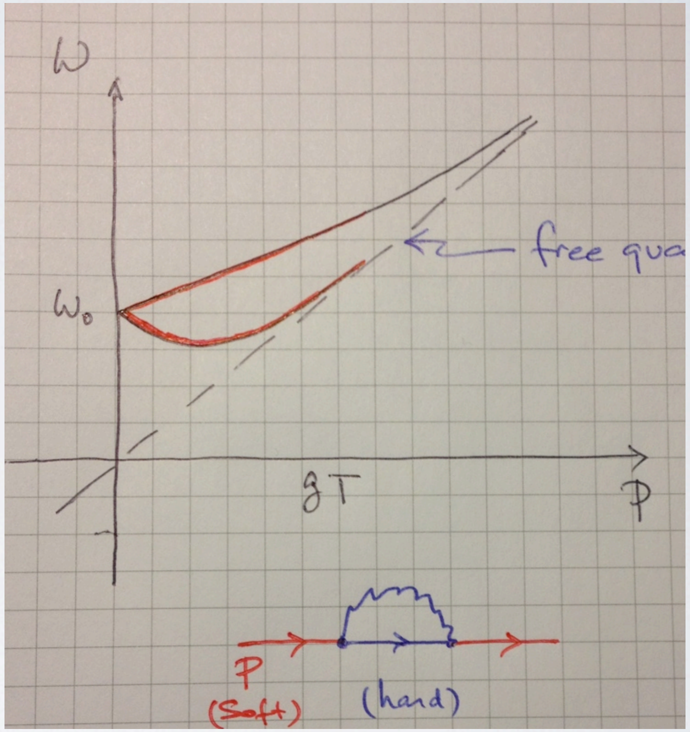
In the rest of this talk, focus on collective phenomena carrying fermionic quantum numbers

THE PLASMINO

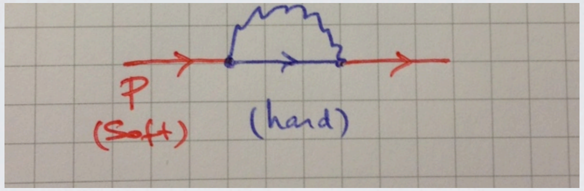
Gluon (boson)

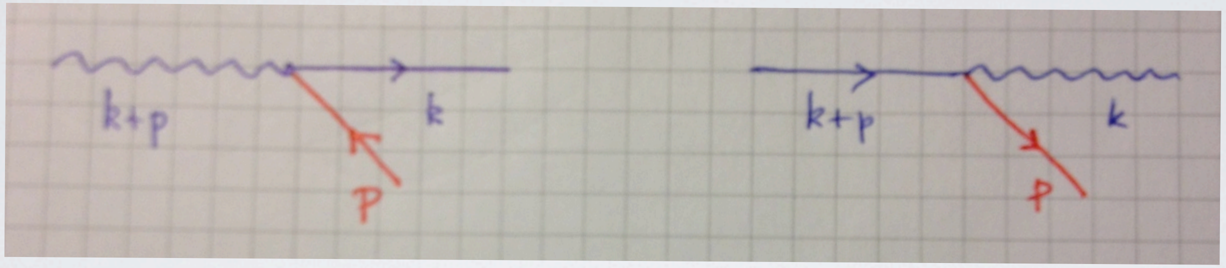


Quark (fermion)

