

Title: Low energy challenges for high energy physicists: the vibrational modes of soft matter

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Abstract: <p>I will discuss how holographic and effective field theory methods could shed light on important open questions in low energy condensed matter systems. I will focus on the study of the vibrational degrees of freedom, i.e. "phonons", in liquids, solids and disordered systems like glasses. Building intuition from the holographic systems I will tackle the problem of the low frequency elastic response in liquids and the universal emergence of the boson peak in ordered crystals and amorphous solids.</p>

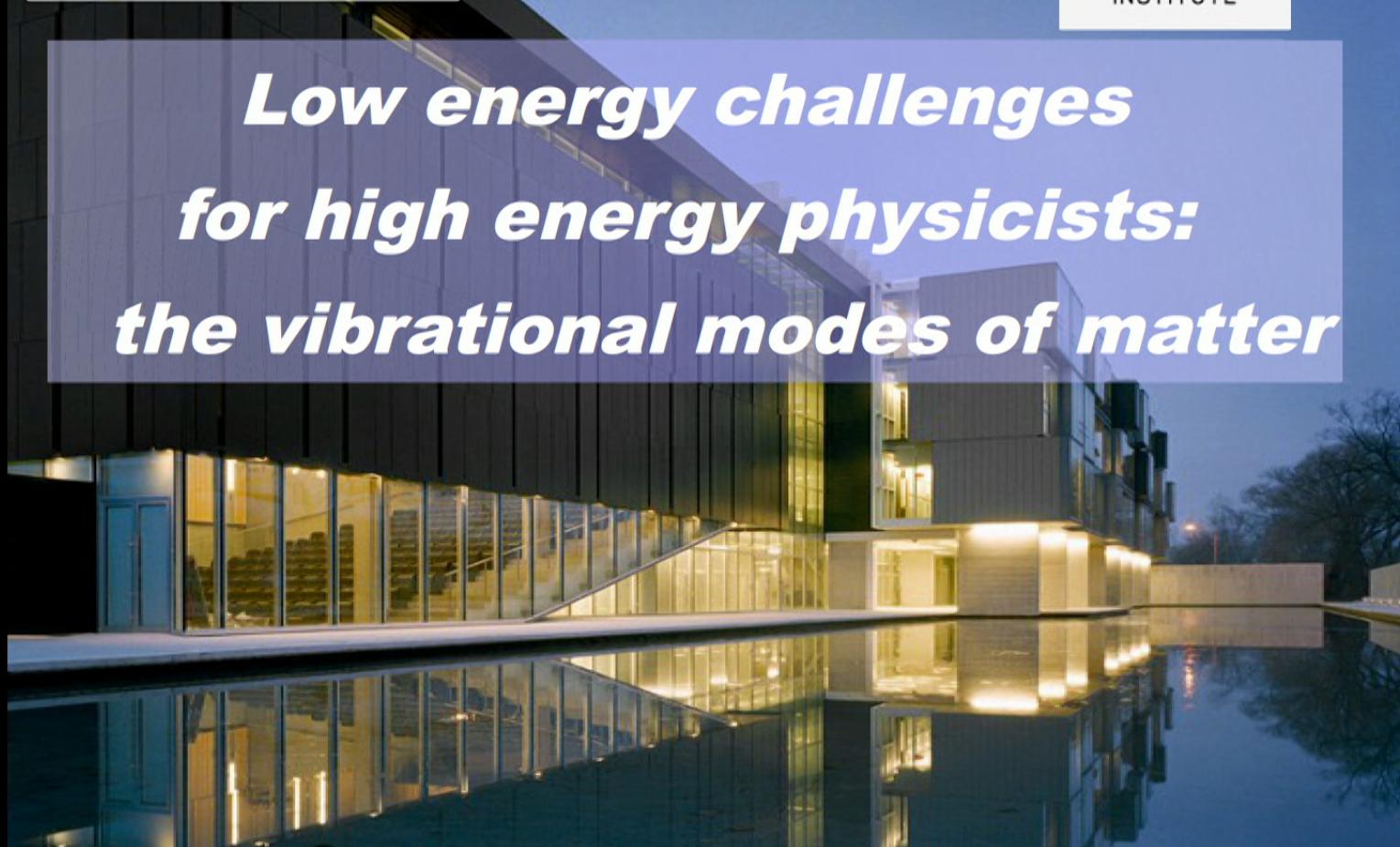


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IFT Madrid



***Low energy challenges
for high energy physicists:
the vibrational modes of matter***





Home » Low Energy Challenges for High Energy Physicists

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LOW ENERGY CHALLENGES FOR HIGH ENERGY PHYSICISTS

Low Energy Challenges for High Energy Physicists

Collection/Series: Low Energy Challenges for High Energy Physicists

More Information: <http://perimeterinstitute.ca/conferences/low-energy-challenges-high-energy-physicists>

Event Type: Conference

Event Date: Monday, May 26, 2014 - 08:30 to Friday, May 30, 2014 - 18:00

Location: Bob Room

Room #: 405

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(University of Jena)

Oriol Pujolas
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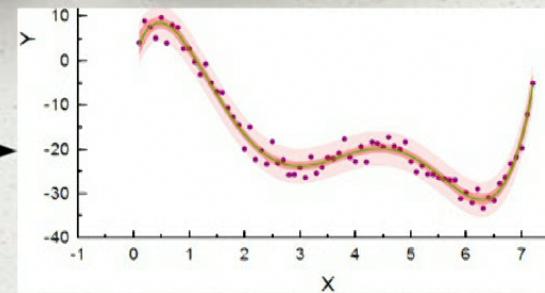
Sebastian Grieninger
(University of Jena)

Ke Yang
(SCUT, China)

HOLOGRAPHY \longleftrightarrow EFT \longleftrightarrow CONDENSED MATTER

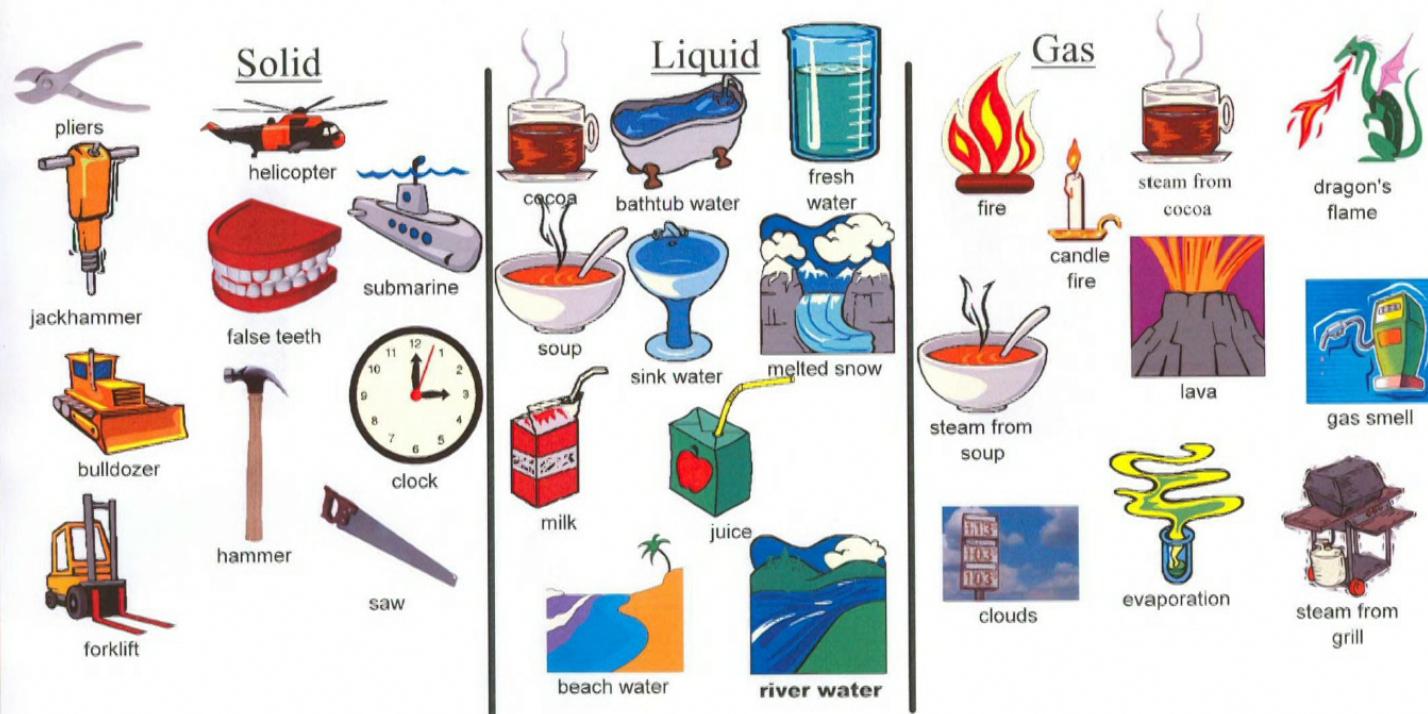


$$\begin{aligned}
 & g \vec{E} \cdot \vec{d}k = \mu_e \sum I_i, \quad k = \pm \sqrt{\frac{m}{\epsilon_0} (\epsilon - \epsilon_b)} \quad \text{Since } \epsilon_b = \frac{\epsilon_0 + \omega_0^2}{2} T = b, \quad E = \frac{1}{2} \hbar \sqrt{\epsilon_0} Y_{00} = \frac{1}{2} \sqrt{\epsilon_0} \sin \frac{n \pi x}{L} \quad F = \frac{\hbar^2 k^2}{2m} \\
 & \lambda = \frac{\hbar}{M_e v} = h/(2M_e E)^{1/2} K = \frac{h^2}{2m} \sqrt{\beta} \quad V_0 = \omega_0 L \quad P = UI \quad \Phi = NBS \quad E = \hbar \omega \quad L = \frac{2\pi}{\omega} \\
 & R_L = \sqrt{E_0 / \rho_L} \quad E_0 = \epsilon_0 / n \quad (K_B - \omega_0) \\
 & J_m = \frac{C}{T} R = \frac{U}{T} \frac{\Delta f}{\Delta T} = \frac{\Delta x}{\lambda} = \frac{x_2 - x_1}{\lambda} \quad V = C \int_{x_1}^{x_2} \frac{dx}{2m} \frac{d^2 V}{dx^2} + V_0 = E \Psi \\
 & T = \frac{4 \pi n_1 n_2}{(n_1 + n_2)^2} \quad PV = nRT \\
 & Z = \frac{Z'}{f} = \frac{\Delta}{f_1} - \frac{f}{f_2} = Z_1 - Z_2 \cdot f_1 \\
 & \Delta t = \frac{\Delta f}{C_1} \quad f = \frac{t_2 - t_1}{Z} = \frac{d}{dt} V_0 / (1 + \beta \omega_0) \\
 & k = \frac{2\pi}{4\pi G_F} \quad Z = 2 \cdot \frac{1}{f_1} \quad f_1 = \frac{\Delta}{f} = \frac{\Delta f}{C_1} = \frac{f_2 - f_1}{Z} = \frac{1}{2\pi R_L} \quad m = N m_p \cdot \frac{Q}{N_A} \quad M_m = 2 \cdot \frac{h}{4\pi G_F} \\
 & V_0 = \frac{2\pi T}{m_e} = \frac{3 \pi T N_A}{M_m} = \frac{3 R_m T}{M_A} \quad P = \frac{F}{A} = \frac{m A \dot{x}}{2\pi R_L} = \frac{m A^2 U_{eff}}{2\pi R_L^2} = \frac{m}{2\pi R_L} \frac{M_A}{N_A} = \frac{M_A 10^{-3} H_0}{2\pi R_L} \frac{\partial H_0}{\partial x} \\
 & T_m = U_m^2 \left[\frac{1}{R_m^2} + \left(\frac{X_m}{X_c} - \frac{X_m}{X_L} \right)^2 \right] \quad \Delta U = \frac{2\pi \Delta X_m}{R_m^2} \frac{2\pi d \sin \theta}{2\pi d y} = \frac{2\pi d y}{R_m^2} \quad F_m = \frac{F_m}{R_m^2} \cdot \frac{I_m}{I_c} \cdot \frac{I_c}{2\pi d} \cdot \frac{2\pi d}{R_m^2} \cdot X \\
 & R = R_0 \cdot \sqrt{A} \quad W = F \cdot d \cdot 0.0001 \quad \omega = \frac{2\pi d \sin \theta}{R_m^2} \quad X_m = U_m = \omega L = 2\pi d^2 f
 \end{aligned}$$



