Zwarte gaten als quantum computers en de vreemde materie.

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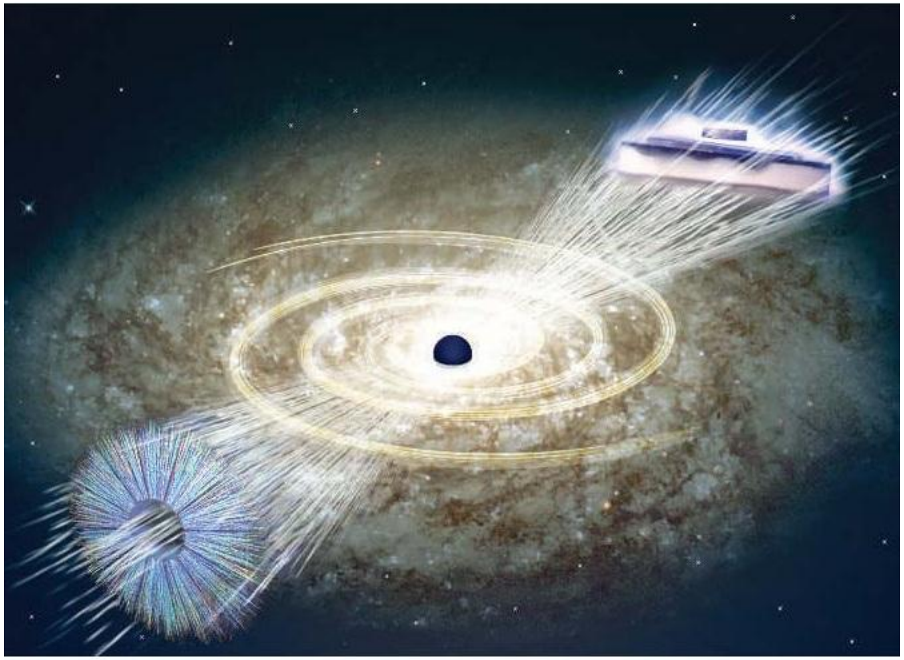
NWO
Netherlands Organisation for Scientific Research



Take home message

Quantum Many body entanglement makes the difference!

The matter explained in physics books (including standard model): "short range entangled product" = ruled by the principles of classical physics on the macroscopic scale.

News

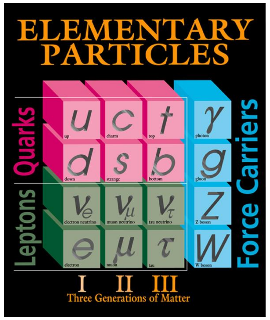
"Quantum supreme matter" = "stuff that quantum computes all by itself", "everything is entangled with everything on the macroscopic scale".

Ruled by "physical laws" of an entirely new kind, believing the black holes …

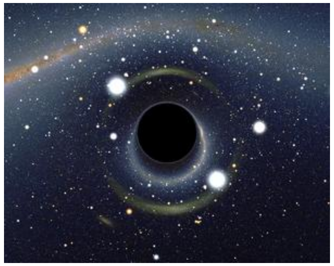
The fruitflies of physics

Boltzmann: Classical matter

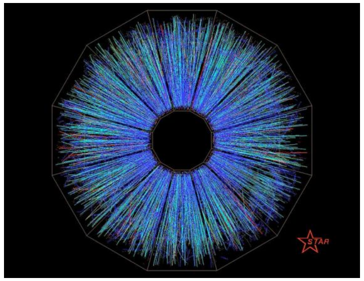
Gas-liquid-solid phases (van der Waals)



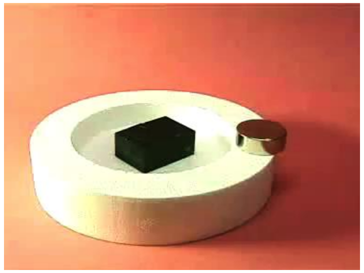
Quantum supreme matter



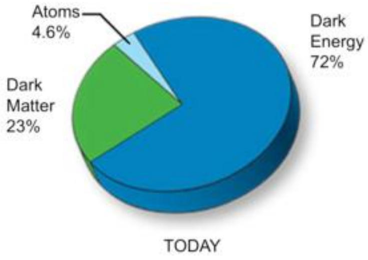
Quark-gluon plasma



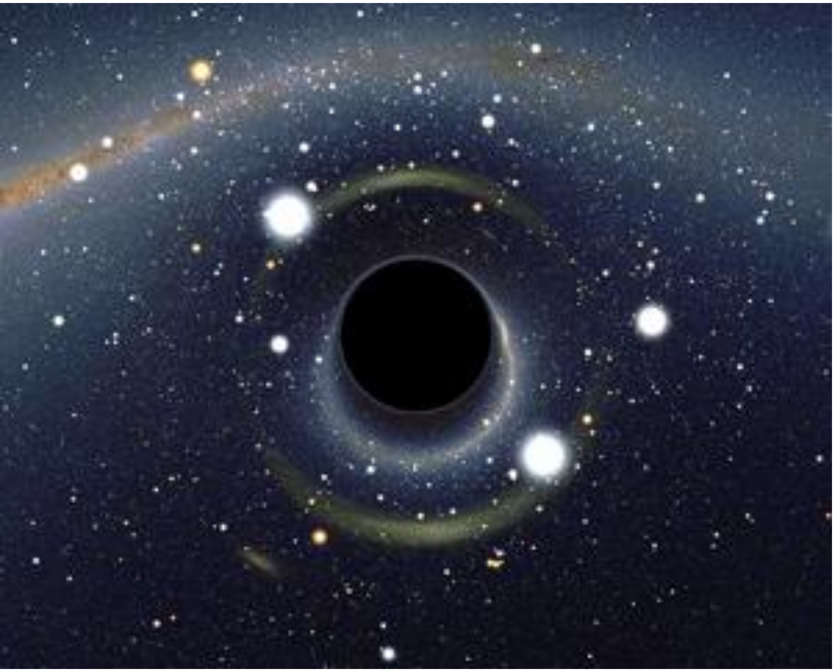
High Tc superconductors



Dark sector??



Black holes as “maximal entanglement” quantum computers” !?



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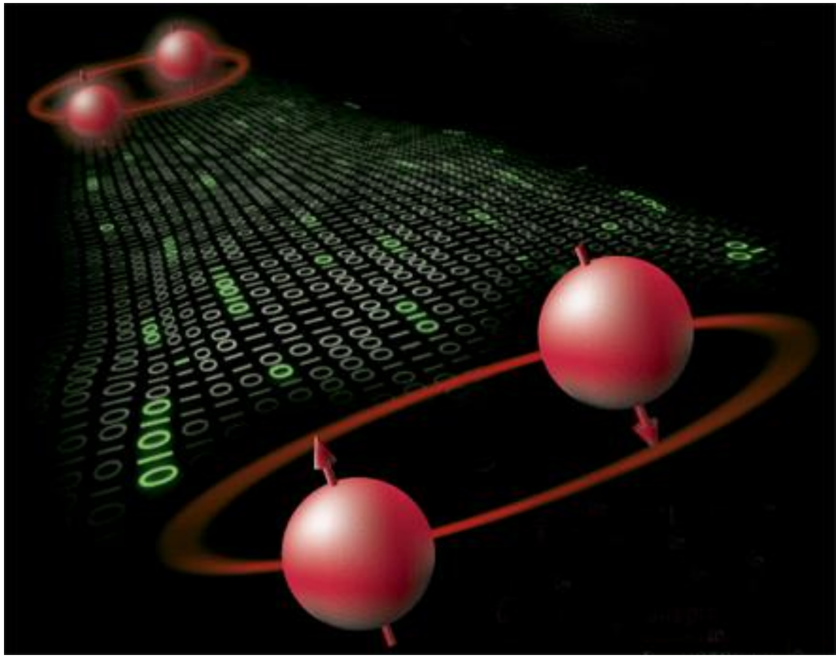


“Natuurkunde is niet moeilijk, het is vooral erg raar”

en het is ook best wel erg veel …

De grens van de Natuurkunde: “Holographische dualiteit”.

Hoe werkt de quantum computer?

Coherent superposition, particle-wave duality, entanglement, NP-hardness, quantum supremacy, short range entangled product states, eigenstate thermalization.

Wat is Gecondenseerde Materie en Quantum Velden Theorie?

Spontane symmetrie breking, BCS theorie =supergeleiding, “semiclassics”: wat is een deeltje? De kritische toestand en de renormalisatie groep, het quark-gluon plasma, hoge Tc supergeleiding, pump-probe spectroscopy.

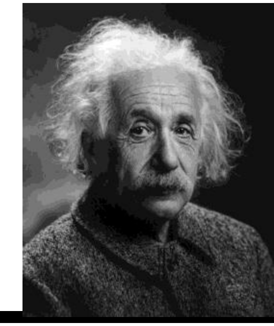
Wie begrijpt Algemene Relativiteit?

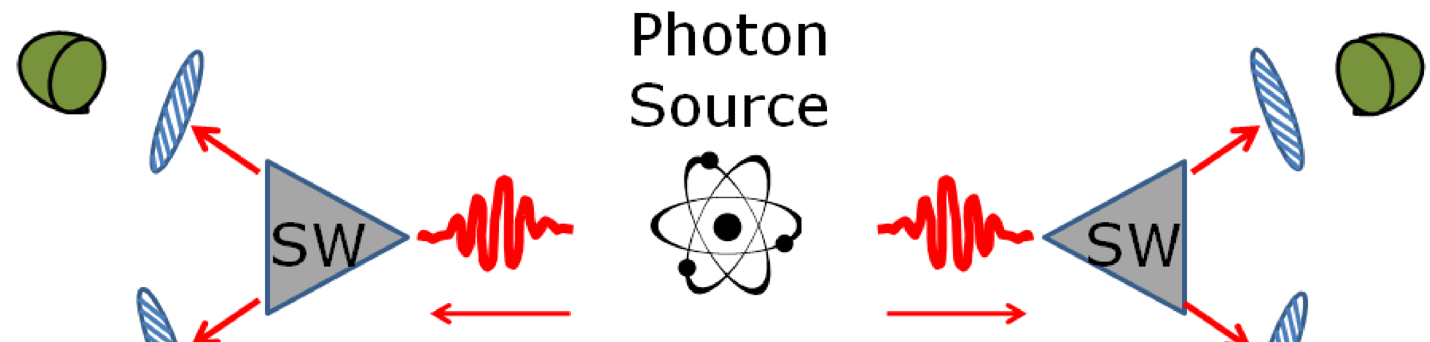
Anti-de-Sitter ruimte, Geodesics, Schwarzschild metriek, Reissner-Nordstrom zwart gat, Hawking straling, Penrose diagram, Vaidya metriek.

Wat is de AdS/CFT correspondentie?

Snaartheorie en quantum zwaartekracht, de tweede snaar revolutie: branes en open-closed string duality, Maldacena, “the boundary is maximally entangled”, AdS/CMT.

“Spooky action on a distance”.





$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle)$$

“Alice” “Bell pair” **“Bob”**

Als Alice 0 (1) meet weet zij dat Bob ook 0 (1) heeft. Dit lijkt sneller dan het licht overdracht van informatie (Einstein) maar dit is dus niet zo …

Many body/bit Hilbert space.

Two qubits: Hilbert space dimension $2^2 = 4$

$$|00\rangle, |01\rangle, |10\rangle, |11\rangle$$

Three qubits: Hilbert space dimension $2^3 = 8$

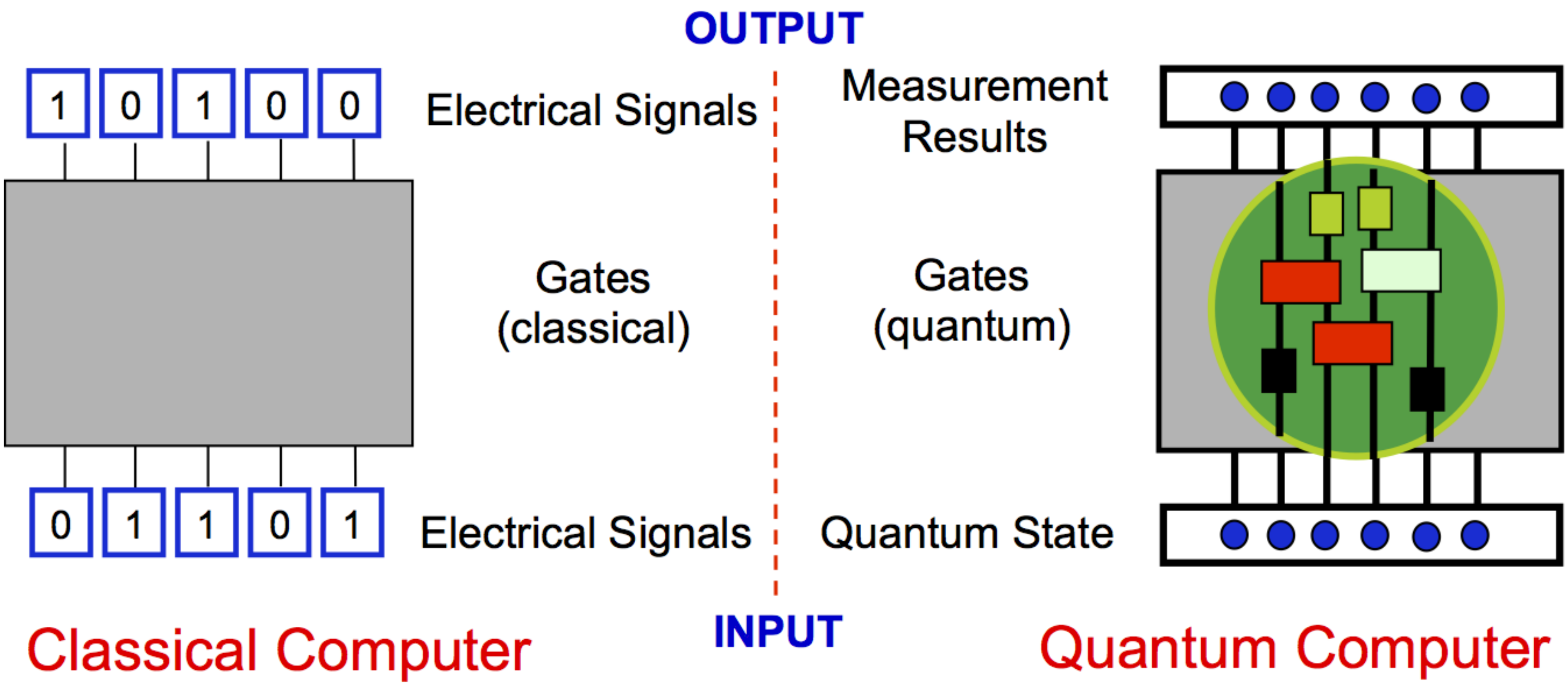
$$|000\rangle, |001\rangle, |010\rangle, |011\rangle, |100\rangle, |101\rangle, |110\rangle, |111\rangle,$$

Physical world 10^{23} "qubits": Hilbert space dimension $2^{10^{23}}$

$$|\Psi_n\rangle = \sum_{config.i} C_i^n |config.i\rangle$$

Overwhelming amount of quantum information.

The supremacy of the quantum computer.



Sequential one- and two bit operations: engineering pursuit based on well understood parts.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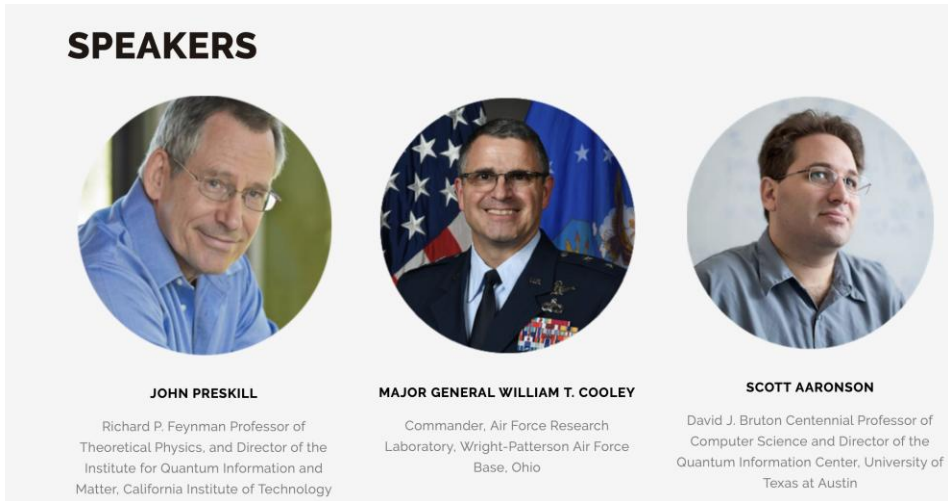
Looking for friends?



"Quantum supremacy": 55 qubits will outperform any classical computer.

Present pitch: it will be good for cancer (quantum chemistry) and sustainable energy (room temperature superconductivity).

Let's use natural occurring quantum computers for benchmarking, "quantum supreme matter".

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Physical world 10^{23} "qubits": Hilbert space dimension $2^{10^{23}}$

$$|\Psi_n\rangle = \sum_{config.i} C_i^n |config.i\rangle$$

Overwhelming amount of quantum information.

"The classical condensates: from crystals to Fermi-liquids."

States of matter that we understand are short ranged entangled product!

$$\left|\Psi_0\left\{\Omega_i\right\}\right\rangle = \Pi_i \hat{X}_i^+\left(\Omega_i\right)\left|vac\right\rangle$$

- Crystals: put atoms in real space wave packets $X_i^+\left(R_i^0\right) \mu\ e^{(R_i^0 - r)\wedge 2 / s^2} y^+\left(r\right)$

- Magnets: put spins in generalized coherent state

$$X_i^+\left(\vec{n}_i\right) \propto e^{i\varphi_i/2}\cos\left(\theta_i/2\right)c_{i\uparrow}^+ + e^{-i\varphi_i/2}\sin\left(\theta_i/2\right)c_{i\downarrow}^+$$

- Superconductors/superfluids: put bosons/Cooper pairs in coherent superposition

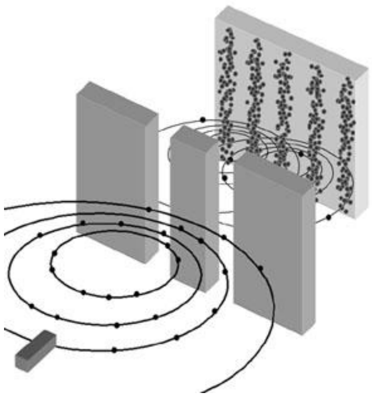
$$X_{k/i}^{\ +}\ \mu\ u_k + v_k c_{k-}^+ c_{-k-}^+, \quad u_i + v_i e^{ij_i} b_i^+$$

- Fermi gas/liquid: product state in momentum space (mod Pauli principle).

$$\left|Y_{FL}\right\rangle = P_k^{k_F} c_k^+\left|vac\right\rangle$$

Entanglement is representation independent.

