4th INTERNATIONAL CONFERENCE on HOLOGRAPHY, STRING THEORY and DISCRETE APPROACH in HANOI, VIETNAM

NEW HINTS TOWARDS TRANSPORT UNIVERSALITY

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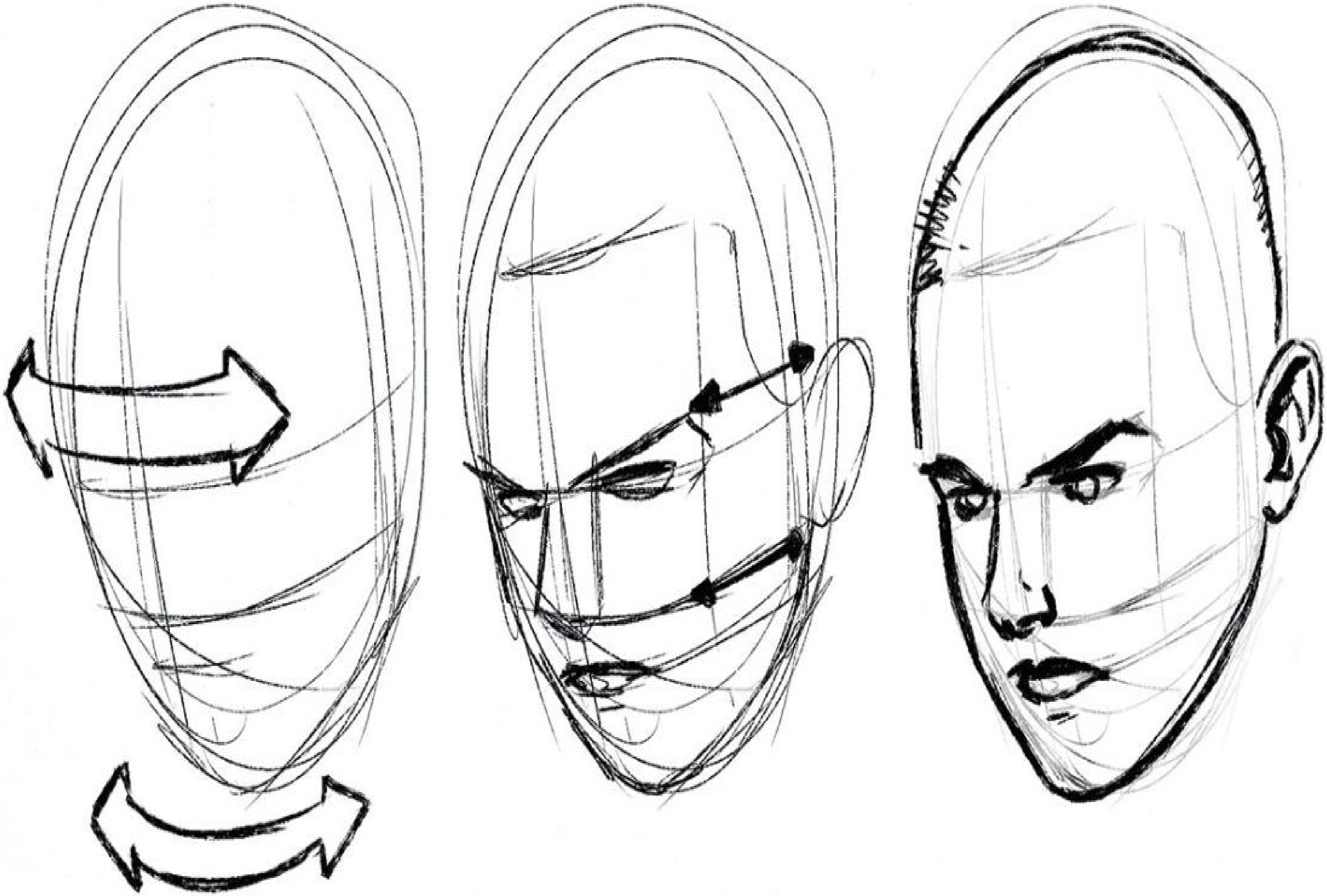
SOON

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

THANKS A LOT SHINGO SAN

UNIVERSALITY



References & collaborators

arXiv:2005.06482 [pdf, other] hep-th cond-mat.dis-nn cond-mat.str-el quant-ph

Universal Bounds on Transport in Holographic Systems with Broken Translations

Authors: Matteo Baggioli, Wei-Jia Li

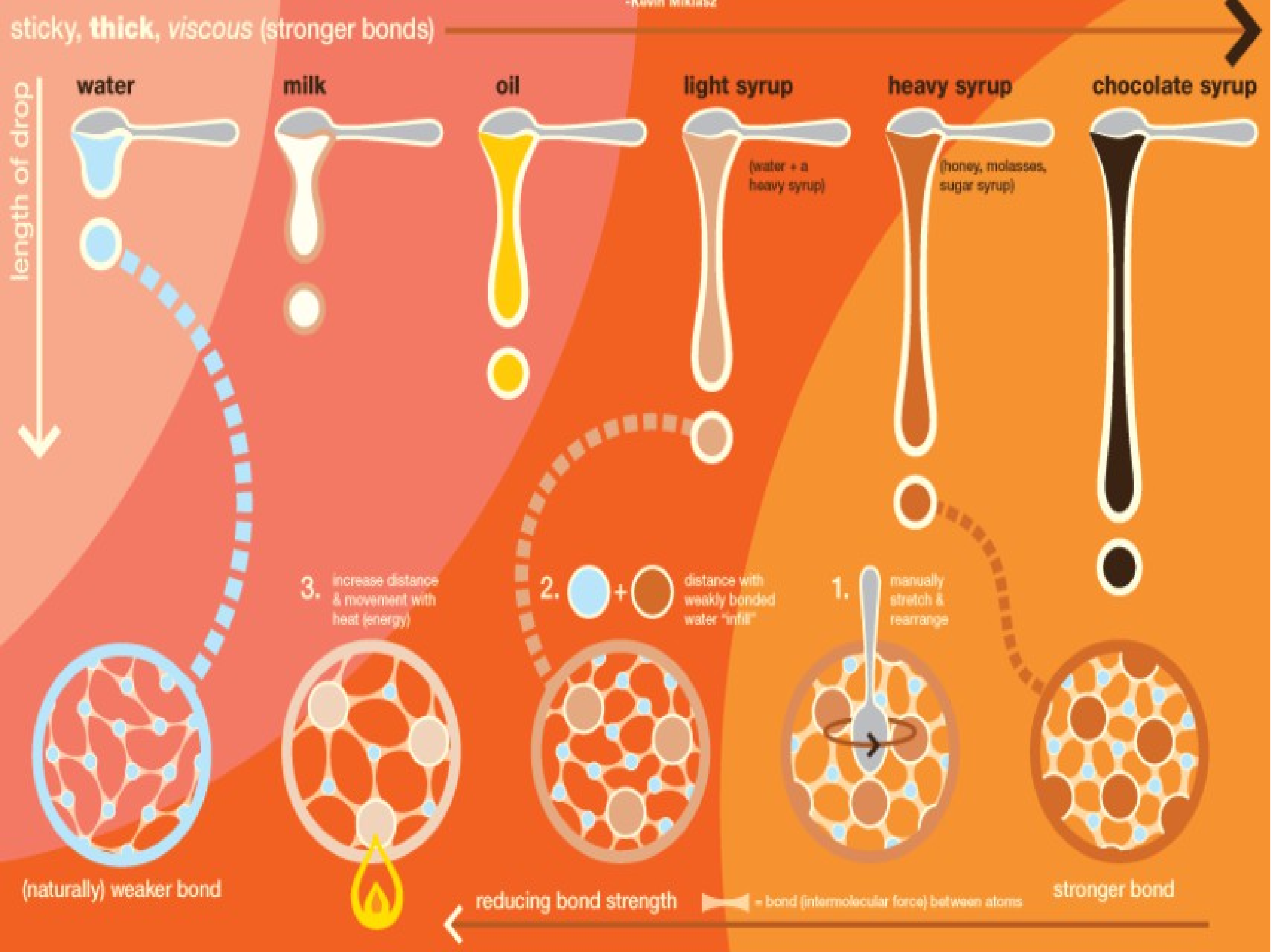
arXiv:2003.13506 [pdf, other] hep-th cond-mat.soft nucl-th

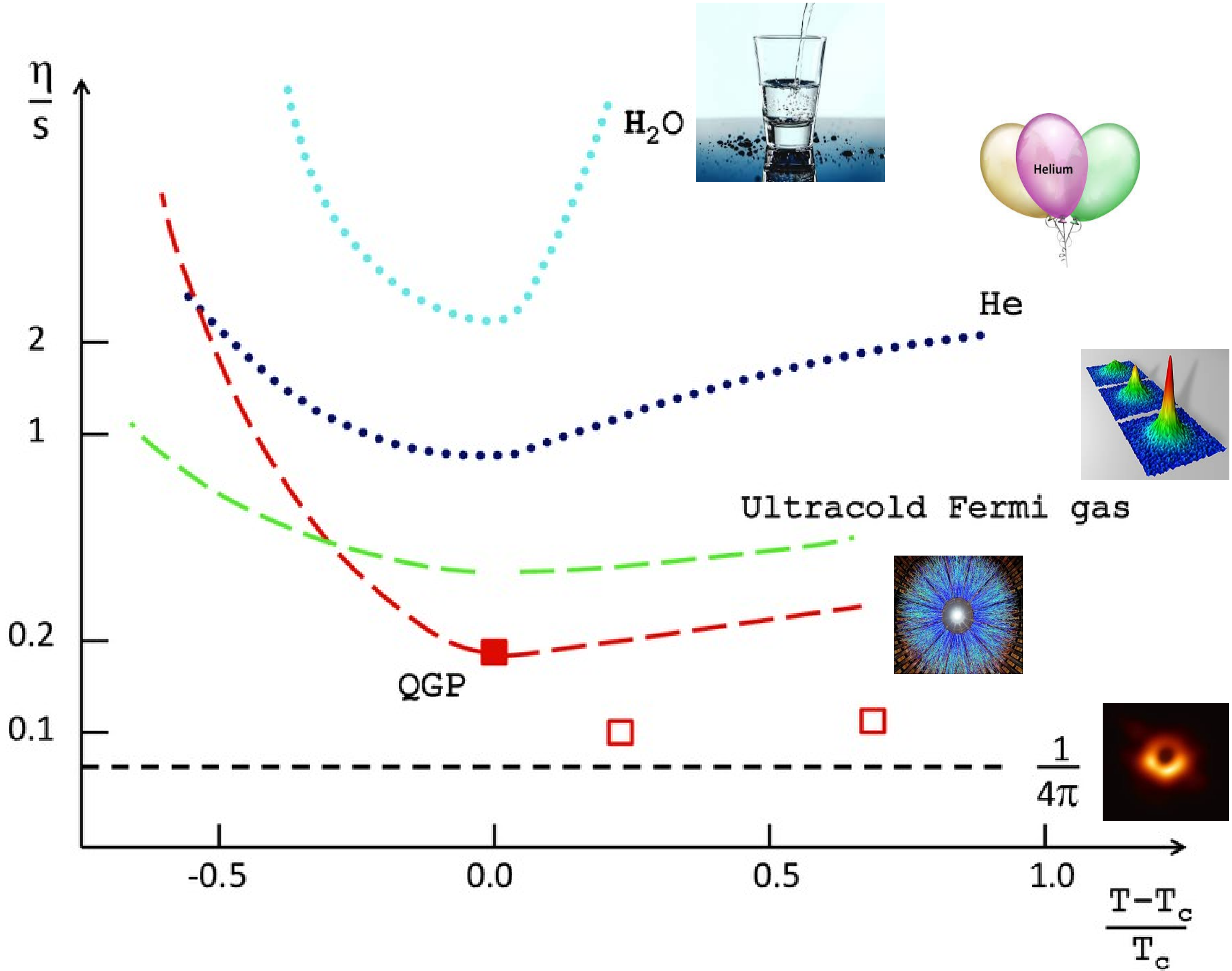
Similarity between the kinematic viscosity of quark-gluon plasma and liquids at the viscosity minimum

Authors: Matteo Baggioli, Vadim Brazhkin, Kostya Trachenko

"Universal lower bounds in energy and momentum diffusion in liquids"

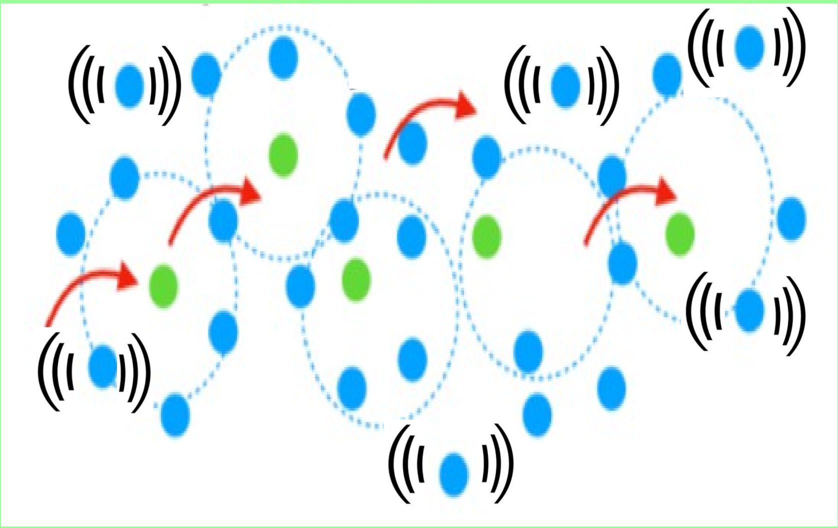
Coming soon! MB, Trachenko, Behnia, Brazhkin