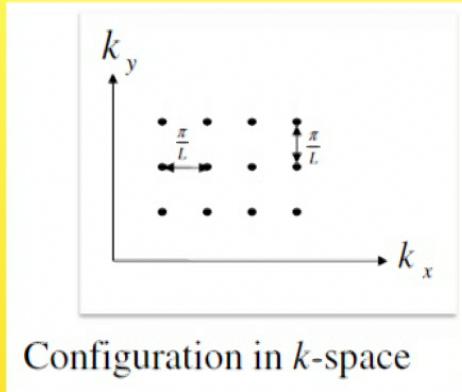
LONG TERM TARGET

CLASSIFY AND UNDERSTAND DIFFERENT PHASES OF MATTER



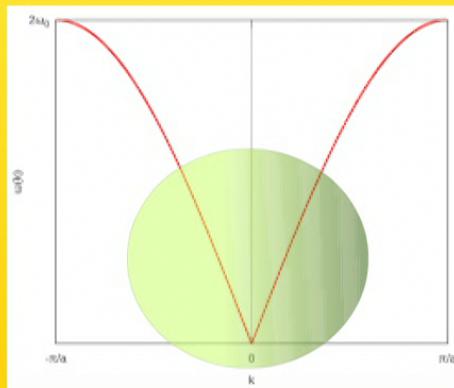
The Debye model

1) A periodic lattice



Configuration in k -space

2) Plane waves



$$\omega = v_s k$$

3) Cutoff frequency

$$\omega_D$$

VDOS

STEPS :

$$\rho(k) = \frac{V k^2}{2\pi^2}$$

Density of states in
Momentum space

$$g(\omega)d\omega = \rho(k)dk$$

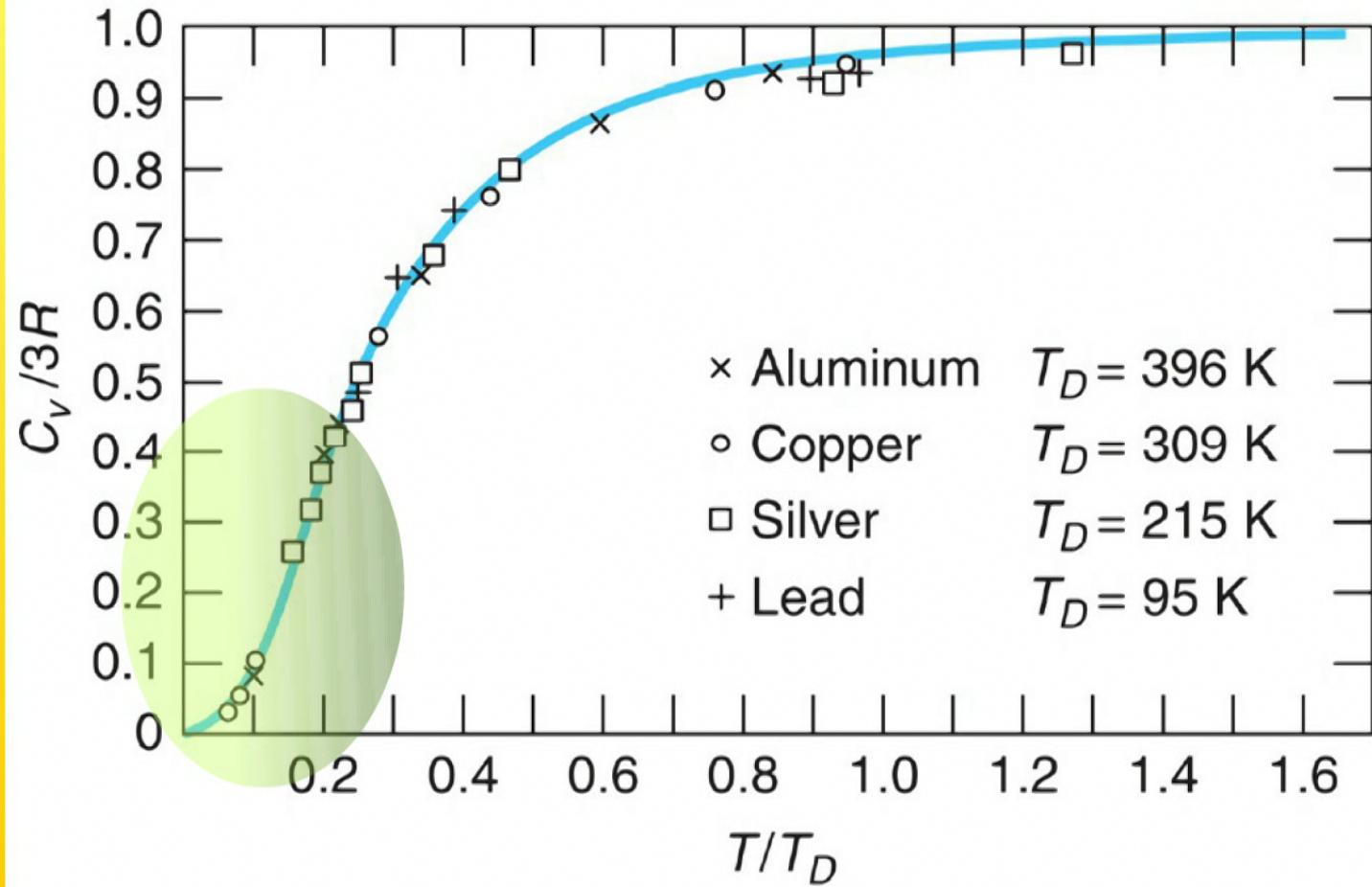
+

$$\omega = v_s k$$

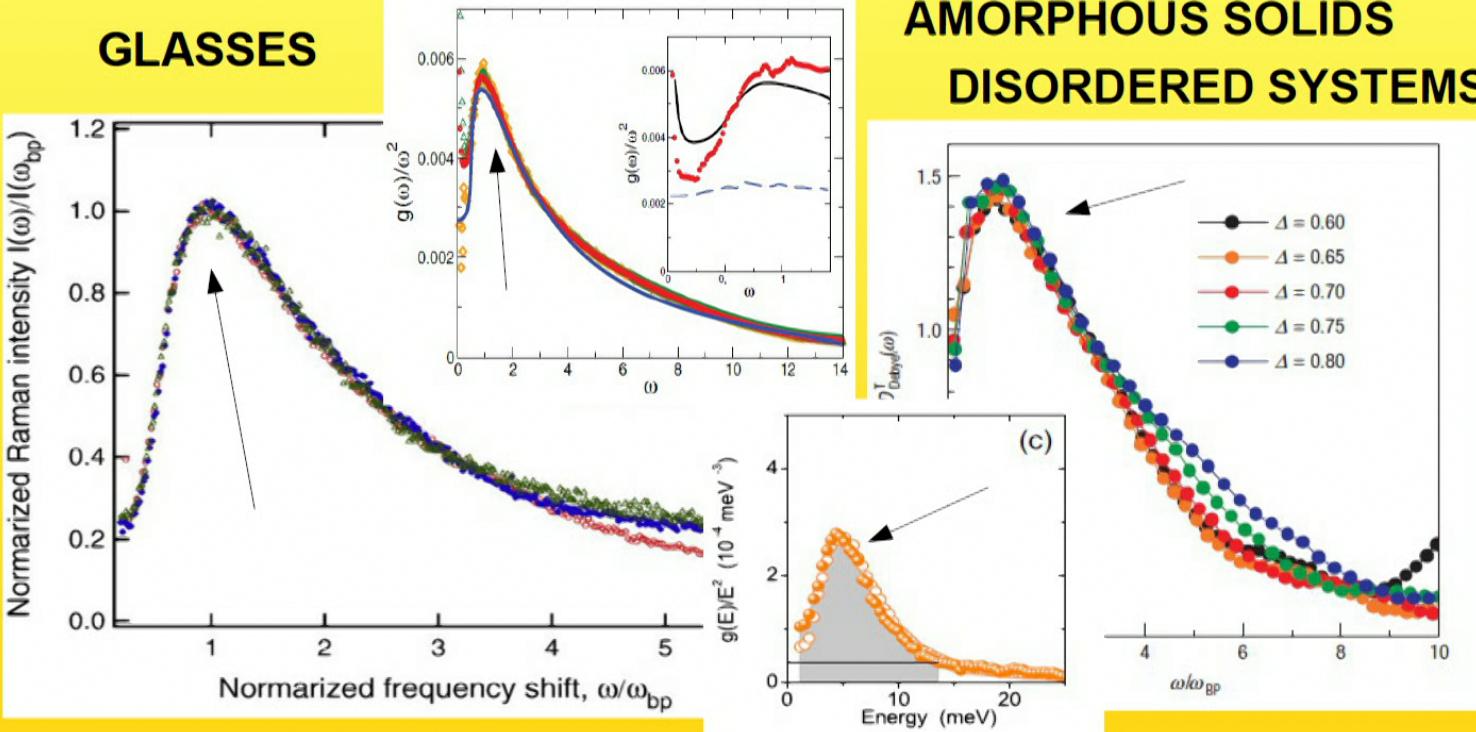
$$g(\omega) = \frac{V\omega^2}{2\pi^2} \left(\frac{1}{v_L^3} + \frac{2}{v_T^3} \right)$$