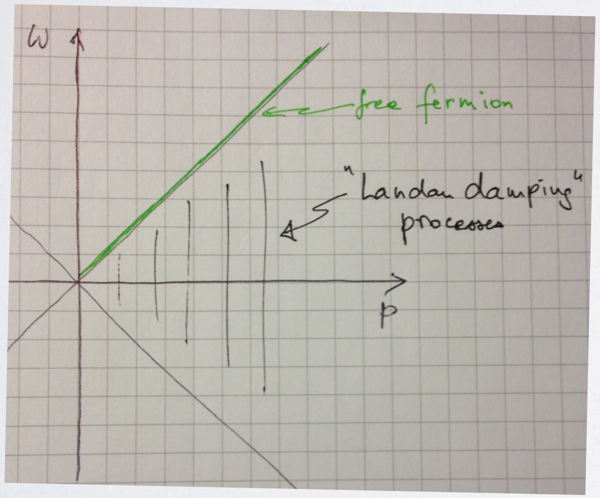


Origin of the split dispersion relation

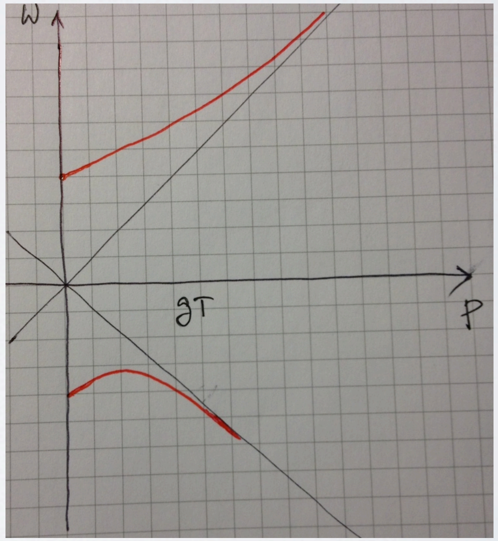




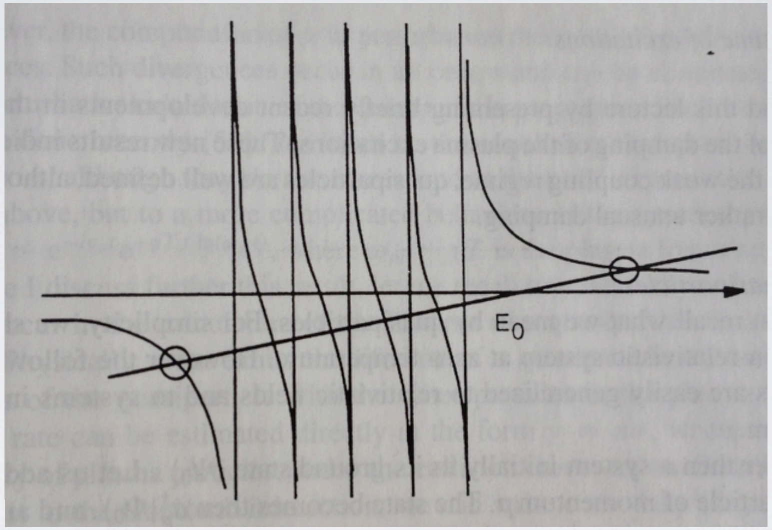
$$\epsilon_{k+p} - \epsilon_k \simeq p \cos\theta$$



Interactions



THE «SCHEMATIC MODEL» INTERPRETATION

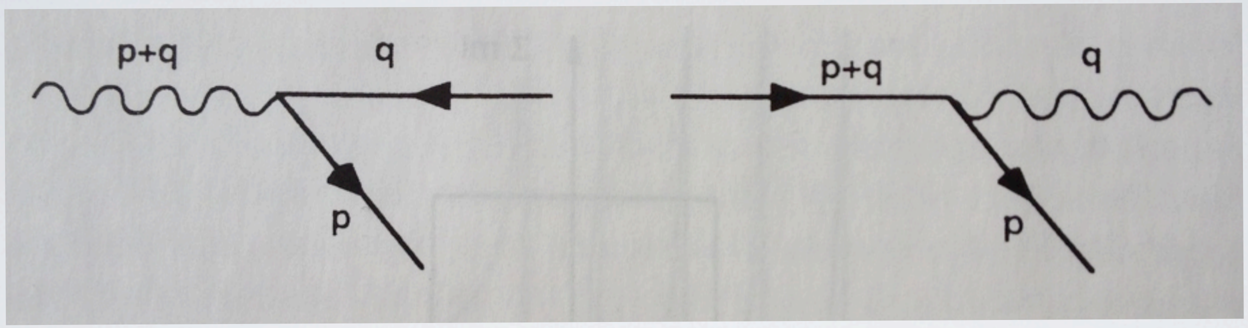


$$\omega - E_0 = \sum_i \frac{g^2}{\omega - E_i} \approx \frac{Ng^2}{\Delta E} \ln \left| \frac{\omega + \Delta E/2}{\omega - \Delta E/2} \right|$$