Particle-wave duality single particle QM:



Momentum:

$$\hat{p}|p\rangle = p|p\rangle$$

Position:

$$\hat{x}|x\rangle = x|x\rangle$$

$$|p\rangle = \int dx \langle x|p\rangle |x\rangle = \int dx e^{ikx}|x\rangle$$

Is $\frac{1}{2}(|0\rangle|0\rangle + |0\rangle|1\rangle + |1\rangle|0\rangle + |1\rangle|1\rangle)$ entangled?

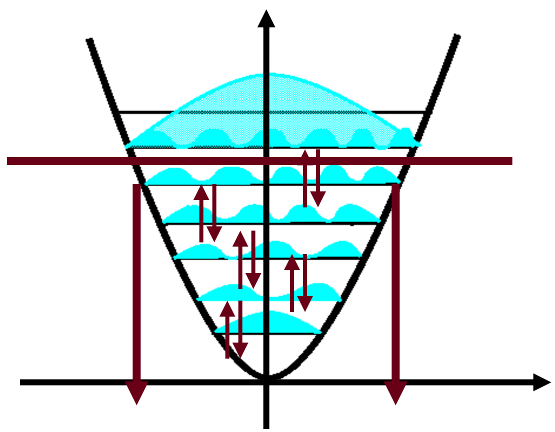
Change representation: $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$

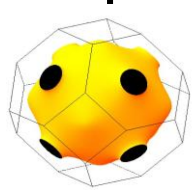
$|+\rangle|+\rangle = \frac{1}{2}(|0\rangle|0\rangle + |0\rangle|1\rangle + |1\rangle|0\rangle + |1\rangle|1\rangle)$ Unentangled product!

Bell pairs = maximally entangled: $\frac{1}{\sqrt{2}}(|0\rangle|0\rangle \pm |1\rangle|1\rangle)$ $\frac{1}{\sqrt{2}}(|0\rangle|1\rangle \pm |1\rangle|0\rangle)$

The conventional quantum fluids: SRE in momentum space.

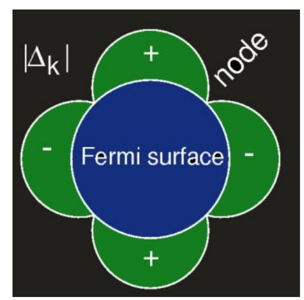
Fermiology

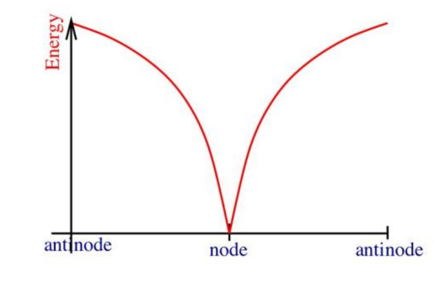




BCS superconductivity

$$\Psi_{BCS} = \Pi_k \left(u_k + v_k c^{+}_{k-} c^{+}_{-k-}\right) \left|vac.\right\rangle$$

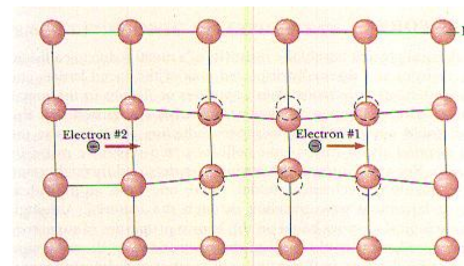




BCS theory: fermions turning into bosons (1957)

Bardeen Cooper Schrieffer

Fermi-liquid + attractive interaction

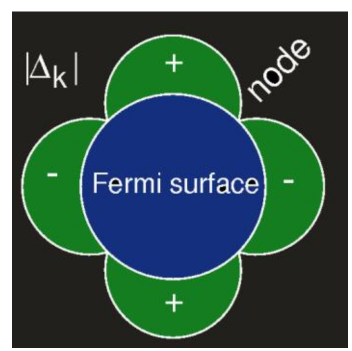


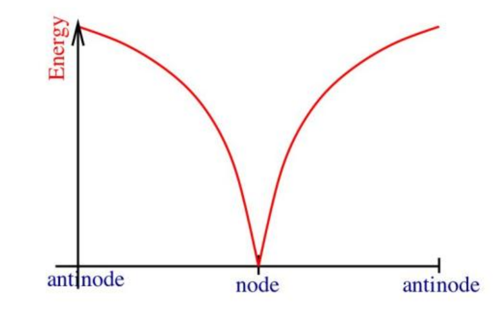
Quasiparticles pair and Bose condense:

Ground state

$$Y_{BCS} = P_k \left(u_k + v_k c^{+}_{k-} c^{+}_{-k-}\right) \left|vac.\right\rangle$$

D-wave SC: Dirac spectrum

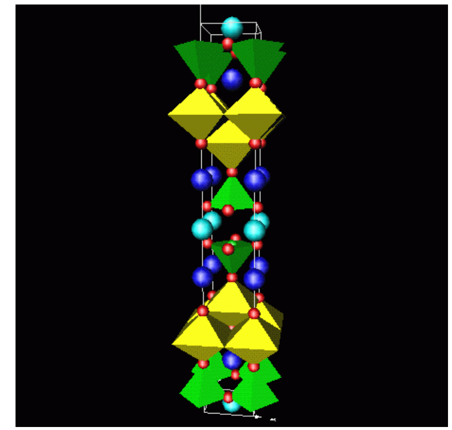


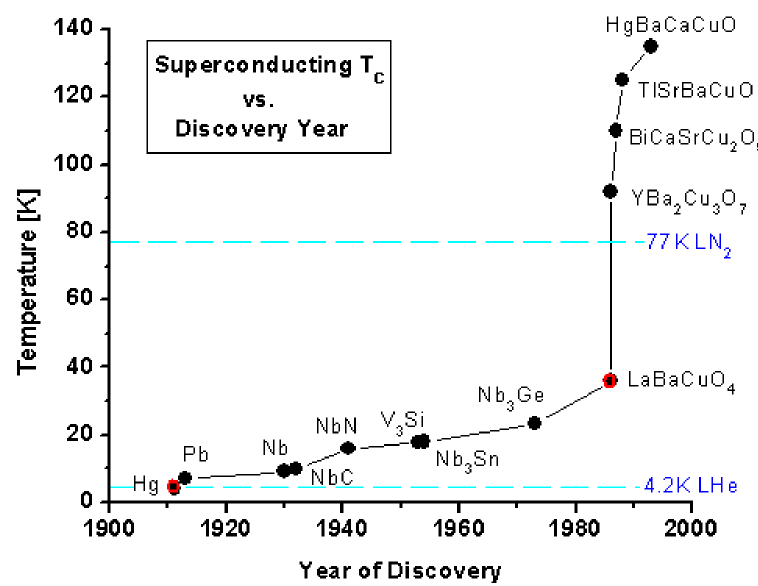


High Tc superconductivity (1986)

Mueller **Bednorz**

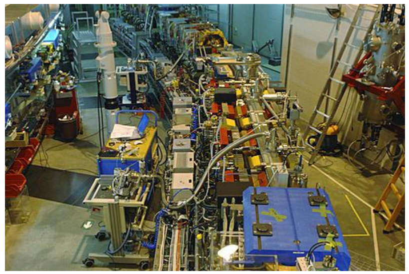
Ceramic CuO’s, likeYBa2Cu3O7

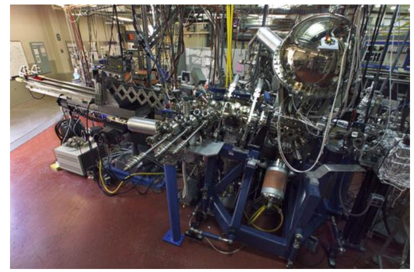


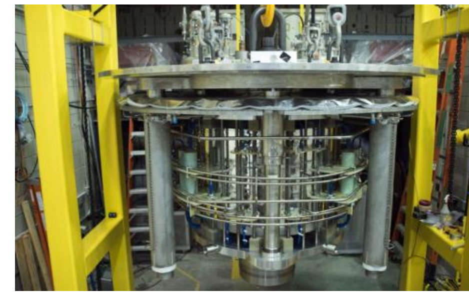


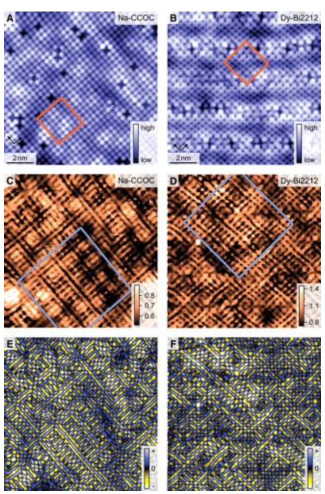
Superconductivity jumps to ‘high’ temperatures

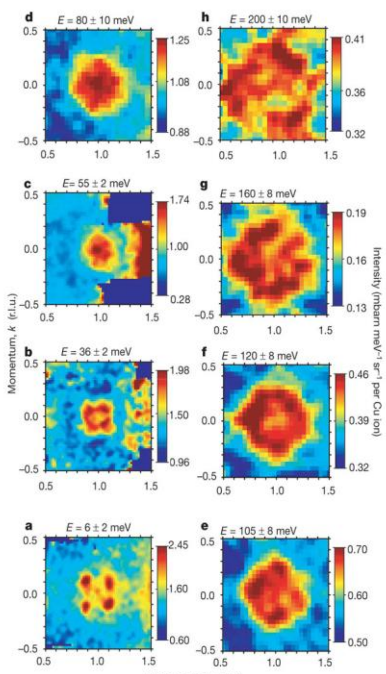
New telescopes for quantum matter

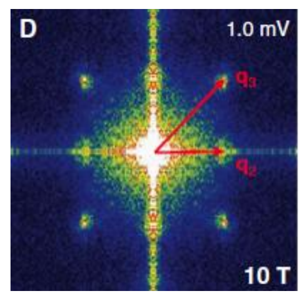


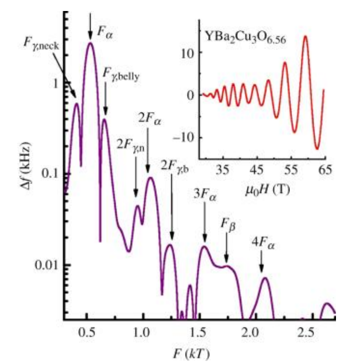


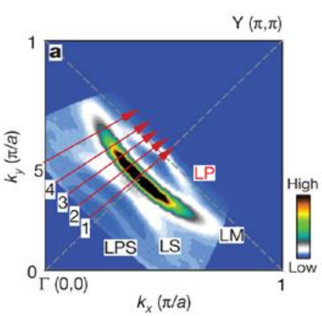


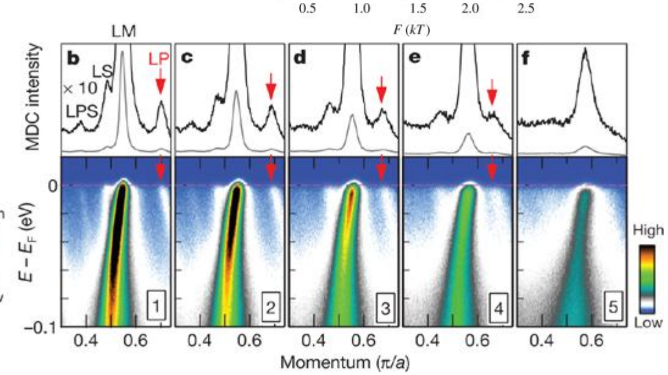












What is a “particle”?

E.g. transversal field Ising model: $$H = -J \sum_{<ij>} \sigma_i^z \sigma_j^z + B \sum_i (\sigma_i^+ + \sigma_i^-)$$

↑ ↑ ↑ ↑ ↑ ↑ ↑ **J << B: product state vacuum**

↑ ↑ ↑ ↓ ↑ ↑ ↑ **Excitation = inject quantum number(s) (S=1)**

↑ ↑ ↑ ↑ ↓ ↑ ↑ **“Particle” delocalizes:** $$G = \frac{1}{\varepsilon_k - \omega}$$

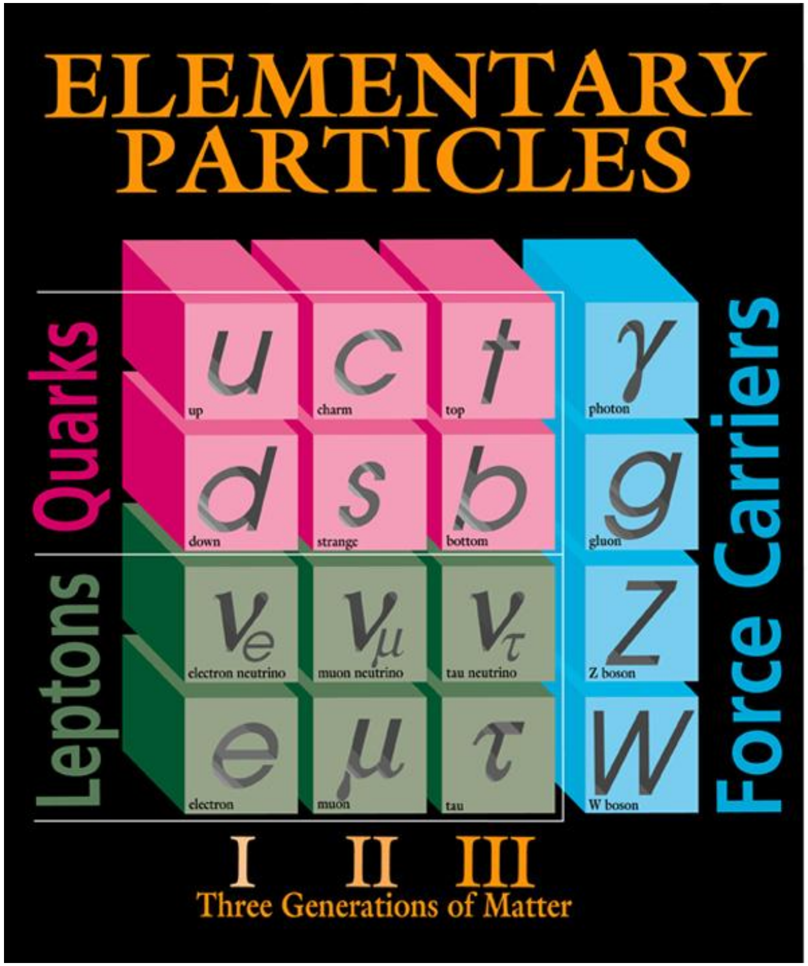
$$A(k, \omega) = Im\; G = \delta(\varepsilon_k - \omega)$$

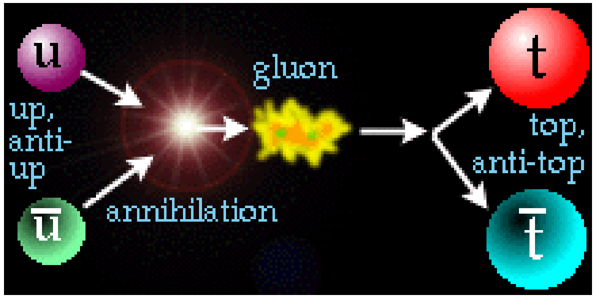
↑ ↓ ↓ ↑ ↓ ↑ ↑ **J < B, SRE product state = perturbative corrections:**

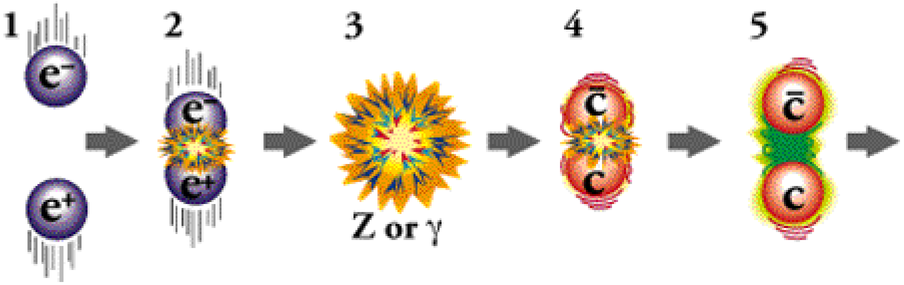
$$|\Psi_0\rangle = A|product\rangle + \sum_i a_i |config, i\rangle \qquad G = \frac{1}{\varepsilon_k - \omega + \Sigma(\omega, k)}$$

“Good” self-energy, at the bottom of the spectrum: $$G = \frac{A^2}{\hat{\varepsilon}_k - \omega} + G_{incoh}$$

Elementary particles = semiclassics.







Quantum supreme matter and unparticle physics.

Given: The vacuum state is infinite party entangled

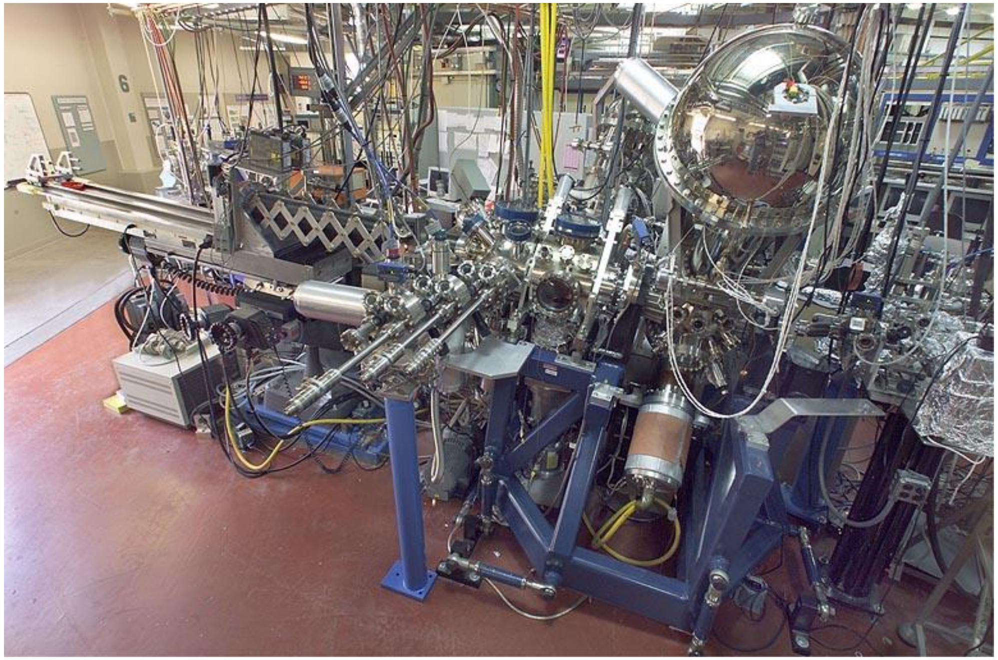
$$|\Psi\rangle = \sum_{configs} A_{configs} |configs\rangle$$

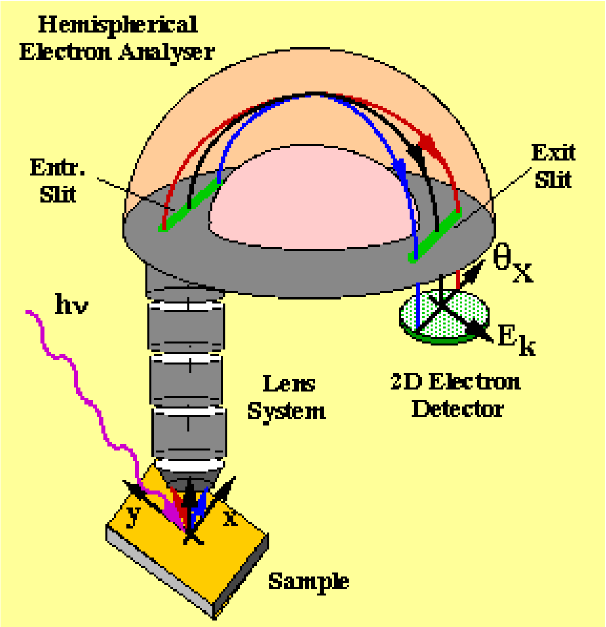
Inject a quantum-number: this information is now "dispersed" in the whole 2^N many body Hilbert space.

