arXiv:1411.1003

arXiv:1601.03384

arXiv:1708.08306

arXiv:1708.08477

Elasticity and (pseudo)-phonons In holography

Many-Body Quantum Chaos, Bad Metals and Holography

With O.Pujolas, M.Ammon, L.Alberte, A.Jimenez, (+ A.Krikun, T.Andrade, N.Poovuttikul)

Matteo Baggioli

UOC & Crete Center for Theoretical Physics

arXiv:1708.08477 + COMING SOON

Holographic transverse PHONONS

With O.Pujolas, M.Ammon, L.Alberte, A.Jimenez

MY FIRST TIME HAVING

Transverse phonons

See also Daniele & Nick talks

Out of Time Talk (OTT)

$$\langle \left[\mathrm{CONCLUSIONS}\,(t,\vec{x})\ ,\ \mathrm{INTRO}\,(0,\vec{x}) \right] \rangle_\beta$$

HOLOGRAPHIC MASSIVE GRAVITY = **BREAKING OF TRANSLATIONS**

3-IN-ONE

1) Explicit

2) Spontaneous

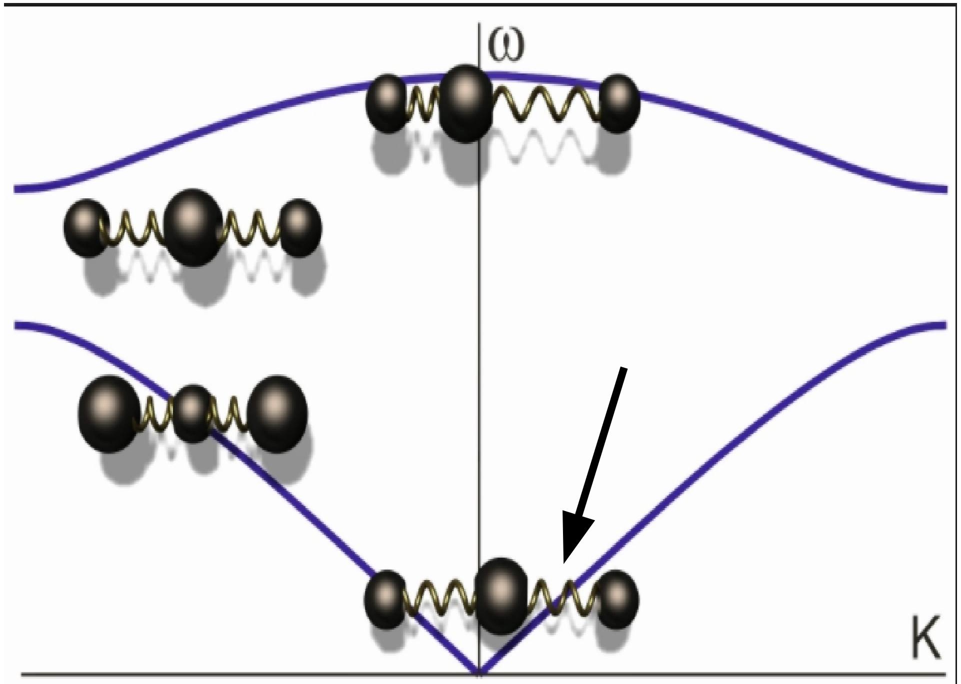
3) Both

WHERE ARE THE
PHONONS ??

IS HOLOGRAPHY
ELASTIC ??

WHICH ARE THE EFFECTS
ON TRANSPORT ??

Phonons as goldstone bosons



$$\lim_{k\to 0} E(k) = 0.$$

$$\omega_T = c_T\, k\,, \qquad \omega_L = c_L\, k$$

Shear sound

"sound"

PHONON = GOLDSTONE FOR TRANSLATIONAL SYMMETRY

Old school EFT

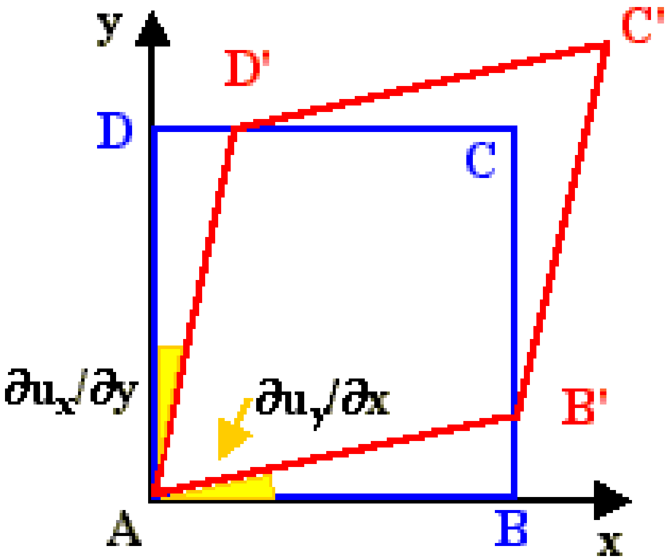
arXiv:hep-ph/9609466

$$\mathcal{L}_2 = \frac{1}{2}\rho_0\, \dot{\xi}_a \dot{\xi}_a - \frac{1}{2}\mu\, \partial_a\xi_b\partial_a\xi_b - \frac{1}{6}(\mu + 3K)\partial_a\xi_a\partial_b\xi_b$$

Modern EFT : Sym. breaking patterns

arXiv:1501.03845

Elasticity



ELASTIC MODULI

$$\lambda \stackrel{\text{def}}{=} \frac{\text{stress}}{\text{strain}}$$

Bulk modulus κ

Shear modulus μ

Strain tensor → **Stress tensor**

$$u_{ij} = \frac{1}{2}(\partial_i u_j + \partial_j u_i) \longrightarrow T_{ij} = \kappa\,\delta_{ij}\,u_{kk} + 2\,\mu\left(u_{ij} - \frac{1}{3}\delta_{ij}\,u_{kk}\right)$$

PHONONS

↕

ELASTICITY

→

$$c_L^2 = \frac{\kappa + \frac{4}{3}\mu}{\rho}, \qquad c_T^2 = \frac{\mu}{\rho}$$

Gapped and Damped Goldstones

arXiv:hep-th/9808176

GOLDSTONE THEOREM $\langle G|\rho(\mathbf{r},t)|\Omega\rangle \neq 0.$

GOLDSTONE BOSON $\lim_{p\to 0} E(p) = 0.$

Relativistic setups : $\omega = v\,p$

PSEUDO - PHONONS

Now add a small Explicit breaking

$\mathcal{H} \to \mathcal{H} + \mathcal{H}_{EB}$

Example: PIONS

$$\omega^2 = \omega_0^2 + v^2 p^2 - i\,\omega\,\Gamma + \dots$$

See also Niko's and Daniele's talks

Mass gap (pinning frequency)

Damping (relaxation rate)

Both have to be small compared to the typical energy scale !!

Implications on (electric) Transport

Purely spontaneous

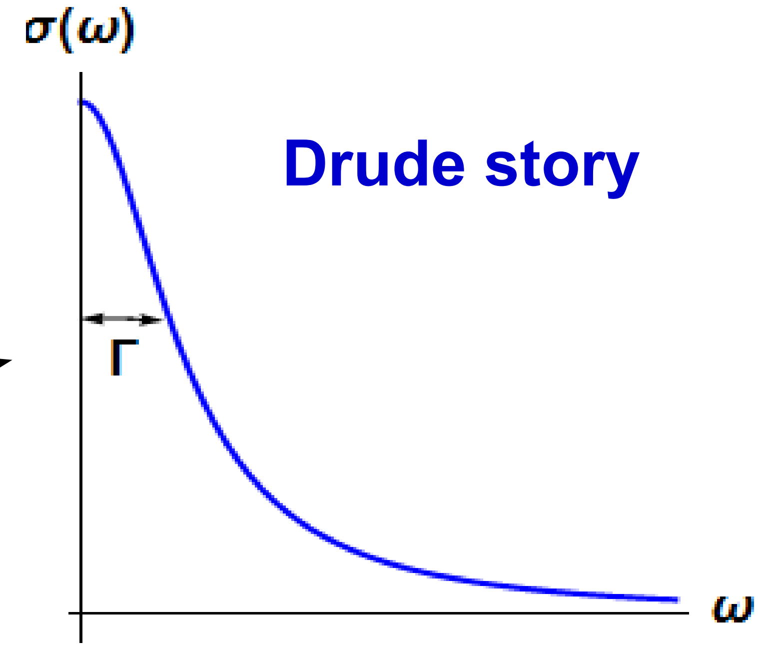
$$\sigma = \sigma_0 + \frac{\rho^2}{\chi_{PP}}\delta(\omega)$$

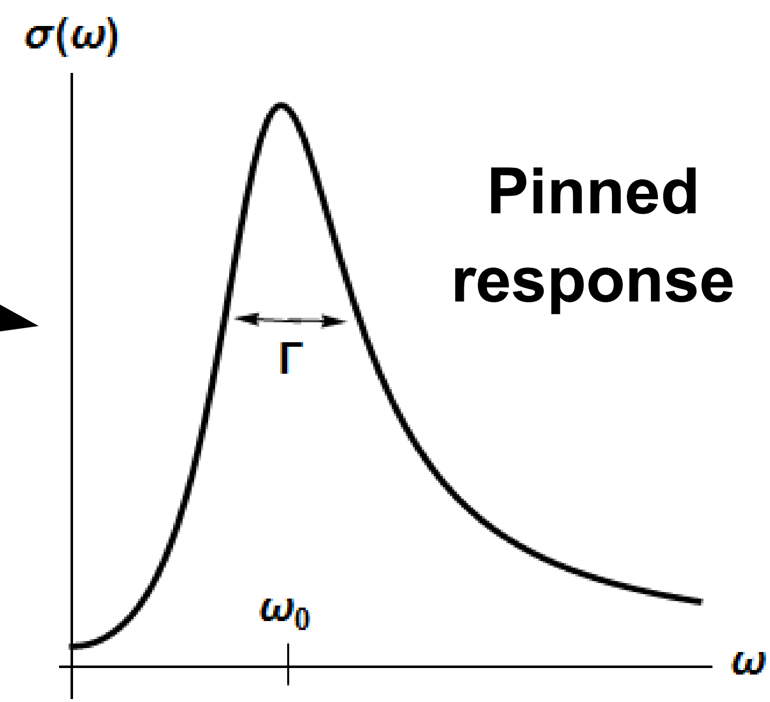
Purely Explicit

$$\sigma = \sigma_0 + \frac{\rho^2}{\chi_{PP}}\frac{1}{\Gamma - i\omega}$$

Explicit + Spontaneous

$$\sigma = \sigma_0 + \frac{\rho^2}{\chi_{PP}}\frac{-i\omega}{-i\omega\left(\Gamma - i\omega\right) + \omega_0^2}$$





"Solid" Massive gravity

arXiv:1411.1003

$$S=\int d^4x\sqrt{-g}\left[\frac{1}{2}\left(R+\frac{6}{l^2}\right)-m^2V(X)\right]$$

$$X\equiv\frac{1}{2}\mathrm{tr}[\mathcal{I}^{IJ}],\qquad \mathcal{I}^{IJ}\equiv\partial_\mu\phi^I\partial^\mu\phi^J,\qquad \hat{\phi}^I=\delta^I_i x^i$$

LORENTZ VIOLATING

HOLOGRAPHIC MASSIVE GRAVITY

Used a lot to implement momentum dissipation

(explicit breaking of translations)

Is it just that??

VS fluid

Massive gravity

$$Z=det\left[\mathcal{I}^{IJ}\right]$$

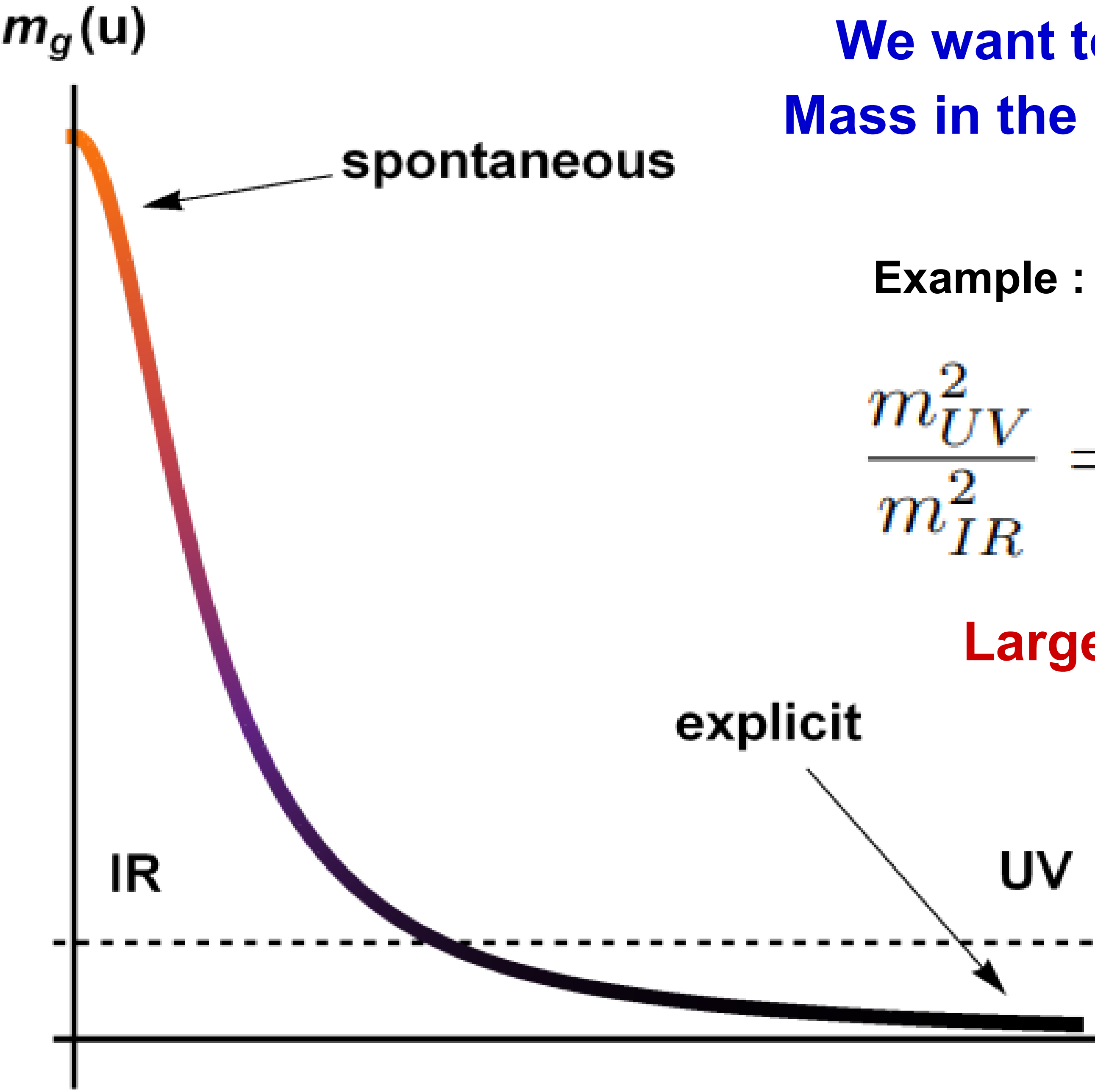
arXiv:1510.09089

Radially dependent graviton mass

(gauge inv. Order parameter)

$$M^2(z)\equiv\tilde{m}^2V_X$$

Explicit + Spontaneous (part I)