$$\omega^2 \approx Ng^2$$

Note how the smallness of the coupling can be overcome by the large number of degrees of freedom (N) to produce a large effect even when g is tiny

Turning bosons into fermions (and vice versa)



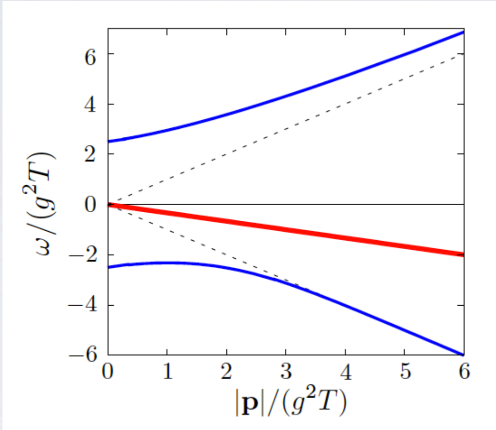
Nature of hard excitation changes from boson to fermion

Soft degree of freedom « oscillates». It can be described as oscillation of fermionic mean field $\langle \psi(x) \rangle$

[see JPB and E. Iancu Phys. Rept. 359 (2002)]

Suggestive of supersymmetry

Ultra soft modes



[Y. Hidaka, D. Satow, T. Kunihiro, arXiv1105.0423 (Yukawa theory)]

Ultra-soft fermionic mode analog of hydrodynamic sound ?
Phonino, 'quasi-goldstino' ?

Indeed the case in simple supersymmetric model (Wess-Zumino model)

$$(\omega = \pm p/3)$$

In QED/QCD supersymmetry emerges in the absence of interaction.

V. V. Lebedev and A. V. Smilga, Nucl. Phys. B 318, 669 (1989).

Other effects come into play (chiral symmetry, charge symmetry)

JPB, Daisuke Satow, work in progress

Phonon and phonino

conservation of energy-momentum $\partial^\mu T_{\mu\nu} = 0$

small deviations from local equilibrium (measured by local temperature T(x,t))

$$\left(\frac{\partial \rho}{\partial T}\,\partial_0^2 - \frac{\partial p}{\partial T}\,\vec{\partial}^2\right)\Delta T(x,t) = 0$$

dispersion relation $\omega = v_s\, p$ $\quad v_S^2 = \dfrac{\partial p/\partial T}{\partial \rho/\partial T}$

conservation of supercurrent $\partial^\mu J_\mu = 0$

$$\partial^\mu \langle \delta_\xi J_\mu(x,t)\rangle = -2i\gamma^\nu \partial^\mu \xi(x,t)\langle T_{\mu\nu}(x,t)\rangle$$

mode equation $(\rho\,\gamma_0\partial_0 + p\,\gamma_i\partial_i)\,\xi(x,t) = 0$

dispersion relation $\omega = v_{ss}\, p$ $\quad v_{SS} = \dfrac{p}{\rho}$

quasi-goldstino in hot QED/QCD

$\mathrm{Re}\,\omega = p/3$ $\quad \mathrm{Im}\,\omega = \zeta_q + \zeta_g = O(g^2 T)$

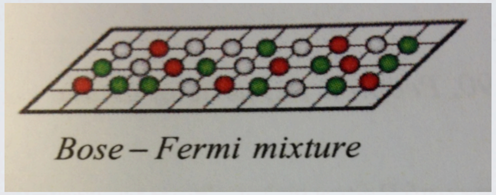
V. V. Lebedev and A. V. Smilga, Nucl. Phys. B 318, 669 (1989).