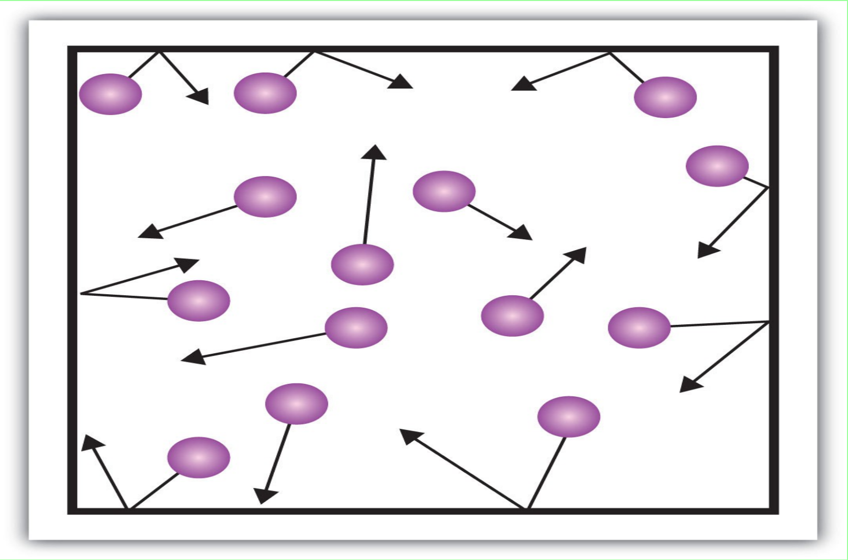

-Kevin Miklasz
sticky, **thick**, *viscous* (stronger bonds)
length of drop
water
milk
oil
light syrup
(water + a heavy syrup)
heavy syrup
(honey, molasses, sugar syrup)
chocolate syrup
3. increase distance & movement with heat (energy)
2. distance with weakly bonded water "infill"
1. manually stretch & rearrange
(naturally) weaker bond
reducing bond strength
= bond (intermolecular force) between atoms
stronger bond



η/s
2
1
0.2
0.1
H2O
Helium
He
Ultracold Fermi gas
QGP
1/4π
-0.5
0.0
0.5
1.0
(T−Tc)/Tc

WHY A MINIMUM?





Oscillatory motion
+
Diffusive jumps

$$\eta = \eta_0 \exp\left(\frac{U}{T}\right)$$

$$D \sim \tau^{-1} \sim \eta^{-1}$$

Ballistic motion
Viscosity comes from collisions

$$\eta = \frac{1}{3}\rho v L$$

$$D \sim \eta \sim l_{mfp}$$

LIQUID DYNAMICS **Tc** **GAS DYNAMICS**

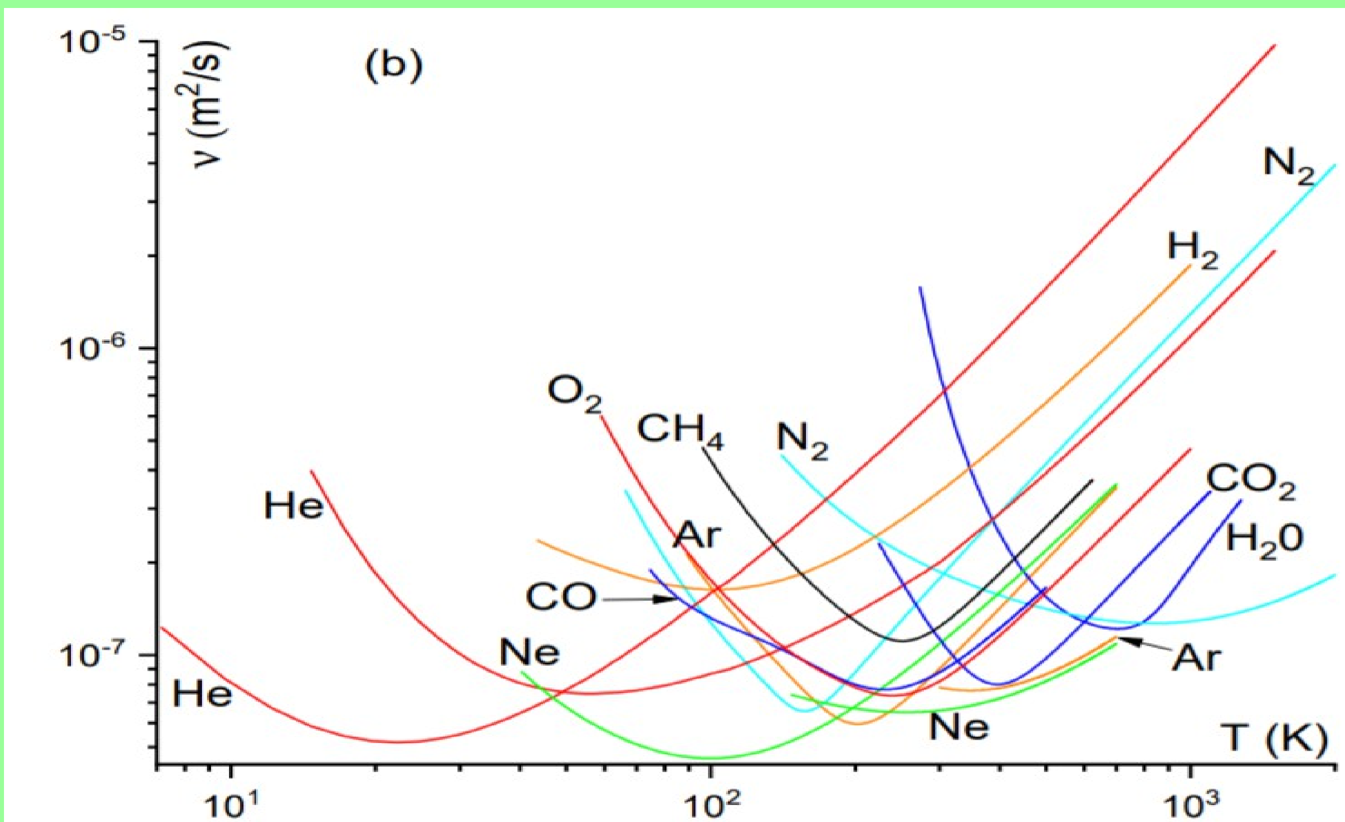
A UNIVERSAL MINIMUM

[Trachenko, Brazhkin, Sci.Advances 2020]

$$\nu_m = \frac{1}{4\pi}\frac{\hbar}{\sqrt{m_e m}}$$

$$\nu_m^{exp} = (0.5-2)\cdot 10^{-7}\ \frac{\mathrm{m}^2}{\mathrm{s}}$$

[See derivation therein]



WHAT ABOUT QGP ?

E/V	$1\ \mathrm{GeV/fm^3}$ [23]
η	$5 \cdot 10^{11}$ Pa$\cdot$ s [7]
m_p	$1.67 \cdot 10^{-27}$ kg
a_p	$0.84 \cdot 10^{-15}$ m
a	$0.5 \cdot 10^{-15}$ m [24]
T_{QGP}	$2 \cdot 10^{12}$ K [7]

THE SHEAR VISCOSITY IS HUGE
(COMPARABLE TO LIQUIDS
AT THE GLASS TRANSITION)

But the density is also huge !

$$D = \frac{a_p^2}{\hbar} k_{\mathrm{B}} T_{\mathrm{QGP}}$$

Compatible with the standard liquid formula and using the Planckian relaxation time !

It can be derived in several ways :
(check the paper 😉)

$$\boxed{\nu_{\mathrm{QGP}}^{exp} \approx 10^{-7} \frac{\mathrm{m}^2}{\mathrm{s}}}$$

CONSEQUENCES

we found that (a) the calculated $\nu_{\rm QGP}^{th}$ in (11) and D_s in (13) are close to the experimental value of $\nu_{\rm QGP}^{exp}$ in (10), and (b) these values of kinematic viscosity of QGP are close to both experimental and theoretical values of kinematic viscosity in liquids at the minimum ν_m.

Given that the dynamic viscosity η and the density of QGP are about 16 orders of magnitude larger than those values in liquids, the similarity of ν is striking.

FIRST CONCLUSION

$\frac{\eta}{s}$ Is very well defined in relativistic systems but away from that it does not govern anything

$\frac{\eta}{s}$

[Hartnoll 2015, Nature]

Momentum Diffusion Constant

THERMAL DIFFUSIVITY

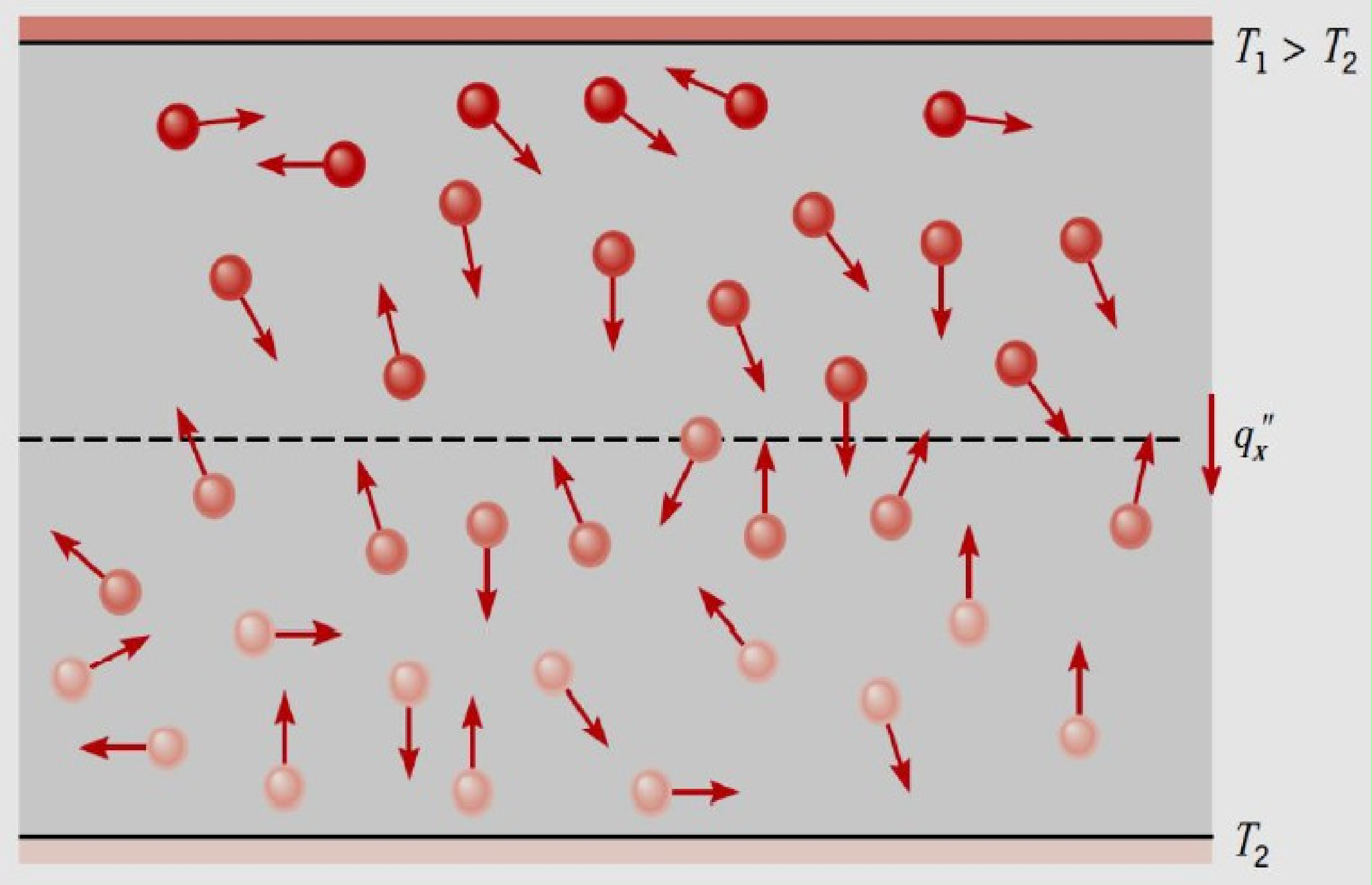
$$J_Q = \kappa \frac{\partial T}{\partial x},$$

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

$$\alpha = \frac{\bar{k}}{c_p};$$

$$\kappa \approx c\, v\, l$$

$$\alpha = v\, l$$



THE MINIMUM

Using $l = a$ and $v = \frac{a}{\tau_{\mathrm{D}}} = \frac{1}{2\pi} a\omega_{\mathrm{D}}$