$$C_v = \frac{d\varepsilon}{dT} = \frac{2}{15} V \pi^2 k_B \left(\frac{1}{v_L^3} + \frac{2}{v_T^3} \right) \left(\frac{k_B T}{\hbar} \right)^3$$

at low temperatures



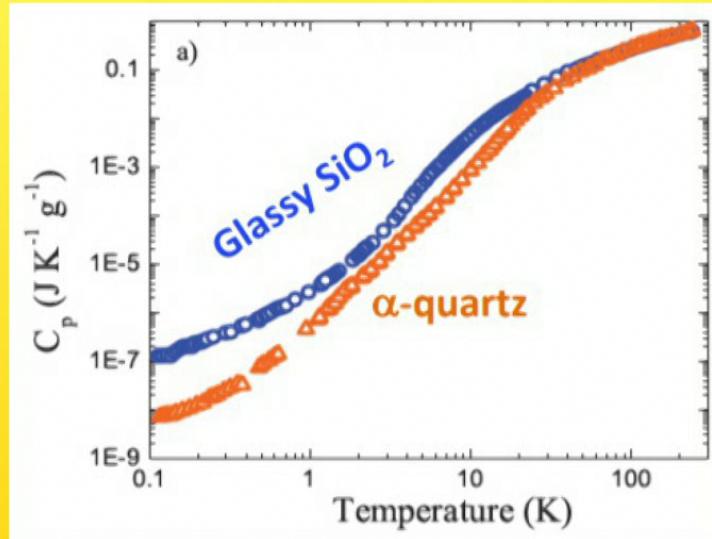
HOUSTON WE HAVE A PROBLEM



**"BOSON" PEAK (1 Thz)
EXCESS OF STATES
DEBYE MODEL FAILS**

ACTUALLY MORE THAN 1 ...

Oxide glasses, molecular glasses, polymers,
molecular crystals, colloidal glasses, etc



Thermal conductivity

$$K_T \propto T^2$$

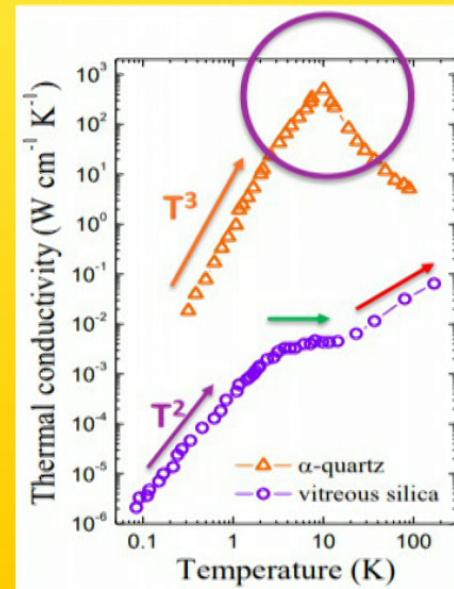
Flattening of k_T around 10 K

Weak increase for $T > 50$ K

Heat capacity anomalies

$$C_p \propto aT^3 + bT$$

Peak at $\sim 10\text{K}$



Solved ??

heterogeneous elasticity theory
[Schirmacher and co-workers]

**randomly-distributed
soft anharmonic modes**
[Gurevich, Shober and co-workers]

**Density fluctuations
Of glass structures**
[Gotze and co-workers]



**Local inversion
Symmetry breaking**
[Zaccone and co-workers]

Phonon-saddle transition
[Parisi and co-workers]

**Broadening/lowering of the
lowest van Hove singularity**
[Schirmacher, Taraskin and co-workers]

**ALL THE MODELS AT HAND RELY
ON THE ASSUMPTION OF DISORDER**

BUT ...

OBSERVATION OF THE BP IN ORDERED SINGLE CRYSTALS WITH NO DISORDER !!!

Role of Disorder in the Thermodynamics and Atomic Dynamics of Glasses

A. I. Chumakov, G. Monaco, A. Fontana, A. Bosak, R. P. Hermann, D. Bessas, B. Wehinger, W. A. Crichton, M. Krisch, R. Rüffer, G. Baldi, G. Carini Jr., G. Carini, G. D'Angelo, E. Gilloli, G. Tripodo, M. Zanatta, B. Winkler, V. Milman, K. Refson, M. T. Dove, N. Dubrovinskaia, L. Dubrovinsky, R. Keding, and Y. Z. Yue
Phys. Rev. Lett. **112**, 025502 – Published 15 January 2014

Glassy Dynamics versus Thermodynamics: The Case of 2-Adamantanone

D. Szewczyk[†], A. Jeżowski[†], G. A Vdovichenko[‡], A. I. Krivchikov[‡], F. J. Bermejo[¶], J. Li. Tamarit[§], L. C. Pardo[§], and J. W. Taylor^{||}

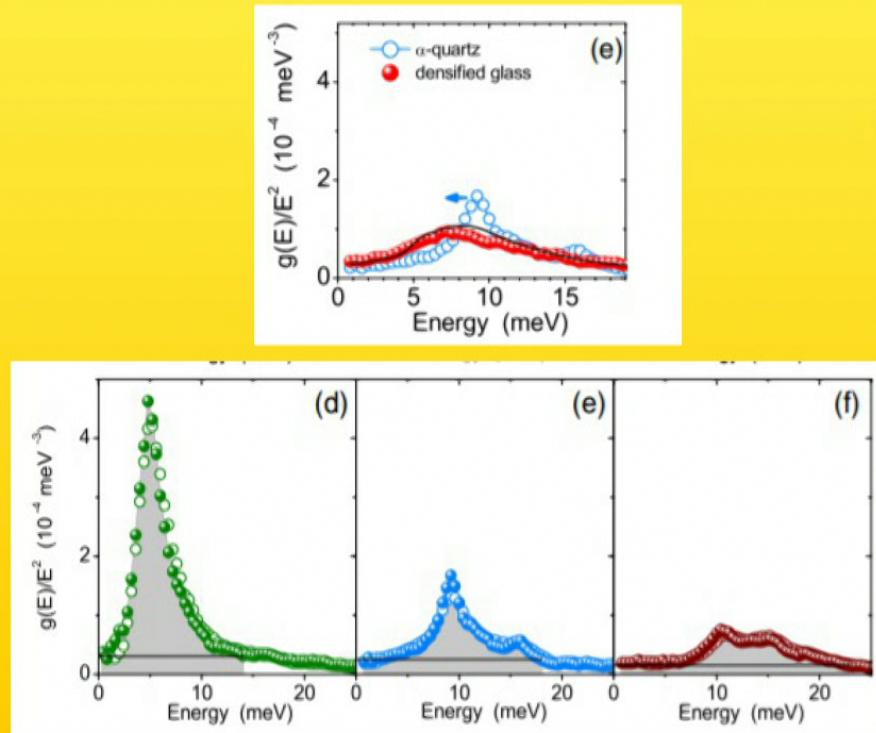
Glassy anomalies in the heat capacity of an ordered 2-bromobenzophenone single crystal

Andrzej Jeżowski, Mikhail A. Strzhemechny, Alexander I. Krivchikov, Nadezhda A. Davydova, Daria Szewczyk, Stepan G. Stepanian, Lyubov M. Buravtseva, and Olesia O. Romantsova
Phys. Rev. B **97**, 201201(R) – Published 23 May 2018

PLUS :

Role of Disorder in the Thermodynamics and Atomic Dynamics of Glasses

A. I. Chumakov,^{1,*} G. Monaco,^{2,1} A. Fontana,^{2,3} A. Bosak,¹ R. P. Hermann,^{4,5} D. Bessas,^{4,5,†} B. Wehinger,¹ W. A. Crichton,^{1,‡} M. Krisch,¹ R. Rüffer,¹ G. Baldi,⁶ G. Carini Jr.,⁷ G. Carini,⁸ G. D'Angelo,⁸ E. Gilioli,⁶ G. Tripodo,⁸ M. Zanatta,^{9,3} B. Winkler,¹⁰ V. Milman,¹¹ K. Refson,¹² M. T. Dove,¹³ N. Dubrovinskaia,¹⁴ L. Dubrovinsky,¹⁵ R. Keding,¹⁶ and Y. Z. Yue^{17,§}



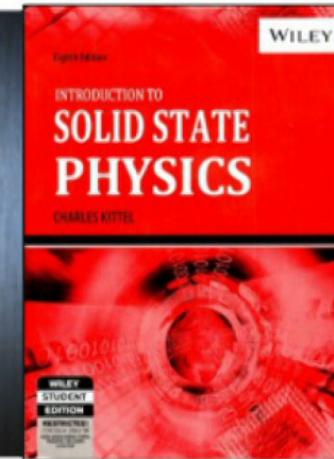
UNEXPLAINED DENSITY
DEPENDENCE OF
THE BP



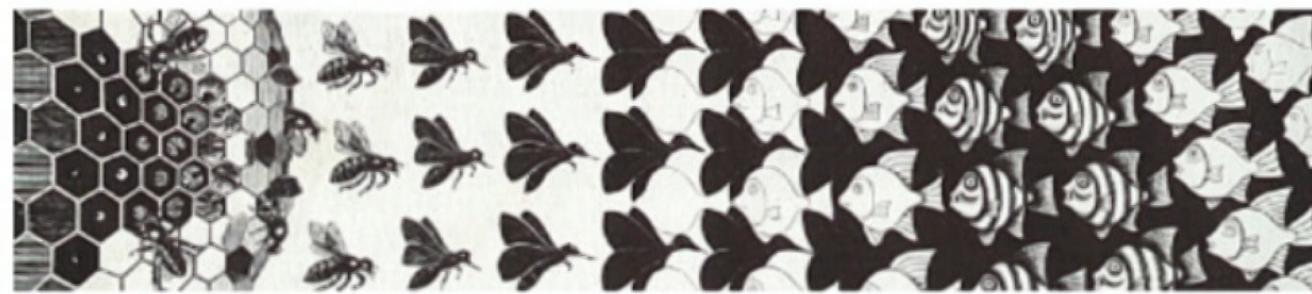
HOLOGRAPHY

General
Relativity

Robert M. Wald



*Use a dual description in terms of different d.o.f.
where the theory is EASIER
and the computations are doable*



BREAKING TRANSLATIONS



$$\partial_i T^{ij} = - \frac{1}{\tau_{rel}} T^{tj} \neq 0$$



$$\frac{1}{\tau_{rel}} \sim \mathcal{M}_h^2(T, k, q, g_i, \dots)$$

[Vegh, 2012]