We want to localize the graviton
Mass in the IR (close to the horizon)

Example : $V(X) = X + \beta X^5$

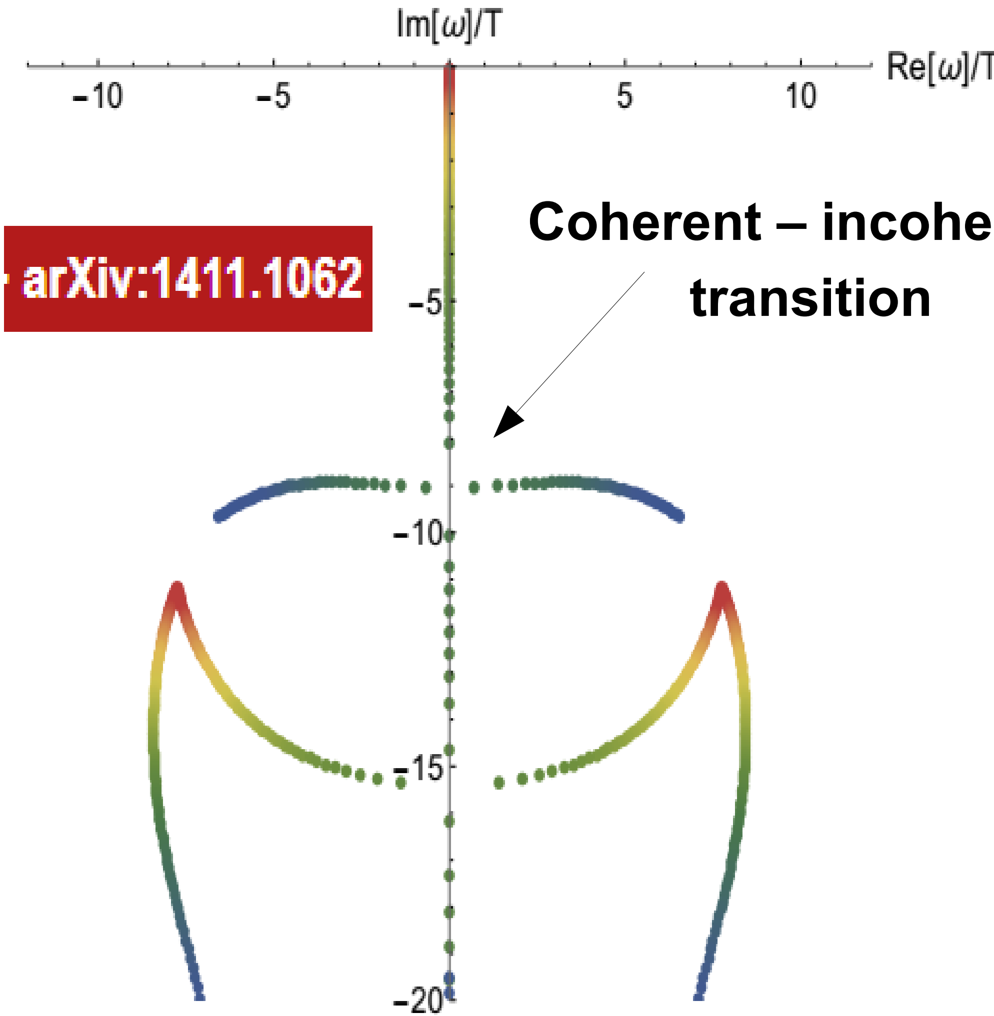
$$\frac{m_{UV}^2}{m_{IR}^2} = \frac{1}{1 + 5\beta\left(\frac{u_h}{l}\right)^8}$$

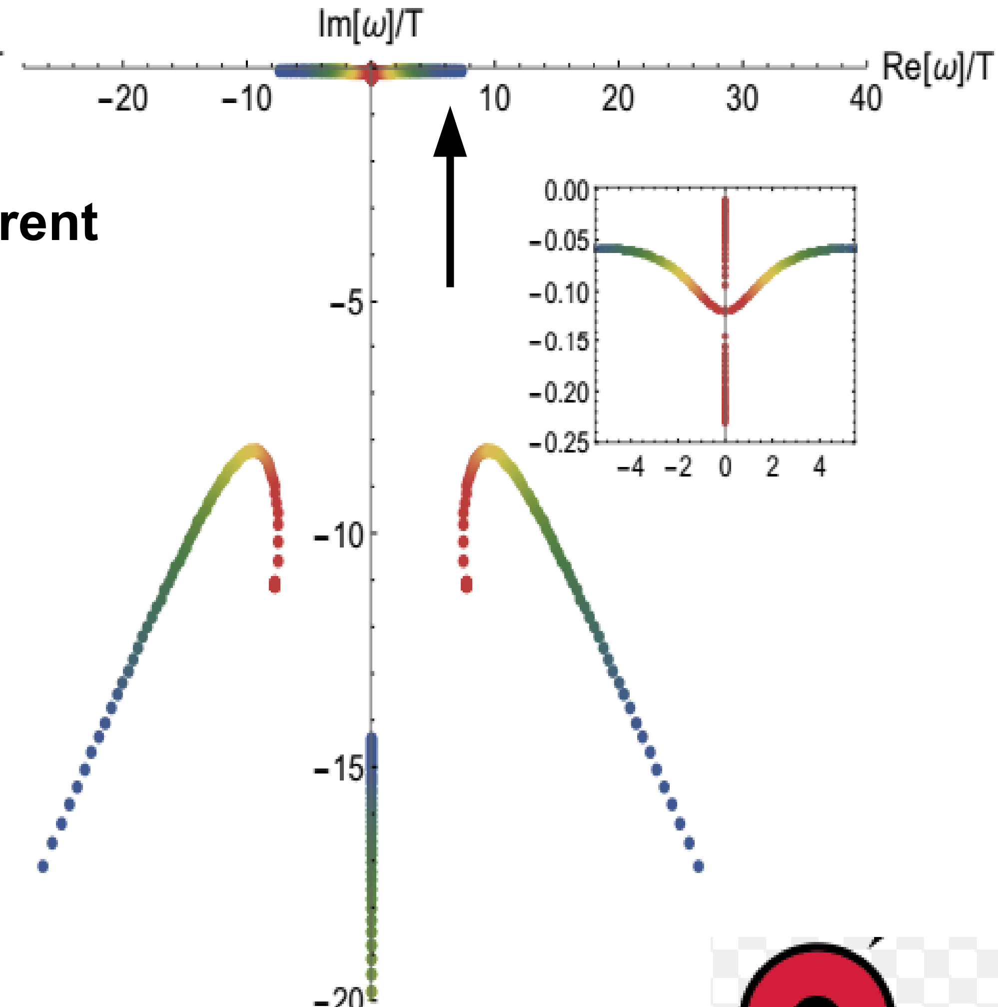
Large "beta" Realizes that !!

KEEP
CALM
AND
LET'S CHECK

The Transverse (Pseudo)-Phonon

arXiv:1708.08477

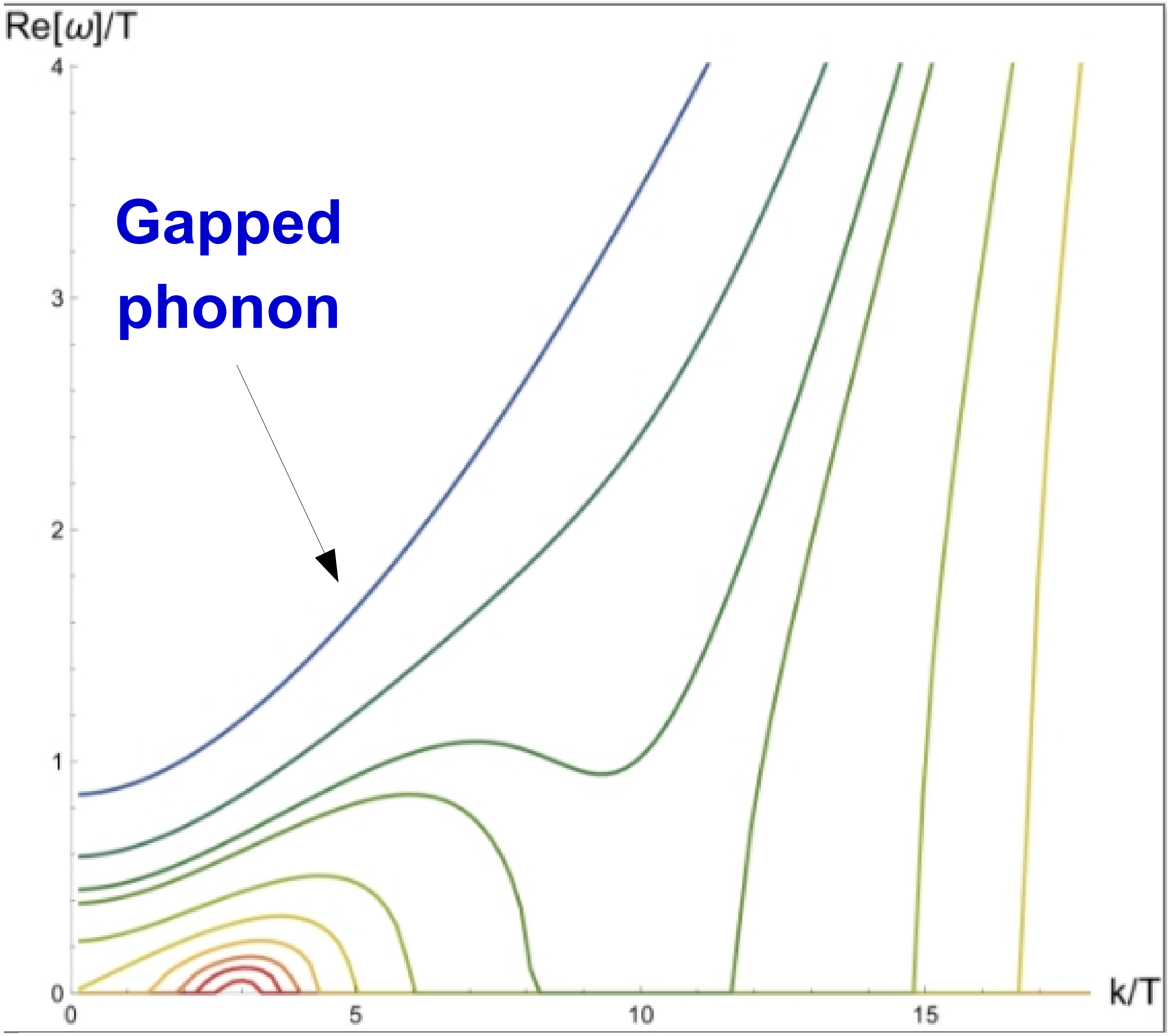




A light and well separated mode appears in the transverse excitations

TRANSVERSE (GAPPED AND DAMPED) PHONON

The Gapped and Damped Phonon



$$\omega = \frac{1}{2}\left(-i\,\Gamma + \sqrt{4\,w_0^2 + c_T^2\,k^2 - \Gamma^2}\right)$$

At small m/T we have

$$(\mathrm{Re}[\omega])^2 = a_1 + a_2\,k^{a_3}\,,$$

$$a_3 = 2 \pm 10^{-4}$$

We can fit and get:

The mass gap ω_0

The speed Of the Shear sound !! c_T^2

Shear Sound and Elastic modulus

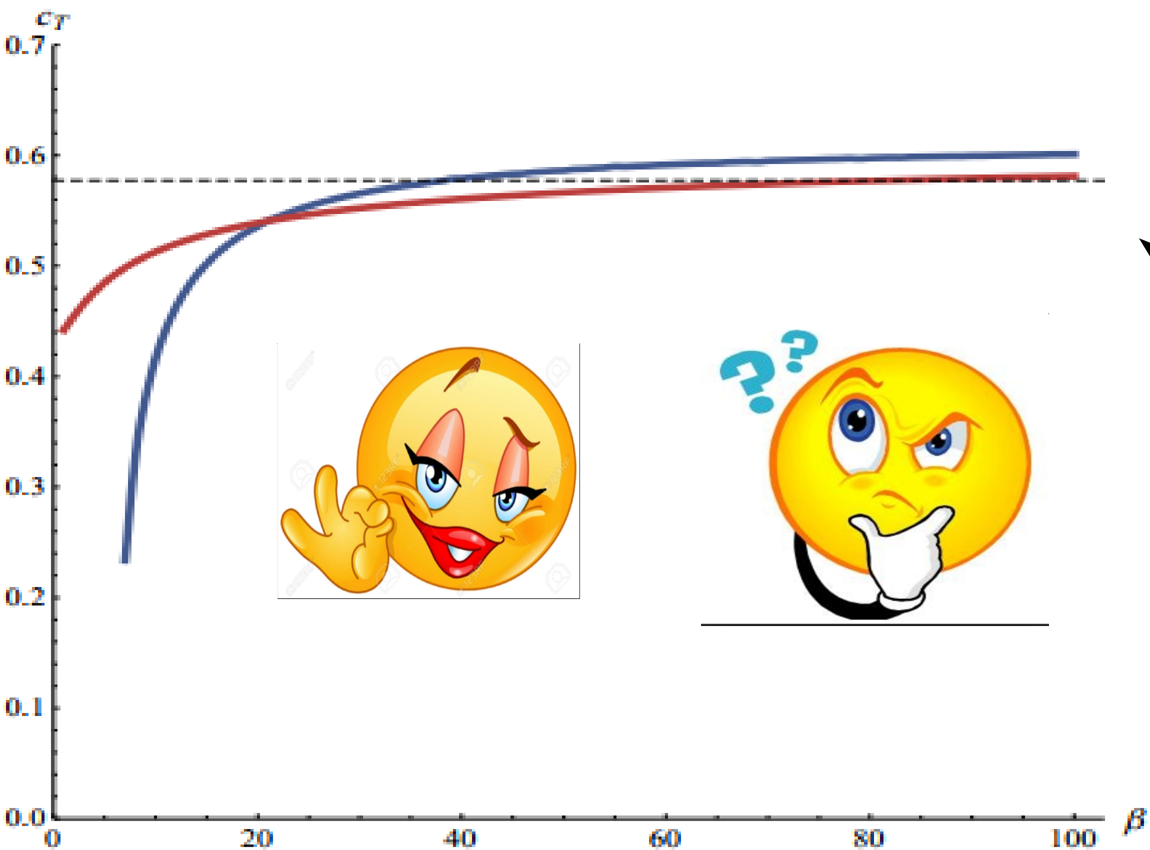
Shear elastic modulus : $\langle T_{ij} \rangle = \mathcal{G}^R_{T_{ij}T_{ij}} \gamma^{(0)}_{ij}$

$$\mu = Re\, \mathcal{G}^R_{T_{ij}T_{ij}}$$

arXiv:1601.03384

SHEAR SOUND SPEED $c_T^2 = \dfrac{\mu}{\chi_{PP}}$

$$\chi_{PP} = T_{00} + T_{xx}$$



Good agreement (but not perfect...)

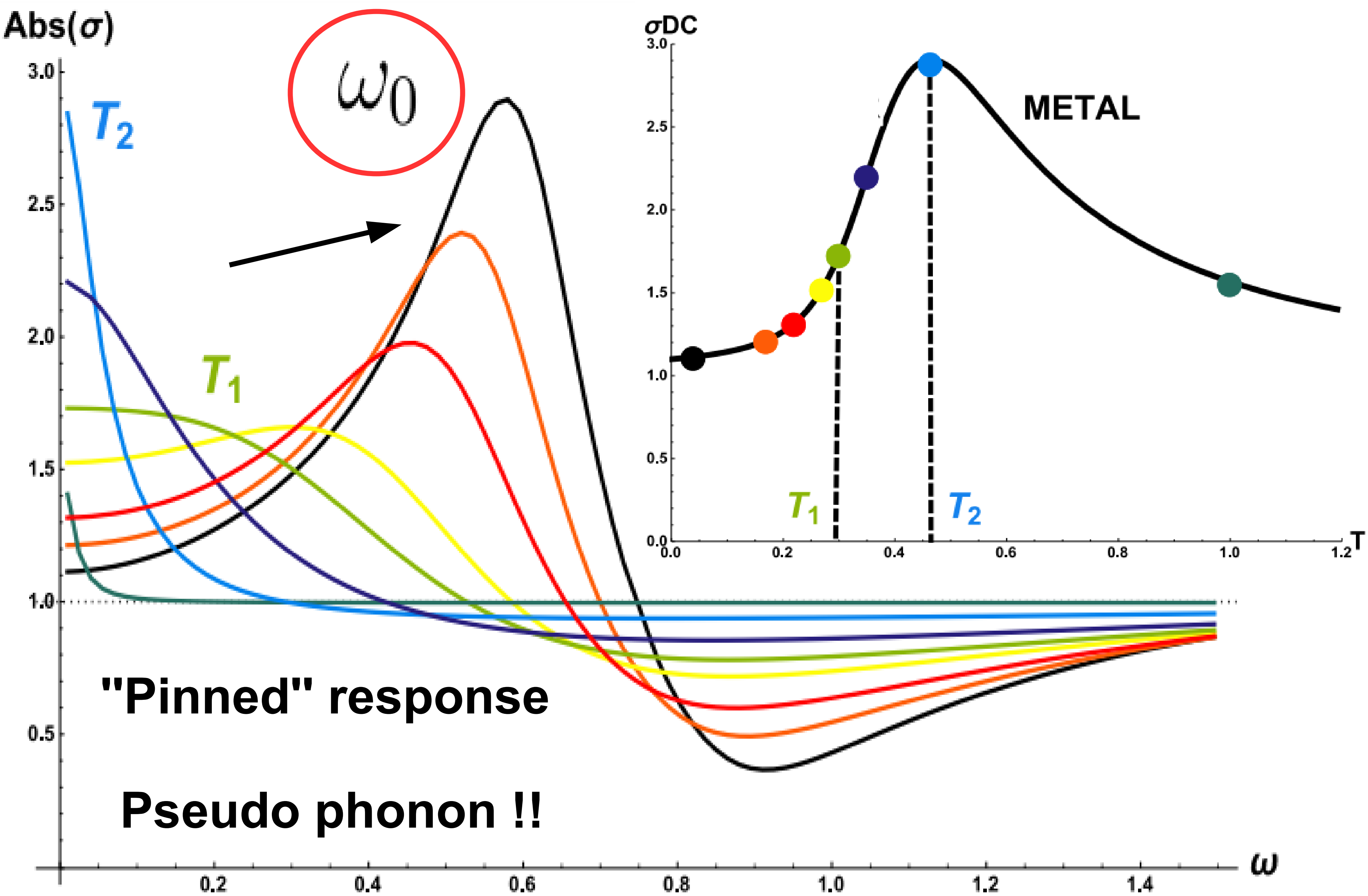
$$\approx \frac{1}{\sqrt{3}}$$

See also : arXiv:1708.09391

We will improve it...

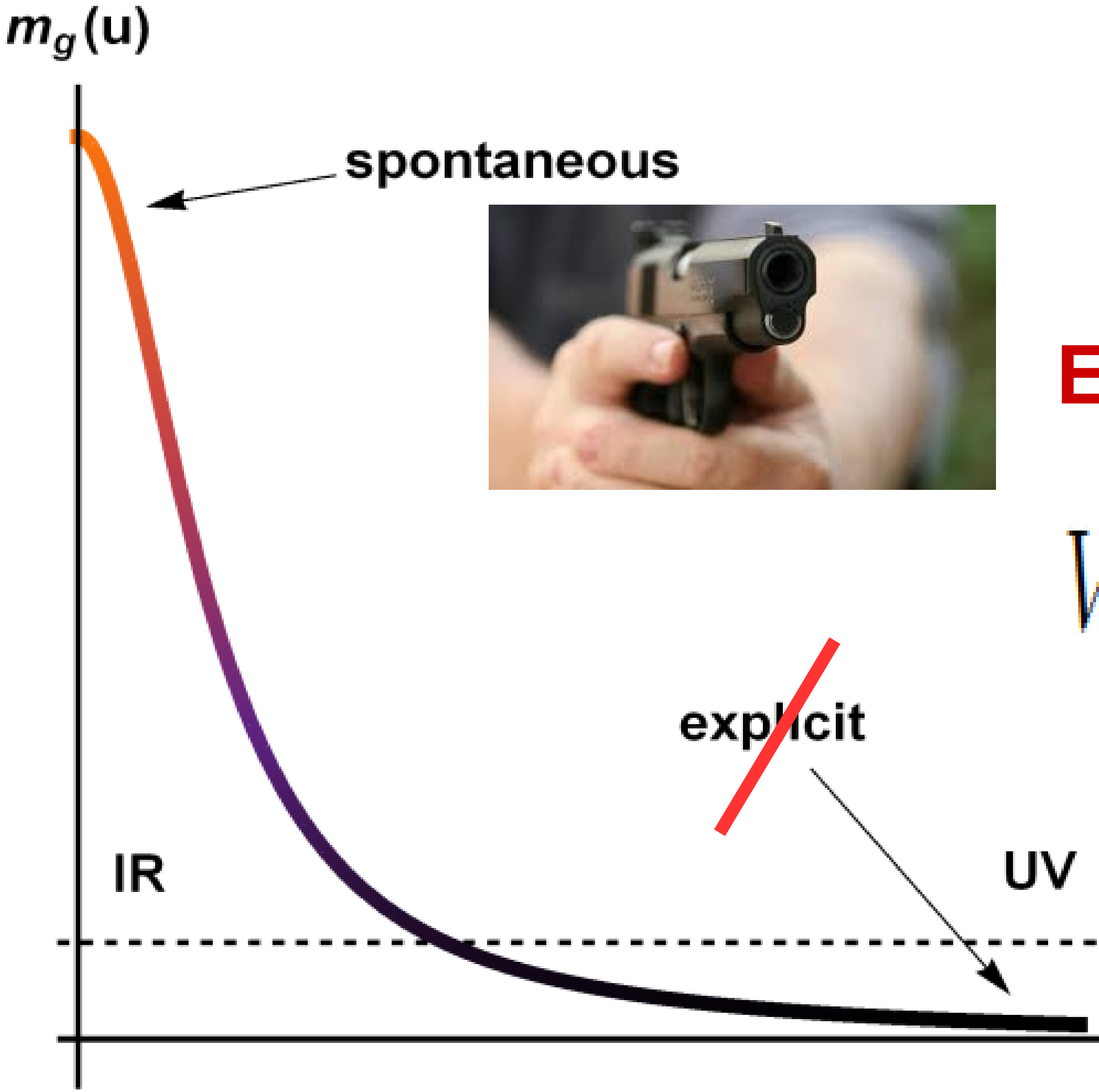
Electric (transport)

arXiv:1411.1003



MASSLESS "TRUE" PHONON

Purely Spontaneous (part II)



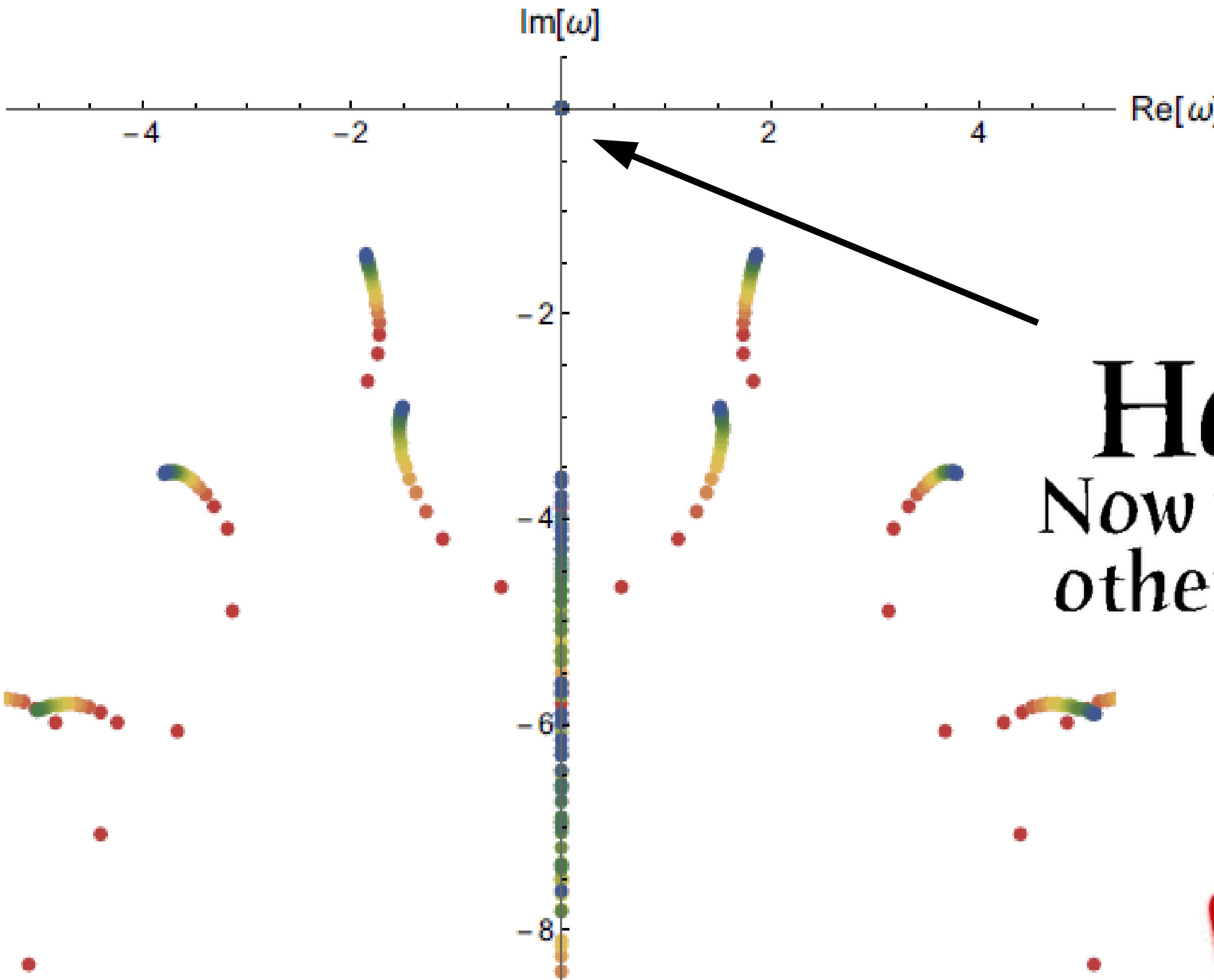
$$M^2(z) \equiv \tilde{m}^2 V_X$$

Killing the Explicit breaking

$$V(X) = \cancel{X} + \beta X^5$$

UV MASS BECOMES ZERO !!!