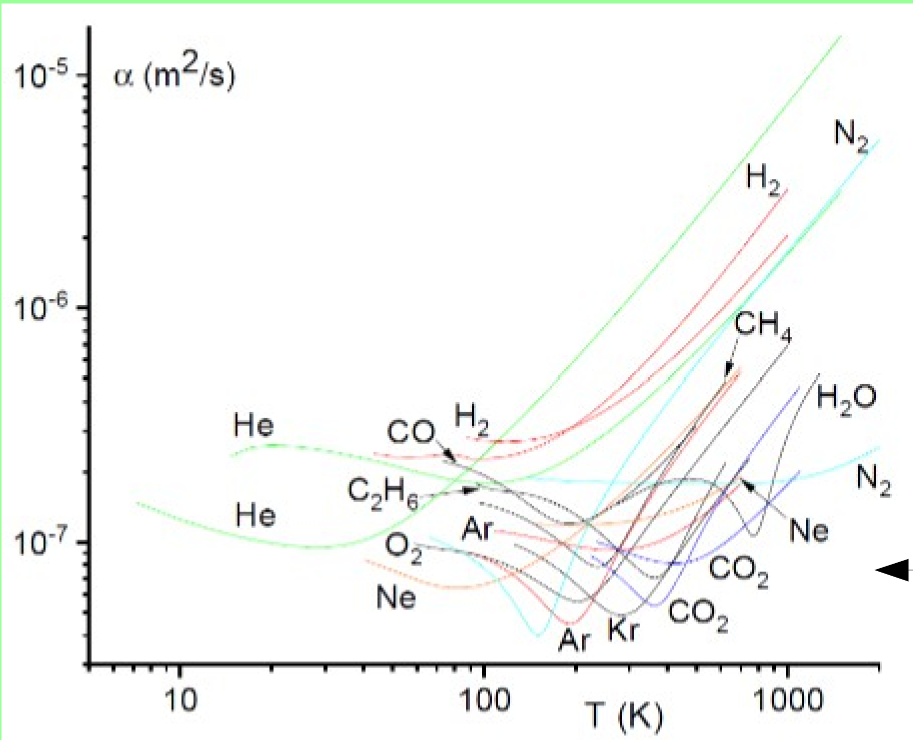
UV CUTOFFS IN CONDENSED MATTER

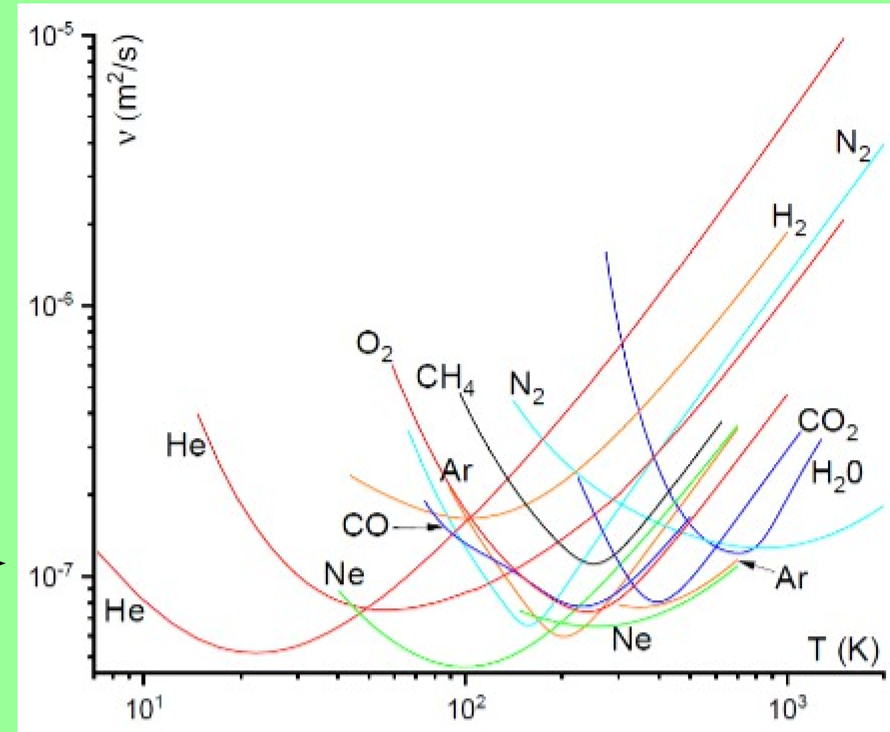
Bohr radius, a_{B},

Rydberg energy, E_{R}

$$\boxed{\alpha_m = \frac{1}{4\pi} \frac{\hbar}{\sqrt{m_e m}}}$$

EXPERIMENTS





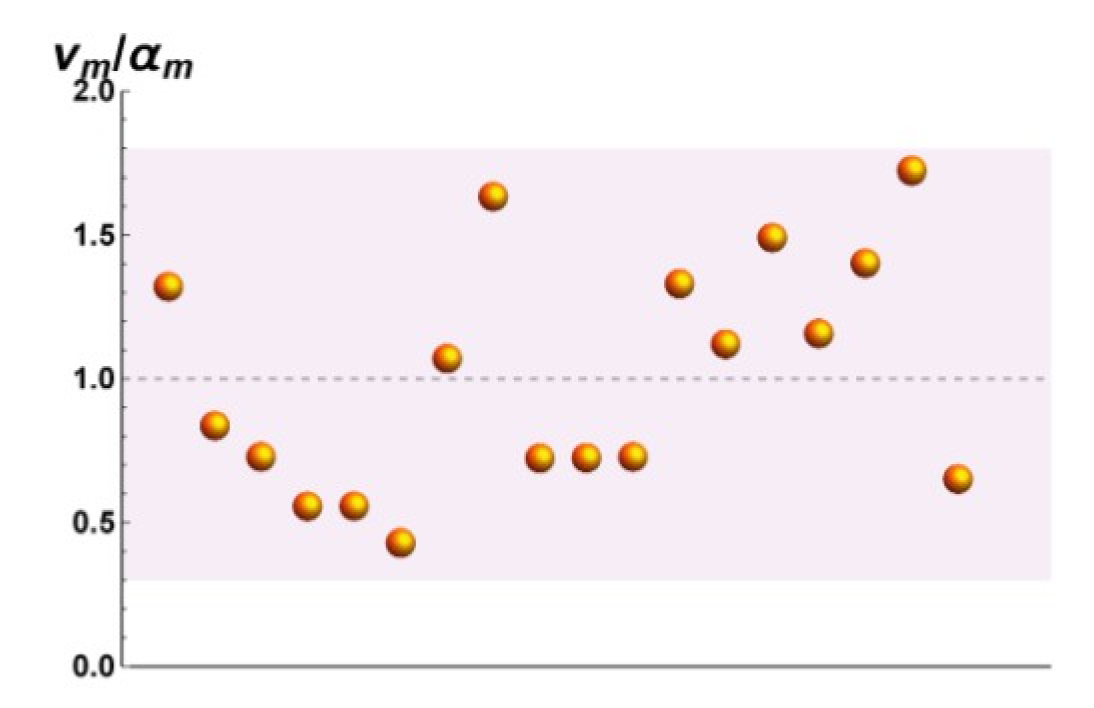
National Institute of Standards and Technology database,
see https://webbook.nist.gov/chemistry/fluid.

Minima at different temperatures but

$$\alpha_m = \mathcal{C}\, \nu_m\,, \quad \mathcal{C} \in [0.4, 1.7], \qquad \frac{1}{4\pi}\frac{\hbar}{\sqrt{m_e m_p}} \approx 10^{-7}\frac{\mathrm{m}^2}{\mathrm{s}}.$$

DATA RECAP

	$\alpha_m^{th} = \nu_m^{th}$	α_m^{exp}	ν_m^{exp}	ν_m/α_m
Ar (20 MPa)	3.4	4.5	5.9	1.3
Ar (100 MPa)	3.4	9.3	7.7	0.8
Ne (50 MPa)	4.8	6.4	4.6	0.7
Ne (300 MPa)	4.8	11.9	6.5	0.6
He (20 MPa)	10.7	9.5	5.2	0.6
He (100 MPa)	10.7	17.9	7.5	0.4
Kr (30 MPa)	2.3	4.9	5.2	1.1
N_2 (10 MPa)	4.1	4.0	6.5	1.6
N_2 (500 MPa)	4.1	17.8	12.7	0.7
H_2 (50 MPa)	15.2	22.8	16.3	0.7
H_2 (100 MPa)	15.2	27.0	19.4	0.7
O_2 (30 MPa)	3.8	5.6	7.4	1.3
H_2O (70 MPa)	5.1	10.7	11.9	1.1
CO_2 (30 MPa)	3.2	5.4	8.0	1.5
CO_2 (90 MPa)	3.2	8.1	9.3	1.2
CH_4 (20 MPa)	5.4	7.9	11.0	1.4
C_2H_6 (20 MPa)	3.9	7.0	12.0	1.7
CO (20 MPa)	4.1	12.0	7.7	0.6



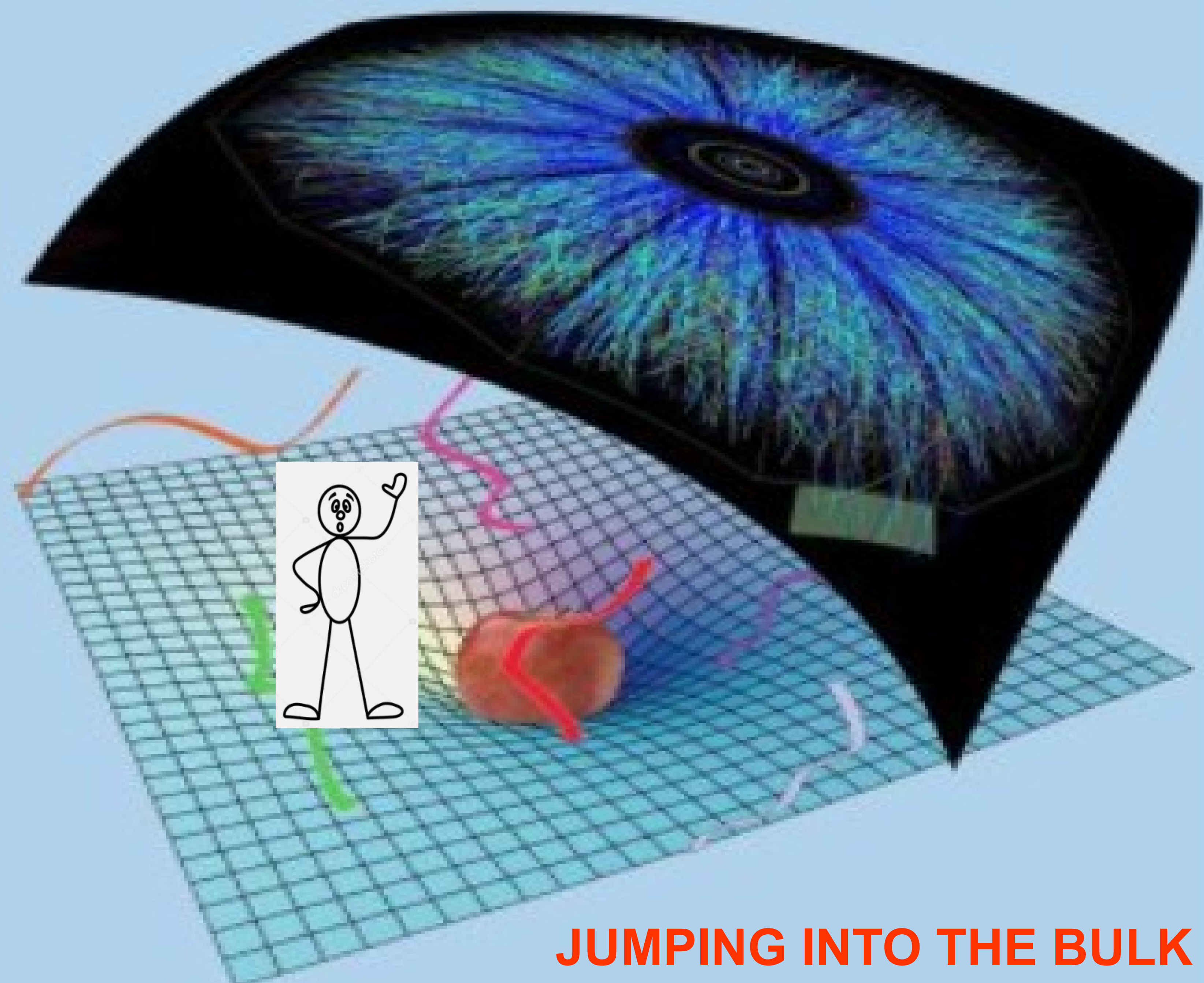
1) PREDICTIONS OF THE MINIMA VERY ACCURATE

2) VALUES AT THE MINIMA VERY CLOSE TO EACH OTHER

SECOND CONCLUSION

STRONG UNIVERSALITY AT THE MINIMUM

No need of weird/fancy materials
to see quantum bounds!
Physics is unavoidably quantum in cond-mat



JUMPING INTO THE BULK

. **From AdS / CFT correspondence to hydrodynamics**

Giuseppe Policastro (Pisa, Scuola Normale Superiore), Dam T. Son, Andrei O. Starinets (Washington U., Seattle). May 2002. 18 pp.