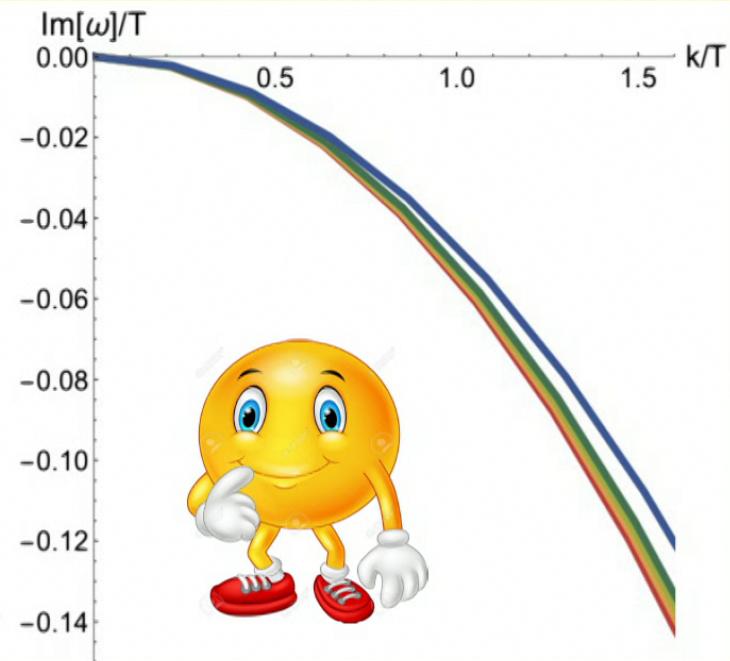
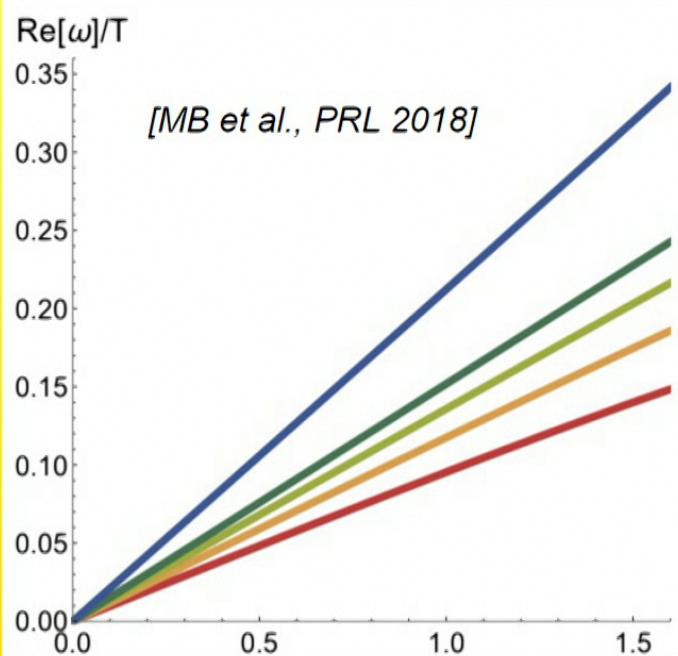
[MB, Pujolas et Al.]

LORENTZ VIOLATING HOLOGRAPHIC MASSIVE GRAVITY

$$\mathcal{H}_0 + \delta\mathcal{H}(\vec{x}) \longrightarrow \text{EXPLICIT BREAKING}$$

$$\langle \mathcal{O}(\vec{x}) \rangle \neq 0 \longrightarrow \text{SSB : PHONONS, ELASTICITY}$$

HOLOGRAPHIC PHONONS



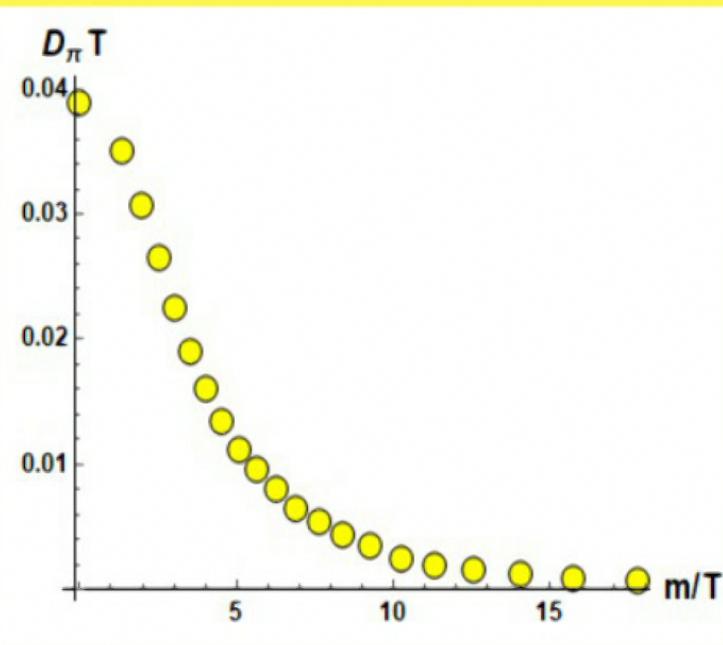
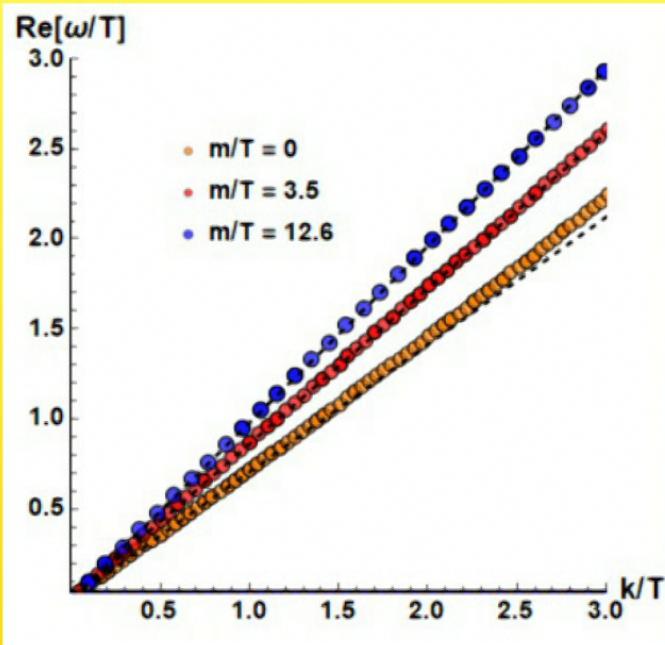
$$\omega = c_T k - i D k^2$$

$$c_T^2 = \frac{\mu}{\epsilon + p}$$

$$D \sim \eta$$

LONGITUDINAL PHONONS

[MB, M.Ammon et Al., in progress]



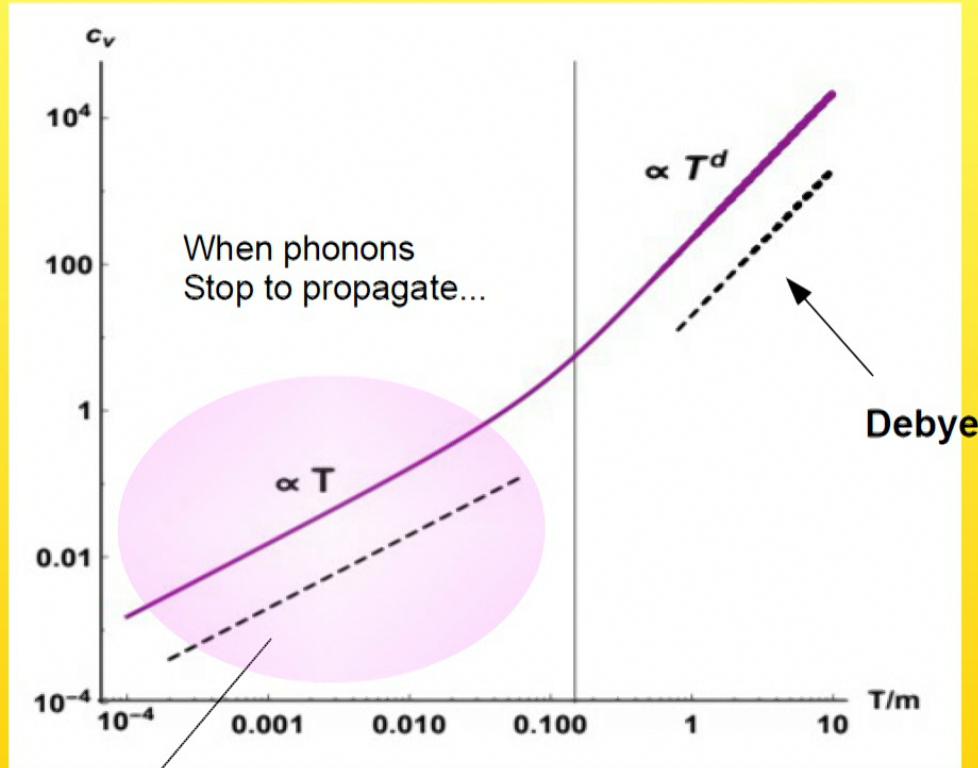
$$\omega = c_L k - i D_L k^2$$

$$c_L^2 = c_T^2 + \frac{1}{2}$$
 [Nicolis et Al. 2017]

$$c_L^2 = \frac{\mu + K}{\epsilon + p} + \frac{1}{2} \frac{s T}{\epsilon + p}$$

[Hartnoll et Al. 2018]

And if you compute the heat capacity...



Anomaly typical of glasses and amorphous materials ...



THE IDEA

$$\omega = v_s k$$

$$\omega = v_s k - i D k^2$$

PROPAGATION

elasticity

Hints:

Holography

[MB et Al.]

Diffusons,

[Allen et Al. 1999]



DIFFUSION

viscosity

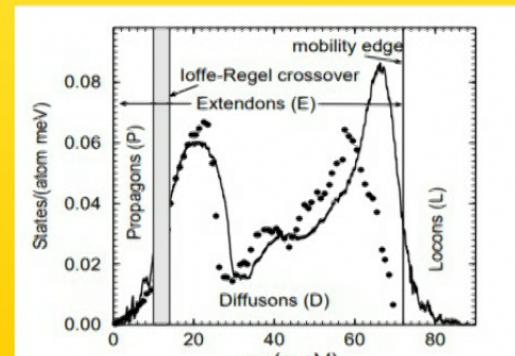


FIG. 1. Density of vibrational states from the 4096-atom model compared with data from Kamitakahara et al. (1987).

Where does D come from ?



In holography it comes from the presence of the horizon !!
Finite temperature effects

It can come from disorder
in disordered materials and amorphous solids

[Beltukov & Parshin, PRB]

It can come from anharmonic interactions
In ordered crystals !!

[Landau & Rumer, 1936]

NO NEED OF DISORDER
Just of diffusive damping !!