THE TRANSVERSE PHONON



Here I am

Now what are your other two wishes?

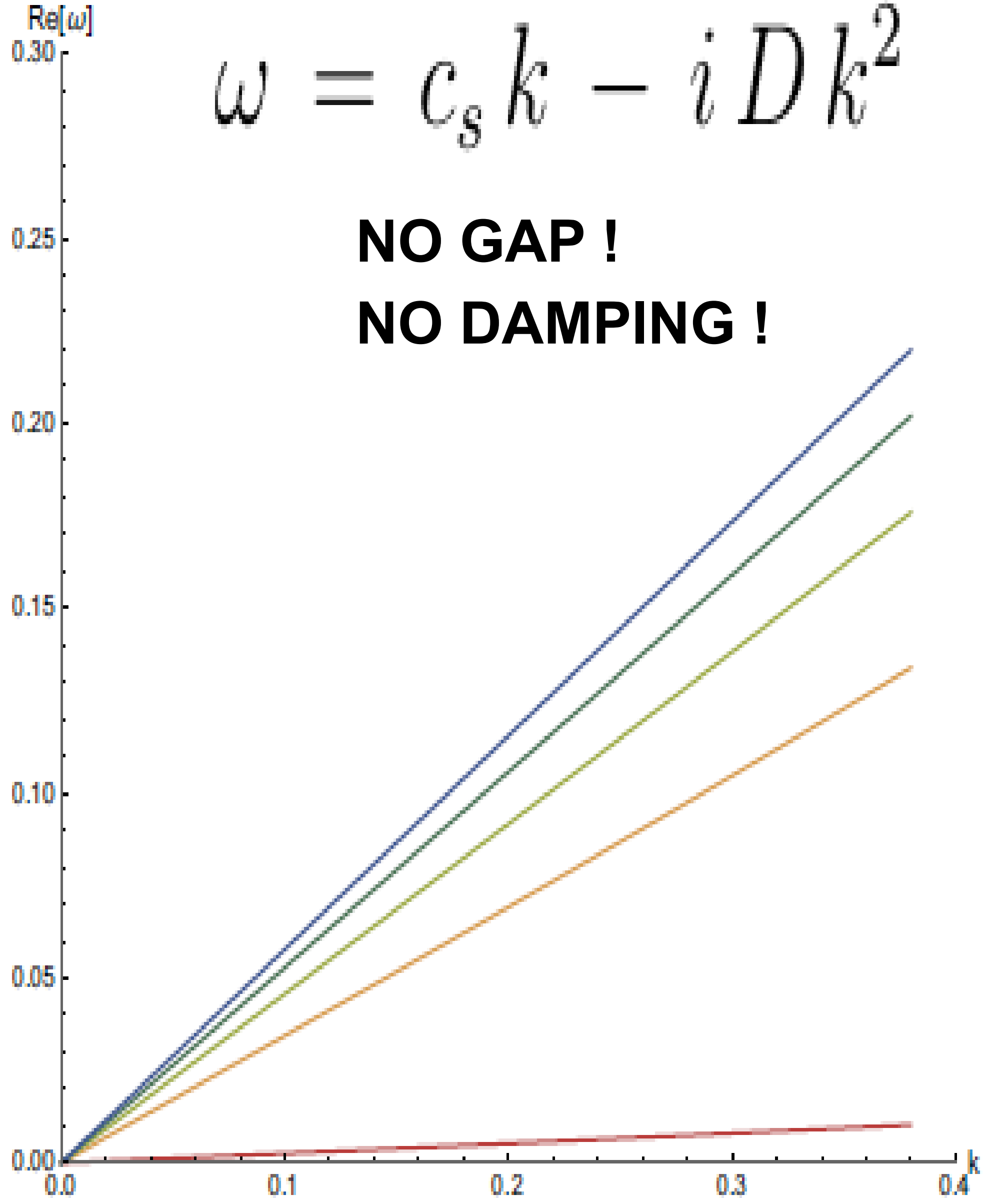
$$V(X) = \cancel{X} + \beta X^5$$

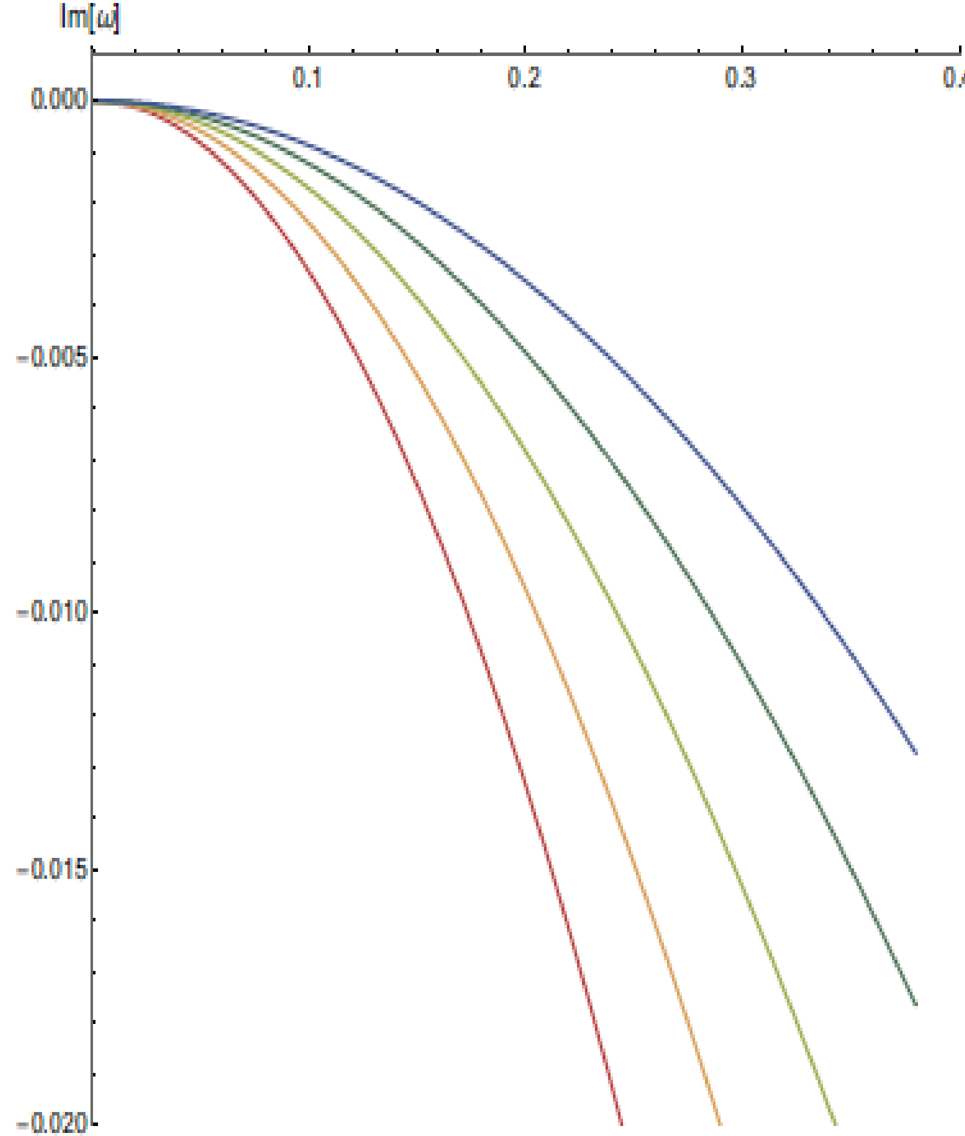
THE TRANSVERSE PHONON

$$\omega = c_s\, k - i\, D\, k^2$$

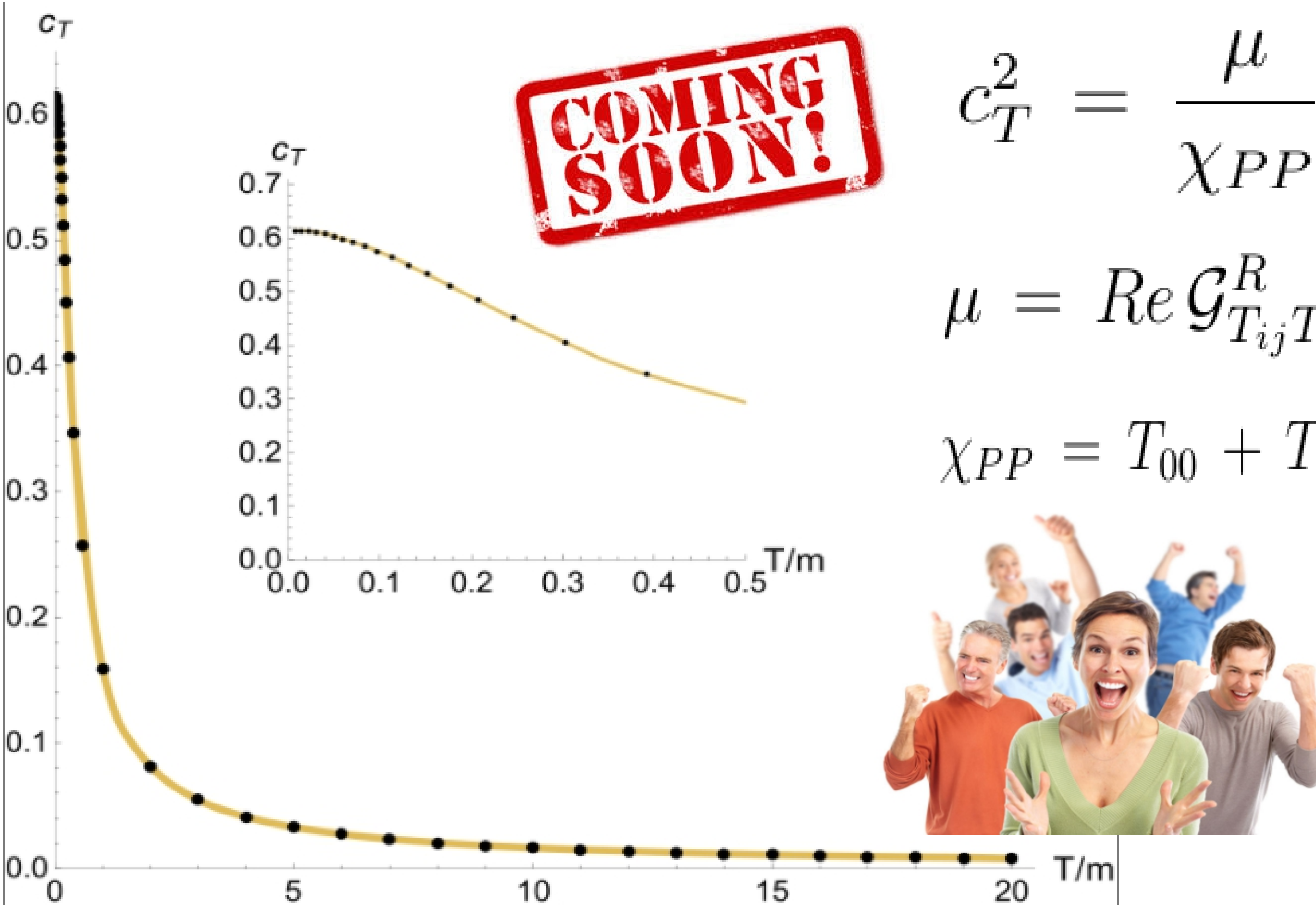
NO GAP !

NO DAMPING !