Published in **JHEP 0209 (2002) 043**
INT-PUB-02-32
DOI: 10.1088/1126-6708/2002/09/043
e-Print: **hep-th/0205052** | **PDF**

Dynamics of black hole horizon —— **Fluid-dynamics**

Relativistic hydrodynamics → Shear diffusion

Sound mode

(fluid-gravity, QNMs, transport)

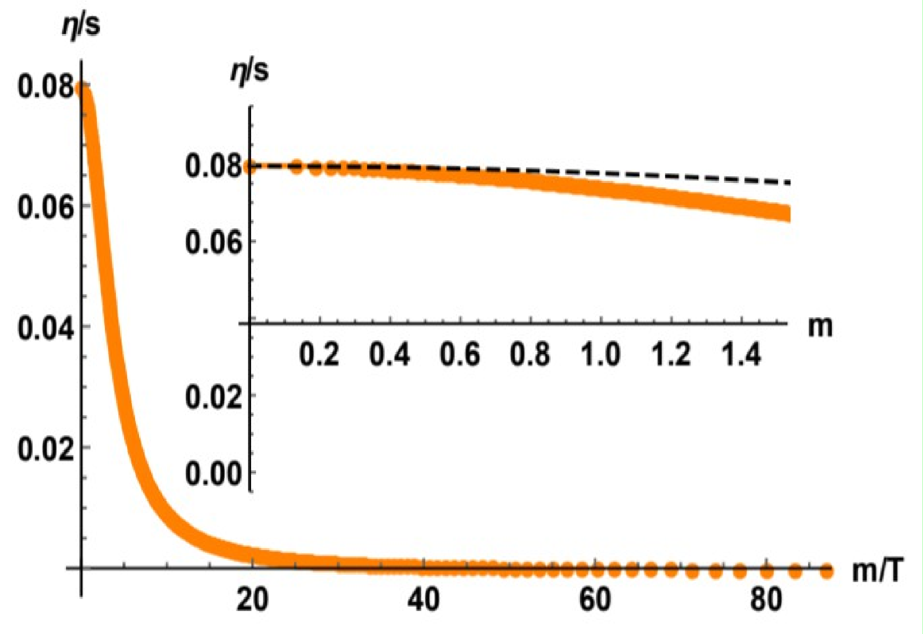
A HOLOGRAPHIC LIE

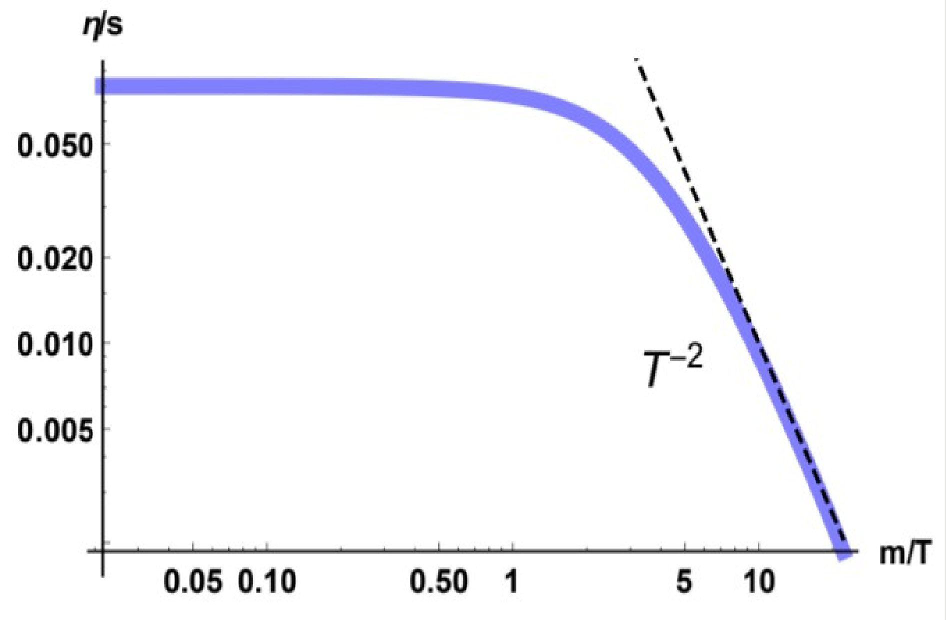
A SPECIFIC CASE

$$\phi^I = \alpha\, x^I$$

[Hartnoll, Ramirez, Santos 2016]

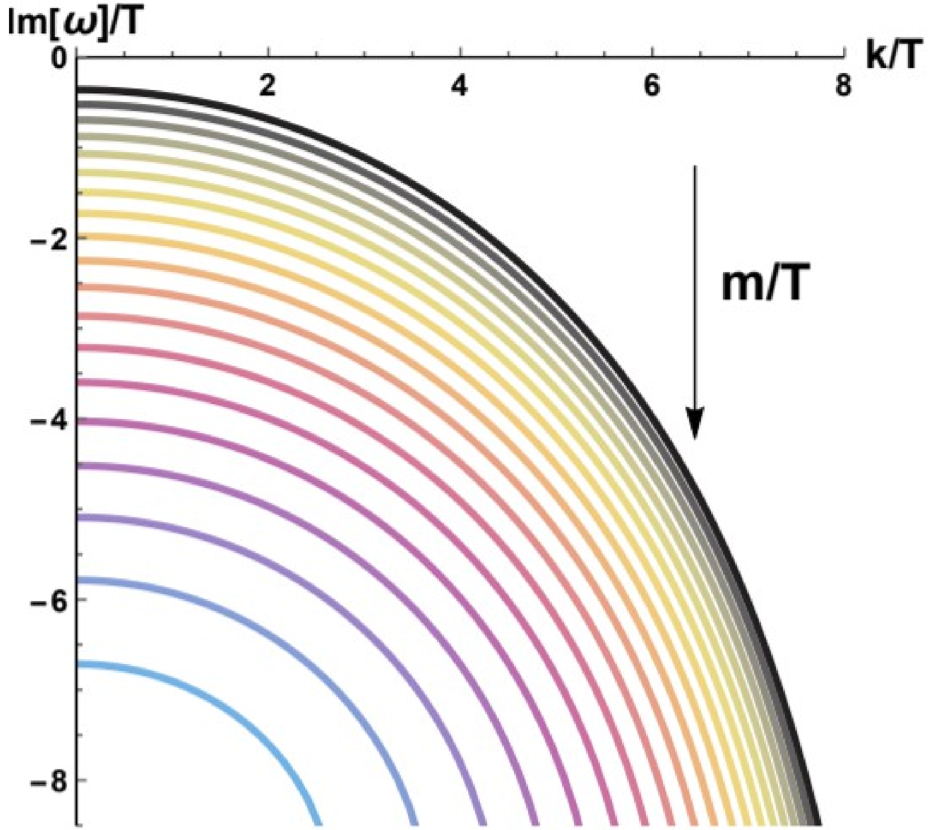
[MB, Alberte, Pujolas 2016 +1 day]

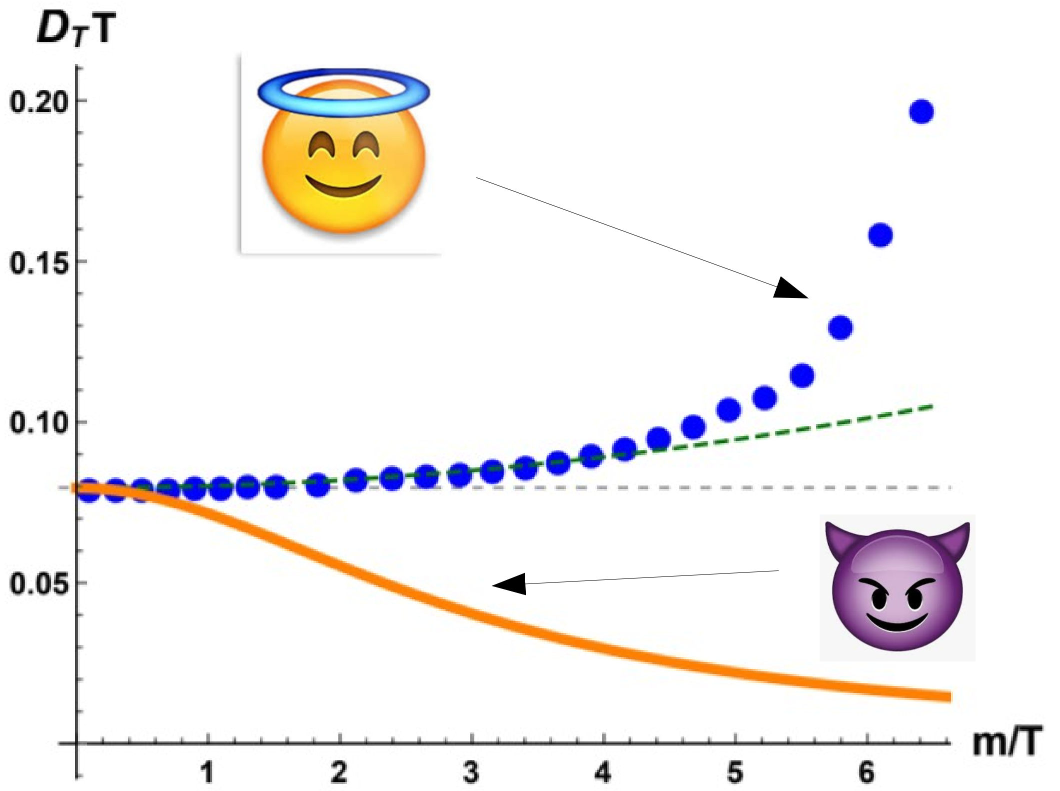




$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 - \frac{4}{3}\, m^2\, u_h^{2N}\, \frac{\mathcal{H}_{\frac{2N}{3}-1}}{2N-3}\right) + \mathcal{O}(m^4)\,,$$

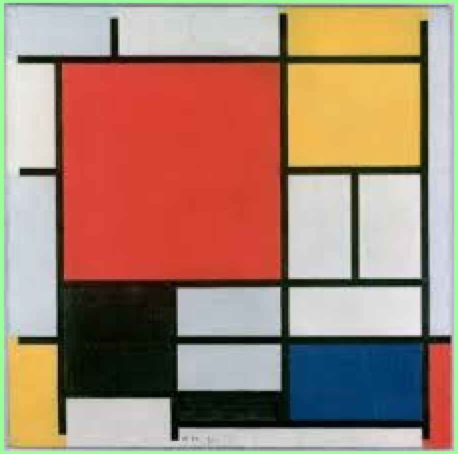
A SIMPLE SOLUTION





$$D_T T \geq \frac{1}{4\pi},$$

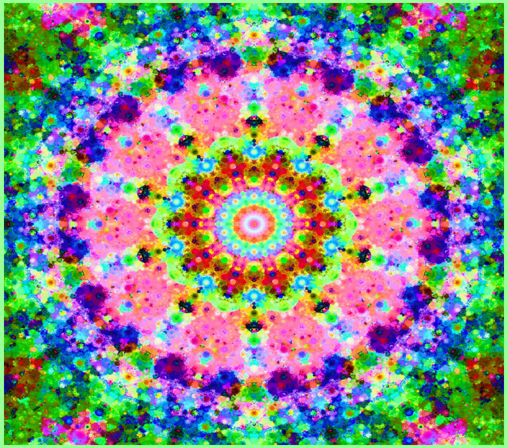
OUTLOOK



$\frac{\eta}{s}$ **loses its universality !**

But the diffusion constant not !

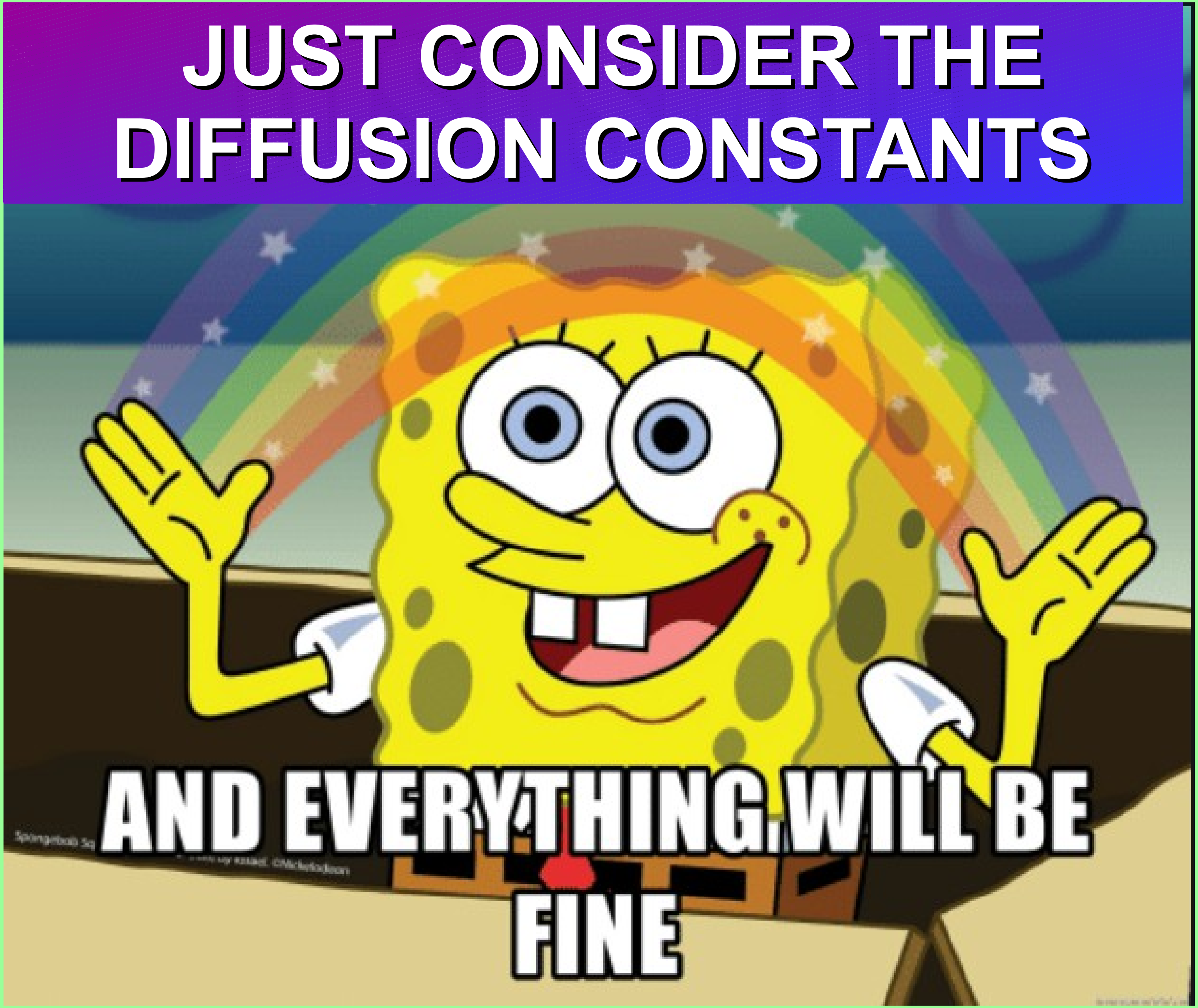
Same happens in systems with broken rotations!