The quantum info is no longer "localizable": there are no particle poles in the spectrum.

Spectral functions are fully incoherent: "unparticle physics" as quantum matter diagnostic!

Anugular Resolved Photoemission: the fermionic precision telescope.

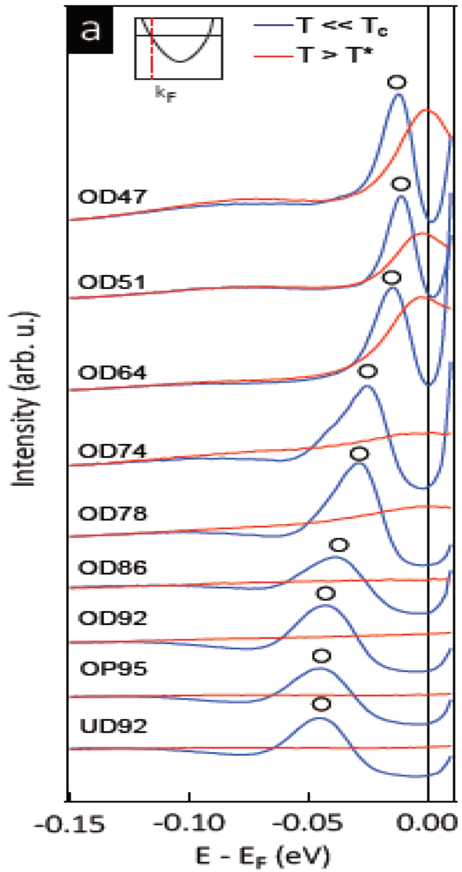




Measures the electron spectral function: the probability to remove an electron at a given energy and momentum (Kelvin energy and 10 nm spatial resolution).

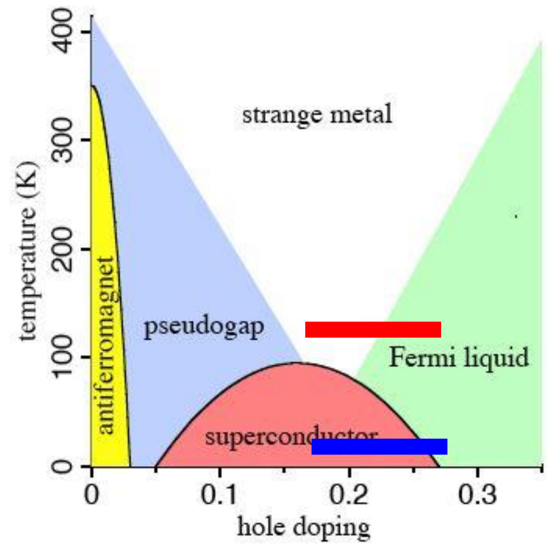
Unparticle physics in high Tc superconductors.

Photoemission spectra at antinodes:



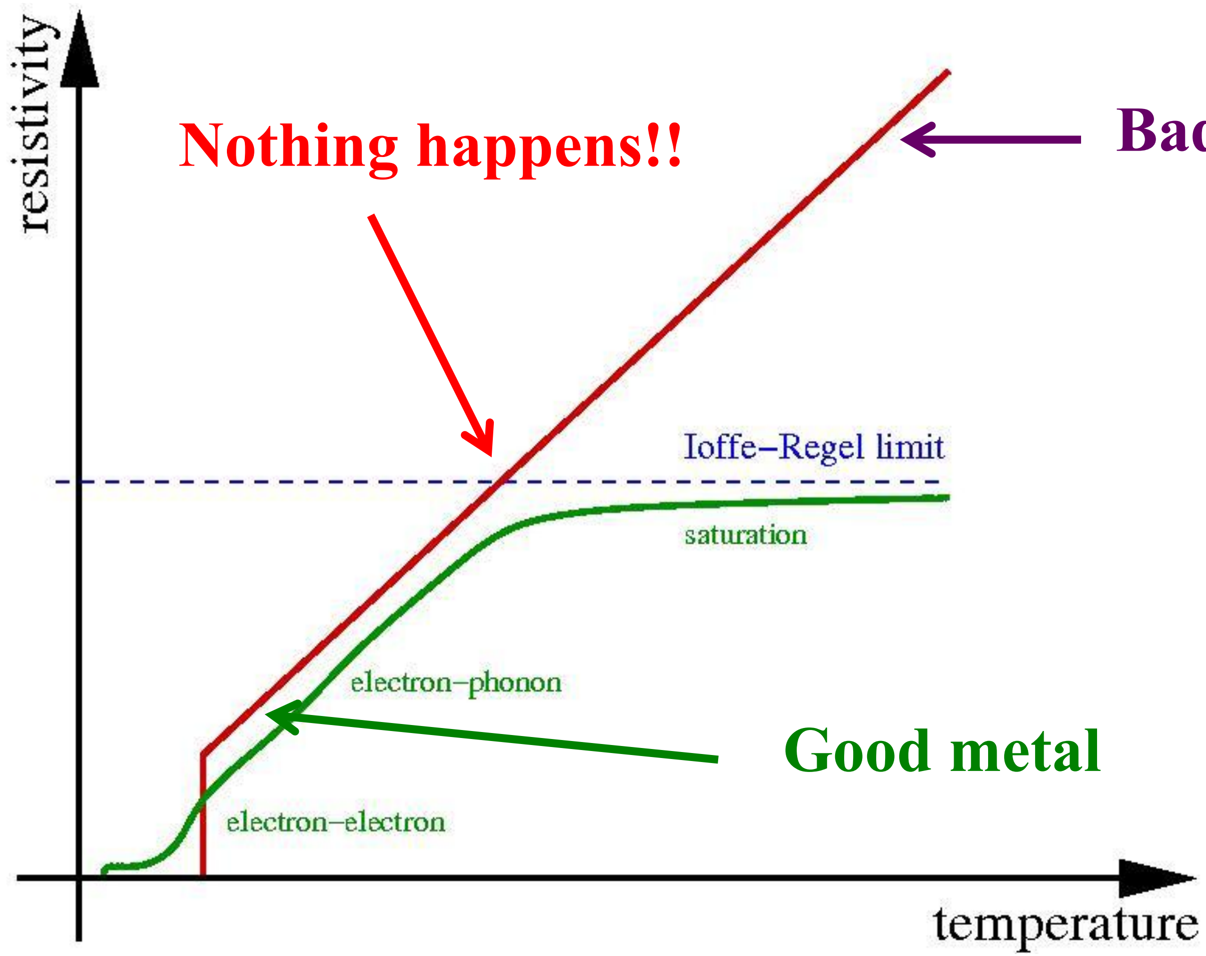
Blue: Bogoliubov quasiparticles deep in the superconducting state.

Red: birth of Fermi-liquid quasiparticles in the normal state



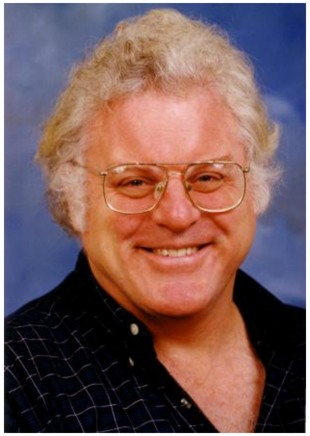
Shen group Stanford: Science 362, 62 (2018)

Divine resistivity



Laughlin's linear resistivity criterium.

" The linear resistivity reflects an extremely simple behavior and extremely simple behaviors in physics need a powerful principle for their protection. Explain this principle."



My answer: universal principle rooted in quantum supremacy.

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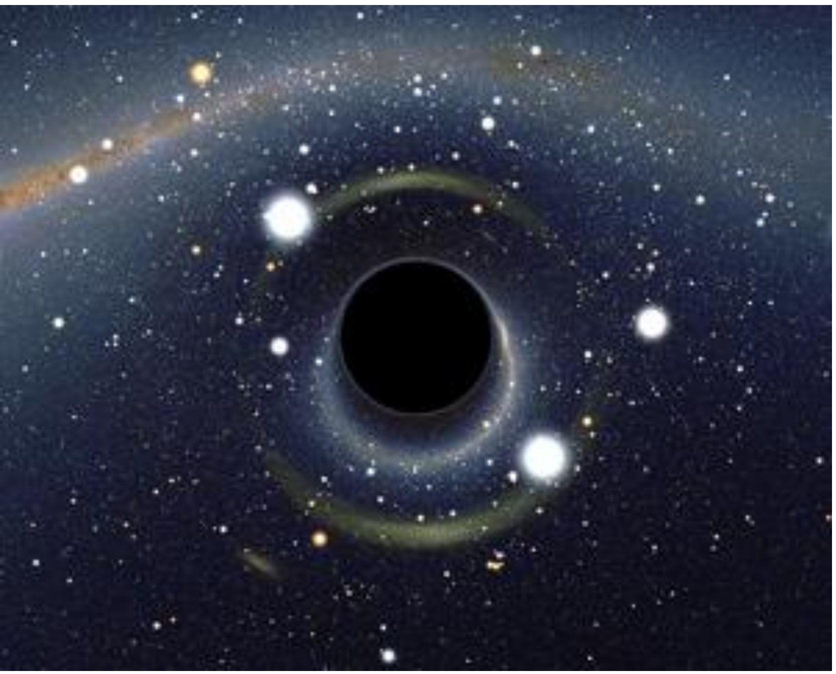

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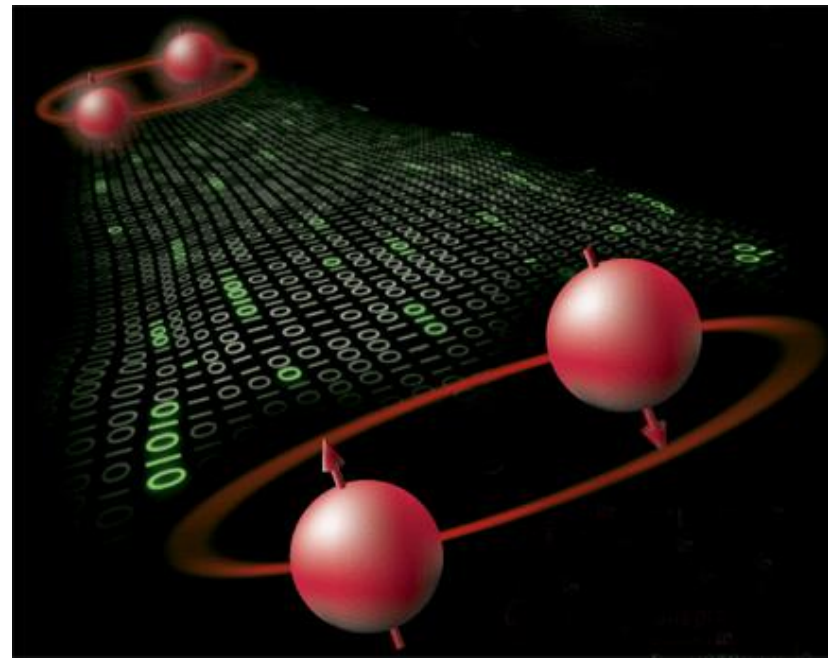
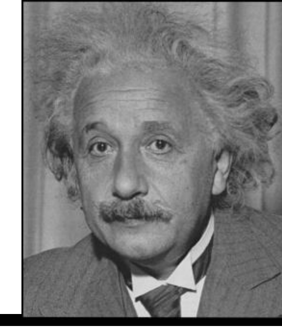
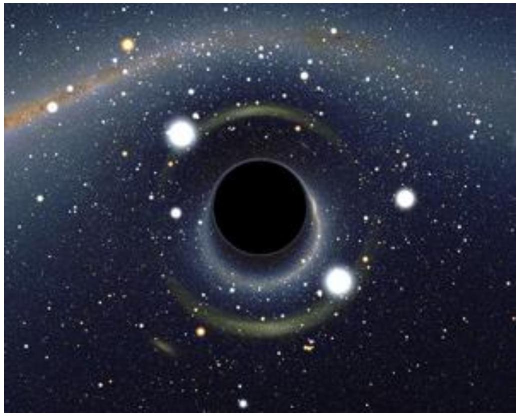


Einstein

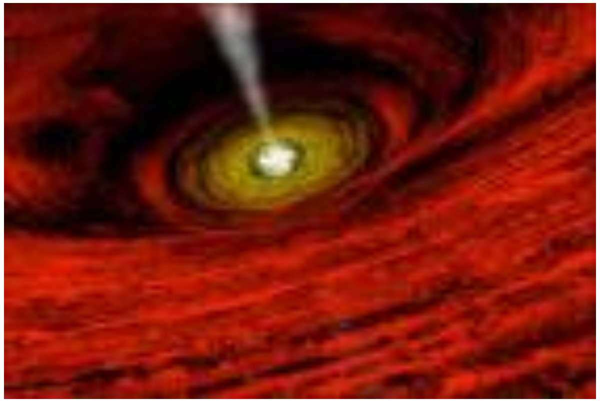


Einstein equations (theory of general relativity):

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

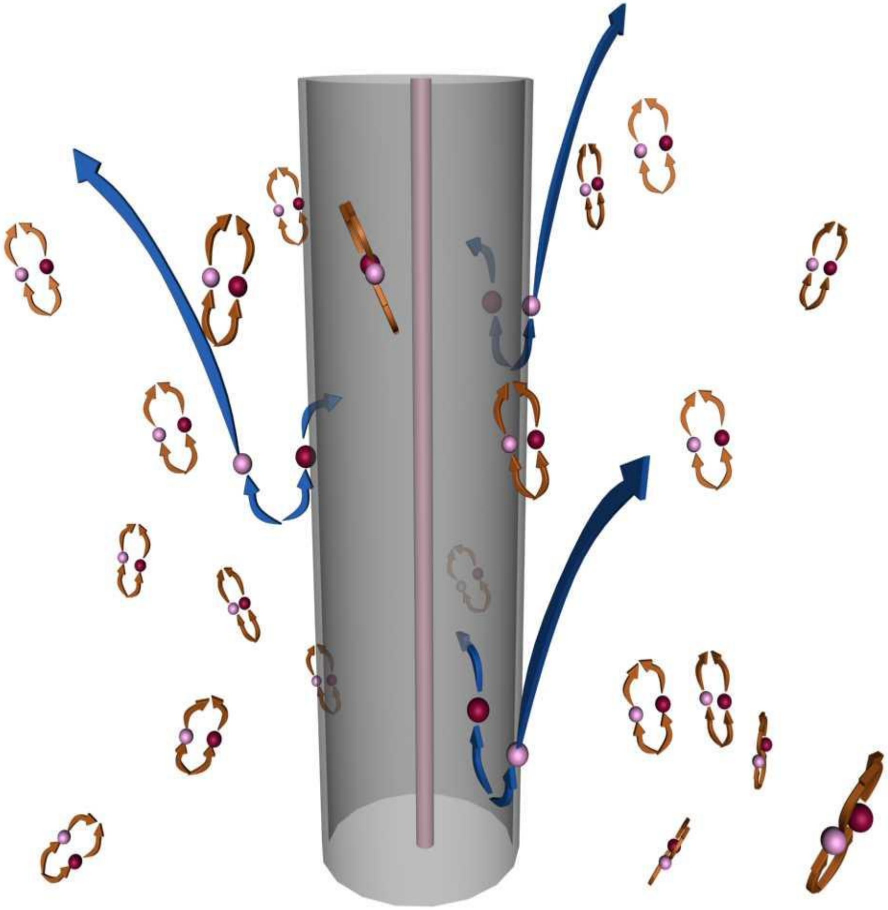


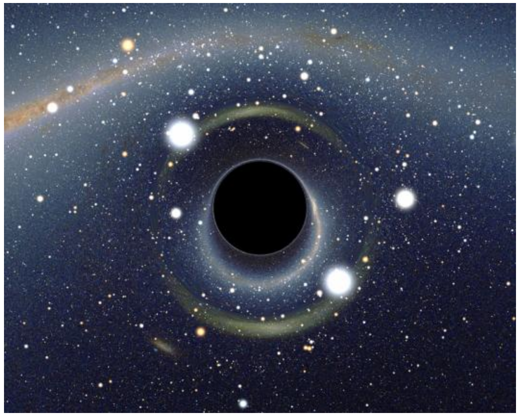
Space time as 'fabric'



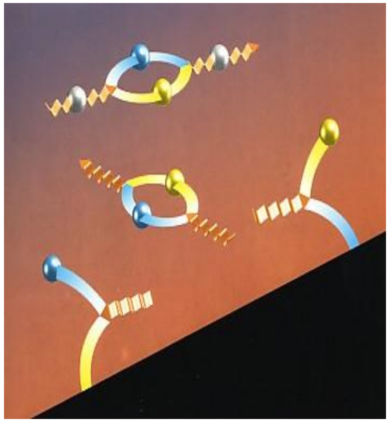
Matter and energy

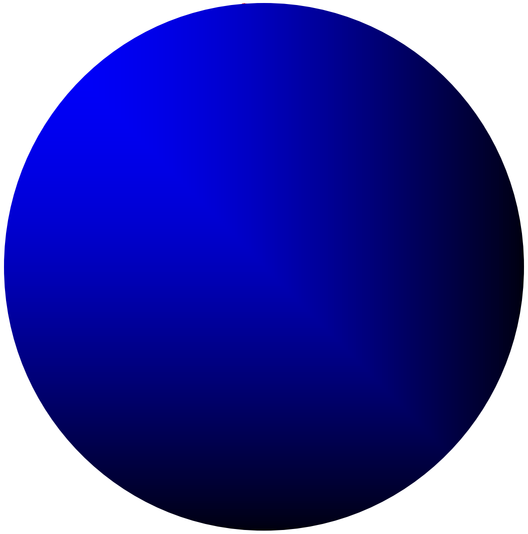
Hawking radiation: space-time turns into material stuff …





‘t Hooft - Susskind holographic principle





Hawking Temperature: $$T = \frac{\hbar g}{2\pi k c}$$

g = acceleration at horizon

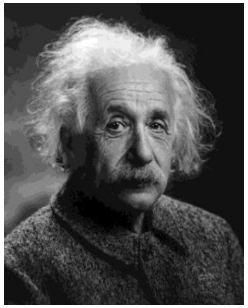
BH entropy: $$S = \frac{k c^3 A}{4\hbar G}$$