SHEAR SOUND AND ELASTICITY

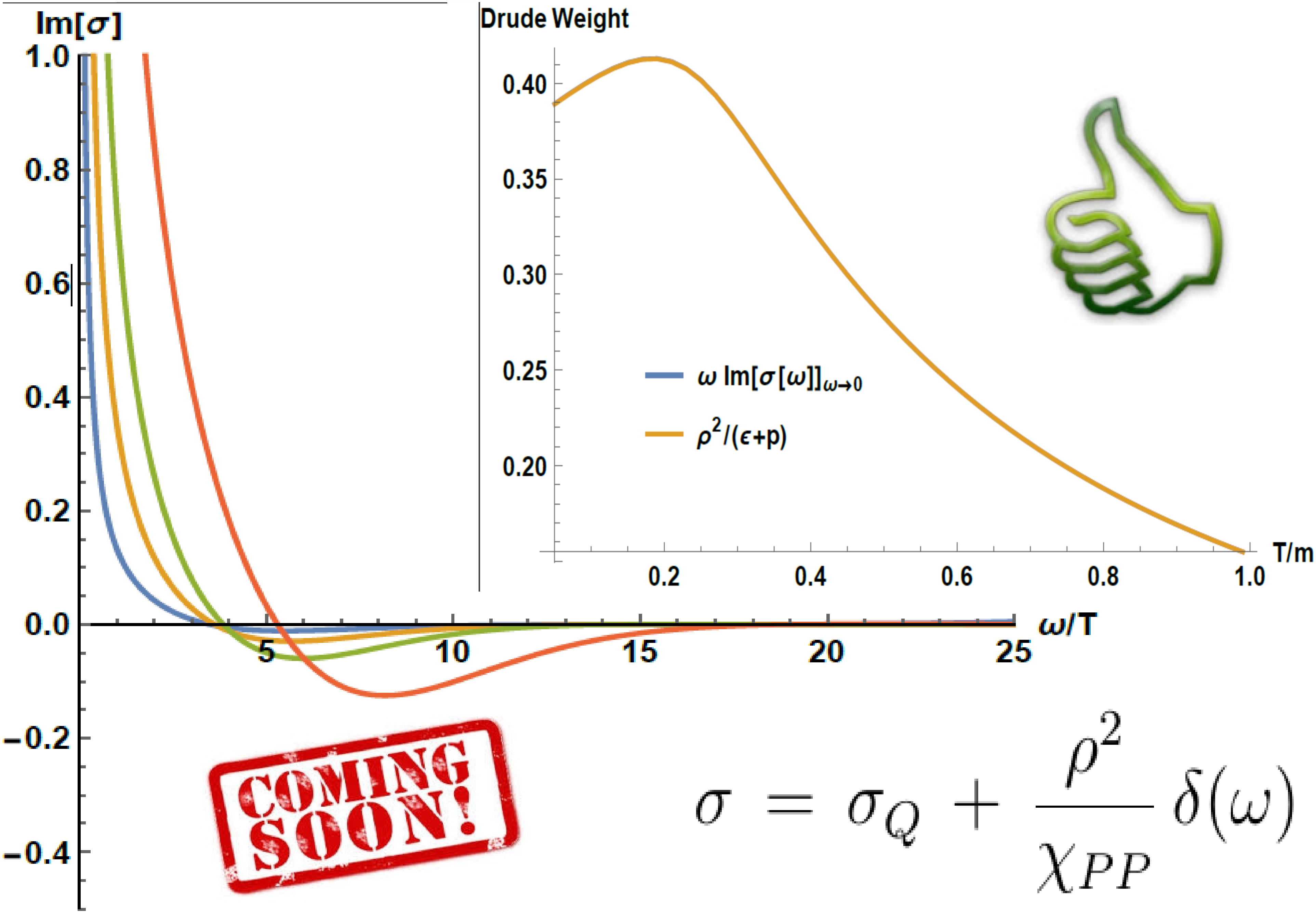


$$c_T^2 = \frac{\mu}{\chi_{PP}}$$

$$\mu = Re\, \mathcal{G}^R_{T_{ij}T_{ij}}$$

$$\chi_{PP} = T_{00} + T_{xx}$$

(ELECTRIC) TRANSPORT I



$$\sigma = \sigma_Q + \frac{\rho^2}{\chi_{PP}}\delta(\omega)$$

fast SUMMARY

HABEMUS PHONONS

HOLOGRAPHIC SOLIDS !!!

(VISCO) ELASTIC HOLOGRAPHY

We have an holographic model which implements :

1) Explicit breaking of translations (momentum relaxation)

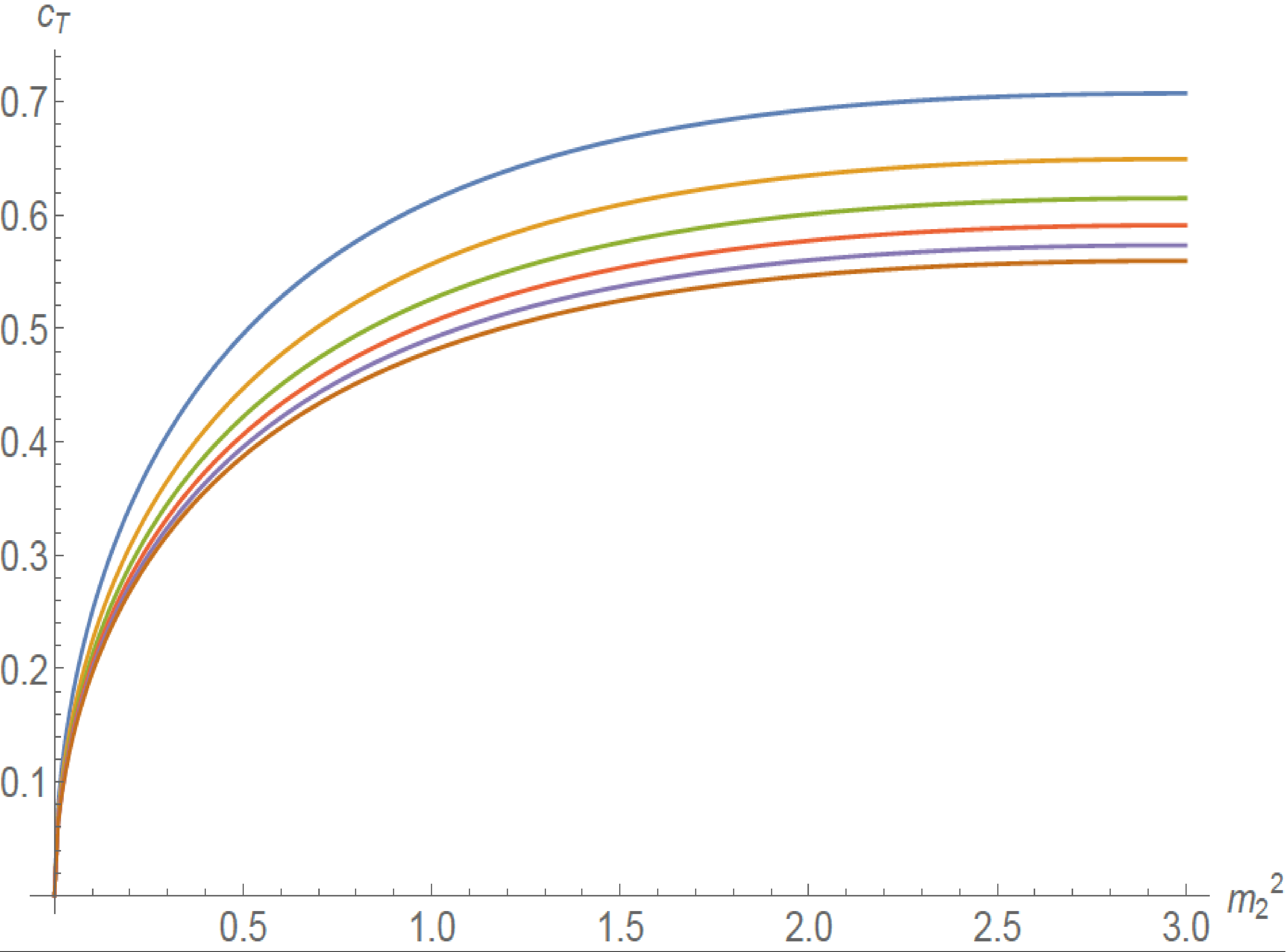
2) Explicit + spontaneous breaking of translations (pseudophonons)

3) Spontaneous breaking of translations (phonons)

$$1)\, V(X) = X\,, \qquad 2)\, V(X) = X + X^5\,, \qquad 3)\, V(X) = X^5$$

NORDITA

Tack så Mycket



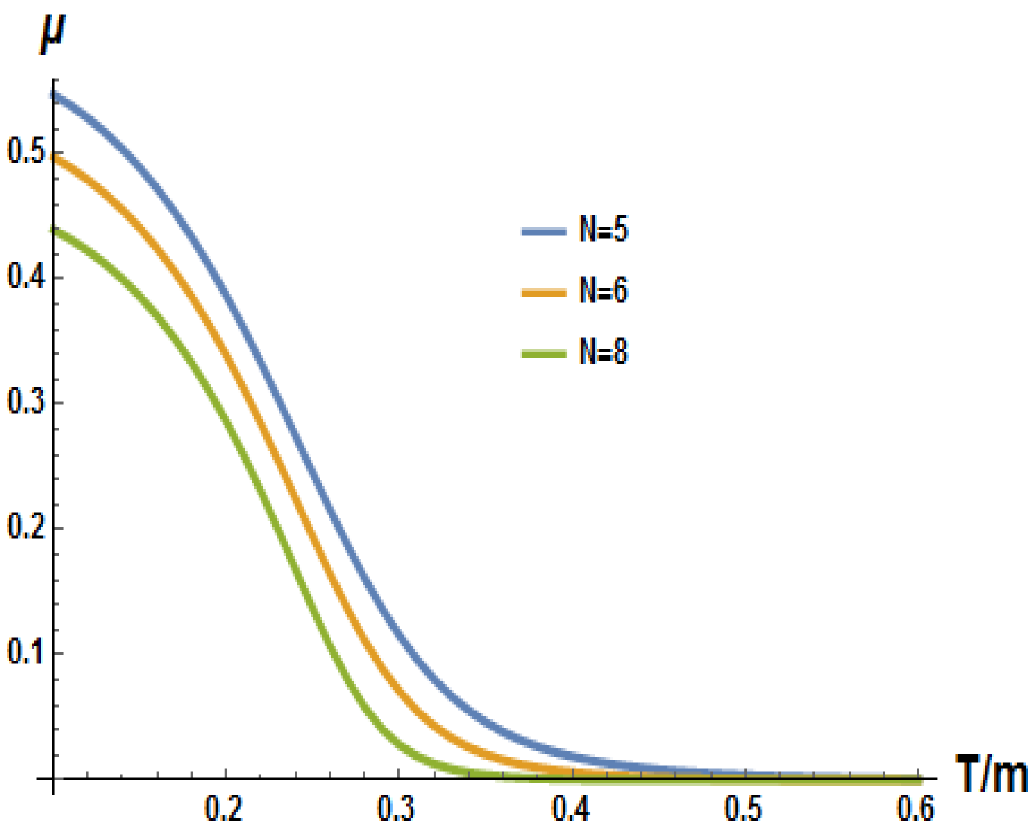
c_T
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.5
1.0
1.5
2.0
2.5
3.0
m_2^2