Y. Hidaka, D. S., and T. Kunihiro, Nucl. Phys. A 876, 93 (2012)
D. S., PRD 87, 096011 (2013).

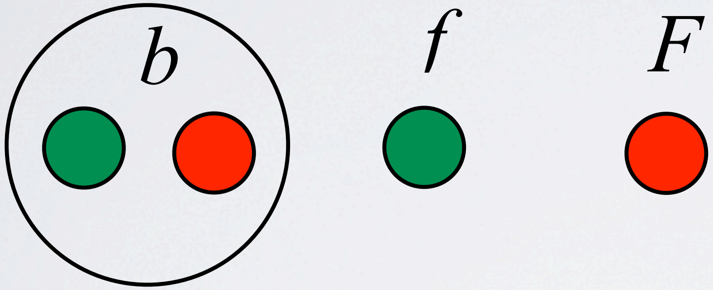
One can study some of these issues in cold atom systems

Suggested experimental setup

T. Shi, Y. Yu, and C. P. Sun, PRA 81, 011604(R) (2010)



Two kinds of fermion (**f**, **F**) and their bound state (**b**: boson) on an optical lattice.



(external field adjusted so that **F decouples**)

$$H = H_0 + H_1$$

$$H_0 = -t \sum_{<ij>} \left(f_i^\dagger f_j + b_i^\dagger b_j \right) - \mu_f \sum_i f_i^\dagger f_i - \mu_b \sum_i b_i^\dagger b_i$$

$$H_1 = \frac{U_{bb}}{2} \sum_i n_i^b \left(n_i^b - 1 \right) + U_{bf} \sum_i n_i^b n_i^f$$

When $\mu_f = \mu_b$ $U_{bb} = U_{bf}$ the hamitonian is supersymmetric

$$[H, Q] = 0 \quad \text{with} \quad Q = \sum_i b_i f_i^\dagger$$

Supersymmetric algebra

(Continuum limit, d=2, no BEC)

Boson and fermion field operators

$$[b(\mathbf{x}), b^\dagger(\mathbf{y})] = \delta^d(\mathbf{x}-\mathbf{y}) \qquad \{f(\mathbf{x}), f^\dagger(\mathbf{y})\} = \delta^d(\mathbf{x}-\mathbf{y})$$

$$N_b = \int d^d\mathbf{x}\, b^\dagger(\mathbf{x}) b(\mathbf{x}) \qquad N_f = \int d^d\mathbf{x}\, f^\dagger(\mathbf{x}) f(\mathbf{x})$$

Supercharge

$$Q \equiv \int d^d\mathbf{x}\, q(\mathbf{x}) \qquad q(\mathbf{x}) \equiv b(\mathbf{x}) f^\dagger(\mathbf{x})$$

Algebra

$$\{Q, Q^\dagger\} = N, \quad [N, Q] = [N, Q^\dagger] = 0, \quad [\Delta N, Q] = Q$$

$$N \equiv N_b + N_f \qquad \Delta N = (N_f - N_b)/2$$

Supersymmetric hamiltonian

$$[Q, H] = 0$$

NOTE: supersymmetry is here only an internal symmetry

Supersymmetry and its breaking

$$[Q,H] = 0 = [N,H] = [\Delta N, H]$$

Explicit breaking

$$H_G = H - \mu_f N_f - \mu_b N_b$$
$$= H - \mu N - \Delta\mu\, \Delta N$$
$$\mu \equiv (\mu_f + \mu_b)/2 \qquad \Delta\mu \equiv \mu_f - \mu_b$$