***A* = area of horizon**

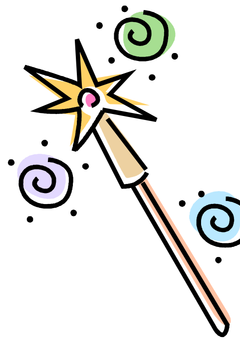
Number of degrees of freedom (field theory) scales with the area and not with the volume (gravity)

General relativity “=“ quantum field theory

General relativity

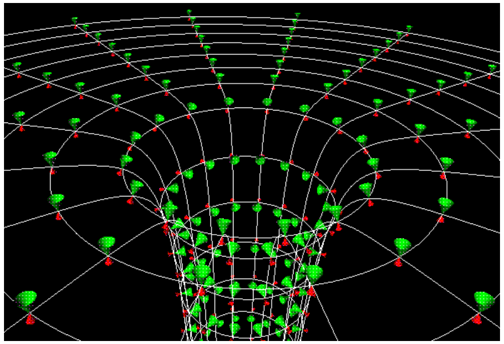


‘AdS/CFT’



Maldacena 1997

Quantum fields



=

General Relativity = Renormalization Group

Extra radial dimension of the bulk <=> **scaling "dimension" in the field theory**

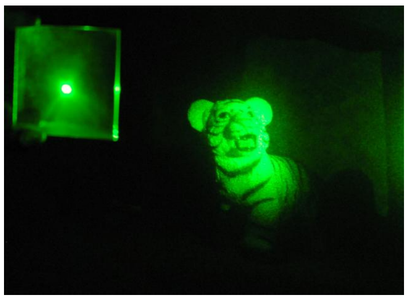
Bulk AdS geometry = **scale invariance of the field theory**

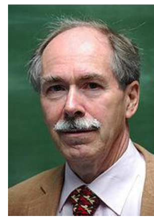
$$dr^2 = -F(r)dt^2 + \frac{dr^2}{F(r)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$F(r) = -\Lambda r^2 + 1, \qquad \Lambda < 0$$

Holographic gauge-gravity duality

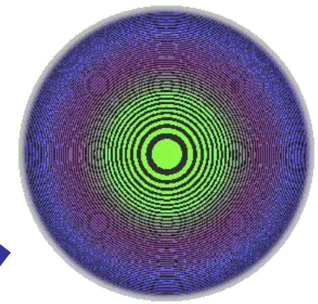
Einstein Universe "AdS"



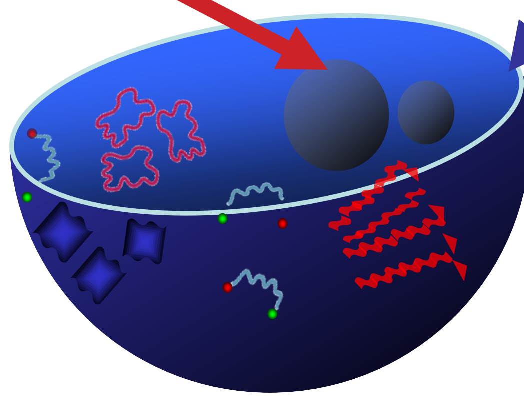


't Hooft-Susskind holographic principle

Quantum field world "CFT"

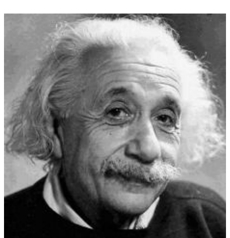


Classical general relativity



Extremely strongly entangled quantum matter

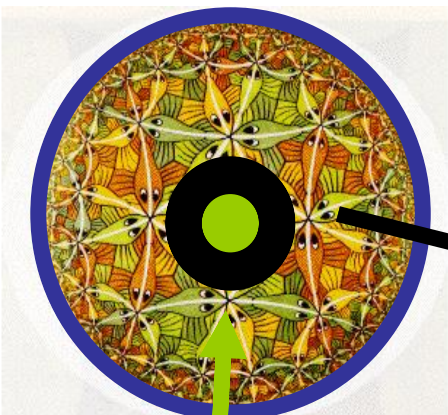
Uniqueness of GR solutions

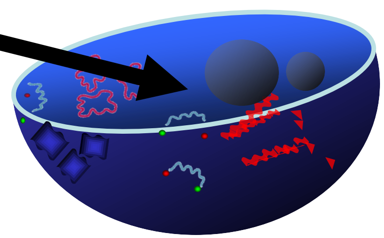


"Generating functional of matter emergence principle"

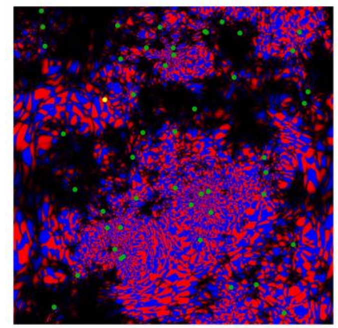
The charged back hole encoding for finite density (2008 - ????)

Anti de Sitter universe.



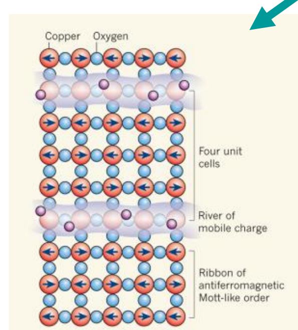


Finite density quantum matter:

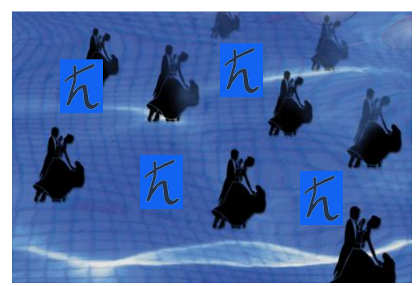


Holographic strange metals

Charged black hole in the middle



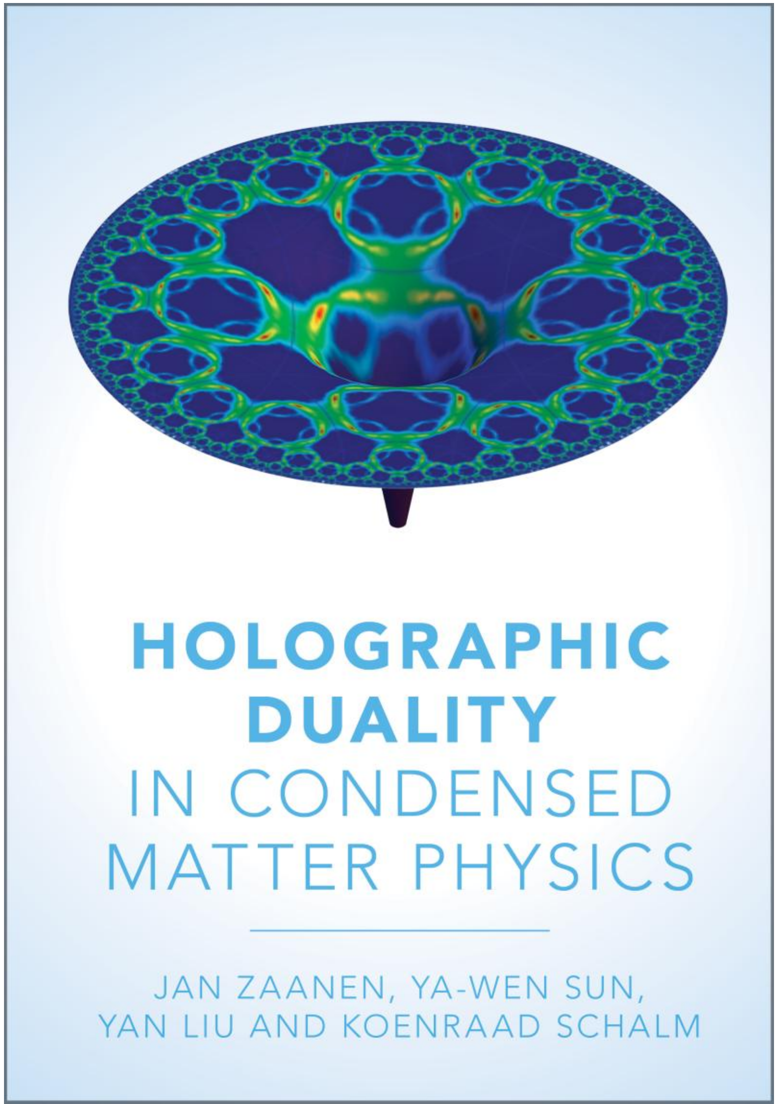
Stripy pseudogap orders



High Tc superconductors

Emergent Fermi liquids

It is 600 pages …



Cambridge University Press

USD 75 at Amazone ...

Holography inspired questions to the CM quantum computer.

“Unparticle physics”: dense entanglement excludes particle poles in the spectrum, the incoherence smoking gun.

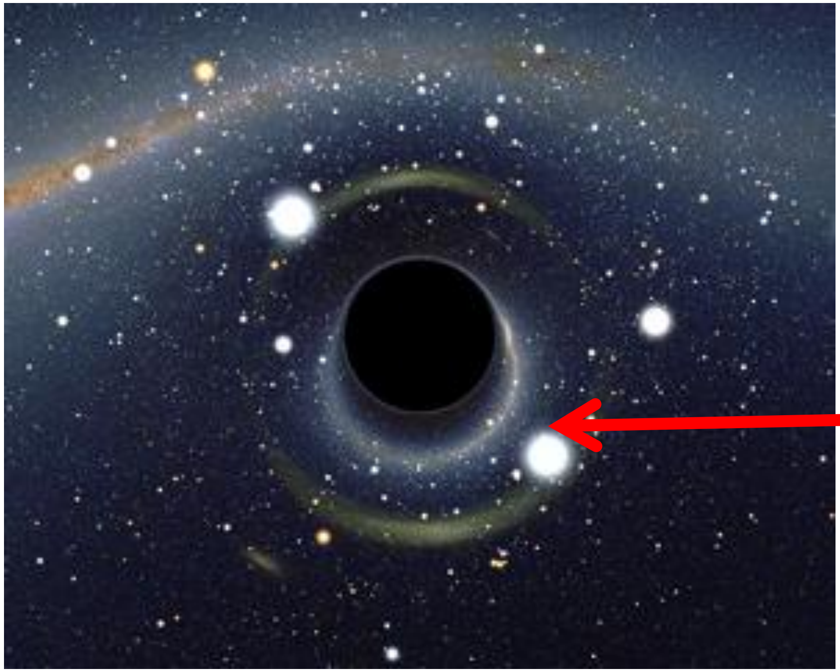
The strange metals as densely entangled generalizations of the Fermi-liquid: the “co-variant” scaling laws.

“Generalized BCS”: the instabilities of the strange metal, intertwined order and why Tc is high.

Non-equilibrium: ETH and the ultrafast thermalization.

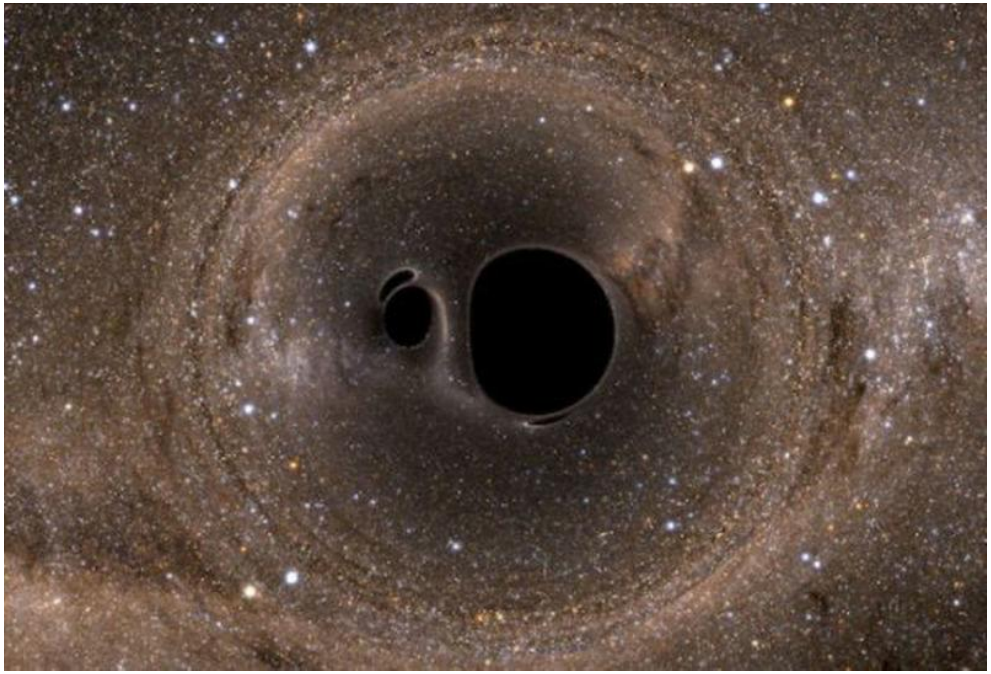
Transport: hydrodynamical flows and Planckian dissipation.

Black holes with dreadlocks.



Pressing the GR frontiers: the most general form of black hole hair in AdS ….

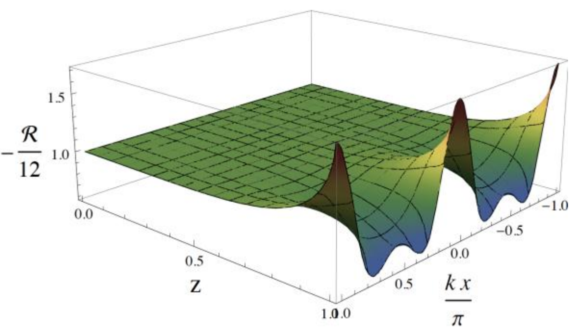
Numerical GR: black hole merger.



No symmetry (isometry), strong fields, relativistic: unleashes all of GR, since 2005 possible to compute numerically.

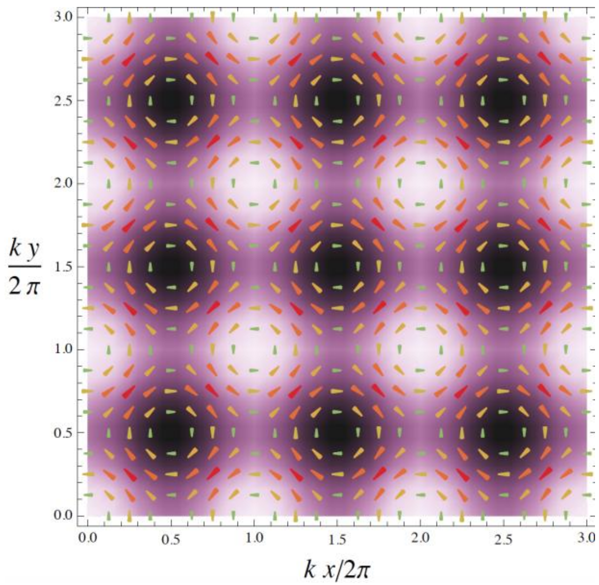
Complex horizons: intertwined charge-current-parity-SC order.

Rong-Gen Cai, Li Li, Yong-Qiang Wang, JZ, PRL 119, 181601 (2017), arXiv:1706.01470

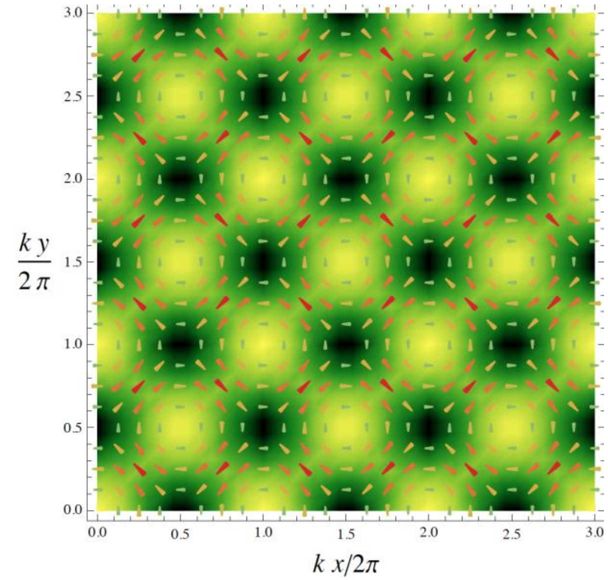


Black-hole hair, rasta style …

Charge and currents



Superconductivity



Charge order intertwined with parity breaking, spontaneous currents and pair density wave order.

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Many body/bit Hilbert space.

Two qubits: Hilbert space dimension $2^2 = 4$

$$|00\rangle, |01\rangle, |10\rangle, |11\rangle$$

Three qubits: Hilbert space dimension $2^3 = 8$

$$|000\rangle, |001\rangle, |010\rangle, |011\rangle, |100\rangle, |101\rangle, |110\rangle, |111\rangle,$$

Physical world 10^{23} "qubits": Hilbert space dimension $2^{10^{23}}$

$$|\Psi_n\rangle = \sum_{config.i} C_i^n |config.i\rangle$$

Overwhelming amount of quantum information.

Eigenstate Thermalization hypothesis (Srednicki, Deutscher, 90's)

"Any local observer gets overwhelmed by the enormous amount of quantum info in the physical world to such an extent that he/she does not know better than that everything becomes a thermal state at long times."