[Blake, 2016, PRL]

[See Dimitrios' next talk]

PROVOCATIVE STATEMENT



HINTS FROM EXPERIMENTS

arXiv:2001.03805 [pdf, other] cond-mat.str-el hep-th doi 10.1073/pnas.1910131116

Thermalization and Possible Signatures of Quantum Chaos in Complex Crystalline Materials

Authors: Jiecheng Zhang, Erik D. Kountz, Kamran Behnia, Aharon Kapitulnik

arXiv:1905.03551 [pdf, other] cond-mat.mtrl-sci cond-mat.stat-mech doi 10.1088/1361-648X/ab2db6

A lower bound to the thermal diffusivity of insulators

Authors: Kamran Behnia, Aharon Kapitulnik

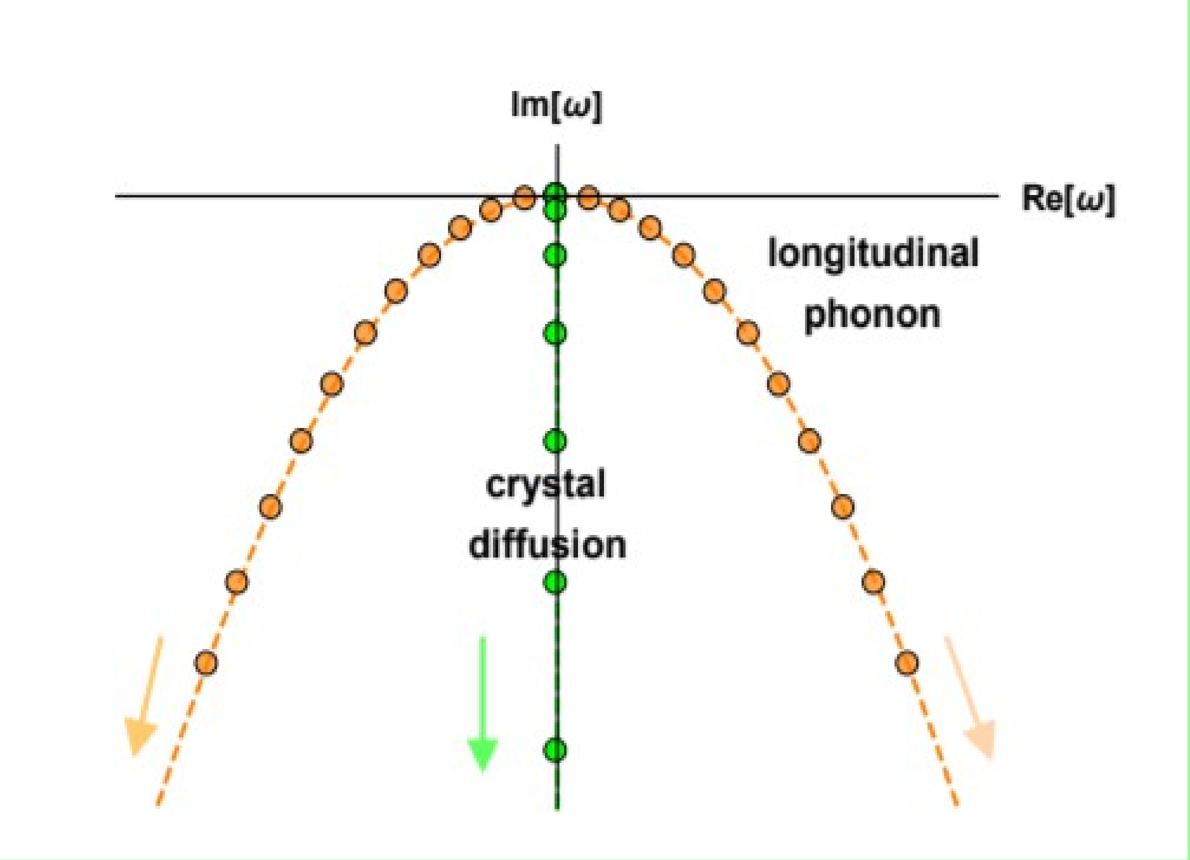
arXiv:1908.04792 [pdf, other] cond-mat.mtrl-sci cond-mat.stat-mech

On the Planckian bound for heat diffusion in insulators

Authors: Connie H. Mousatov, Sean A. Hartnoll

SSB OF TRANSLATIONS

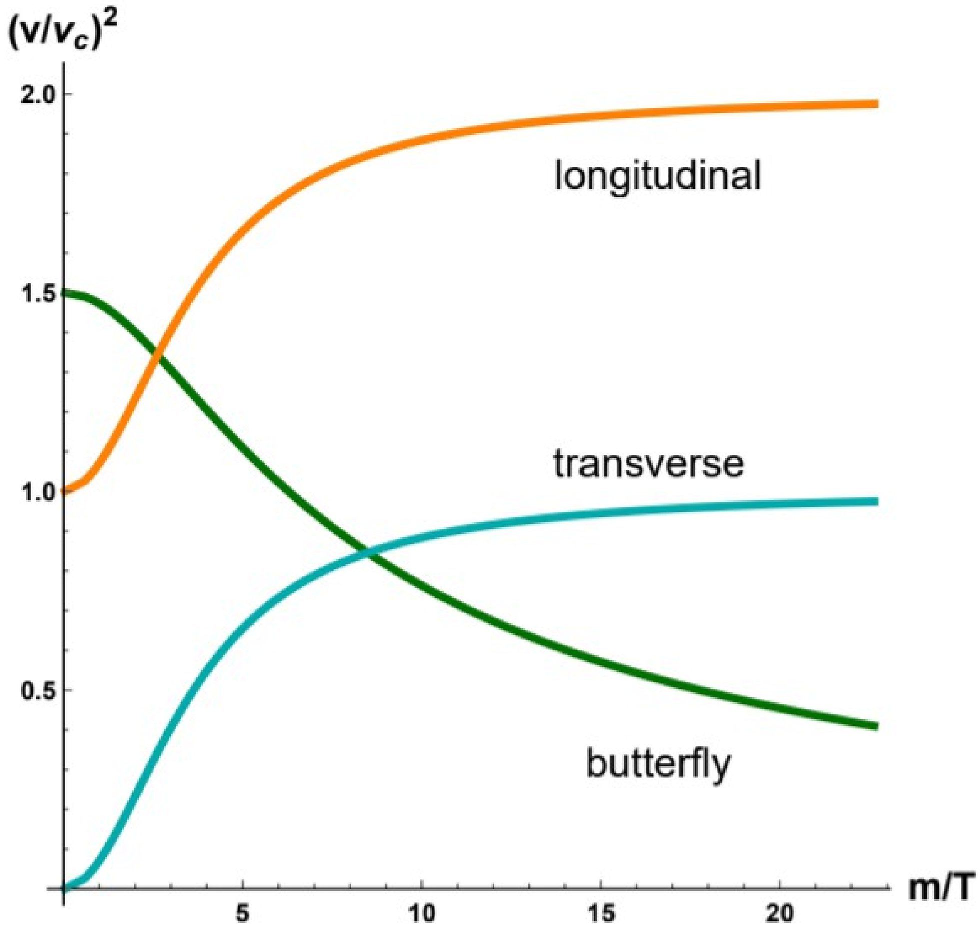
[MB et Al , 2018, JHEP]