Starting from the principles

$$\rho \ddot{u}_i = \nabla_j \sigma_{ij} + f_i^{ext}(\mathbf{r})$$

Newton's Law
Elastodynamics

$$\sigma_{ij} \Rightarrow \sigma_{ij}^{el} + \sigma'_{ij}$$

Elastic term

DISSIPATION
Viscous term

$$\sigma_{ij}^{el} = 2\mu u_{ij} + \lambda u_{ll} \delta_{ij}$$

$$\sigma'_{ij} = \eta_{ijkl} \nabla_k \dot{u}_l$$

The Green Function

$$G_{L,T}(q, \omega) = \frac{1}{\Omega_{L,T}^2(q) - \omega^2 - i\omega\Gamma_{L,T}(q)},$$

with

$$\Omega_{L,T}(q) = c_{L,T} q \quad \Gamma_{L,T}(q) = D_{L,T} q^2,$$

$$\omega_{L,T} = c_{L,T} q - i D_{L,T} q^2,$$

$$D_T = \frac{\eta}{\rho}, \quad D_L = \frac{1}{2\rho} \left[\zeta + \frac{2(d-1)}{d} \eta \right]$$

DOS

$$c_T^2 = \frac{\mu}{\rho}, \quad c_L^2 = \frac{K + \frac{2(d-1)}{d}\mu}{\rho}$$

The (analytic) VDOS

From the Green Functions ...

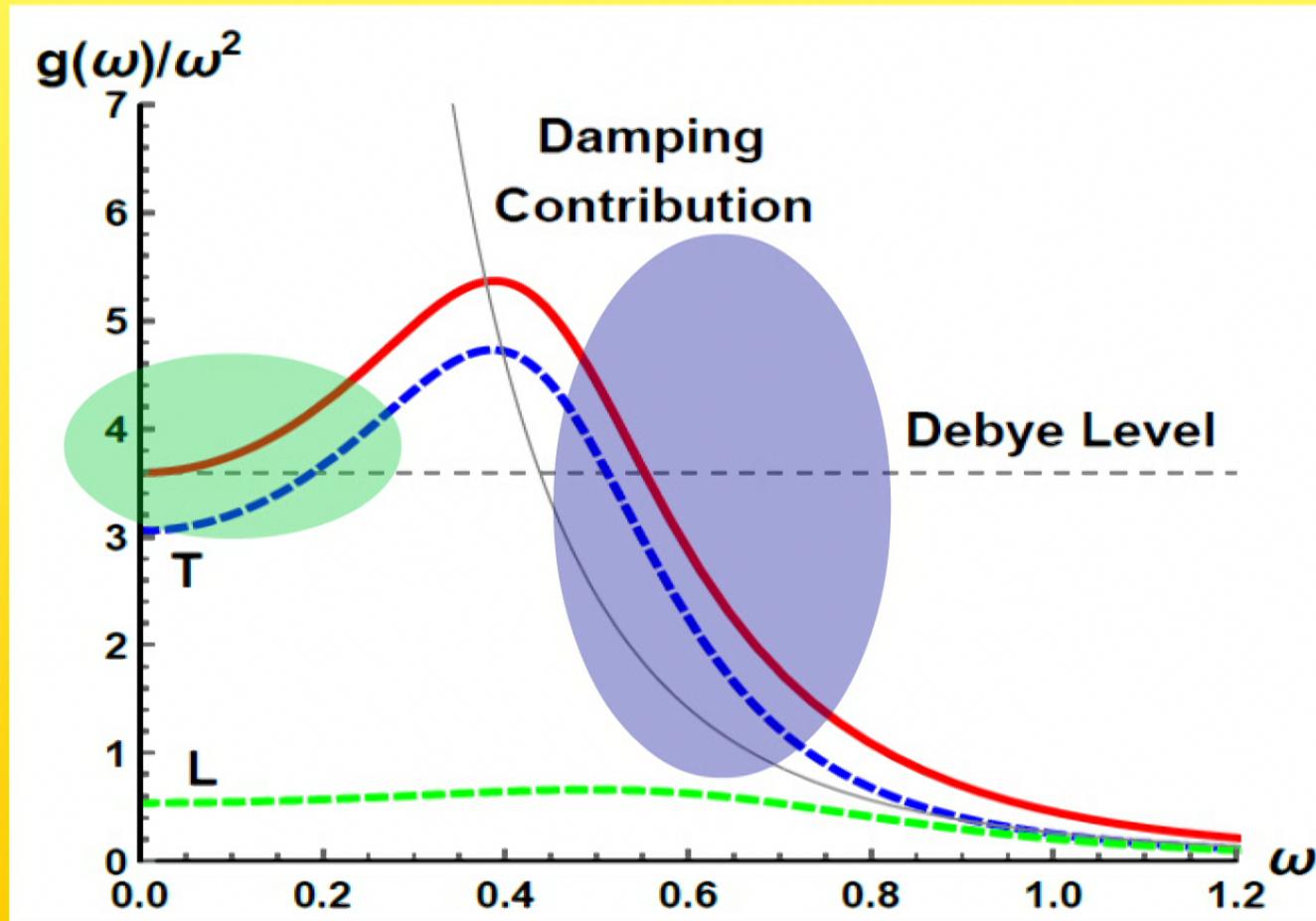
$$g(\omega) = -\frac{2\omega}{3\pi\mathcal{N}} \int_0^{q_D} dq^3 \operatorname{Im} \{2G_T(q, \omega) + G_L(q, \omega)\}, \quad (5)$$

Discretizing the integral ...

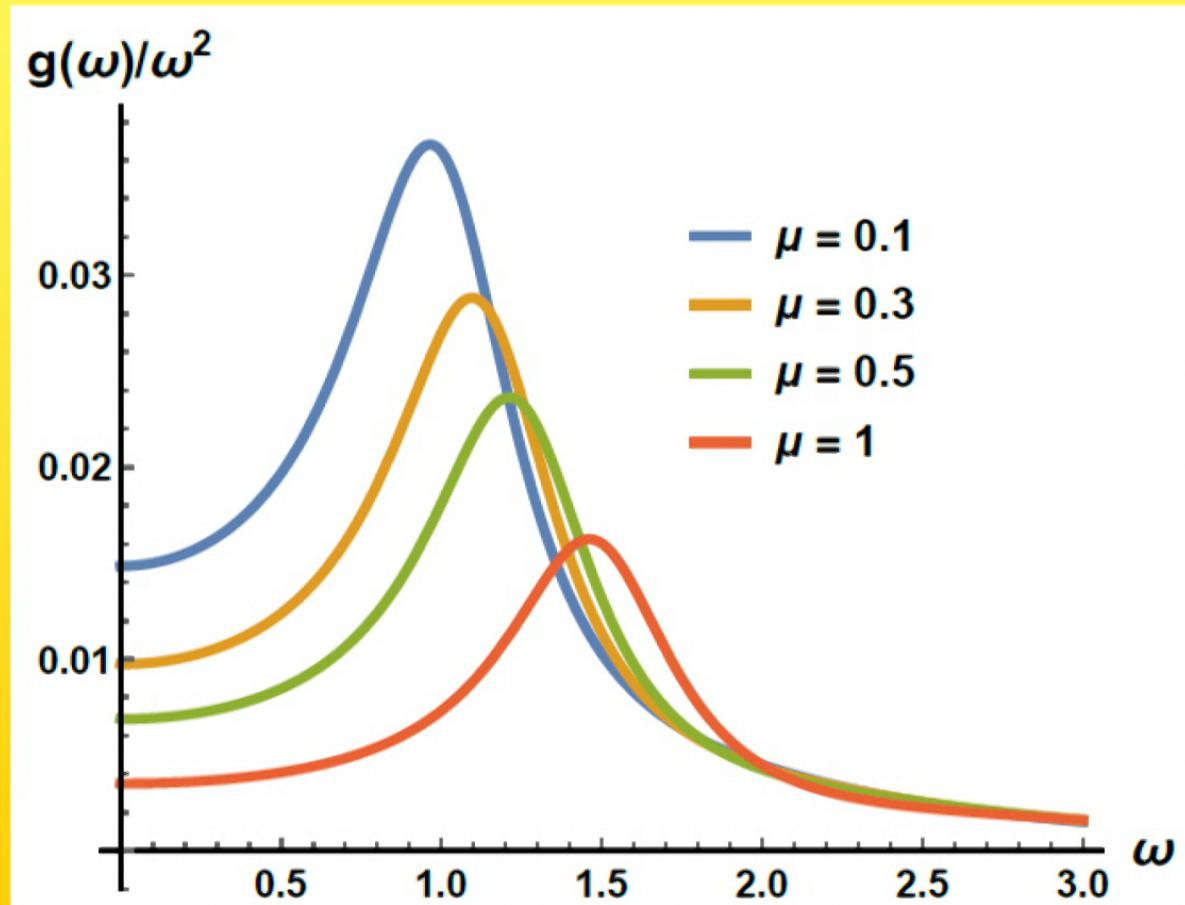
$$\begin{aligned} g(\omega) = & \frac{\omega}{3\pi\mathcal{N}} \operatorname{Im} \left\{ \frac{1}{\omega \sqrt{(-c_L^2 + iD_L\omega)(ic_T^2 + D_T\omega)}} \left[i\sqrt{ic_T^2 + D_T\omega} (\psi(x) - \psi(-x) + \psi(1 + q_D + x) - \psi(1 + q_D - x)) \right] \right. \\ & \left. + \left[(1+i)\sqrt{-2c_L^2 + 2iD_L\omega} (\psi(y) - \psi(-y) + \psi(1 + q_D + y) - \psi(1 + q_D - y)) \right] \right\} \end{aligned} \quad (6)$$

with $x = -\frac{i\omega}{\sqrt{-c_L^2 + iD_L\omega}}, \quad y = \frac{1+i\omega}{\sqrt{2ic_T^2 + 2D_T\omega}}$