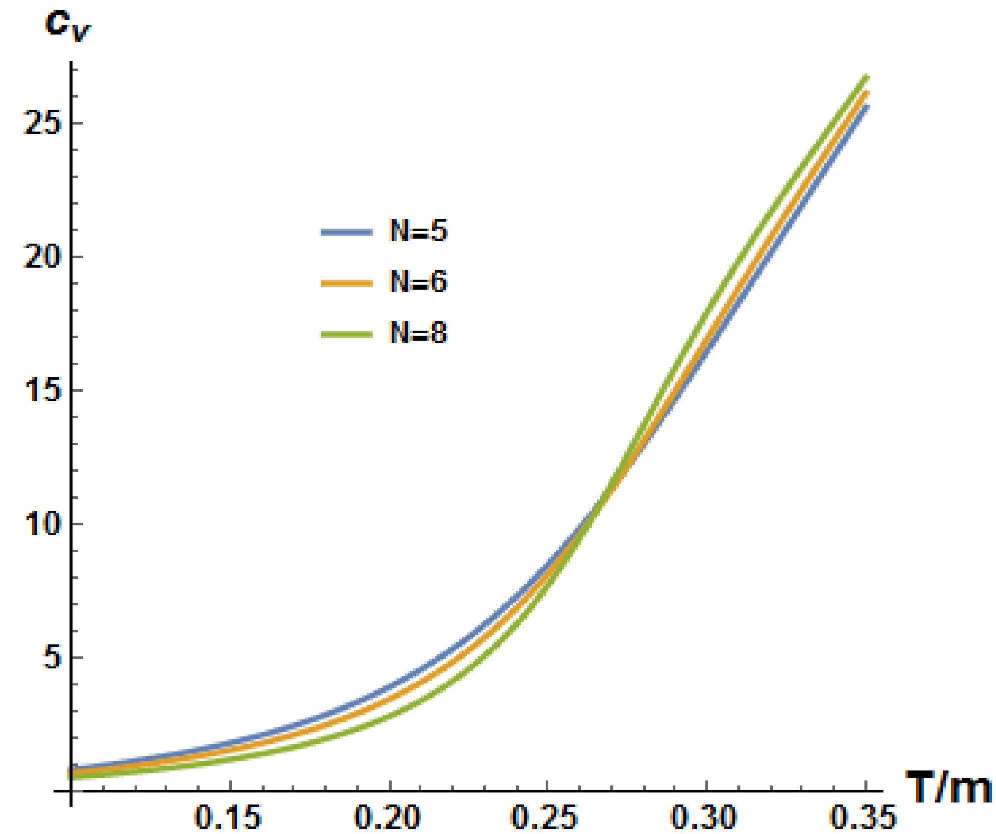
Elastic Holography

IN PROGRESS

$$V(X) = m^2 X^N$$

Massive gravity models with large N



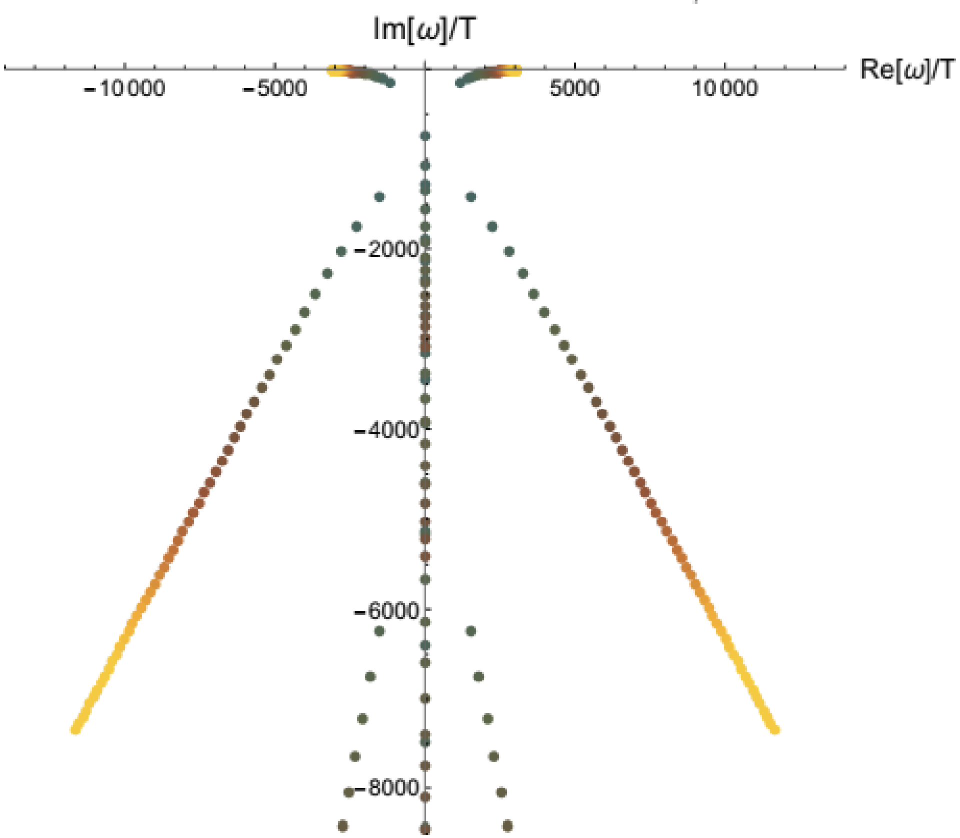


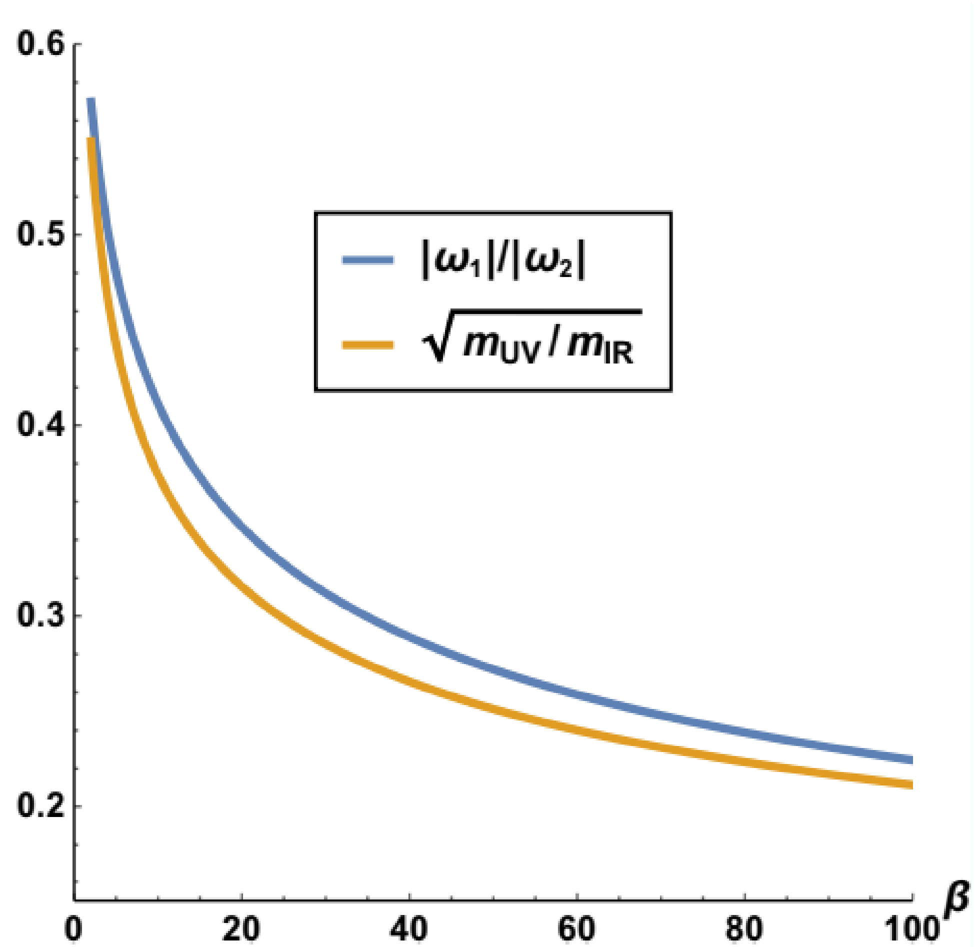
Shear elastic modulus goes to zero increasing temperature

There is no first order phase transition!
It is not melting ! Glass transition ?? Viscoelasticity ??

Spontaneous breaking and EFT

$\beta \gg 1$





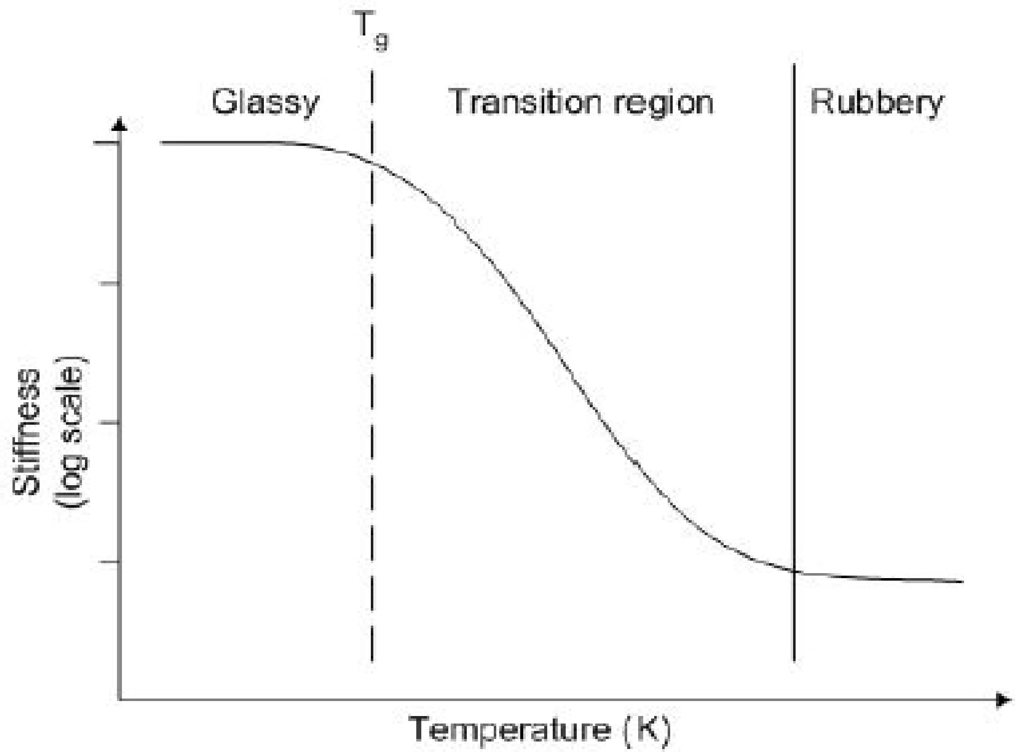
Separation of scales
Breaking mostly "spontaneous"
Small damping

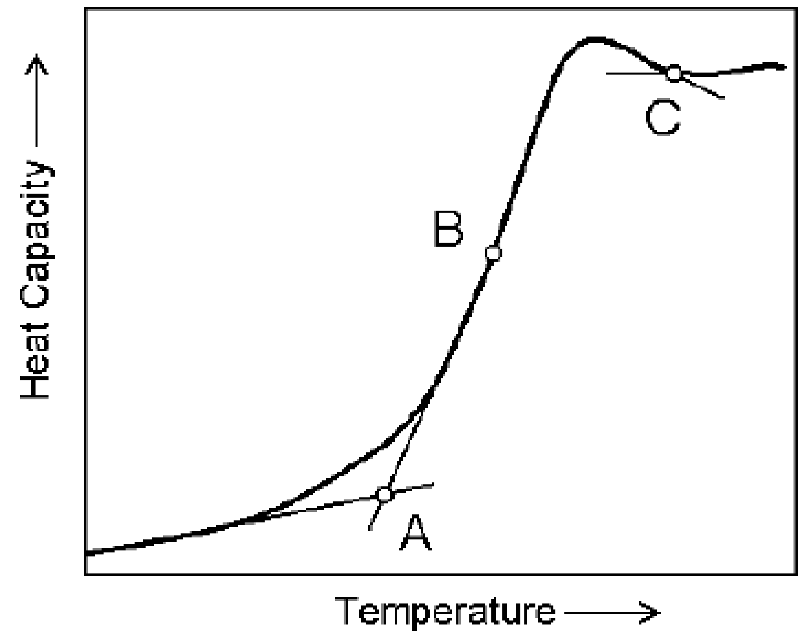
→

Gapped and damped
Transverse phonon
?????

Glassy transition ?? IN PROGRESS

If it is not melting what is it ???





Also the speed of transverse phonons goes to zero with T ...

Is that a GLASS TRANSITION ?

Are these VISCOELASTIC "black holes " ?

Please leave a Comment

Holographic viscoelasticity

arXiv:1510.09089 arXiv:1601.03384

Lorentz violating Massive gravity

$$S=\int d^4x\sqrt{-g}\left[\frac{1}{2}\left(R+\frac{6}{L^2}\right)-\frac{L^2}{4}F_{\mu\nu}F^{\mu\nu}-\frac{m^2}{L^2}V(X,Z)\right]$$

$$X\equiv\frac{1}{2}\mathrm{tr}[\mathcal{I}^{IJ}],\qquad Z\equiv\det[\mathcal{I}^{IJ}],\qquad \mathcal{I}^{IJ}\equiv\partial_\mu\phi^I\partial^\mu\phi^J\,,$$

Helicity 2 graviton mass (different from helicity 1 !!)

$$M^2(r)\equiv\frac{1}{2r^2}\hat{V}_X(r)\,.$$

FLUIDS : $\phi^I\mapsto\psi^I(\phi^J)\,,\qquad \det\left[\frac{\partial\psi^I}{\partial\phi^J}\right]=1\,.$

$$V_{fluids}=V(Z)\longrightarrow M^2(r)=0\,.$$

$$\boxed{\mu=0\,,}\qquad \frac{\eta}{s}=\frac{1}{4\pi}$$

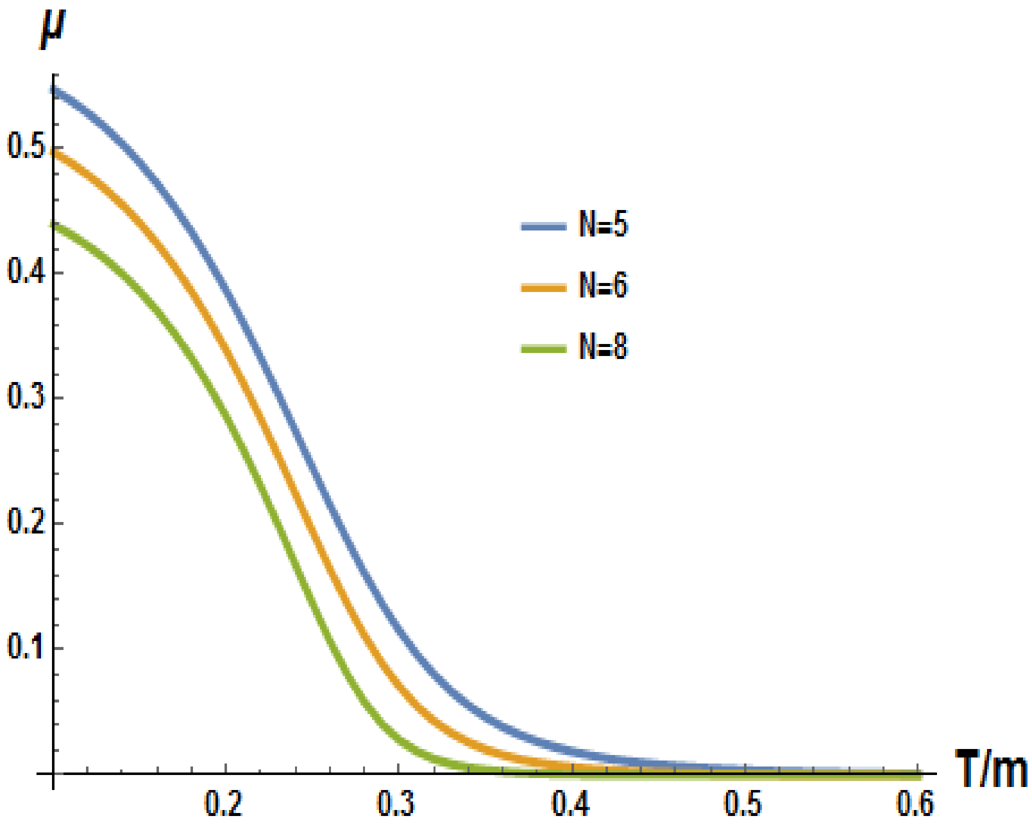
It's a Match!