$$[Q, H_G] = \Delta\mu Q$$

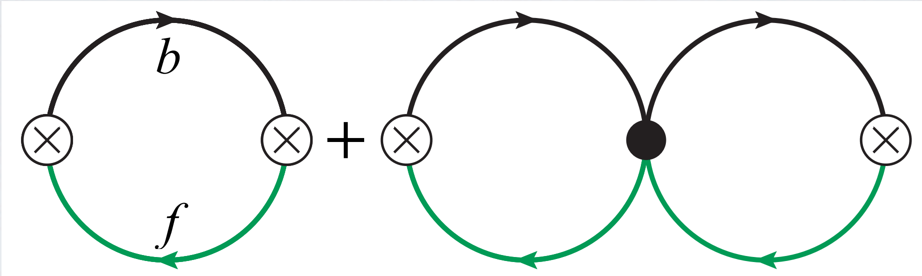
Explicit symmetry breaking when $\mu_f \neq \mu_b$

Spontaneous symmetry breaking by matter

Only supersymmetric state is the vacuum $Q|0\rangle = 0$

Associated Goldstone mode «Goldstino»

Random Phase Approximation

$<Q^\dagger(x)Q(0)>=$  $+\cdots$

$\omega = \Delta\mu \text{ -} \alpha p^2$ (sp strength is unity)

$$\alpha \equiv \frac{1}{\rho}\left(\frac{4\pi t^2\rho_f^2}{U\rho} - t(\rho_f - \rho_b)\right)$$

This spectrum can be understood in terms of symmetry breaking in a model independent way

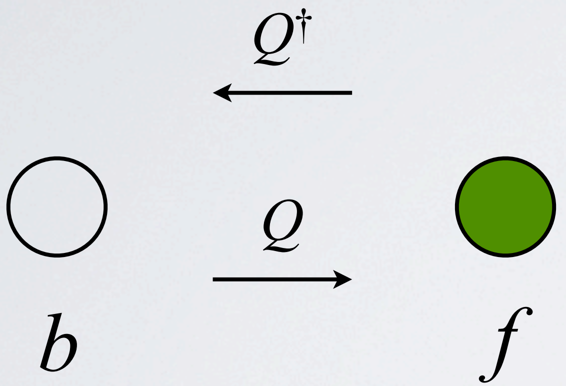
[JPB, Y. Hidaka and D. Satow, wotk in progress]

Analogy with Magnon in Ferromagnet

Goldstino

Conserved Charge: $Q, Q^\dagger, \rho$

$$\langle \{Q, Q^\dagger\} \rangle = \rho$$



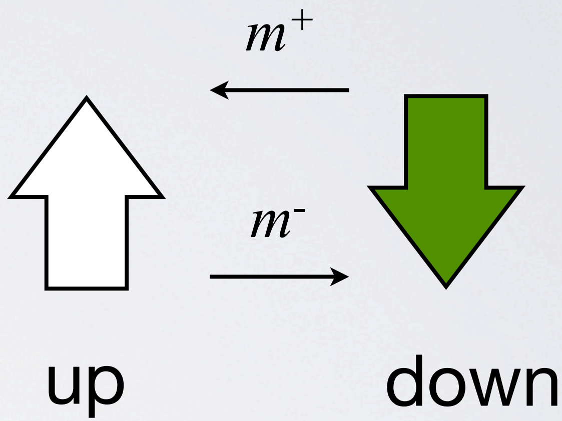
$Q^2 = Q^{\dagger 2} = 0$

$$\omega = \pm \left(\frac{\beta}{\rho} \mathbf{p}^2 + \Delta\mu \right)$$

Magnon in ferromagnet

Conserved Charge: m^+, m^-, m^z

$$\langle [m^+, m^-] \rangle = 2m_0$$



$m^{+2} = m^{-2} = 0$

$$\omega = \pm \left(\frac{\rho_s}{M_0} \mathbf{p}^2 + h \right)$$

Type-II NG mode (while it is Type-I in relativistic model)

H. Watanabe and H. Murayama, PRL 108, 251602 (2012); Y. Hidaka, PRL 110, 091601 (2013)

JPB, Y. Hidaka, D. Satow, work in progress

SOME LEGACIES FROM GERRY

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Many-body physics is fun, and beautiful

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One can learn a lot by looking at, and comparing, different physical systems