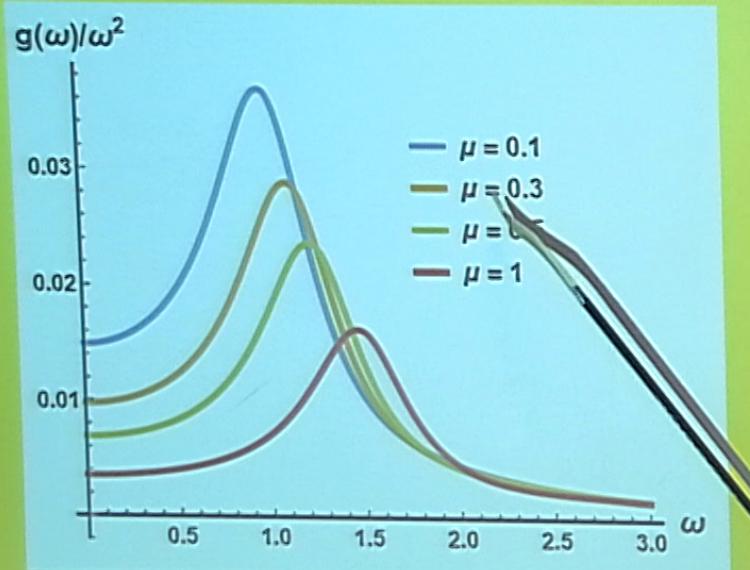
The general picture



Elastic modulus dependence



Elastic modulus dependence

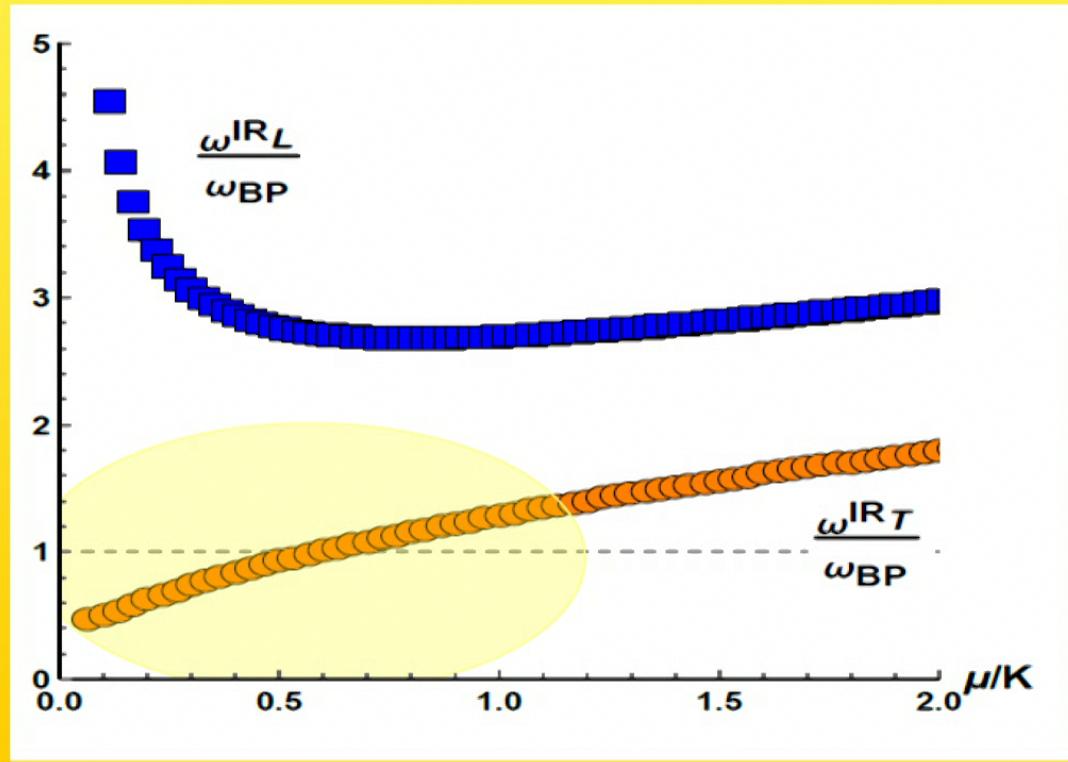




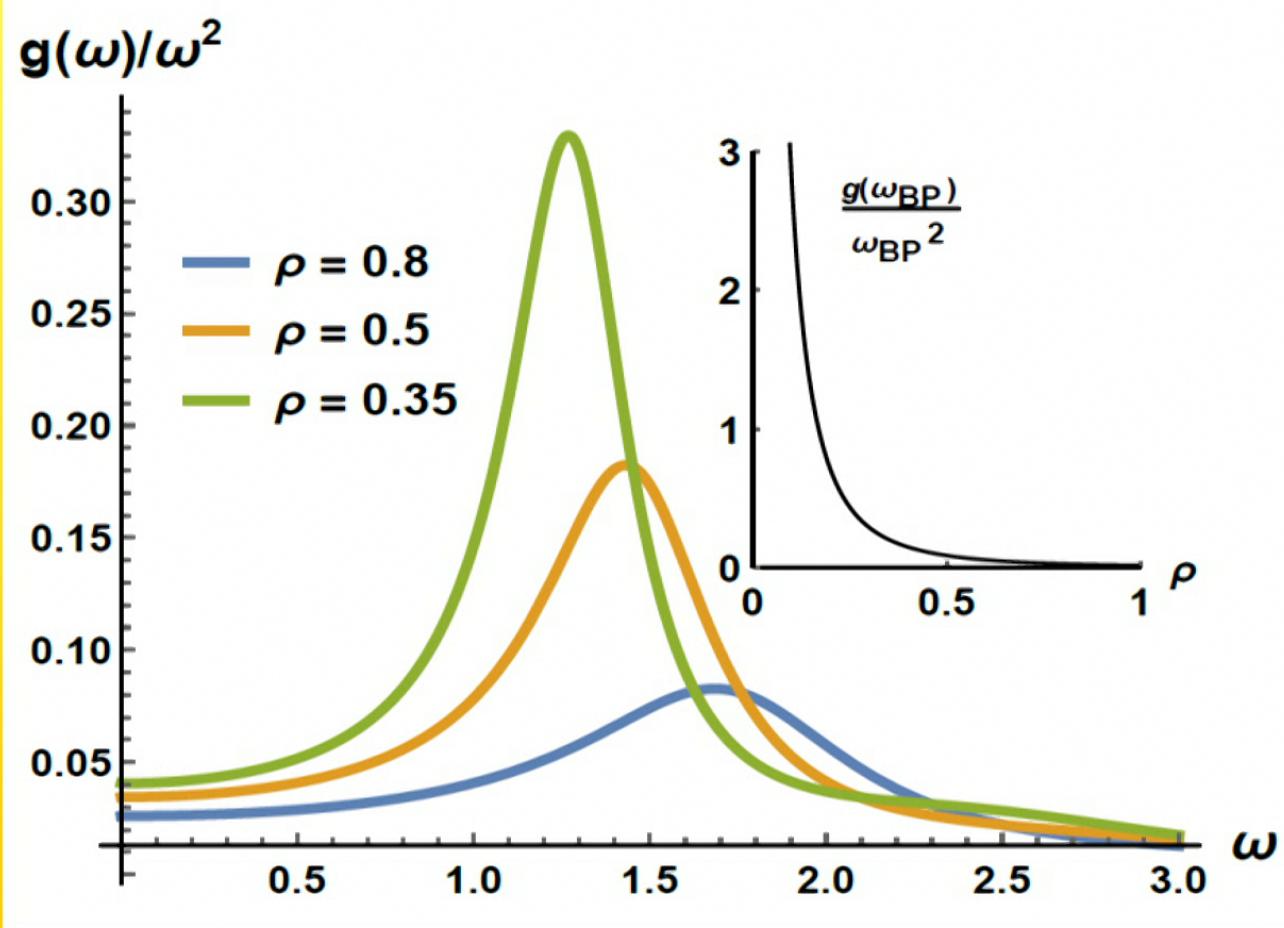
Ioffe-Regel frequencies

$$\omega_{L,T}^{IR} = c_{L,T}^2 / (\pi D_{L,T})$$

[Shintani & Tanaka 2008]



Density dependence



CONCLUSIONS

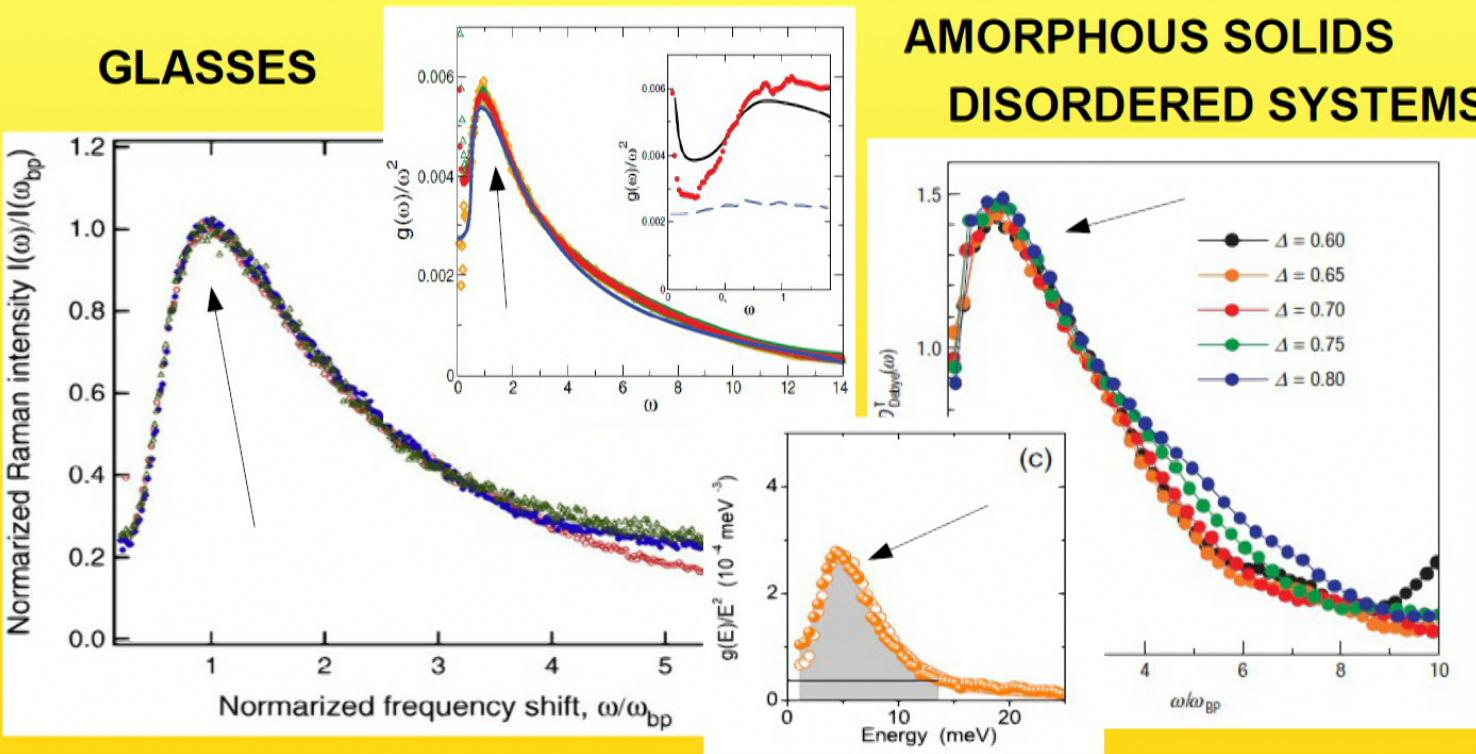
INSPIRED FROM THE HOLOGRAPHIC RESULTS

WE BUILT A SIMPLE MODEL EXPLAINING
FROM FIRST PRINCIPLES AND IN ANALYTIC WAY
THE UNIVERSAL EMERGENCE OF THE BOSON PEAK
IN AMORPHOUS AND DISORDERED SOLIDS AND ALSO
IN ORDERED CRYSTALS

NO ASSUMPTIONS ON THE MICROSCOPIC IS NEEDED
NO DISORDER IS NEEDED
EFT 2.0

HOLOGRAPHY IS ~~TRUE~~ USEFUL

HOUSTON WE HAVE A PROBLEM



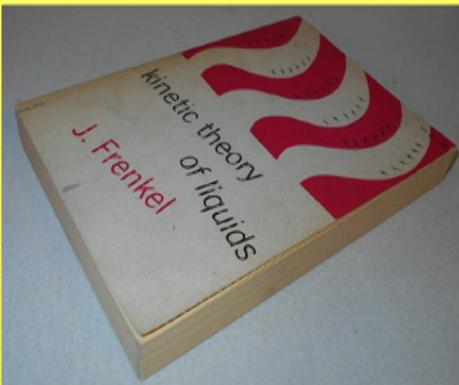
**"BOSON" PEAK (1 Thz)
EXCESS OF STATES
DEBYE MODEL FAILS**



MORE!!