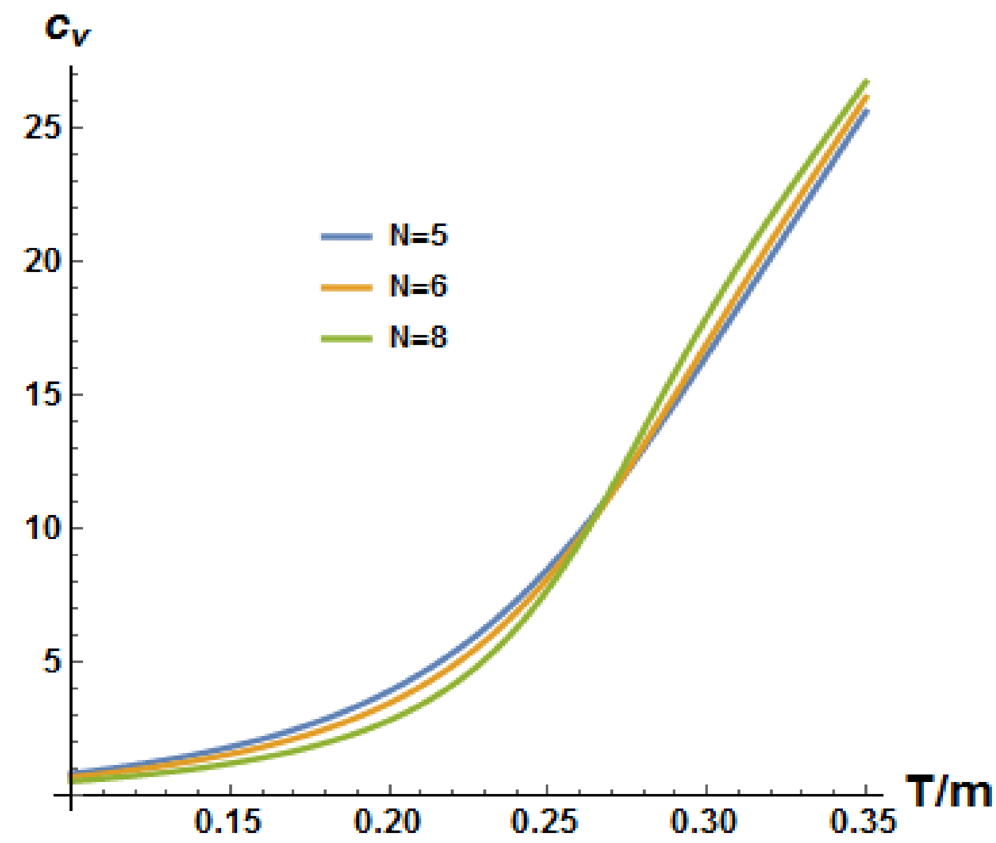
Elastic Holography : part II

IN PROGRESS

$$V(X) = m^2 X^N$$

Massive gravity models with large N





Shear elastic modulus goes to zero increasing temperature

There is no first order phase transition!
It is not melting ! Glass transition ?? Viscoelasticity ??

Viscoelasticity

ELASTIC + VISCOUS

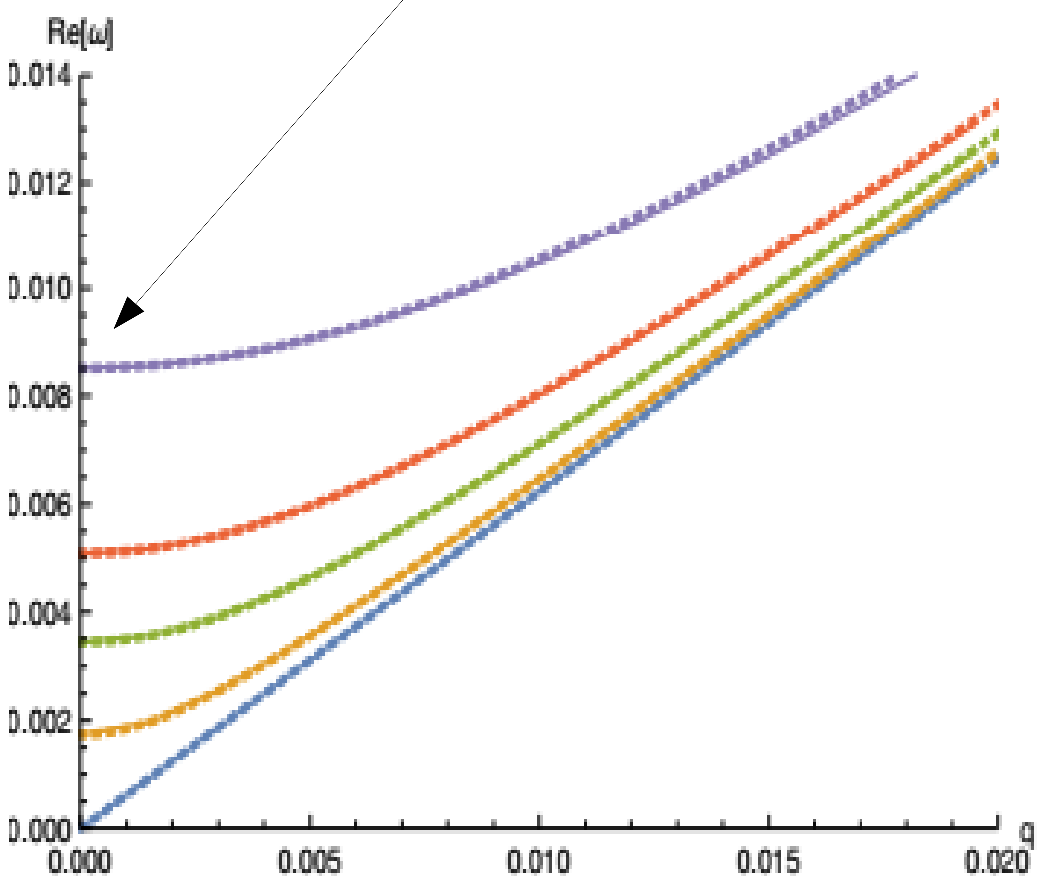
$$T_{ij}^{(T)} = \mu\, u_{ij}^{(T)} + \eta\, \dot{u}_{ij}^{(T)}$$

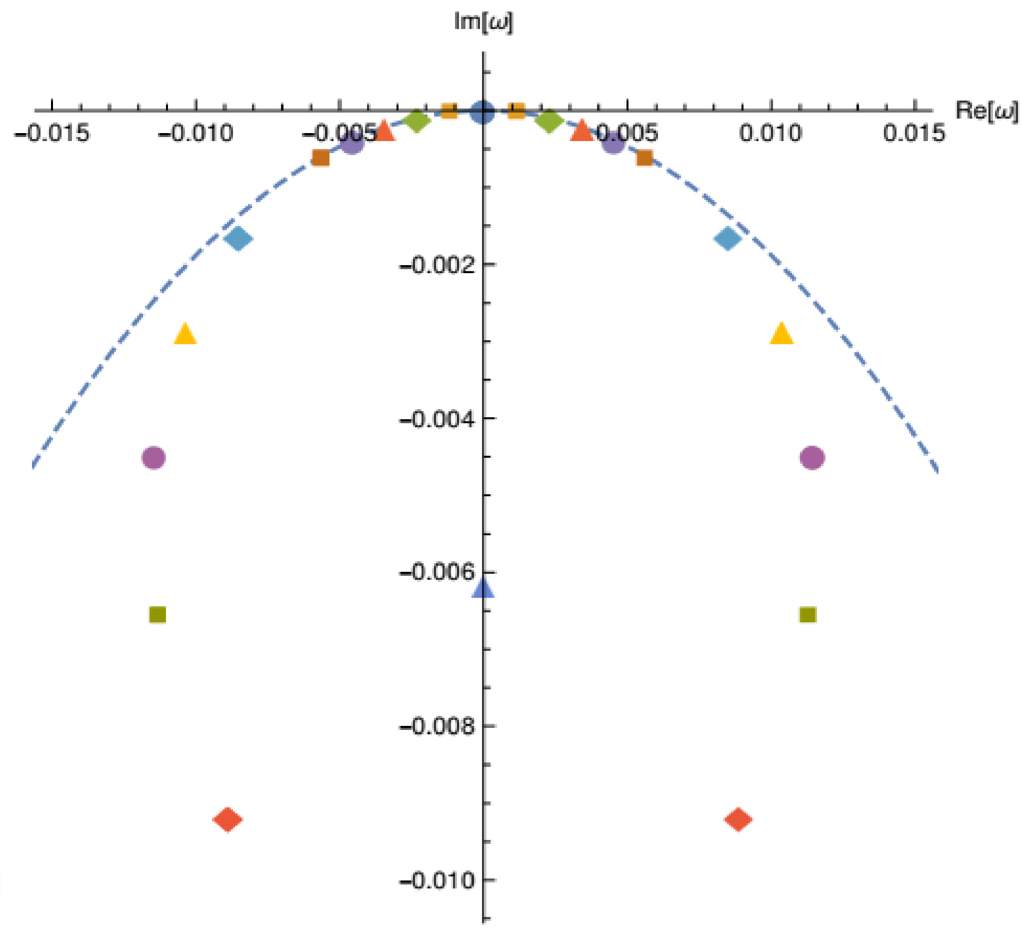
$$\eta \propto \lim_{\omega \to 0} \frac{1}{\omega} Im\, \mathcal{G}^R_{T_{ij}T_{ij}}$$ **VISCOSITY**

$$\mu \propto \lim_{\omega \to 0} Re\, \mathcal{G}^R_{T_{ij}T_{ij}}$$ **SHEAR MODULUS**

Gapping and Damping the Phonon

$$\omega^2 = \underline{-i\omega\Gamma} + \underline{\omega_0^2} + c_s^2 q^2 + \ldots$$





(Real World) Pinned Charge Density Wave

The dynamics of charge-density waves

G. Grüner

Rev. Mod. Phys. **60**, 1129 – Published 1 October 1988

$$\sigma(\omega)=\frac{n_c e^2}{i\omega m^*}\frac{\omega^2}{\omega_0^2-\omega^2-i\omega/\tau}$$

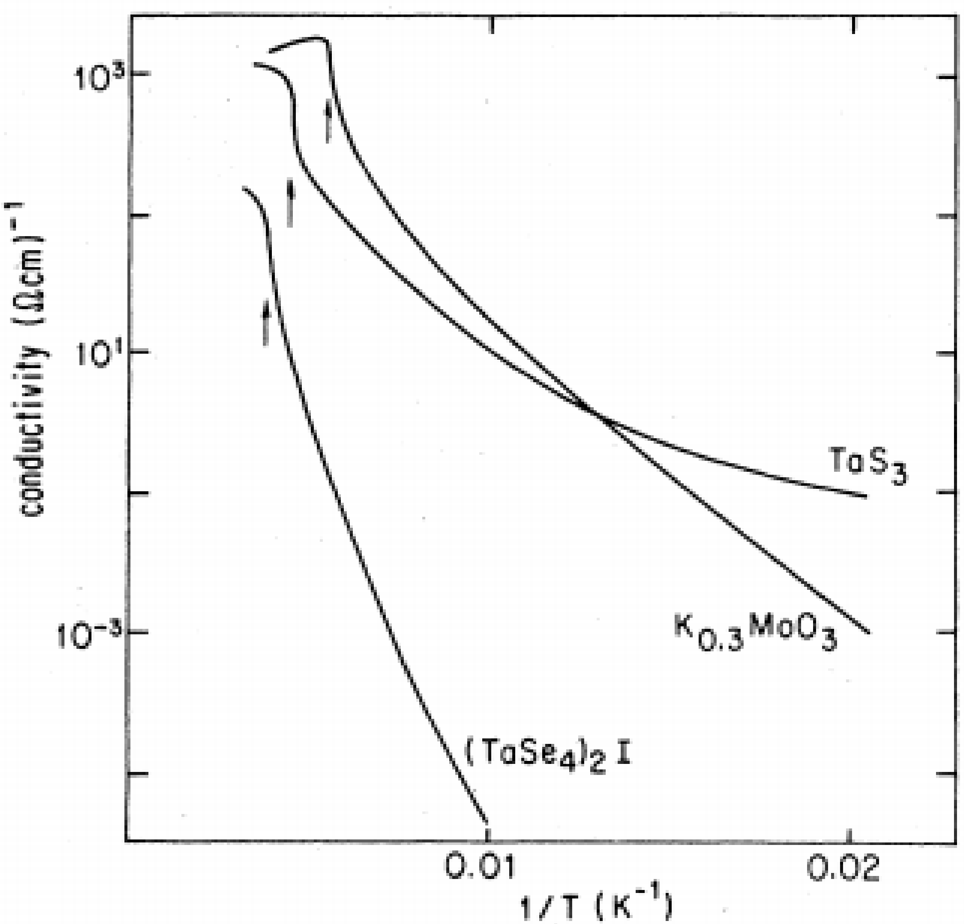


FIG. 4. Temperature dependence of the electrical conductivity in o-TaS$_3$, in (TaSe$_4$)$_2$I, and in K$_{0.3}$MoO$_3$. The arrows represent the Peierls transition temperatures; they are evident by examining the temperature derivatives dR/dT.