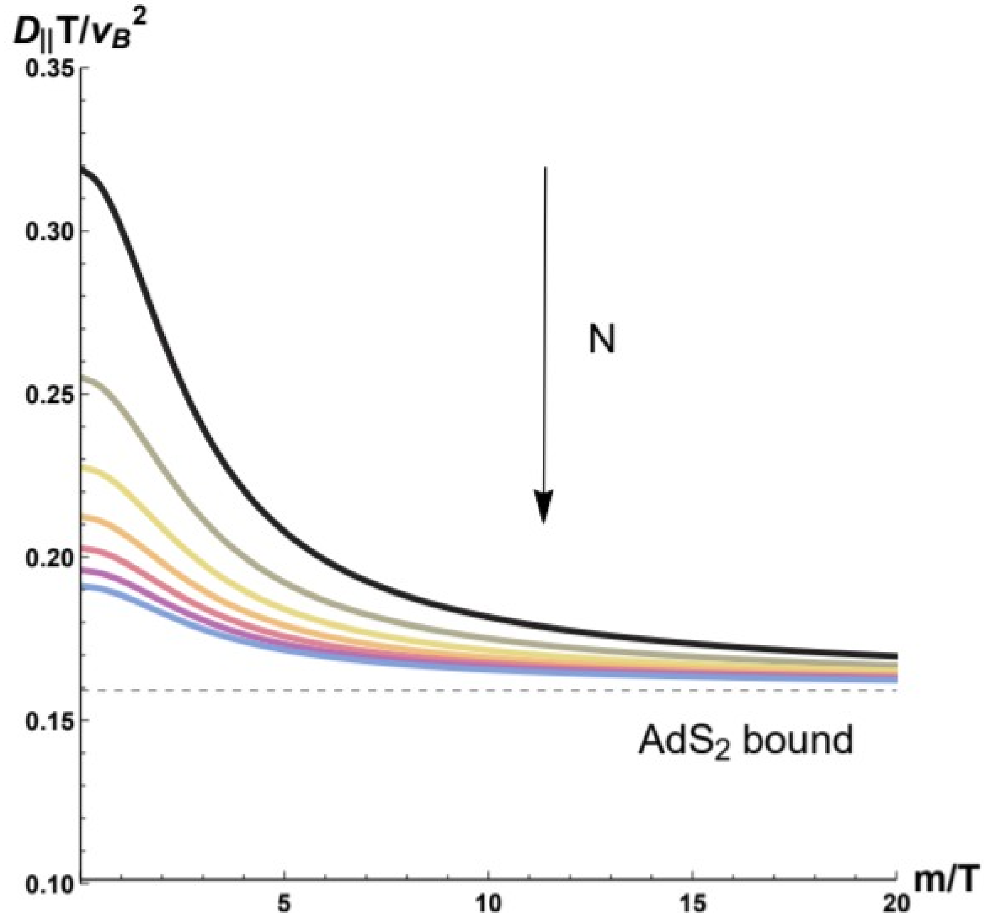


$$\omega = \pm c_L\, k - i\, D_p\, k^2 + \ldots\,,$$ → Longitudinal sound

$$\omega = -\, i\, D_\Phi\, k^2 + \ldots\,,$$ →

CRYSTAL DIFFUSION





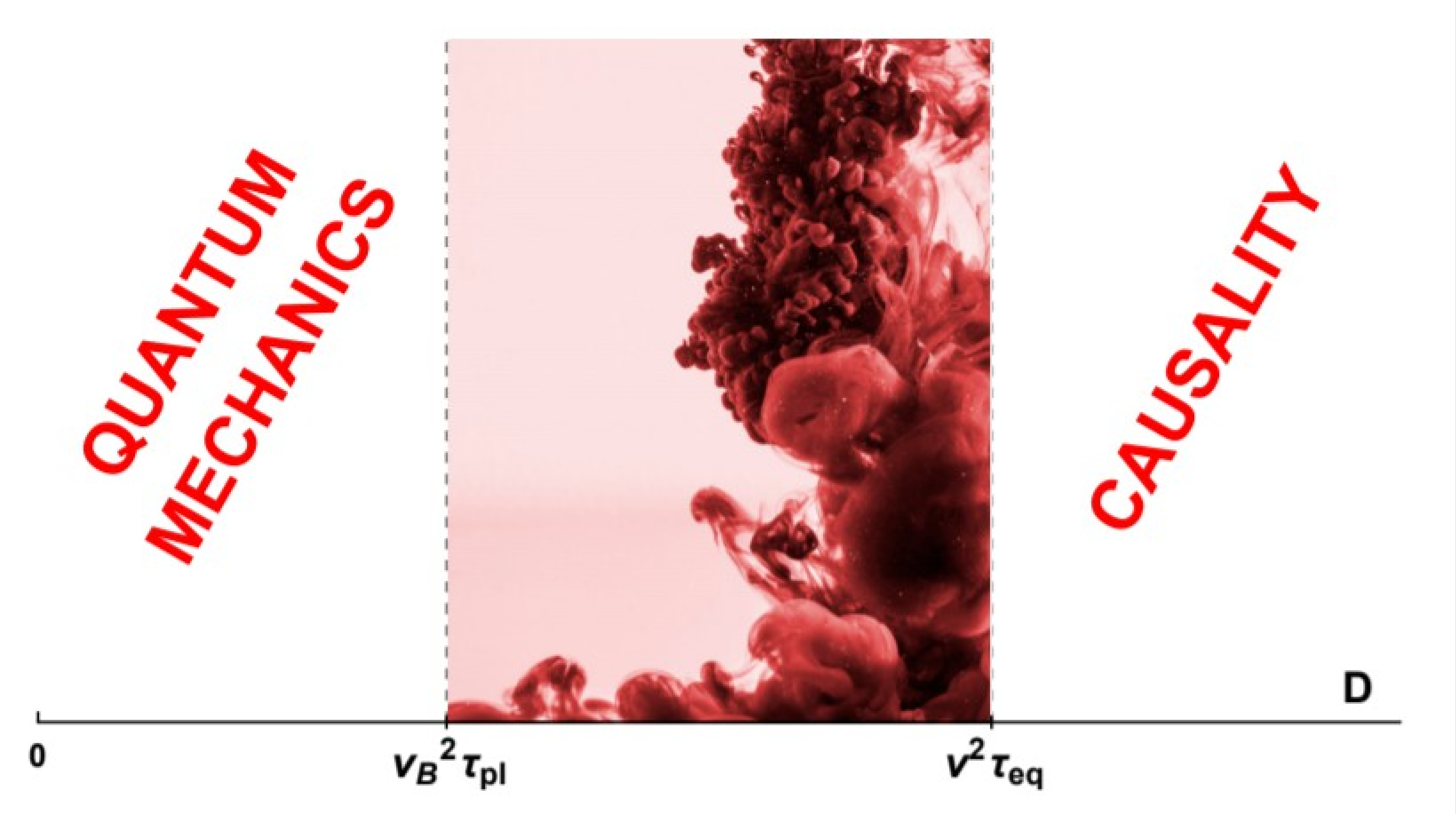
$$\frac{D_{\|}\,T}{v_B^2} \geq \frac{1}{2\,\pi}$$ $\equiv$ AdS_2 bound for energy diffusion

NOT SO TRIVIAL ...

$$D_{\|} = \xi \, \frac{(B + G - \mathcal{P}) \; \chi_{\pi\pi}}{s' \, T^2 \, v_L^2} \,,$$

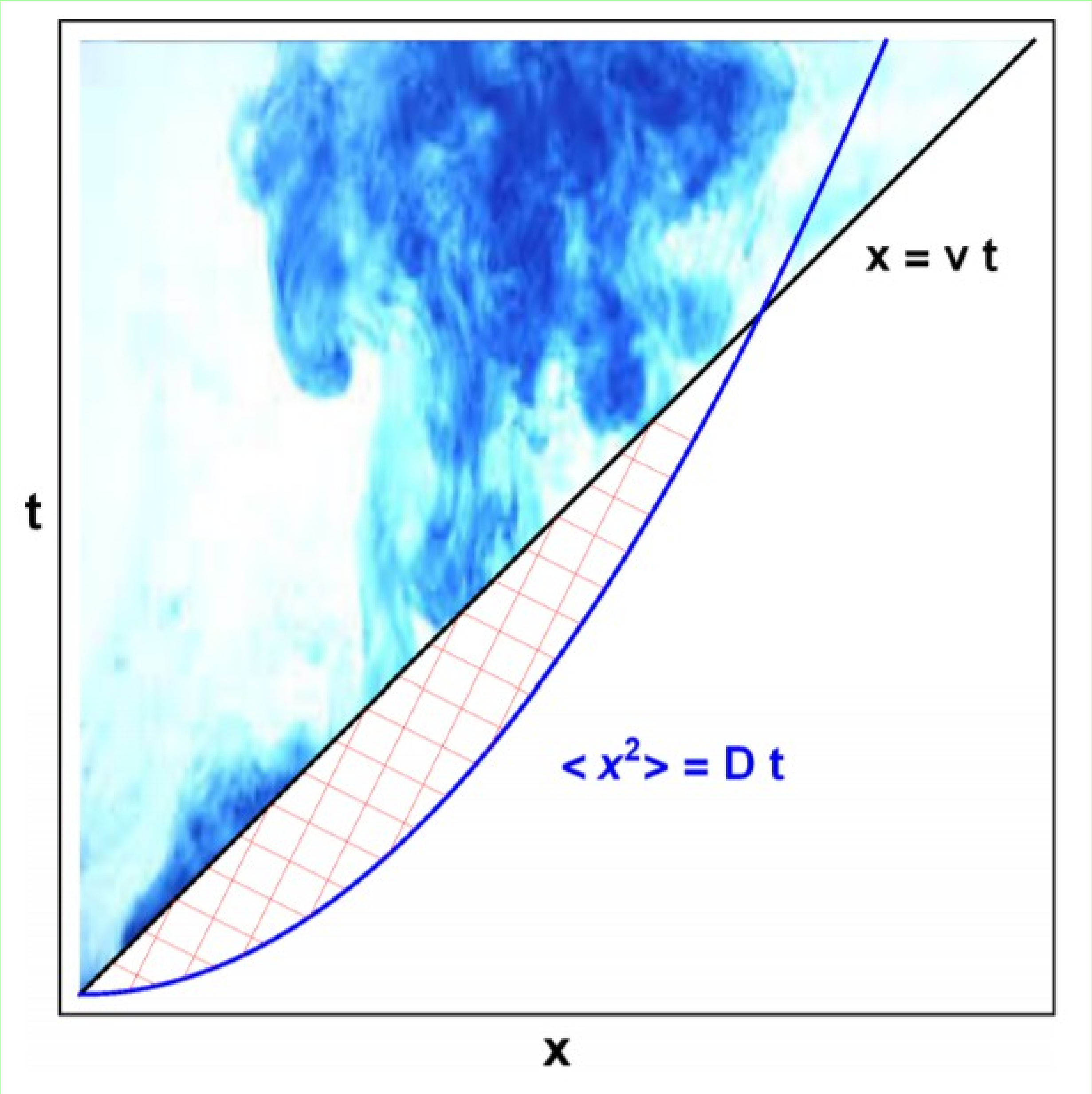
Coefficient	$m/T \to 0$	$m/T \to \infty \; (\delta_m \to 0)$
T	$3/4\pi$	$\delta_m/4\pi$
χ	$3/2$	3
G	m^2	$3/2$
v_T^2	0	$1/2$
v_L^2	$1/2$	1
s'	$16\pi^2/3$	$8\,\pi^2/9$
$\mathcal{P}$	m^2	3
$\mathcal{B}$	$3\,m^2$	$9/2$
ξ	$1/(3\,m^2)$	$\delta_m^2/324$

AN UPPER BOUND



$$v_B^2\,\tau_{pl} \lesssim D \lesssim v_{ligthcone}^2\,\tau_{eq}\,,$$

FROM CAUSALITY



[Hartman,Hartnoll, Mahajan, PRL 2017]

$$\langle x^2 \rangle = D\,t$$

$$\sqrt{D\,t} \leq v_{\mathrm{lightcone}}\,t$$

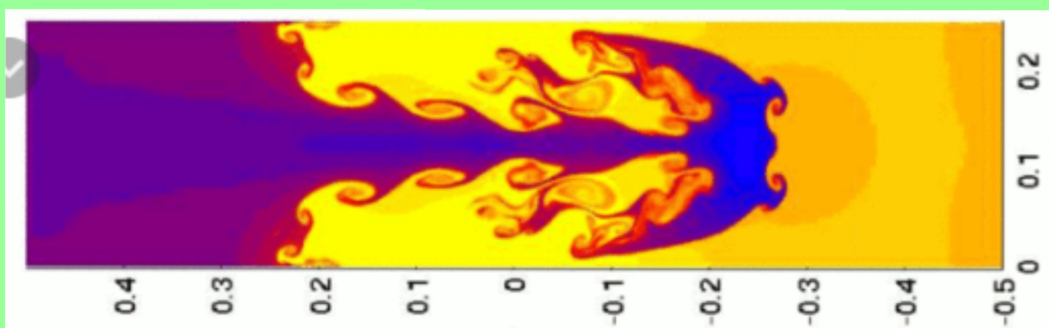
$$D \leq v_{\mathrm{lightcone}}^2\,\tau_{eq}$$

A BEAUTIFUL EXAMPLE

$$\omega = -i \frac{\eta}{\epsilon + p} k^2 \qquad |v| = \left| \frac{\partial \omega}{\partial k} \right| \sim k > c$$

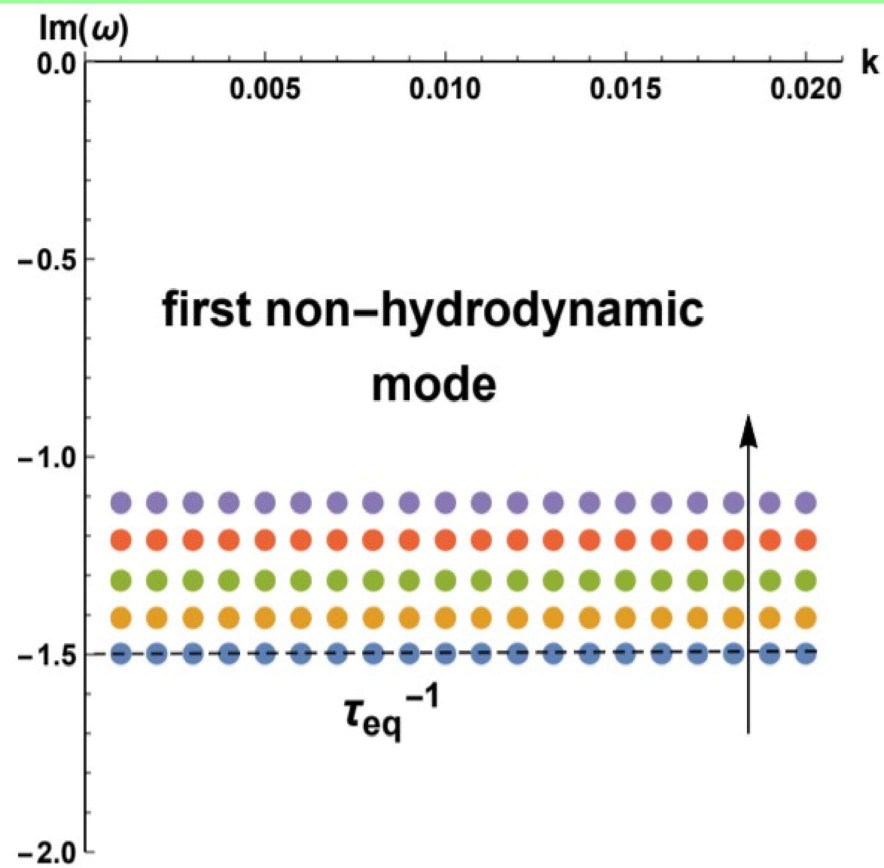
ISRAEL-STEWART FORMALISM

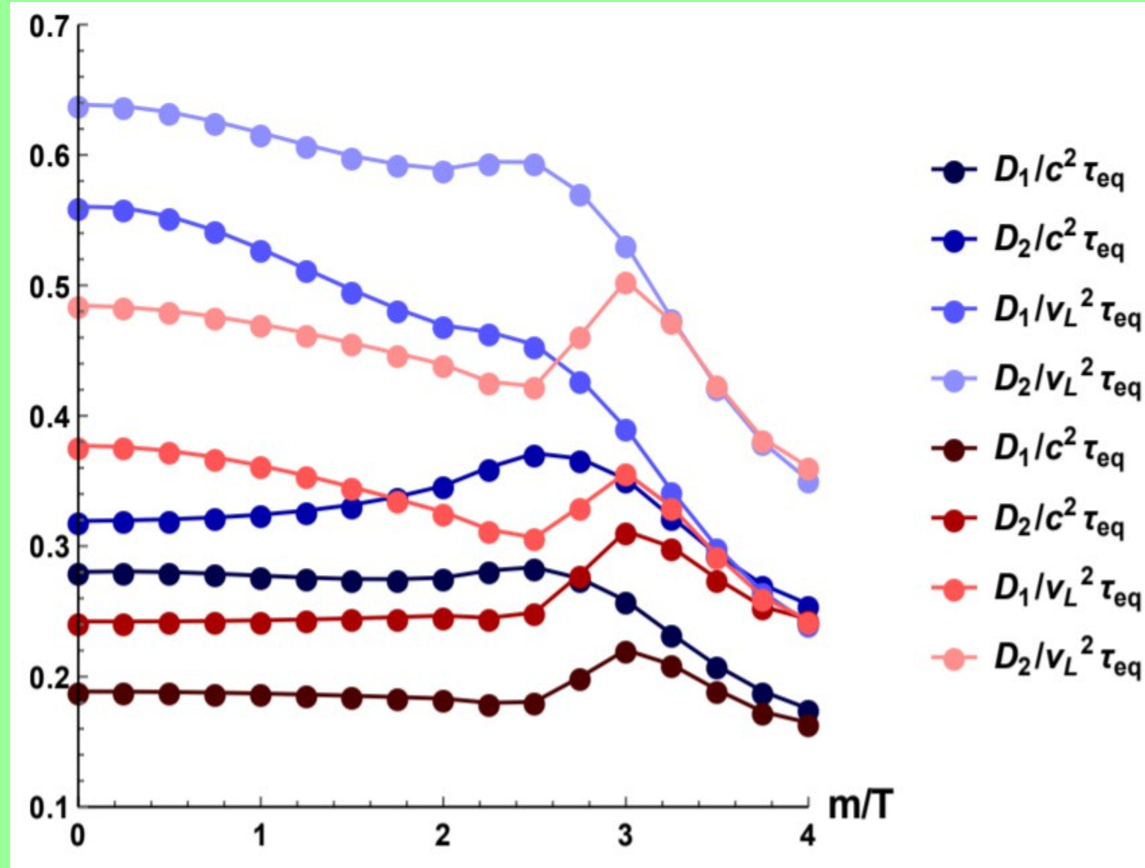
$$\omega^2 + i\omega \tau_\pi^{-1} = v^2 k^2 , \qquad v^2 = \frac{\eta}{(\epsilon + p)\tau_\pi}$$



$$v < c \quad \rightarrow \quad \sqrt{\frac{D}{\tau_\pi}} < c \longrightarrow \boxed{D \leq c^2 \tau_\pi}$$