WHAT ABOUT LIQUIDS ?

AND.... WHAT IS A LIQUID ?



ARE LIQUIDS AND SOLIDS
REALLY DIFFERENT ?

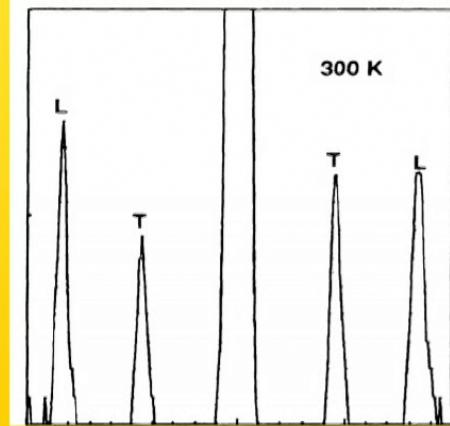
NOT IF

$$\omega > \omega_F \equiv \frac{1}{\tau}$$

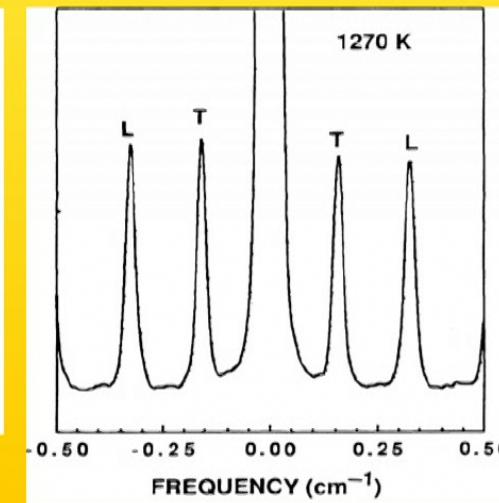
Proved in several experiments !!

High-frequency longitudinal and transverse dynamics in water

INTENSITY (arb. units)



300 K

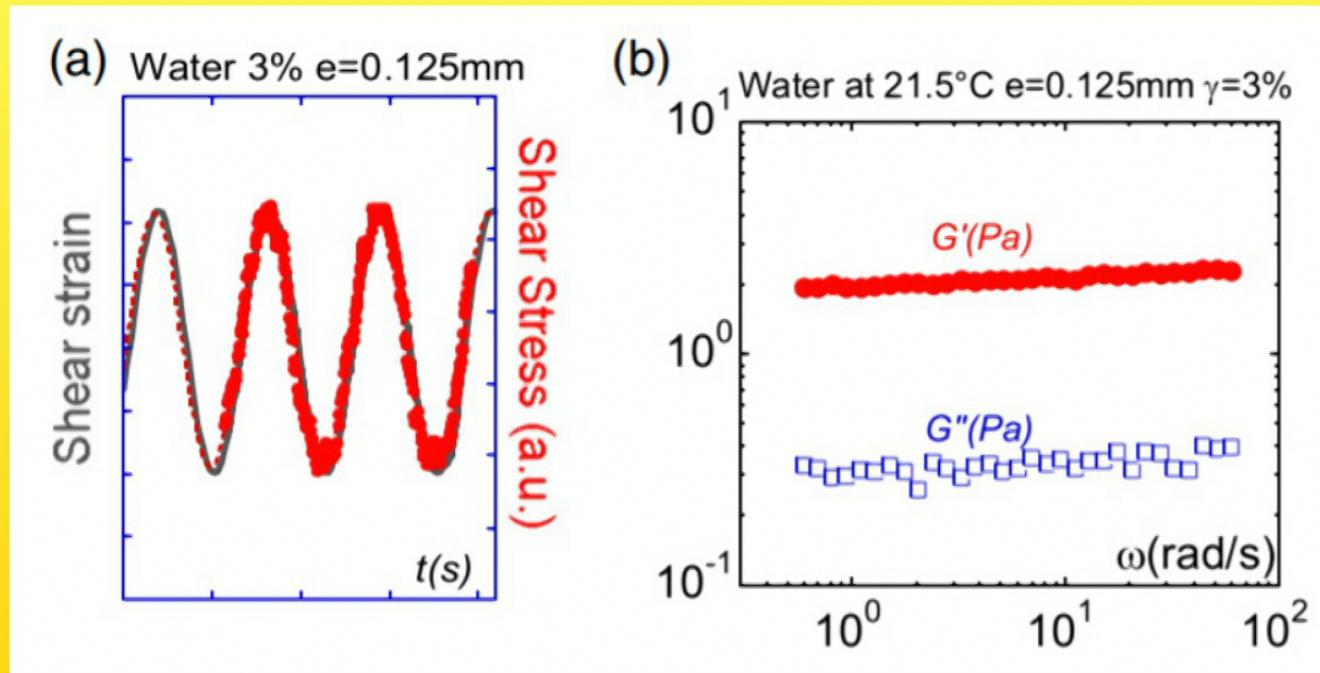


1270 K

FREQUENCY (cm⁻¹)

THAT'S IT ?? NO !

Experiments by Noirez's group in Paris



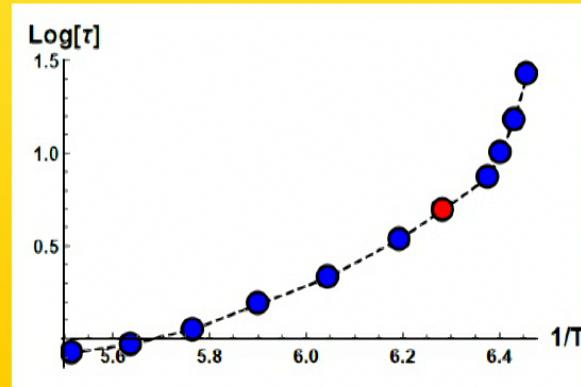
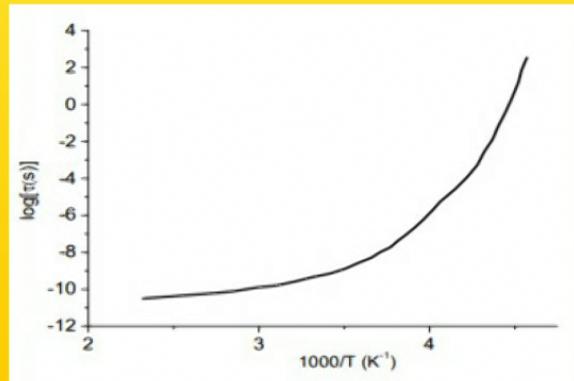
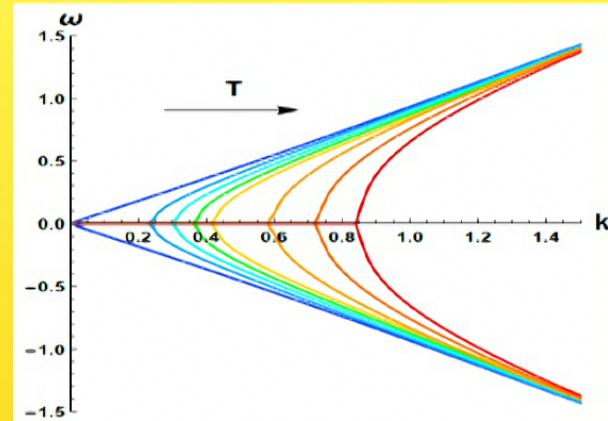
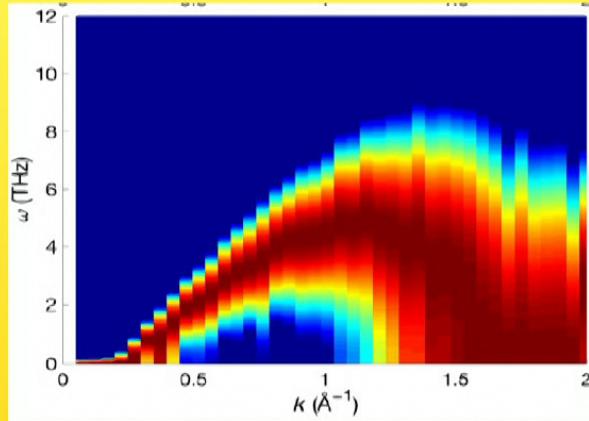
LIQUIDS SUPPORT PROPAGATING SHEAR WAVES ALSO AT LOW FREQUENCIES !!!
LIQUIDS BEHAVE LIKE ELASTIC SOLIDS ALSO AT LOW FREQUENCY !!!

And now ??????

Liquids vs Solids

[MB & Trachenko, 2018]

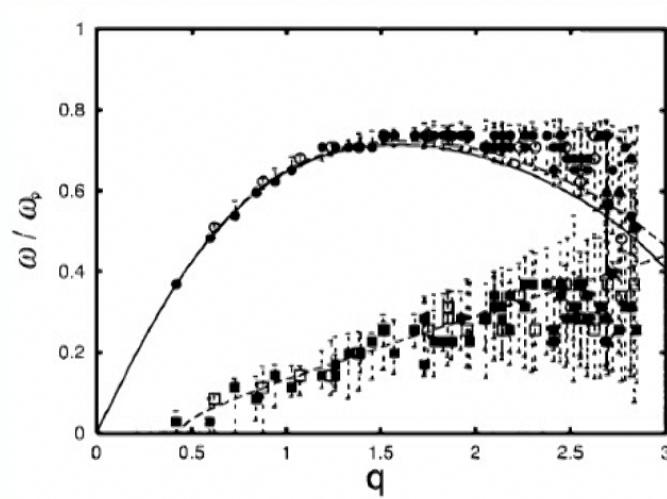
$$\omega = \sqrt{c^2 k^2 - \frac{1}{\tau^2}}$$