Precise formulation:

$$|\Psi(0)\rangle = \sum_n c_n |E_n\rangle$$

$$|\Psi(t)\rangle = \sum_n c_n e^{-iE_n t/\hbar} |E_n\rangle$$

$$\langle \Psi(t)|A|\Psi(t)\rangle = \sum_{n,n'} c_n c_{n'} e^{-i(E_{n'}-E_n)t/\hbar} A_{n,n'} \to Tr\left[\rho_T A\right]$$

$$\rho_T = \sum e^{-E_n/(k_B T)} |E_n\rangle\langle E_n|$$

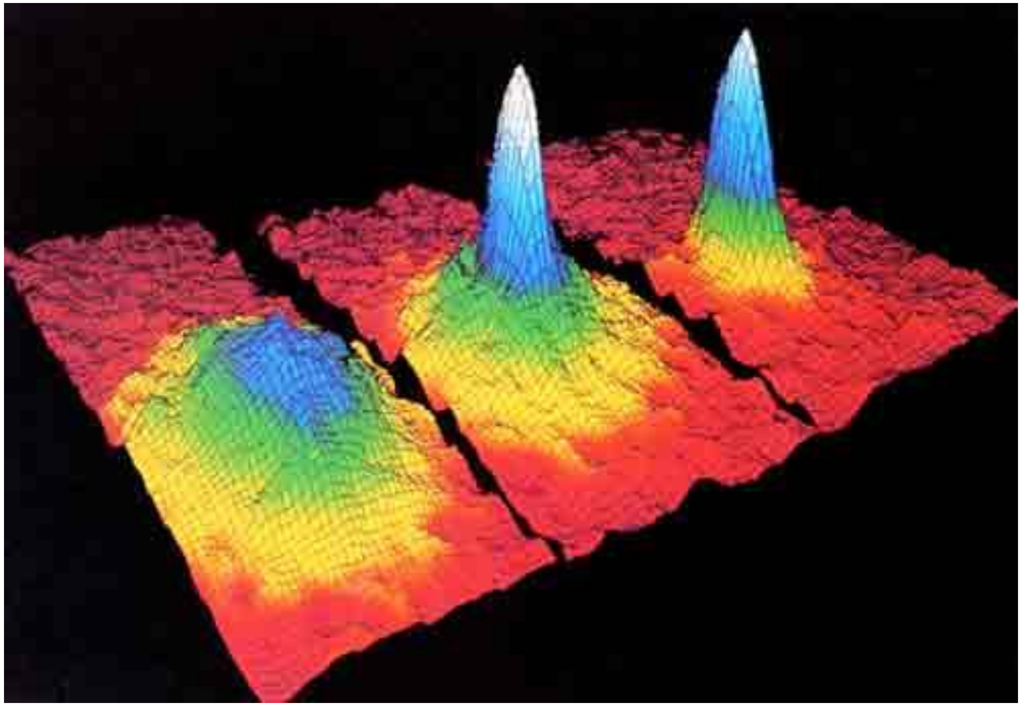
We keep moving because of hbar ..

$$\rho_T = \sum_n e^{-E_n/(k_B T)} |E_n\rangle\langle E_n|$$

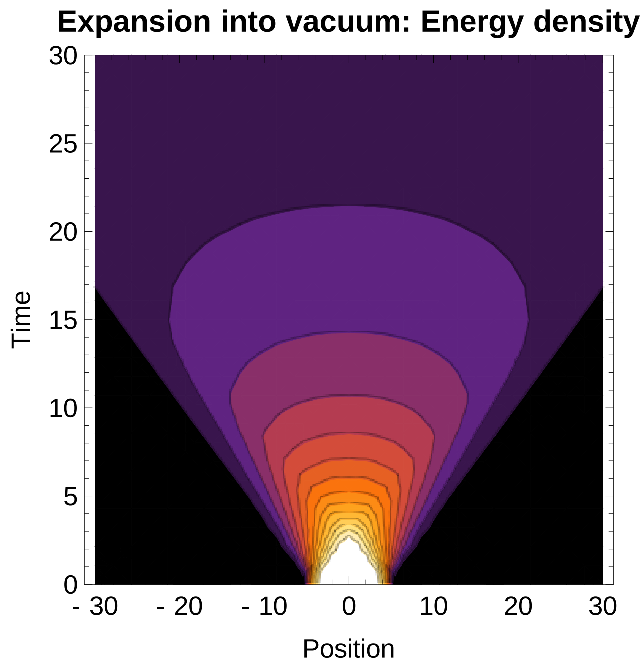
But every highy excited energy state is a hugely entangled "quantum-field computer" !? The thermal world of humans falls prey to the ultimate information overload!

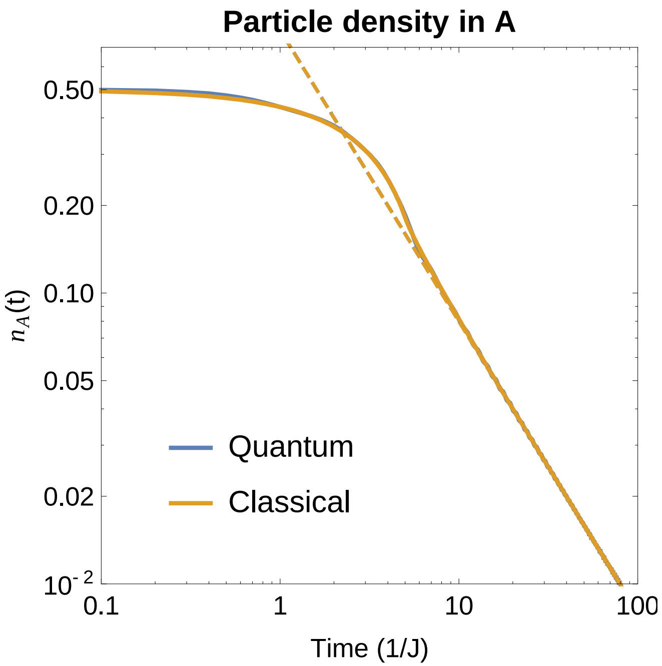
Quantum thermalization and the expansion of atomic clouds…

Louk Rademaker, JZ, Scientific Reports 7, 6118 (2017) (arXiv:1703.02489)



Expansion and the initial momentum distribution.





Louk's tric: evolve the modular hamiltonian …

Modular Hamiltonian is the log of the density matrix: $\mathcal{M} = -\log \rho.$

Initial density matrix: "A" = reservoir, "B" = bath $\rho_0 = \frac{1}{Z_A Z_B} e^{-\beta_A \mathcal{H}_A} \otimes e^{-\beta_B \mathcal{H}_B}$

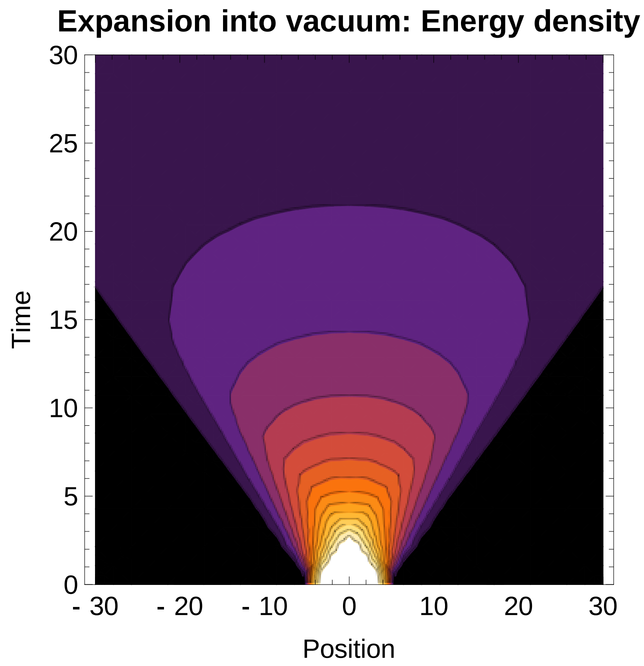
Time evolution: $\mathcal{M}(t) = e^{-i\mathcal{H}t} \mathcal{M}_0 e^{i\mathcal{H}t}.$ Free system: $\mathcal{H} = \sum_k \xi_k n_k$

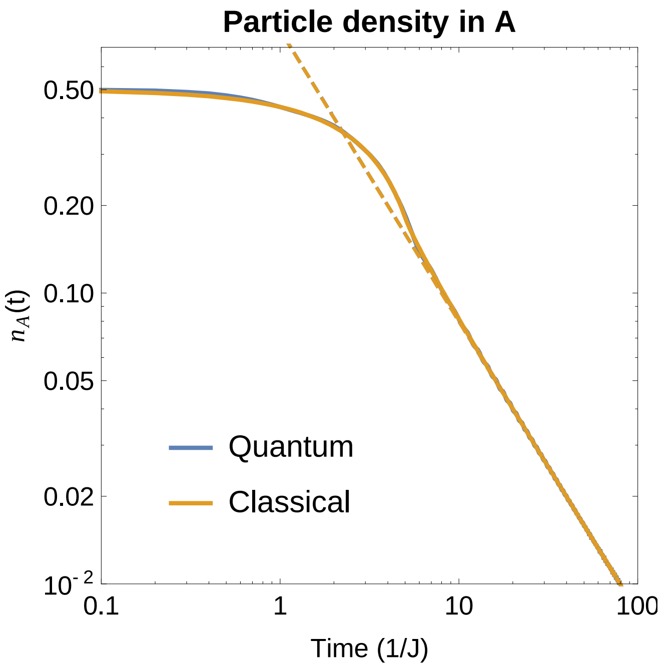
General form: $\mathcal{M}(t) = \sum_{kk'} m_{kk'}(t)\ \hat{c}_k^\dagger \hat{c}_{k'} + \log Z$

$$m_{jl}(t) = \beta_B \delta_{|j-l|=1} + (\beta_A - \beta_B) \int \frac{d^d\mathbf{k} d^d\mathbf{k}'}{(2\pi)^{2d}} e^{-i\mathbf{k}\mathbf{r}_j + i\mathbf{k}'\mathbf{r}_l} \left(\sum_{i=1}^{d} e^{ik_i} + e^{-ik_i'} \right) \left(\prod_{i=1}^{d} \frac{e^{i(k_i - k_i')(L_A - 1)} - 1}{e^{i(k_i - k_i')} - 1} \right) e^{i(\epsilon_{\mathbf{k}} - \epsilon_{\mathbf{k}'})\,t}$$

Observables: $G_{ij}(t) = \mathrm{Tr}\left[\ \hat{c}_i^\dagger \hat{c}_j \rho(t)\right]$ $\hat{G}(t) = \left[e^{\hat{m}(t)} - \eta\right]^{-1}.$

Expansion and the initial momentum distribution.



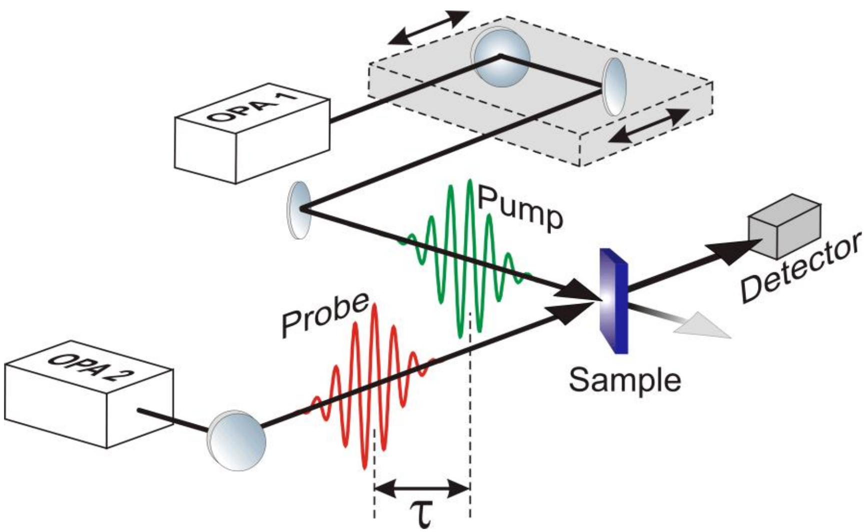


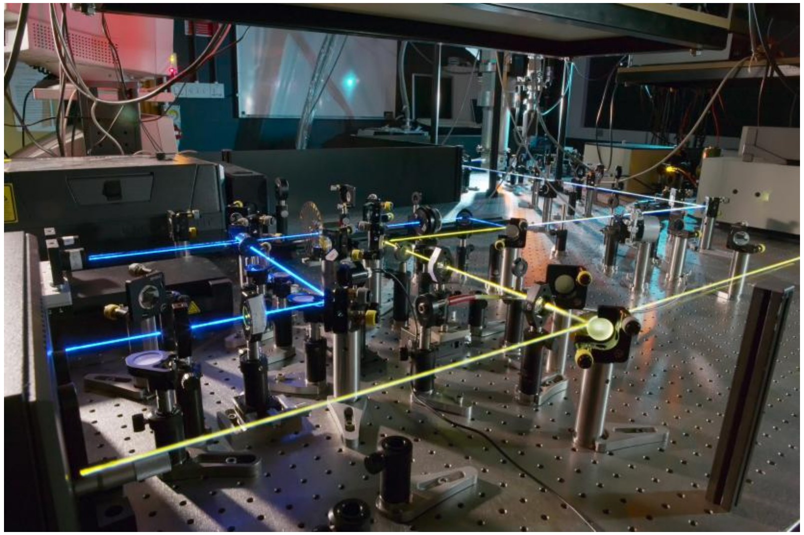
Observing quantum thermalization.

Established wisdom: given the eigenstate thermalization principle, invariably a classical dynamical analogue system can be identified that represents perfectly the knowledge of a 'classical' observer regarding the full many body unitary time evolution.

Can circumstances be identified where it is impossible to construct such a classical analogue of the quantum thermalization?

Pump probe spectroscopy.





- Pump with very short intense laser pulse.

- Measure the time evolution of e.g. the optical conductivity with small "probe" light pulses on a femtosecond time scale.

Strange metal optical pump-probe spectroscopy arXiv:1708.08279

Holography and thermalization in optical pump-probe spectroscopy

A. Bagrov,[a] B. Craps,[b] F. Galli,[c] V. Keränen,[d] E. Keski-Vakkuri,[d] J. Zaanen[e]

Einstein-Maxwell + linear axion: RN strange metal + momentum dissipation:

$$S = \frac{1}{2\kappa_4^2}\int d^4x\,\sqrt{-g}\Big[R - 2\Lambda - \frac{1}{2}\sum_{I=1}^{2}(\partial\phi_I)^2 - \frac{1}{4}F^2\Big]$$

Finite density: solve numerically for a homogeneous pulse using the Ansatz

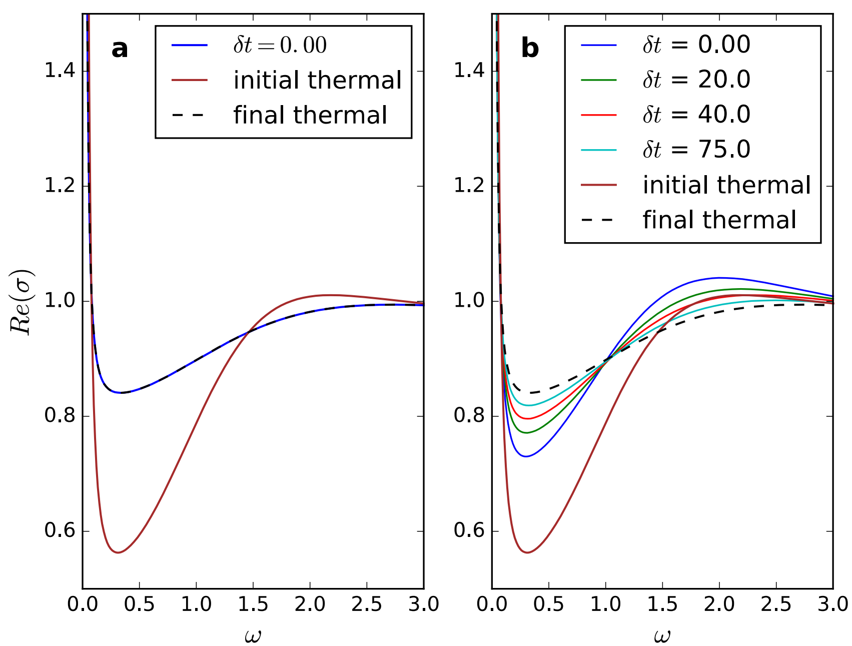
$$ds^2 = -F_z(z,v)dv^2 - \frac{2}{z^2}dvdz + 2F_x(z,v)dxdv + \Sigma(z,v)^2(e^{-B(z,v)}dx^2 + e^{B(z,v)}dy^2)$$
$$A = (E_x(v)x + a_v(z,v))dv + a_x(z,v)dx$$
$$\phi_1 = kx + \Phi(z,v)\,, \quad \phi_2 = ky$$

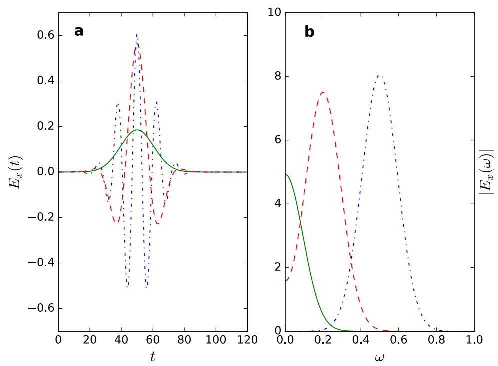
For a given electrical field profile in the boundary: $E_x(v=t, z=0)$

Holographic pump-probe spectroscopy (III).

Panel a: “blue pulse”, no zero frequency component = instantaneous thermalization

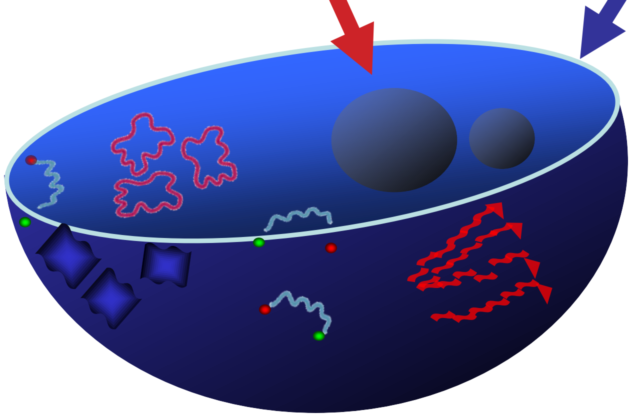
Panel b: “green/red” pulse, zero frequency component = finite thermalization time.





The triumph: gravitational encoding of all thermal physics!

Schwarzschild black hole
in the bulk



Boundary: the emergence theories of finite temperature matter.