HOLOGRAPHIC RESULTS

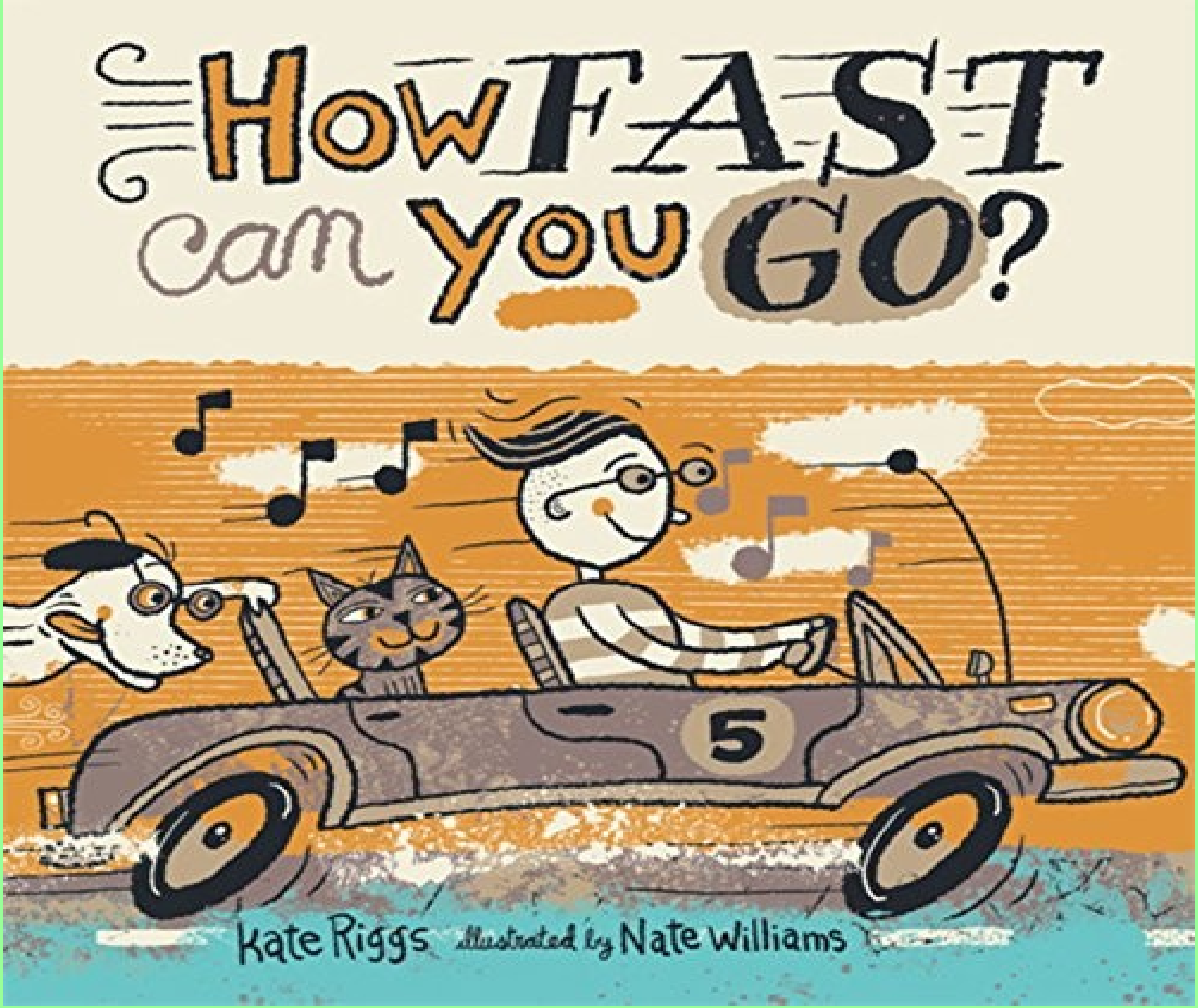




$$\tau_{eq}^{-1} \equiv \mathrm{Im}\,\omega_{\mathrm{QNM}},$$

$$D_{1,2} \le \mathfrak{N}\, v_L^2\, \tau_{eq}$$

WHAT ABOUT SOUND ?

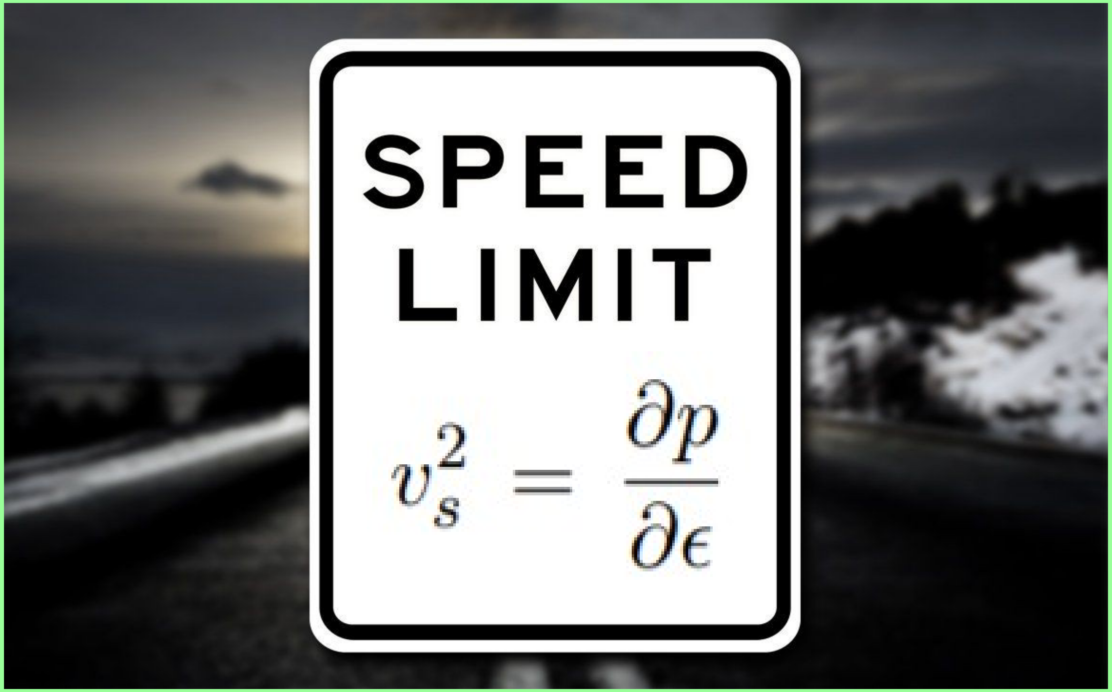


OLD IDEAS

[Hohler,Stephanov 2009 PRD]

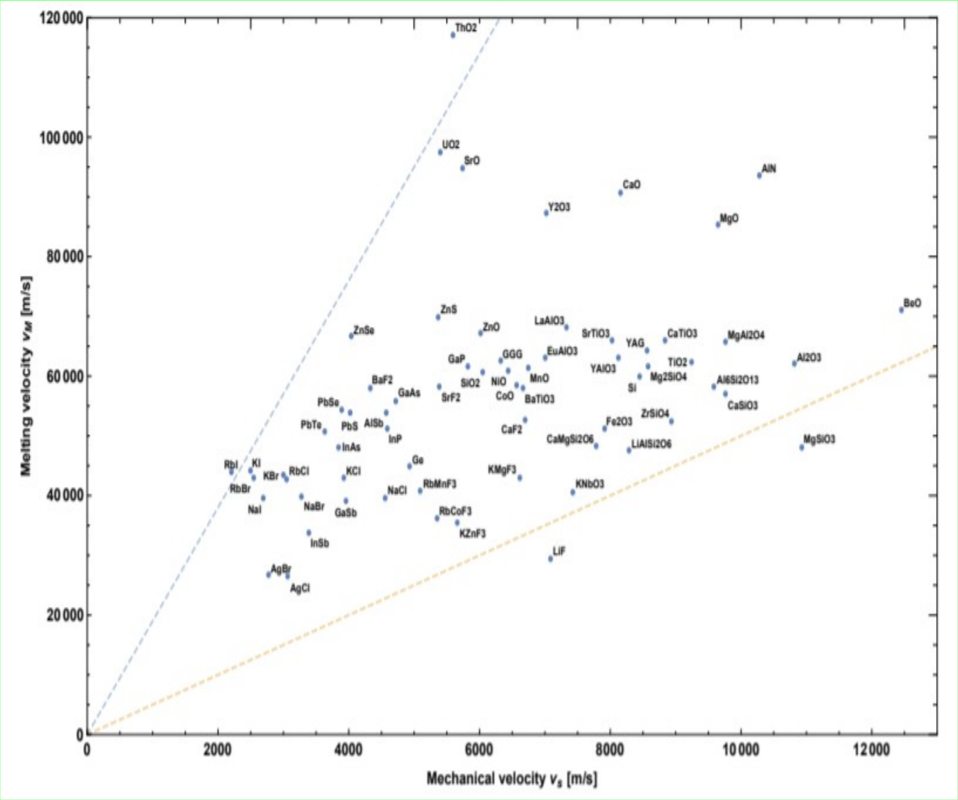
[Cherman, Cohen, Nellore 2009 PRD]

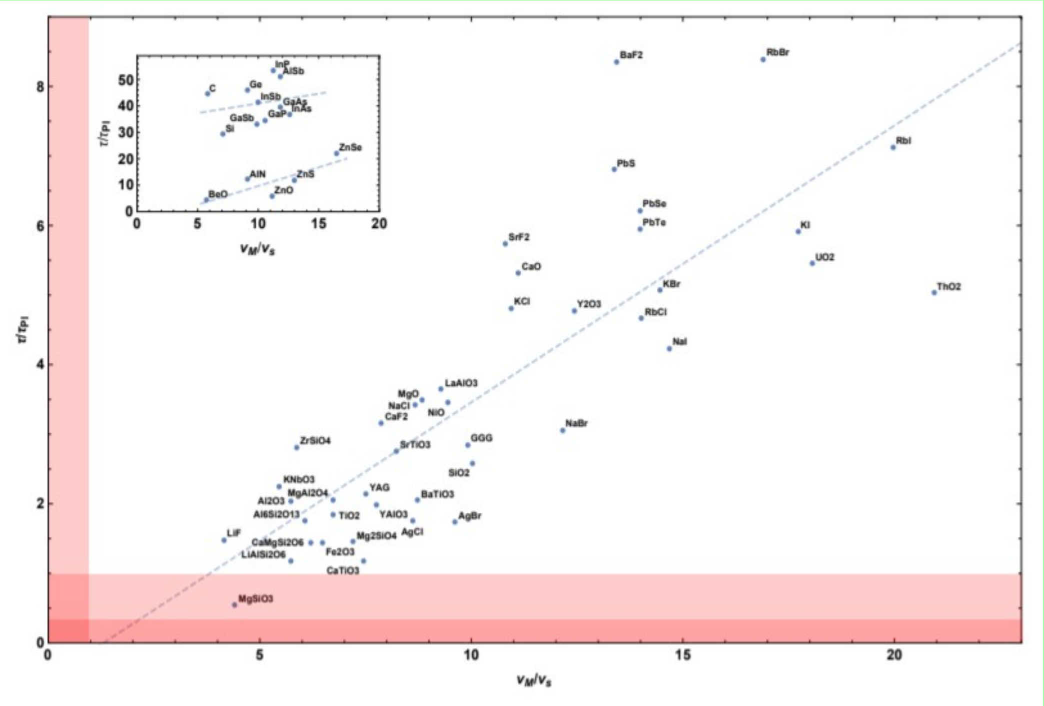
CFT $\longrightarrow$ $v_c^2 \equiv \frac{1}{d-1} c^2$



NEW IDEAS

[Mousatov, Hartnoll 2019]