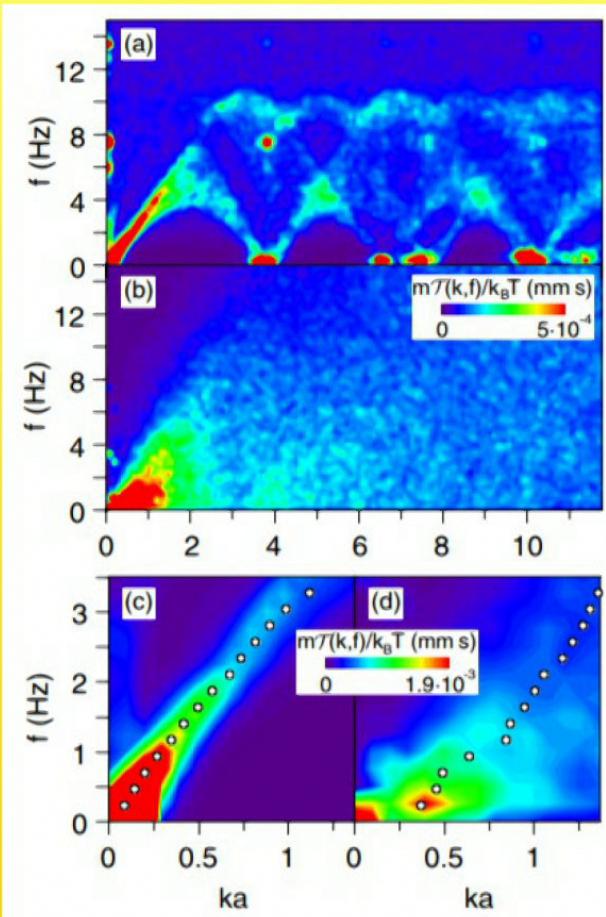


OBSERVED
IN PLASMAS

[Ohta et Al., 2000]



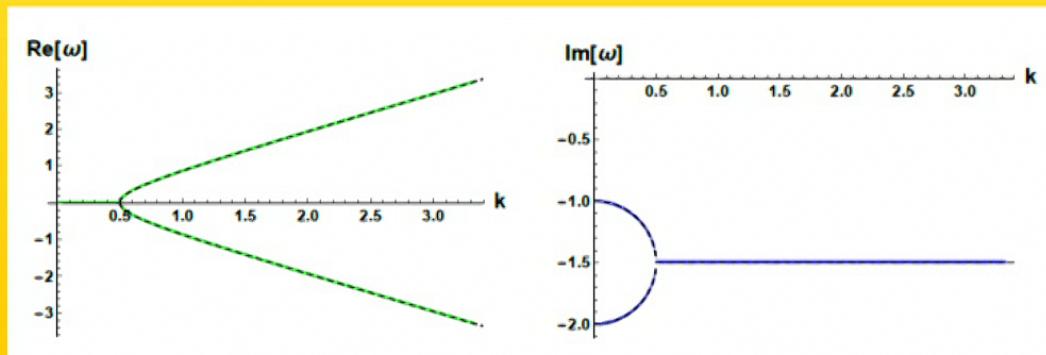
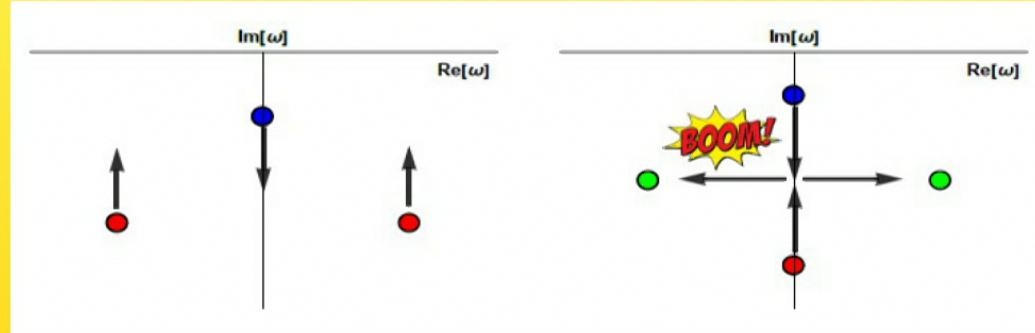
[Nosenko et Al., 2006]



QUASIHYDRODYNAMICS

[Lucas, Grozdanov, Povoottikul , '18]

$$\partial_t \langle \rho_a \rangle + \partial_i \mathcal{J}_a^i = 0, \quad \partial_t \langle \mathcal{O} \rangle + \partial_i \mathcal{J}_{\mathcal{O}}^i = - \frac{\langle \mathcal{O} \rangle}{\tau}$$



CHIRAL MAGNETIC WAVES

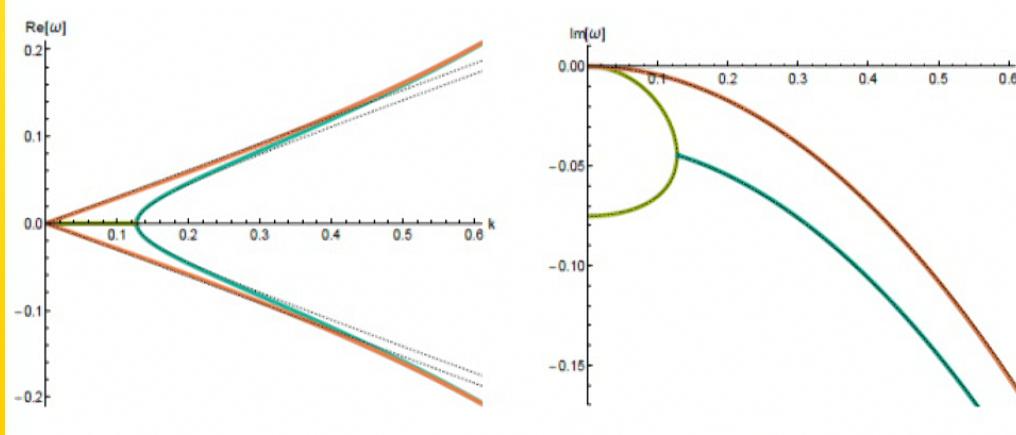
[Landsteiner et Al, '14]

[Stephanov et Al, '15]

$$j_A = \frac{\kappa B \rho_V}{\chi_V} - D \partial_x \rho_A, \quad j_V = \frac{\kappa B \rho_A}{\chi_A} - D \partial_x \rho_V$$

$$\partial_\mu j_V^\mu = 0, \quad \partial_\mu j_A^\mu = -\frac{1}{\tau_A} \rho_A$$

$$\omega = -\frac{i}{2\tau_A} \pm \sqrt{\frac{B^2 k^2 \kappa^2}{\chi_A \chi_V} - \frac{1}{4\tau_A^2}} - iDk^2$$



CONCLUSIONS PART II

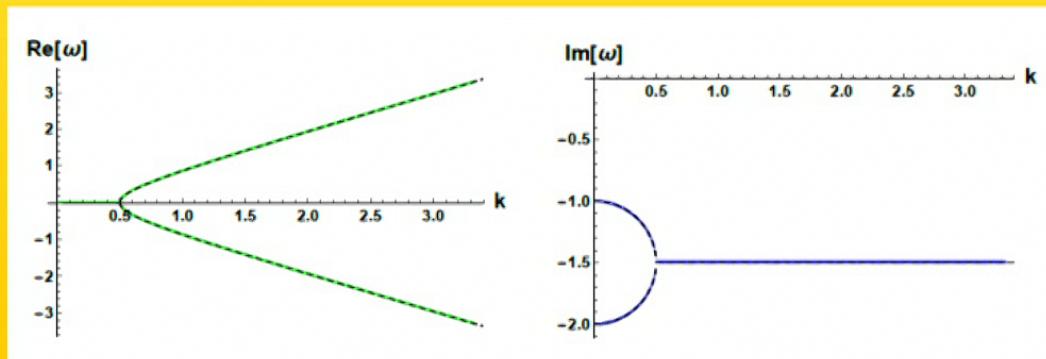
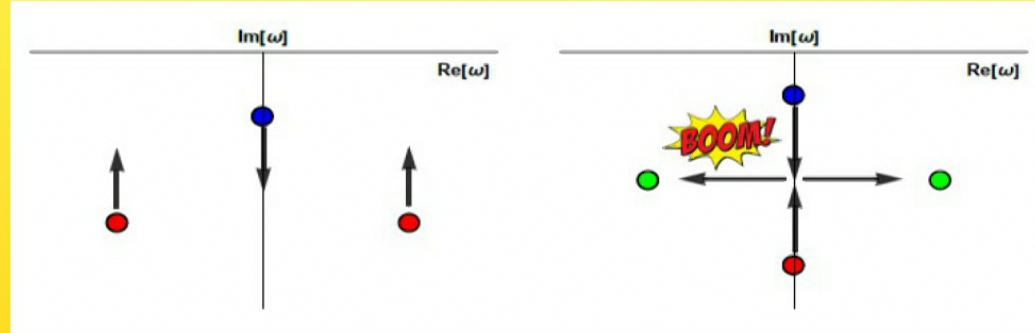
K-gap dispersion relation can explain the mysterious experiments

- Can be obtained directly from Navier-Stokes via Maxwell interpolation
- "Quasihydodynamics" , Israel-Stewart, GB, etc... *[Grozdanov et Al., 2018]*
- It is much more general: plasma, hydro, Keldish-Schwinger,
Holography, anomalous transport, Sine-Gordon
Equation ... *[MB et Al., to appear]*
- It has been observed in plasmas;
Can it be observed in chiral magnetic waves ?
Next march: experiments in liquid at ISIS Oxford (stay tuned)

QUASIHYDRODYNAMICS

[Lucas, Grozdanov, Povoottikul , '18]

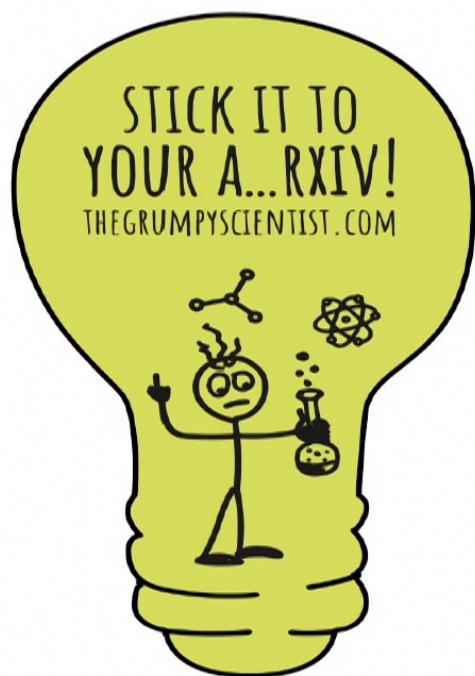
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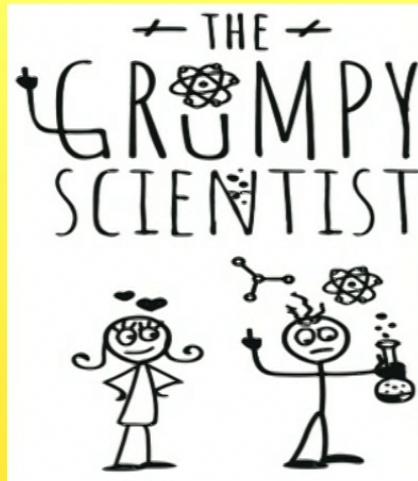
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INSTABILITY
DEPRESSION
MENTAL ILLNESS
In academia



thegrumpyscientist

**STAY GRUMPY,
STAY SCIENTIST**

GRUMPINESS