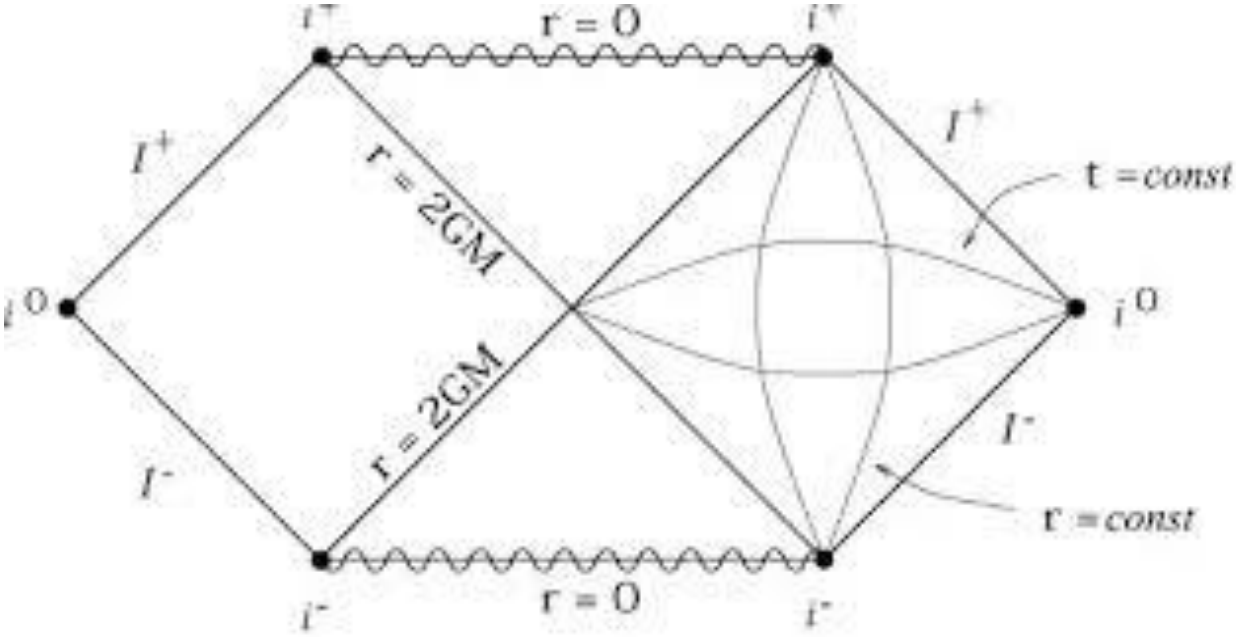
- **All of thermodynamics! Caveat: phase transitions are mean field (large N limit).**

- **Precise encoding of Navier-Stokes hydrodynamics! Right now used to debug complicated hydrodynamics (e.g. anomalies).**

- **For special "Planckian dissipation" values of parameters (quantum criticality):**

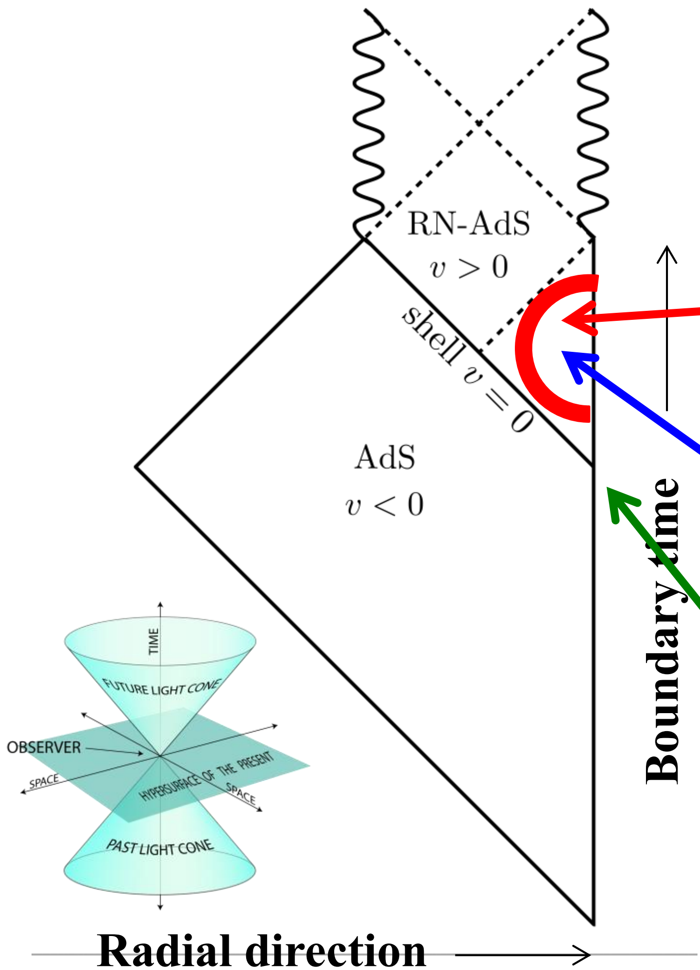
$$\tau_\hbar = const.\frac{\hbar}{k_B T}, \quad const. = O(1)$$

Penrose diagram eternal Schwarzschild black hole.



Vaidya = holographic pump probe.

Ben Craps



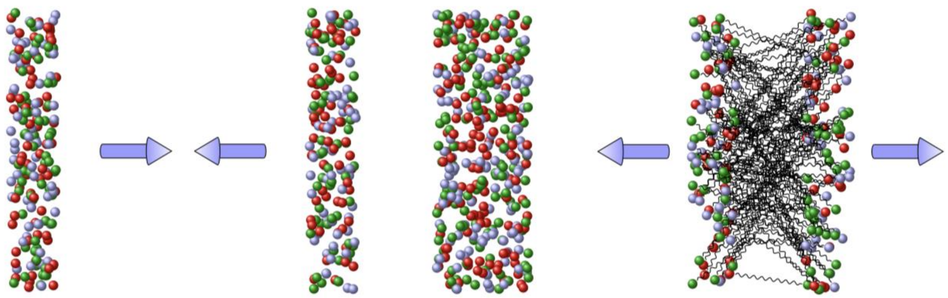
Equal time propagators, non-local operators (entanglement entropy) show finite thermalization time.

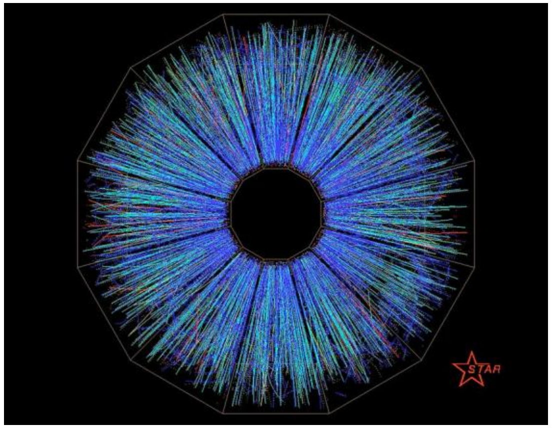
Causal two point propagators reveal instanteneous thermalization

Black hole space time forms immediately after the pulse

Null shell is released = pulse of transversal electric field in the CFT

Inspiration: the quark gluon plasma.





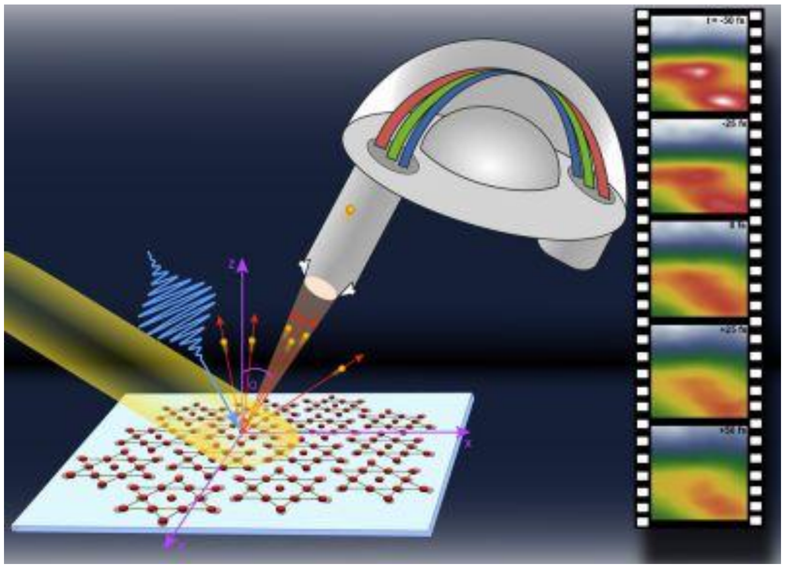
- “Fast hydrodynamization”: within the time it takes a quark to traverse half a proton radius local quark-gluon equilibrium is established.

-“Minimal viscosity”: $$\frac{\eta}{s} \simeq \frac{1}{4\pi}\frac{\hbar}{k_B}$$

associated with “Planckian relaxation time”: $$\tau_\hbar \simeq \frac{\hbar}{k_B T}$$

Time resolved ARPES.


Z.X. Shen Sobota



Electrons even in normal metals are very fast: thermal equilibrium in 200 femtoseconds.

State of the art time resolution: 50 femtoseconds.

Non-equilibrium distributions have been detected in simple metals.

The Stanford group is presently looking for signs of ultra-rapid equilibration in Cuprate strange metals.

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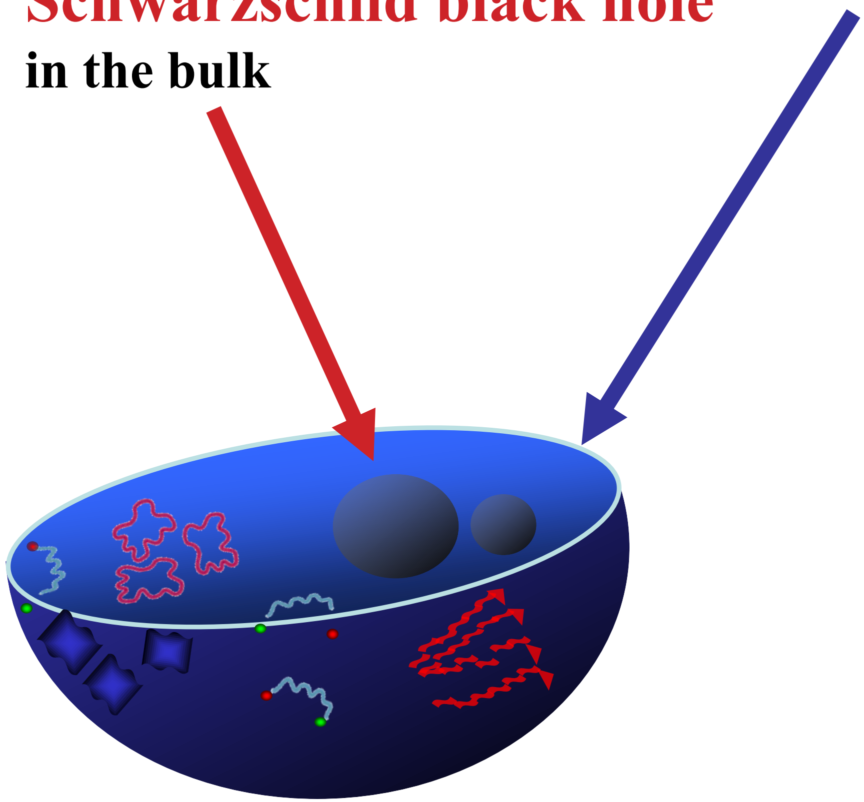

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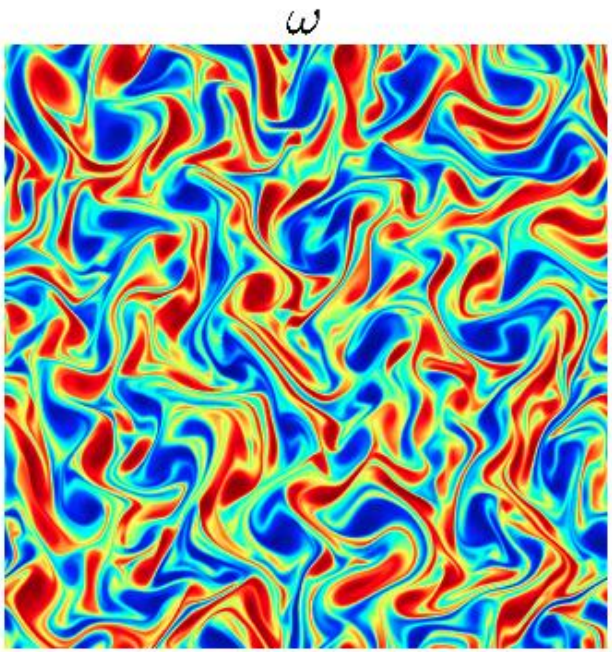
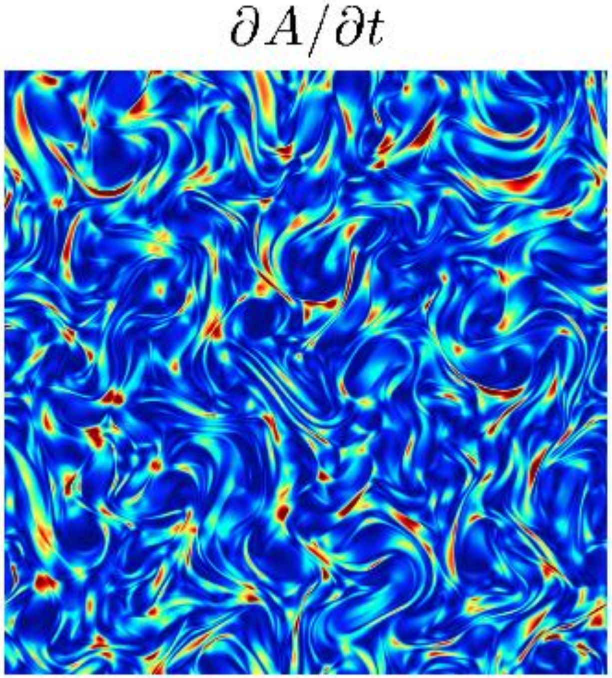
Fluid-gravity duality and the turbulence black hole.

Chesler Yaffe

Holography and numerical GR



Vorticity in the liquid (Kolmagorov scaling)



Near horizon geometry (fractal)

Dissipation = absorption of classical waves by Black hole!

Policastro-Son-Starinets (2002):

Viscosity: absorption cross section of gravitons by black hole

$$\eta = \frac{\sigma_{abs}(0)}{16\pi G}$$

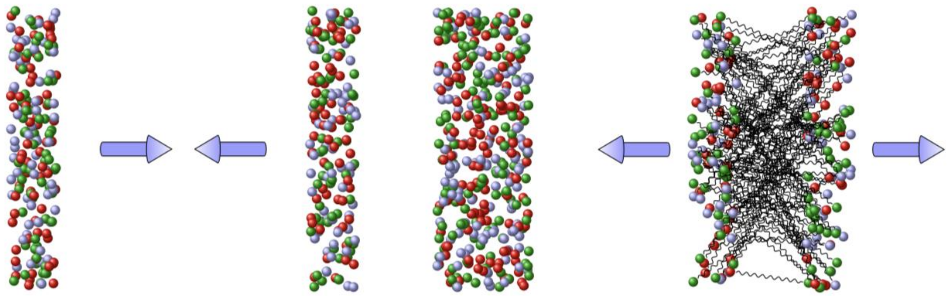
= area of horizon (GR theorems)

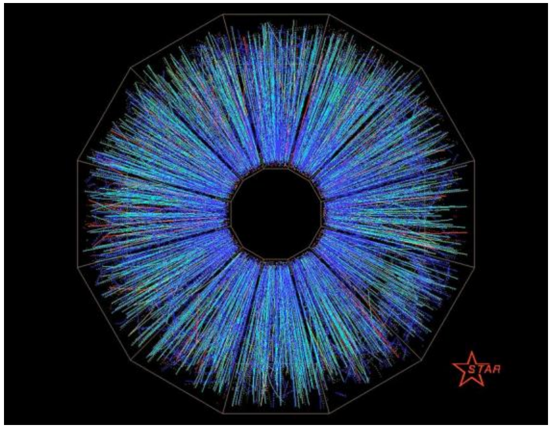
Entropy density s: Bekenstein-Hawking BH entropy = area of horizon

Universal viscosity-entropy ratio for CFT's with gravitational dual limited in large N by:

$$\frac{\eta}{s} = \frac{1}{4\pi}\frac{\hbar}{k_B}$$

Inspiration: the quark gluon plasma.





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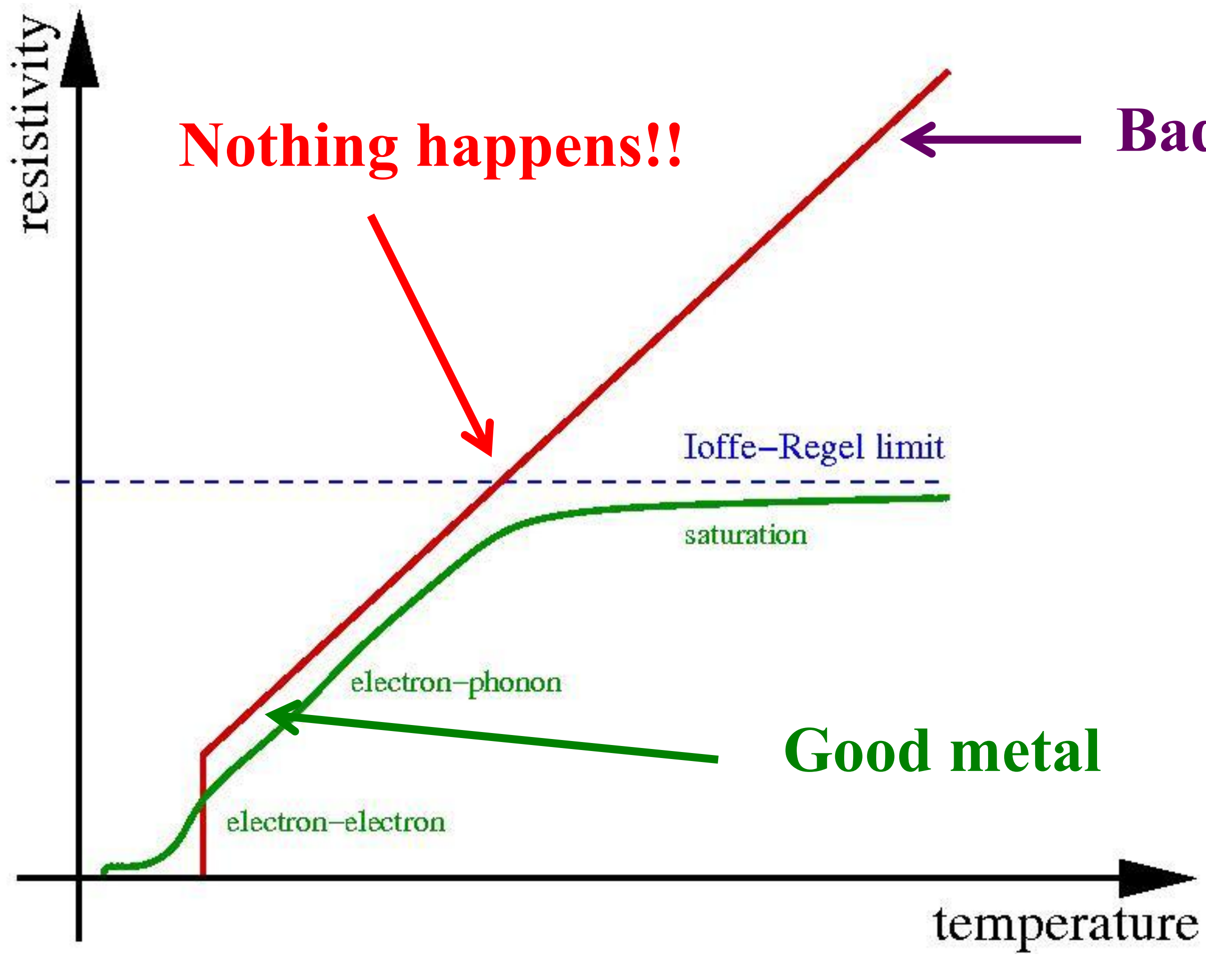
Divine resistivity



Holographic linear resistivity

(PRB 89, 2451161, 2014).

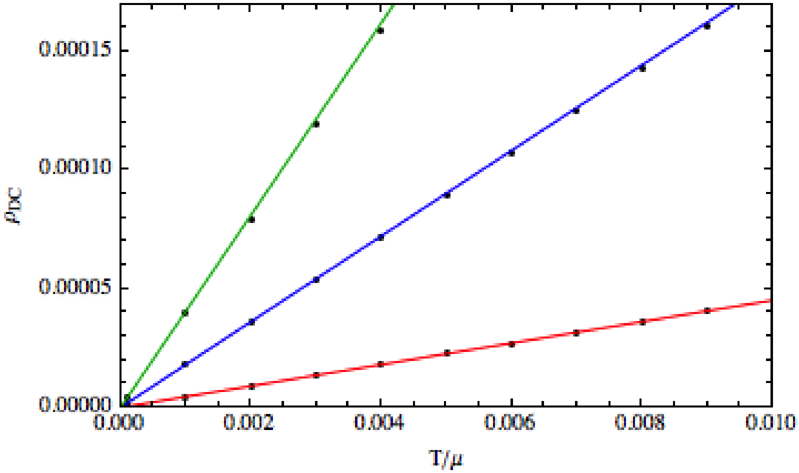
Richard Davison

Steve Gubser

"Conformal to AdS2" strange metal: Einstein-Maxwell-dilaton (consistent truncation), local quantum critical, marginal Fermi-liquid (3+1D), susceptible to holo. superconductivity, healthy thermodynamics: unique ground state, Sommerfeld thermal entropy.