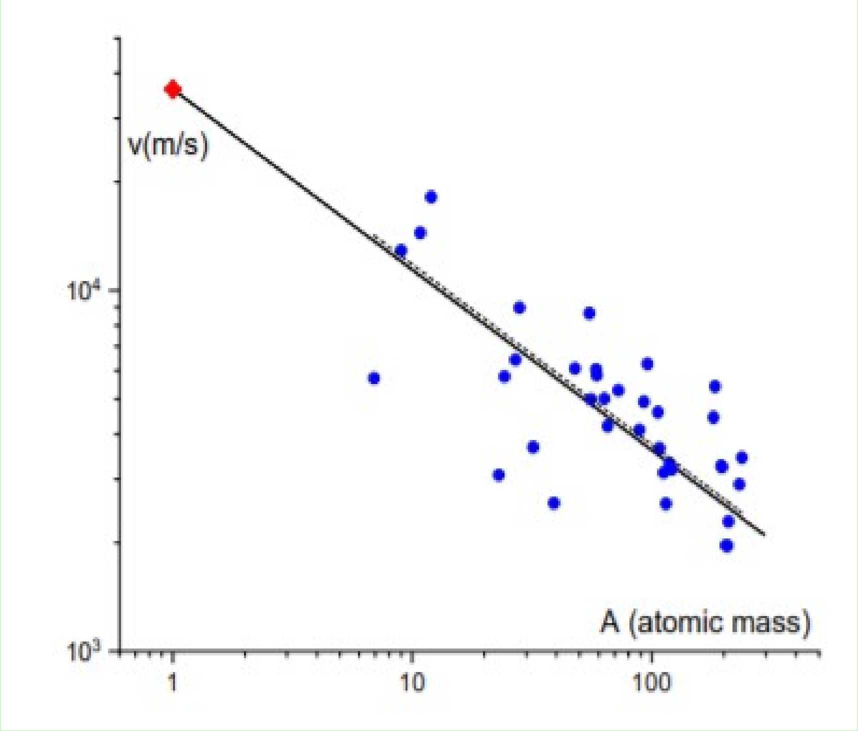
$$v_s \leq v_m \equiv \frac{k_B T_m a}{\hbar},$$

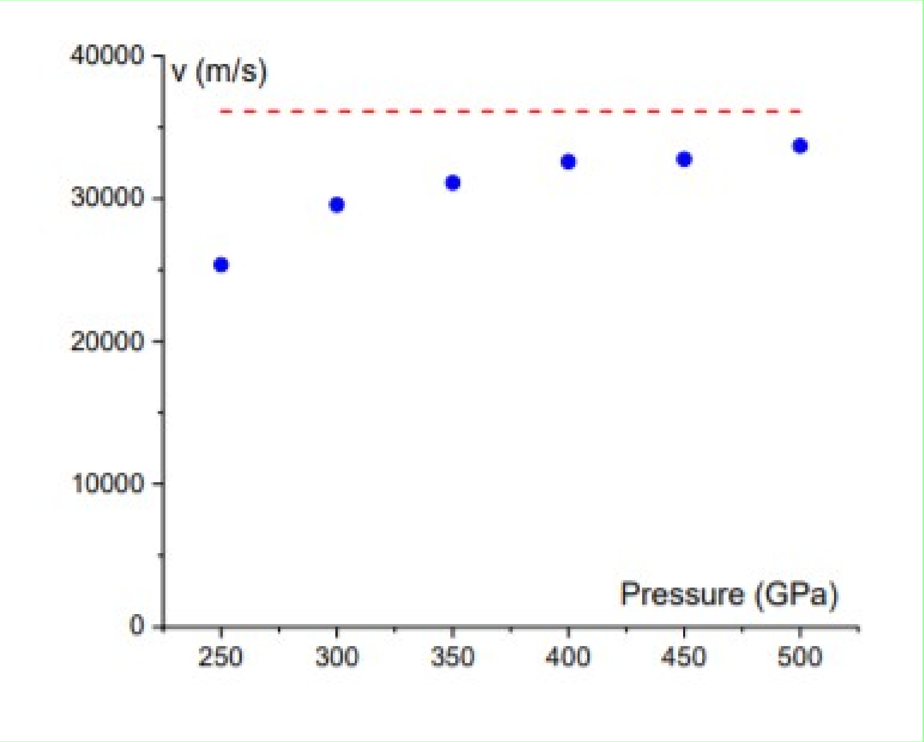
$$\frac{\tau}{\tau_{\mathrm{Pl}}} \sim \frac{v_M}{v_s} \gtrsim 1$$

NEW IDEAS

[Trachenko, Monserrat, Pickard, Brazhkin 2020]

$$v_s \leq \alpha \left(\frac{m_e}{2\, m_p} \right)^{1/2} c$$





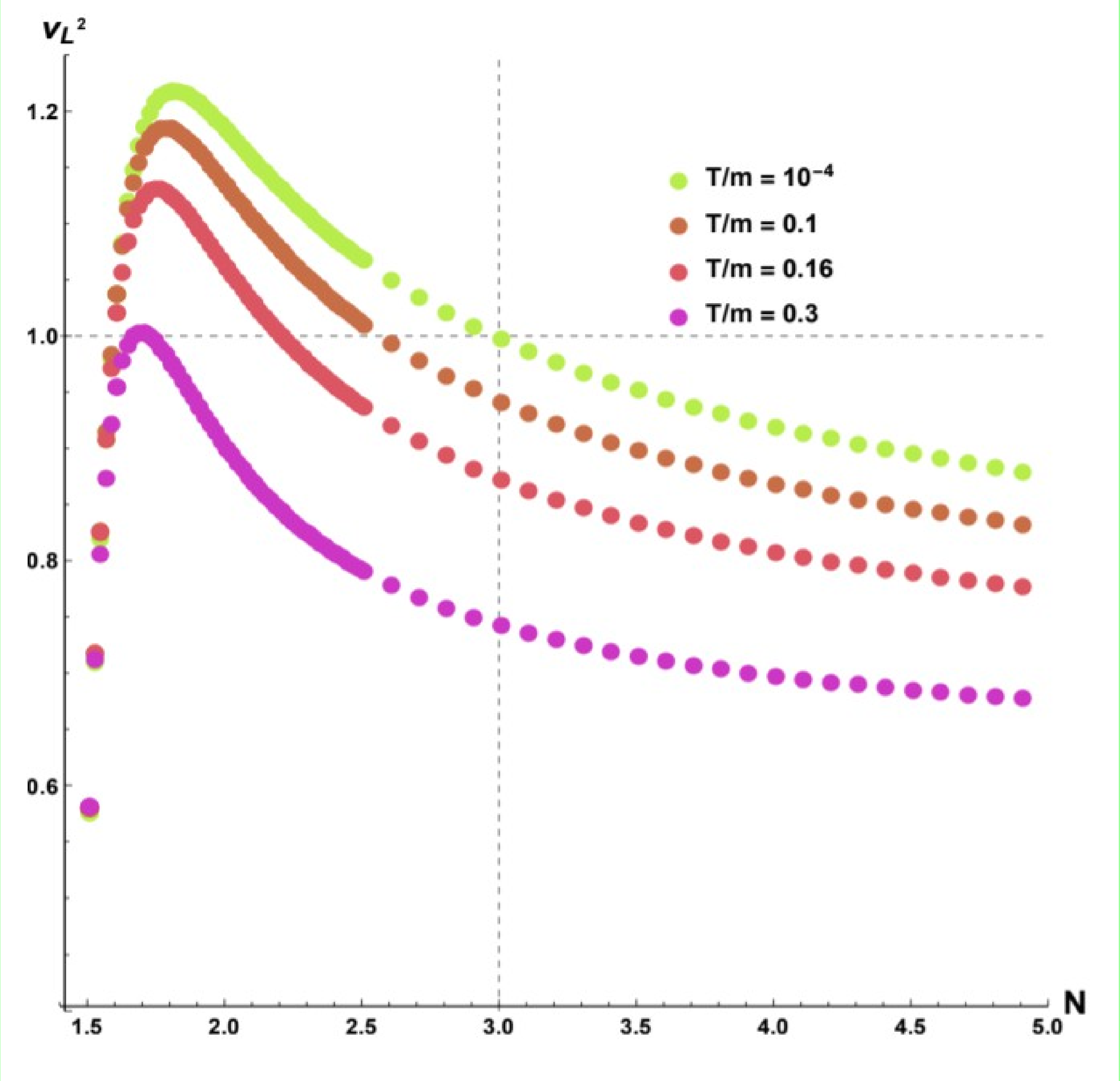
A CONFORMAL SOLID

[Esposito,Garcia-Saenz,Nicolis,Penco, JHEP 2017]

$$v_L^2 = \frac{1}{2} + \frac{G}{\chi_{\pi\pi}}$$

$$v_L^2 \geq \frac{1}{2}$$

HOLOGRAPHIC RESULTS



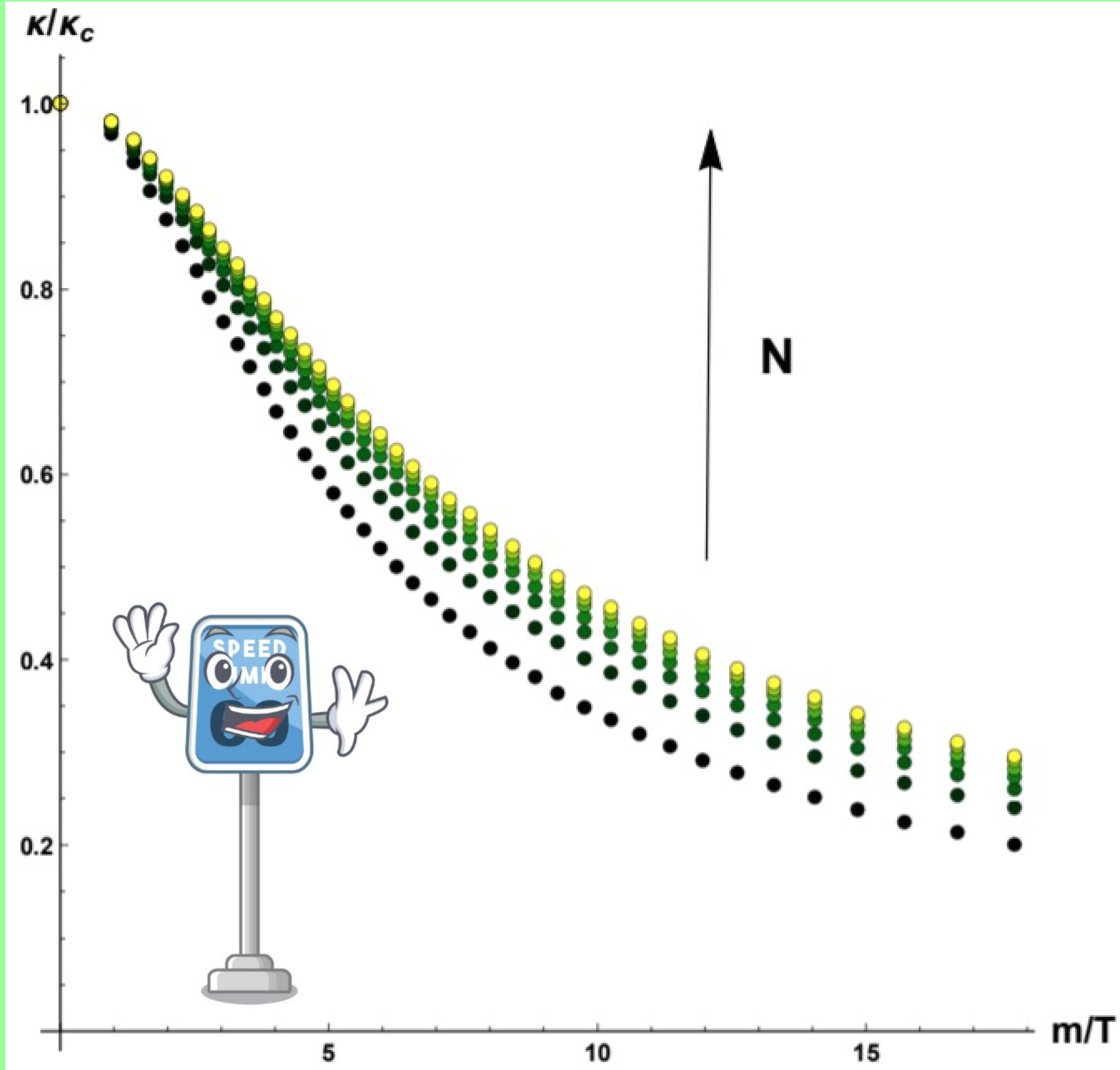
BUT ....

STIFFNESS

$$\kappa \equiv \frac{\partial p}{\partial \epsilon}$$

$$\kappa_c \equiv \frac{1}{d-1}$$

$$\boxed{\kappa \leq \kappa_c}$$



CONCLUSIONS

Forget about $\frac{\eta}{s}$

UNIVERSAL NOTHING

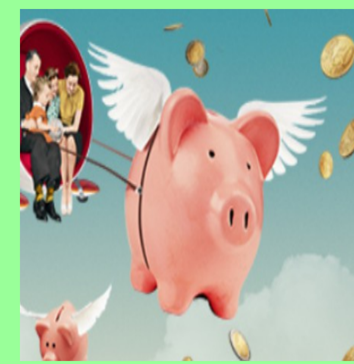
Universality in the Diffusion constants

Evidences from holography and Experimental data (QGP, insulators)

CONCLUSIONS

Upper bound on diffusion from causality
Respected in holographic models

In systems with no UV cutoff there seems to
Be no bound for the speed of sound



What is bounded from above
Is the stiffness !

FUTURE

Electronic thermal conductivity

Solids VS Liquids VS glasses

Standard VS exotic materials

Anisotropy and magnetic field

[See Dimitrios next talk]

4th INTERNATIONAL CONFERENCE
on HOLOGRAPHY, STRING THEORY and DISCRETE APPROACH
in HANOI, VIETNAM

THANKS A LOT
(waiting for next year to visit Vietnam again)