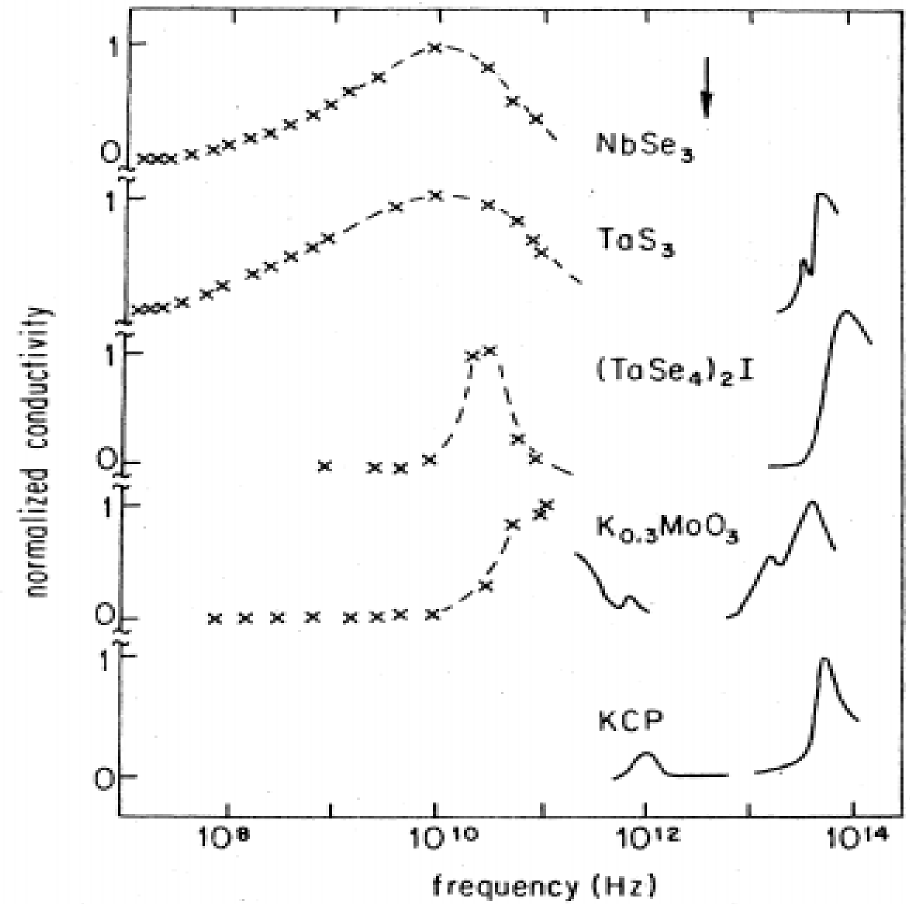
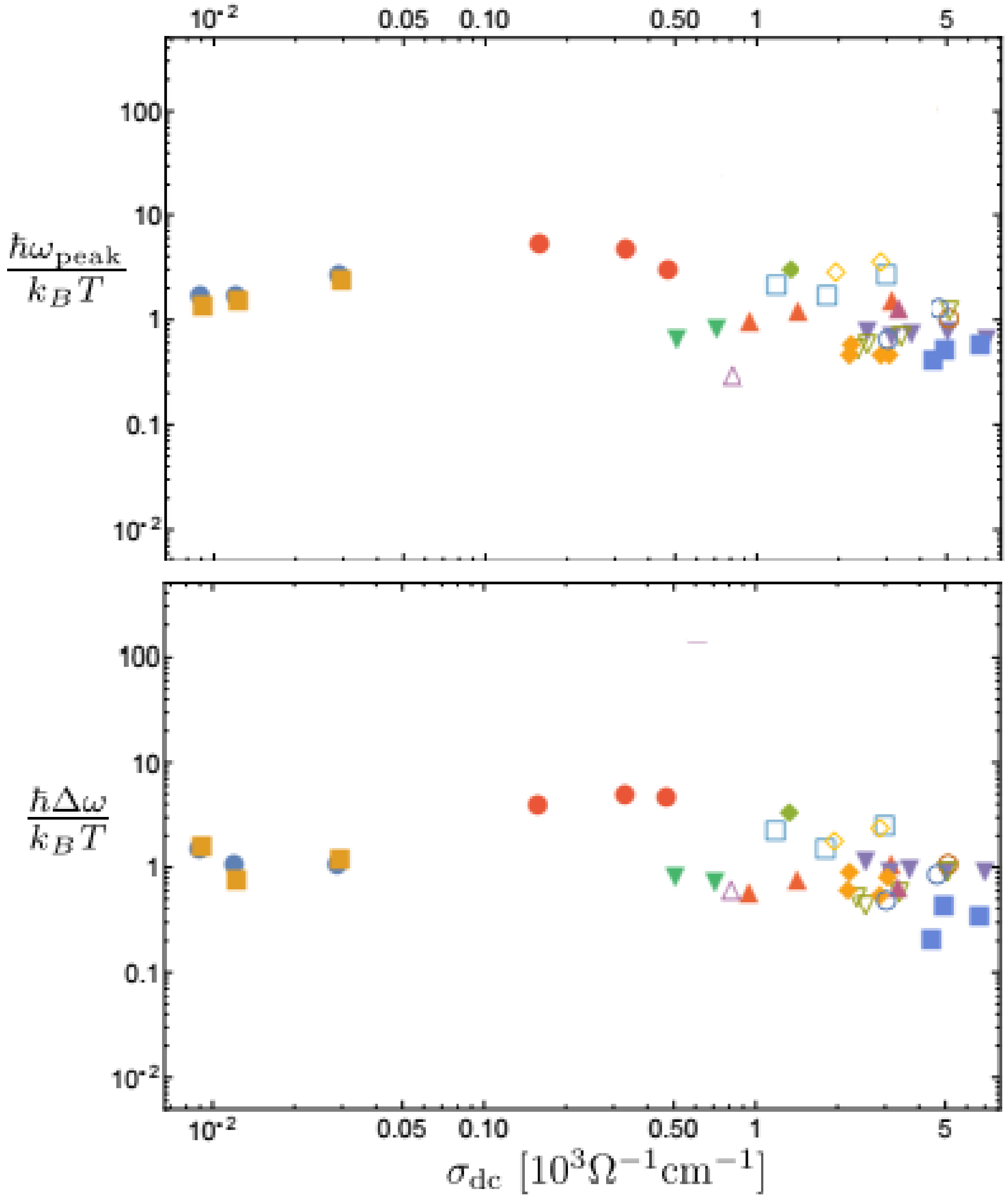


FIG. 9. The frequency-dependent conductivity of NbSe$_3$, o-TaS$_3$ and (TaSe$_4$)$_2$I, and K$_{0.3}$MoO$_3$. The solid lines represent the regions where the drop signals the single-particle gaps; the strong peaks in the millimeter wave spectral range are due to the response of the pinned collective mode.

The Bad Metal Proposal

arXiv:1612.04381



$$\sigma(\omega) = \sigma_o + \frac{\rho^2}{\chi_{\pi\pi}} \frac{\Omega - i\omega}{(\Omega - i\omega)(\Gamma - i\omega) + \omega_o^2} .$$

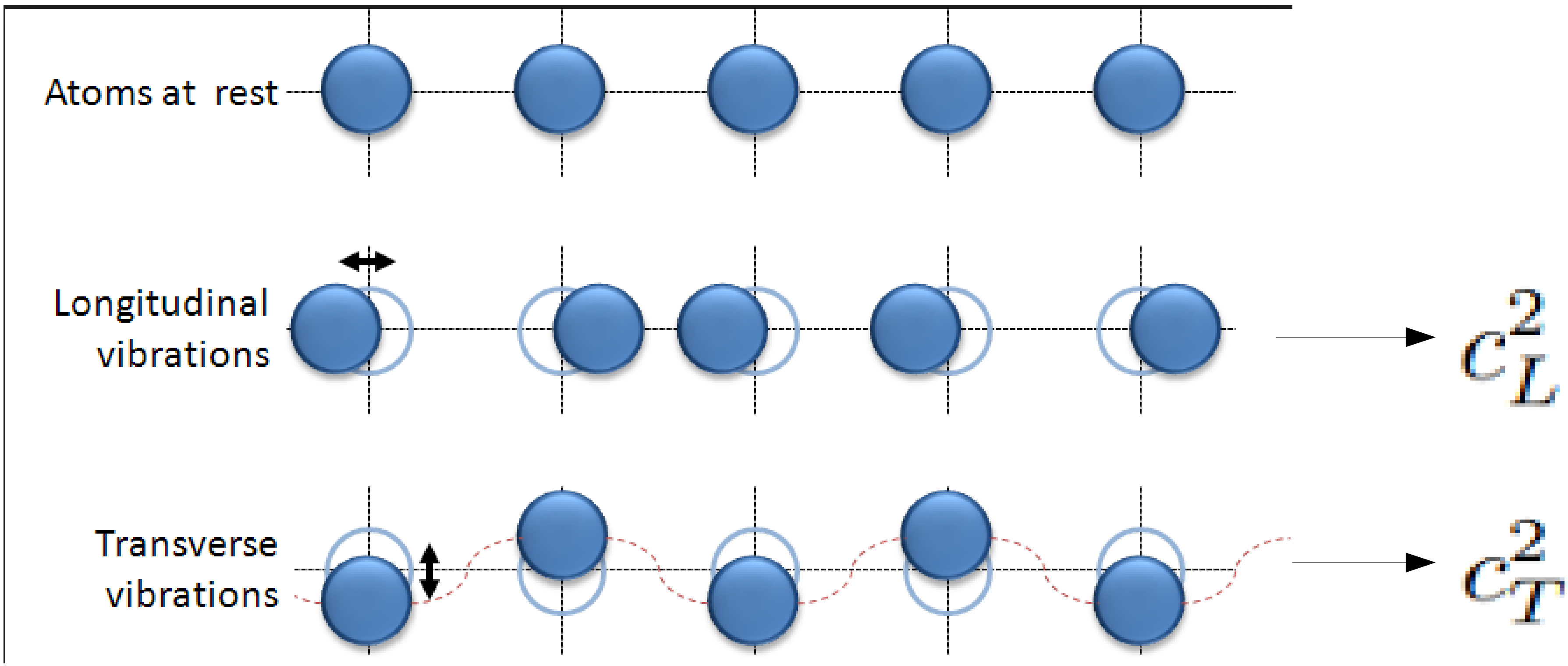
$$\hbar\omega_{\text{peak}} = \alpha(T)\, k_B T ,$$

$$\hbar\Delta\omega = \beta(T)\, k_B T$$

Spontaneous + explicit
Could explain transport
In bad metals

The pinning frequency
Is controlled by the same
"universal" scale
Of the relaxation time

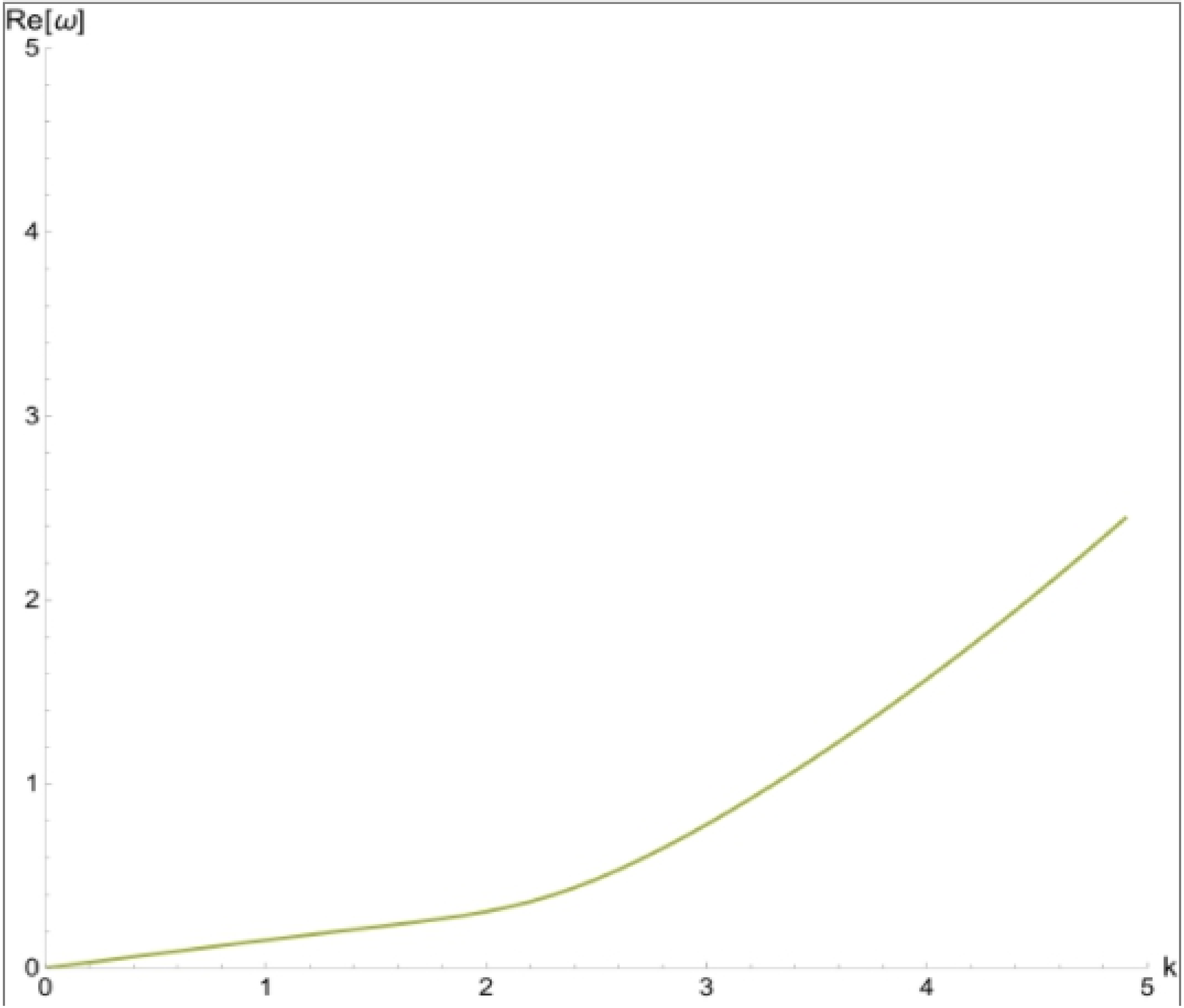
Solids VS Fluids



In fluids

$$\mu = 0 \rightarrow c_T = 0\,.$$

NO SHEAR SOUND!



Re[ω]
5
4
3
2
1
0
0
1
2
3
4
5
k