David Vegh

Breaking of Galilean invariance (finite conductivities) due to quenched disorder: "massive gravity" = "Higgsing" space-like diffeomorphisms in the bulk !?



$$S = \frac{1}{2\kappa_4^2}\int d^4x\sqrt{-g}\Big[\mathcal{R} - \frac{1}{4}e^{\phi}F_{\mu\nu}F^{\mu\nu} - \frac{3}{2}\partial_\mu\phi\partial^\mu\phi + \frac{6}{L^2}\cosh\phi - \frac{1}{2}m^2\left(\mathrm{Tr}\left(\mathcal{K}\right)^2 - \mathrm{Tr}\left(\mathcal{K}^2\right)\right)\Big]$$

Explicit holographic construction explaining linear resistivity!

The secret of the linear resistivity (PRB 89, 2451161, 2014).


Davison

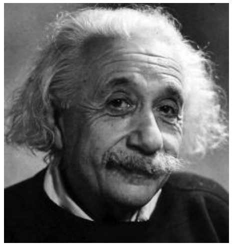

Hartnoll

Planckian dissipation = very rapid local equilibration: a hydrodynamical fluid is established before it realizes that momentum is non conserved due to the lattice potential (not true in Fermi-gas: Umklapp time is of order collision time).


Stokes

Resistivity in hydrodynamics

$$r(T)\ \mu\ \frac{1}{t_{rel}} = \frac{D}{l^2}$$


Einstein

Einstein relation:

$$D = \frac{h}{m_e n_e}$$



Sachdev **Son**

Planckian viscosity

$$\eta = A \frac{\hbar}{k_B} s$$

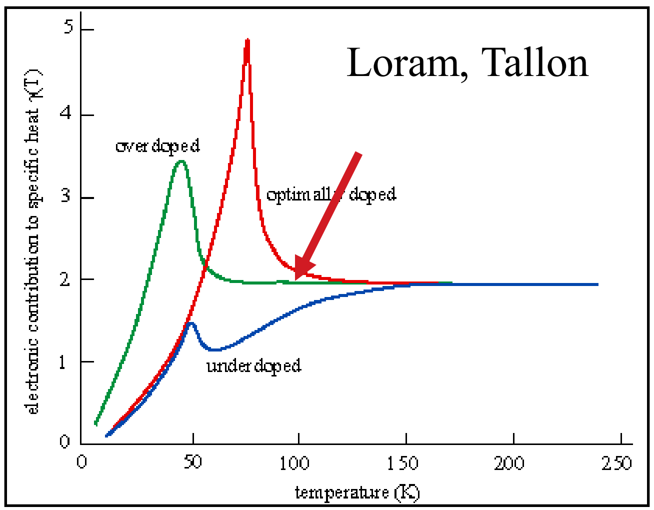
$$\rho(T) = \frac{1}{\omega_p^2 \tau_{rel}} = A \frac{\hbar}{\omega_p^2 l^2 m_e} \frac{S}{k_B}$$

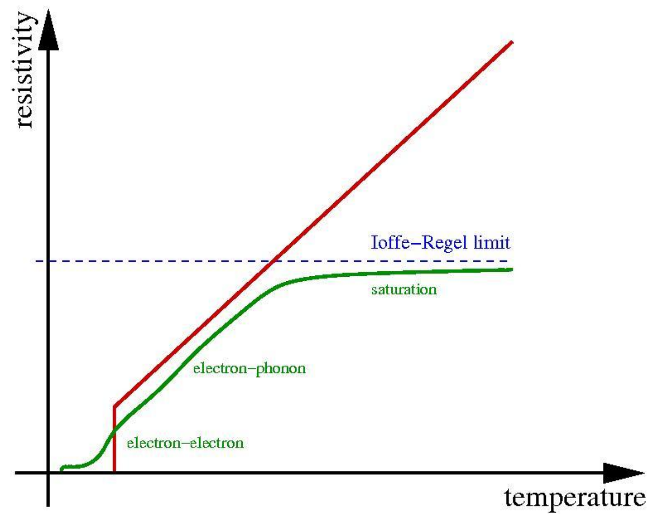
Entropy versus transport: optimal doping

Optimally doped

$$C = \gamma T \Rightarrow S = T/\eta$$

$$\rho \propto \frac{1}{\tau_{rel}} \propto S \propto T$$

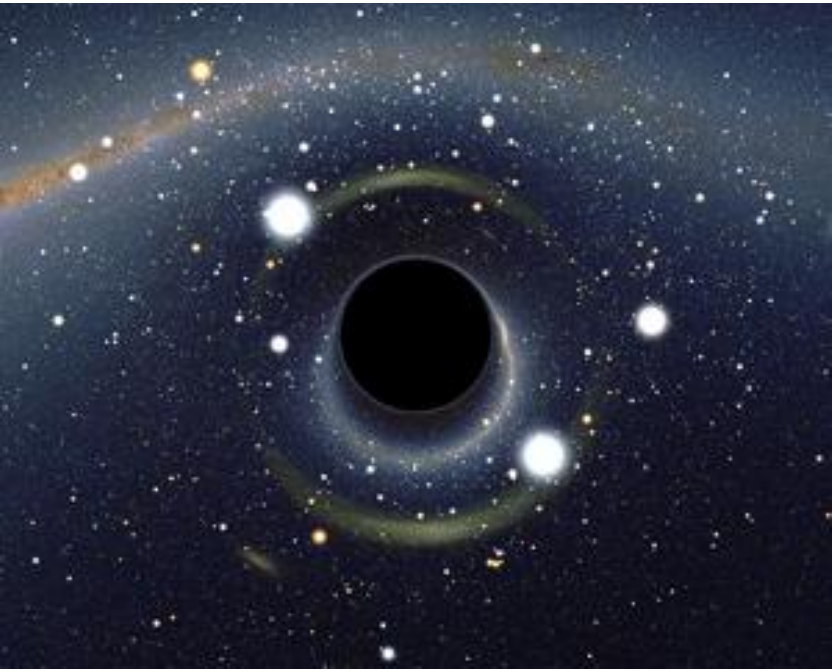




Plugging in numbers: "mean-free path" $l \approx 10^{-9}\, m$

Quite dirty but no residual resistivity since the fluid becomes perfect at T =0 !

Black holes as “maximal entanglement” quantum computers” !?



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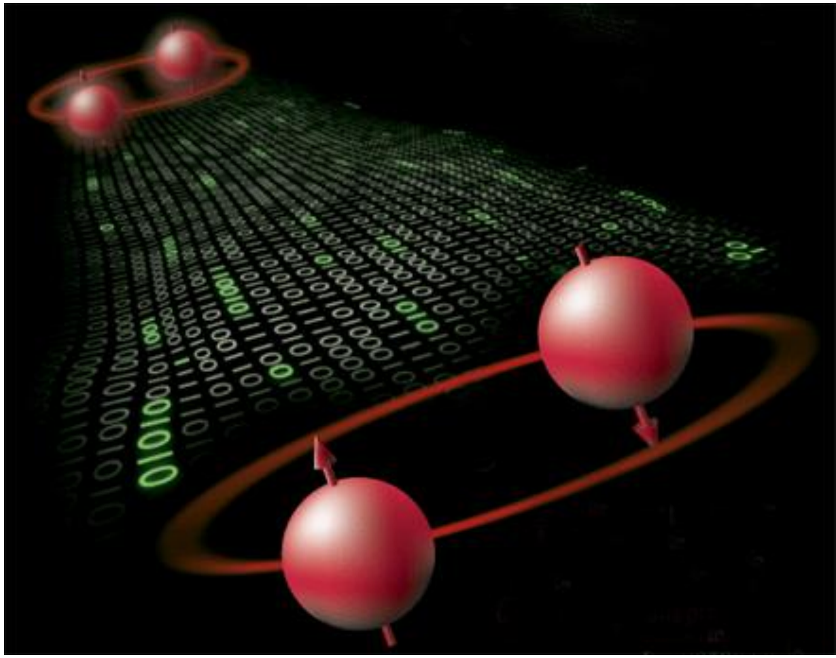
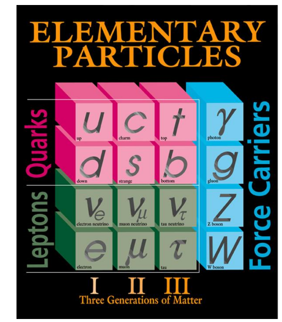


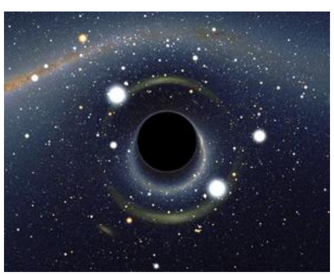
The fruitflies of physics

Boltzmann: Classical matter

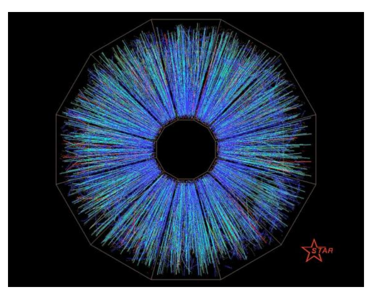
Gas-liquid-solid phases (van der Waals)



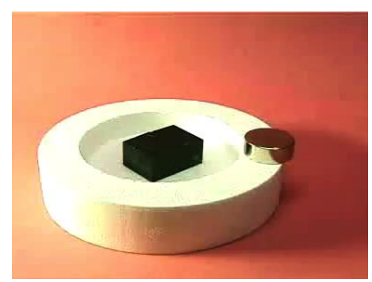
Quantum supreme matter



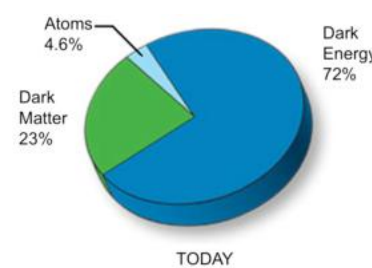
Quark-gluon plasma



High Tc superconductors



Dark sector??

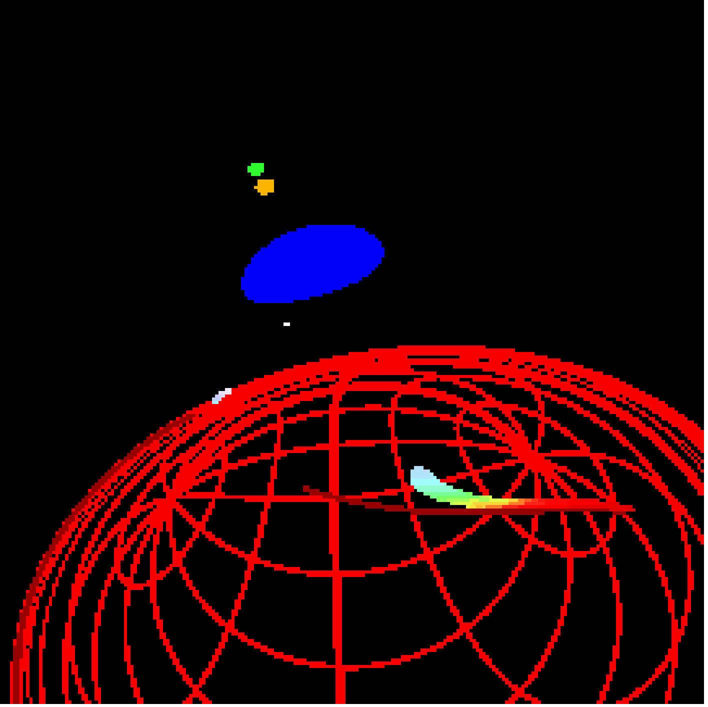


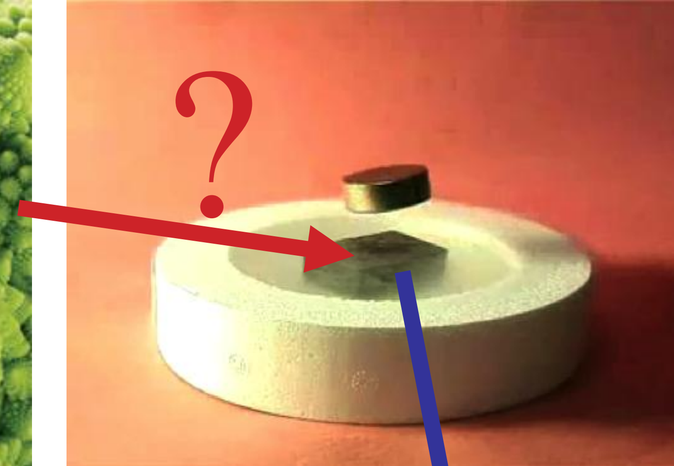
Empty.

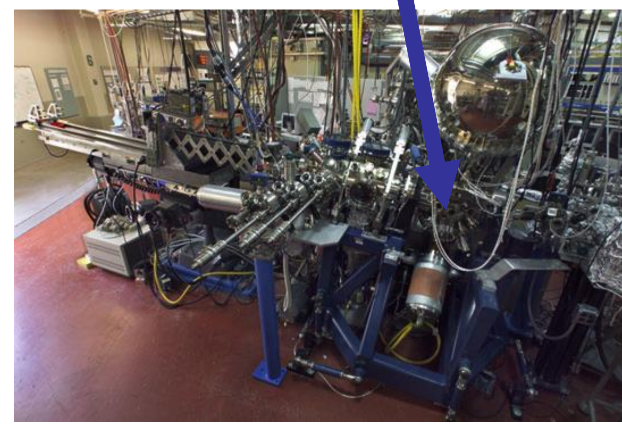
Empty.

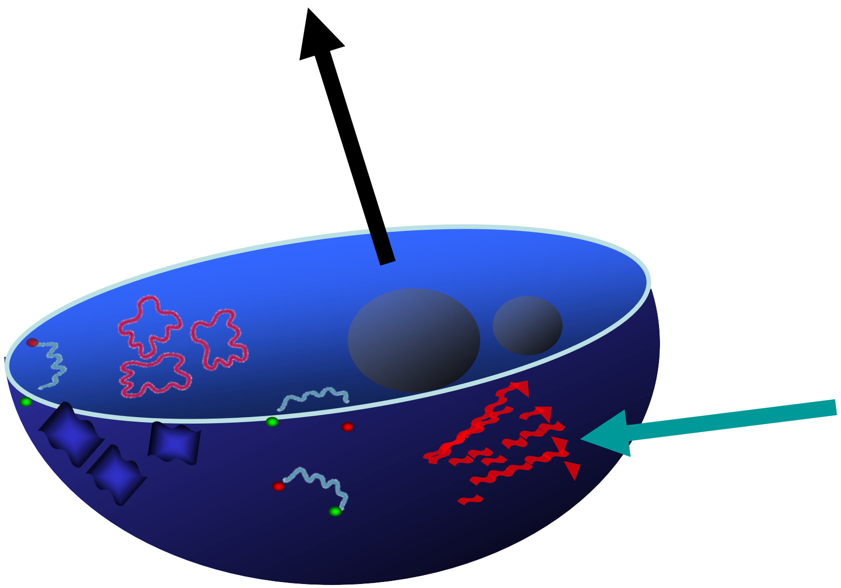
Empty.

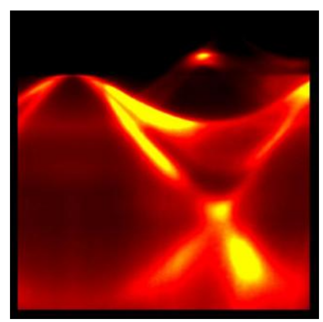
Empty.



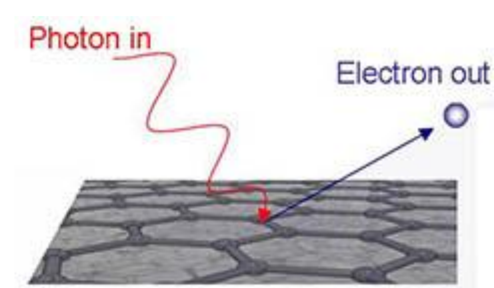








Photoemission spectrum



29 years later: the "consensus document".

Nature **518,** 179 (2015)

REVIEW

doi:10.1038/nature14165

From quantum matter to high-temperature superconductivity in copper oxides

B. Keimer[1], S. A. Kivelson[2], M. R. Norman[3], S. Uchida[4] & J. Zaanen[5]

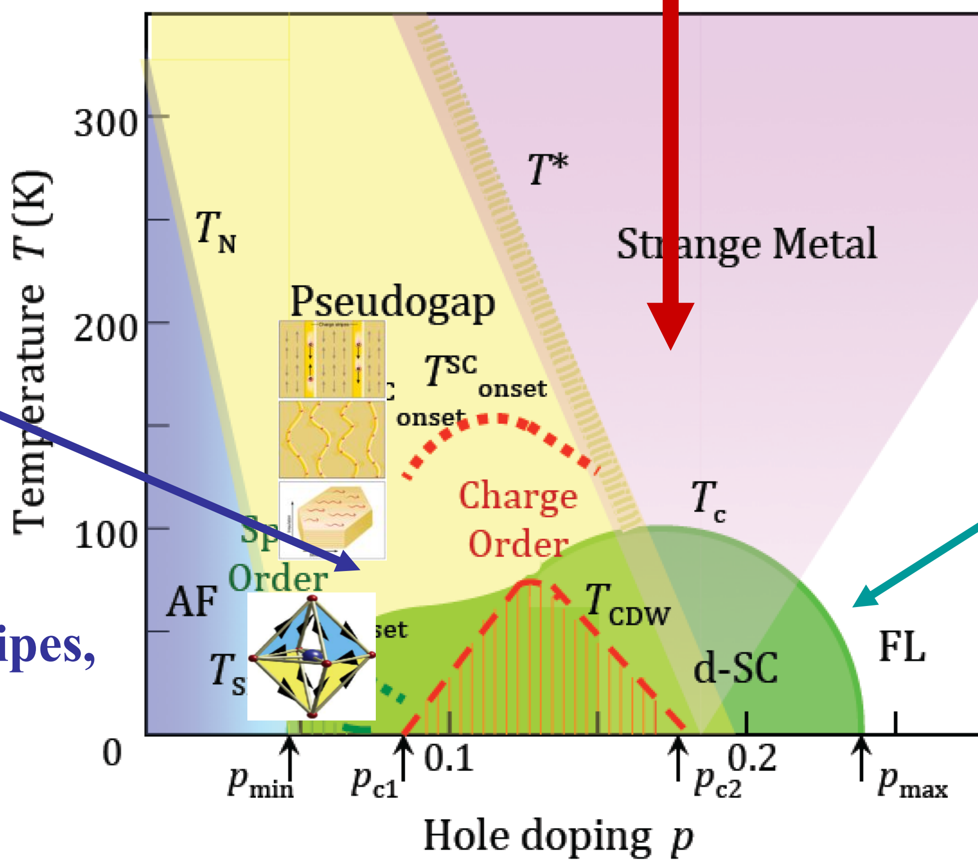
The discovery of high-temperature superconductivity in the copper oxides in 1986 triggered a huge amount of innovative scientific inquiry. In the almost three decades since, much has been learned about the novel forms of quantum matter that are exhibited in these strongly correlated electron systems. A qualitative understanding of the nature of the superconducting state itself has been achieved. However, unresolved issues include the astonishing complexity of the phase diagram, the unprecedented prominence of various forms of collective fluctuations, and the simplicity and insensitivity to material details of the 'normal' state at elevated temperatures.

Phase diagram high Tc superconductors (Nature 518, 181, 2015)

The clash: the strange metal

… which is good for superconductivity!

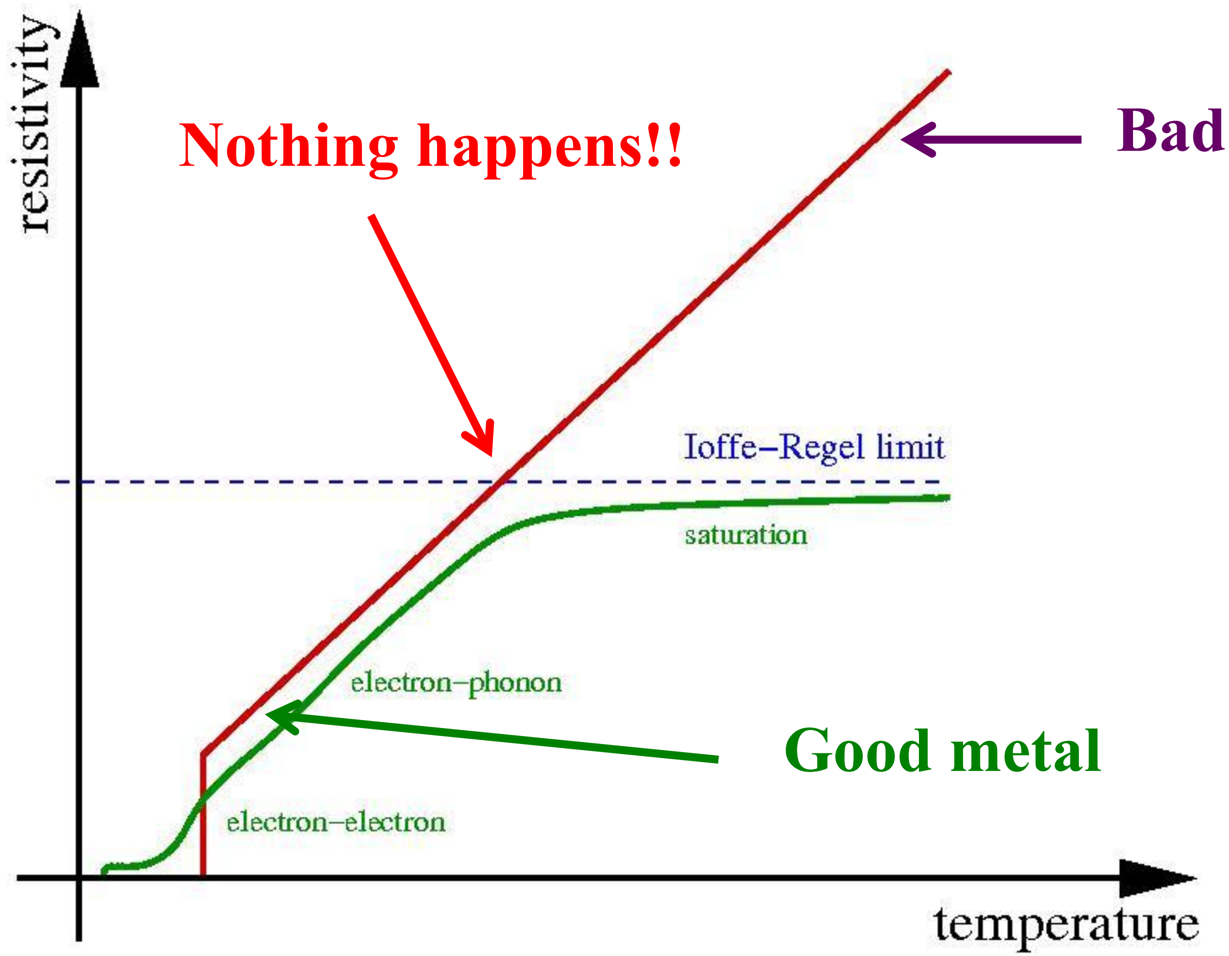
The quantized traffic jam



Normalcy (The Fermi liquid) returns

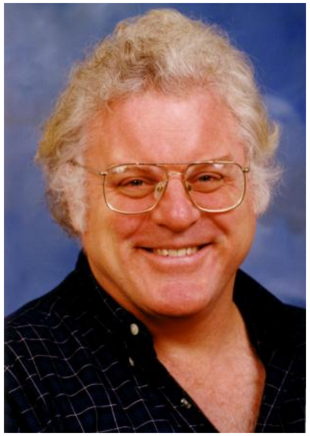
Exotic orders: stripes, orbital currents, nematics …

Divine resistivity



Laughlin's linear resistivity criterium.

" The linear resistivity reflects an extremely simple behavior and extremely simple behaviors in physics need a powerful principle for their protection. Explain this principle."



My answer: universal principle rooted in quantum supremacy.

“The classical condensates: from crystals to Fermi-liquids.”

States of matter that we understand are short ranged entangled product!

$$\left|\Psi_0\{\Omega_i\}\right\rangle = \Pi_i \hat{X}_i^+(\Omega_i)\left|vac\right\rangle$$

- Crystals: put atoms in real space wave packets $\quad X_i^+(R_i^0)\ \mu\ e^{(R_i^0 - r)^\wedge 2 / s^2}\, y^+(r)$

- Magnets: put spins in generalized coherent state

$$X_i^+(\vec{n}_i) \propto e^{i\varphi_i/2}\cos(\theta_i/2)c_{i\uparrow}^+ + e^{-i\varphi_i/2}\sin(\theta_i/2)c_{i\downarrow}^+$$

- Superconductors/superfluids: put bosons/Cooper pairs in coherent superposition

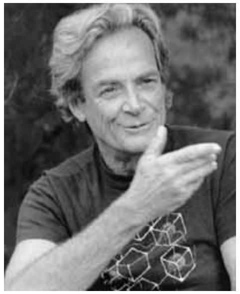
$$X_{k/i}{}^{+}\ \mu\ u_k + v_k c_{k-}^+ c_{-k-}^+, \quad u_i + v_i e^{ij_i} b_i^+$$

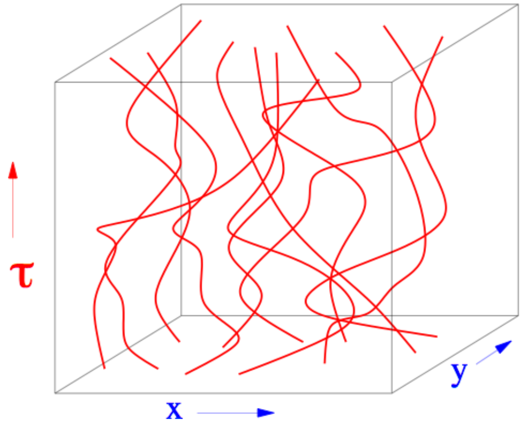
- Fermi gas/liquid: product state in momentum space (mod Pauli principle).

$$\left|\mathrm{Y}_{FL}\right\rangle = \mathrm{P}_k^{k_F} c_k^+\left|vac\right\rangle$$

Fermions at a finite density: the sign problem.

Imaginary time first quantized path-integral formulation





$$\begin{aligned}\mathcal{Z} &= \mathrm{Tr}\exp(-\beta\hat{\mathcal{H}}) \\ &= \int \mathrm{d}\mathbf{R}\,\rho(\mathbf{R},\mathbf{R};\beta)\end{aligned}$$

$$\mathbf{R} = (\mathbf{r}_1,\ldots,\mathbf{r}_N) \in \mathbb{R}^{Nd}$$

$$\begin{aligned}\rho_{B/F}(\mathbf{R},\mathbf{R};\beta) &= \frac{1}{N!}\sum_{\mathcal{P}}(\pm 1)^{\mathcal{P}}\rho_D(\mathbf{R},\mathcal{P}\mathbf{R};\beta) \\ &= \frac{1}{N!}\sum_{\mathcal{P}}(\pm 1)^{\mathcal{P}}\int_{\mathbf{R}\to\mathcal{P}\mathbf{R}}\mathcal{D}\mathbf{R}(\tau)\exp\left\{-\frac{1}{\hbar}\int_0^{\hbar/T}\mathrm{d}\tau\left(\frac{m}{2}\dot{\mathbf{R}}^2(\tau)+V(\mathbf{R}(\tau))\right)\right\}\end{aligned}$$

Boltzmannons or Bosons:

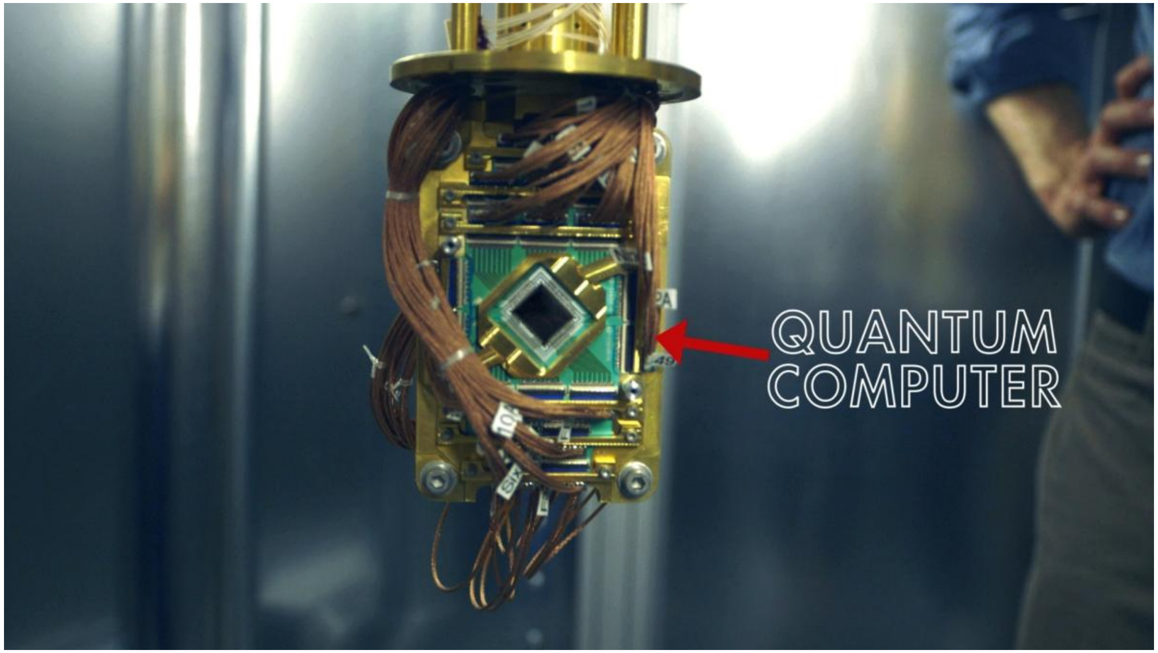
- integrand non-negative
- probability of equivalent classical system: (crosslinked) ringpolymers

Fermions:

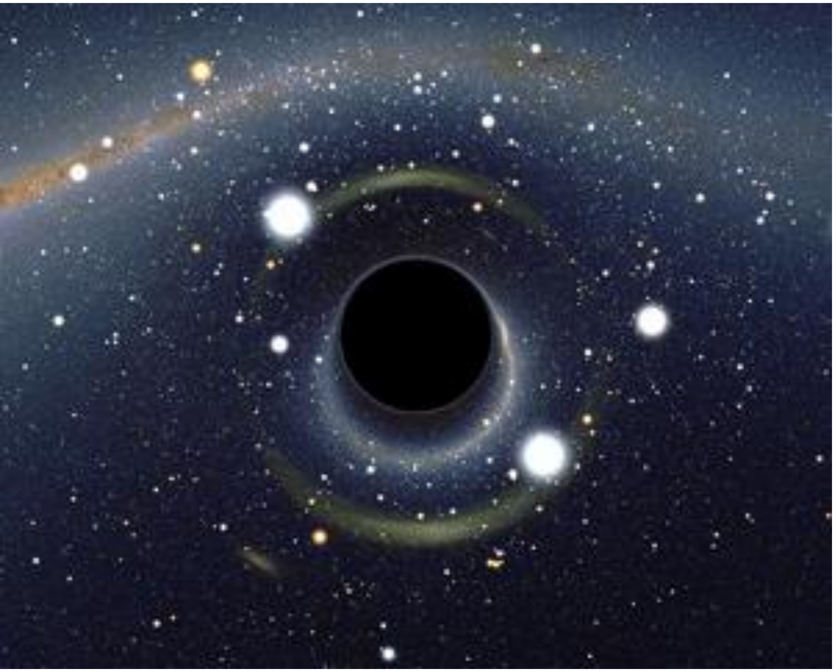
- negative Boltzmann weights
- in general NP-hard problem (Troyer, Wiese)!!!

Solving the sign problem: the Troyer way.

The ground state is densely entangled: I need a quantum computer!



Black holes as "maximal entanglement" quantum computers" !?



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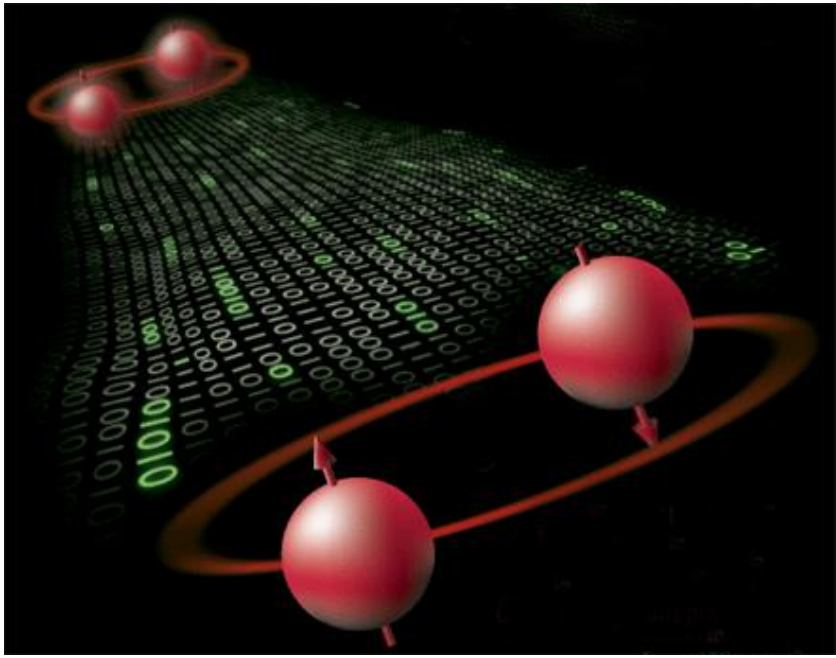
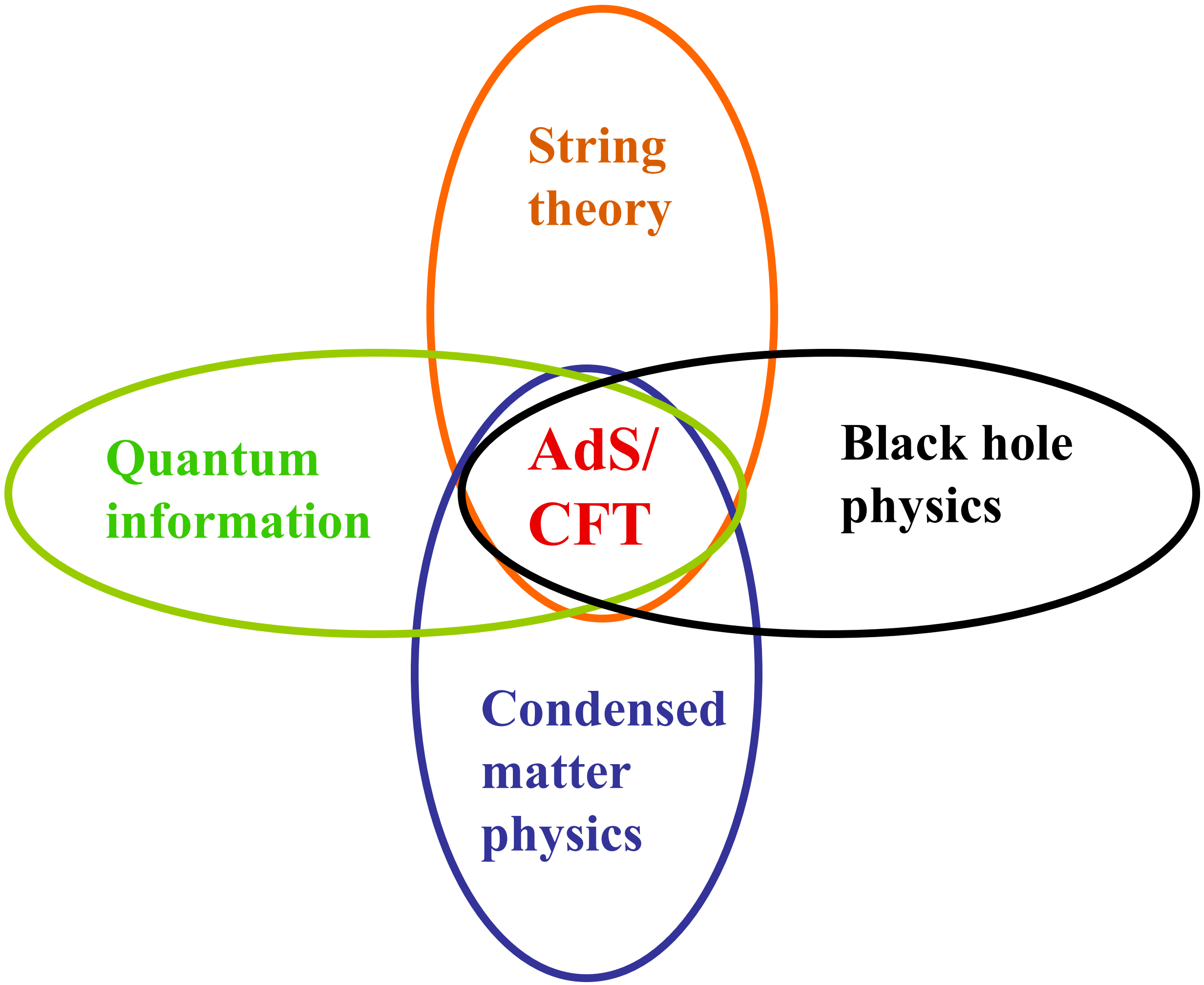
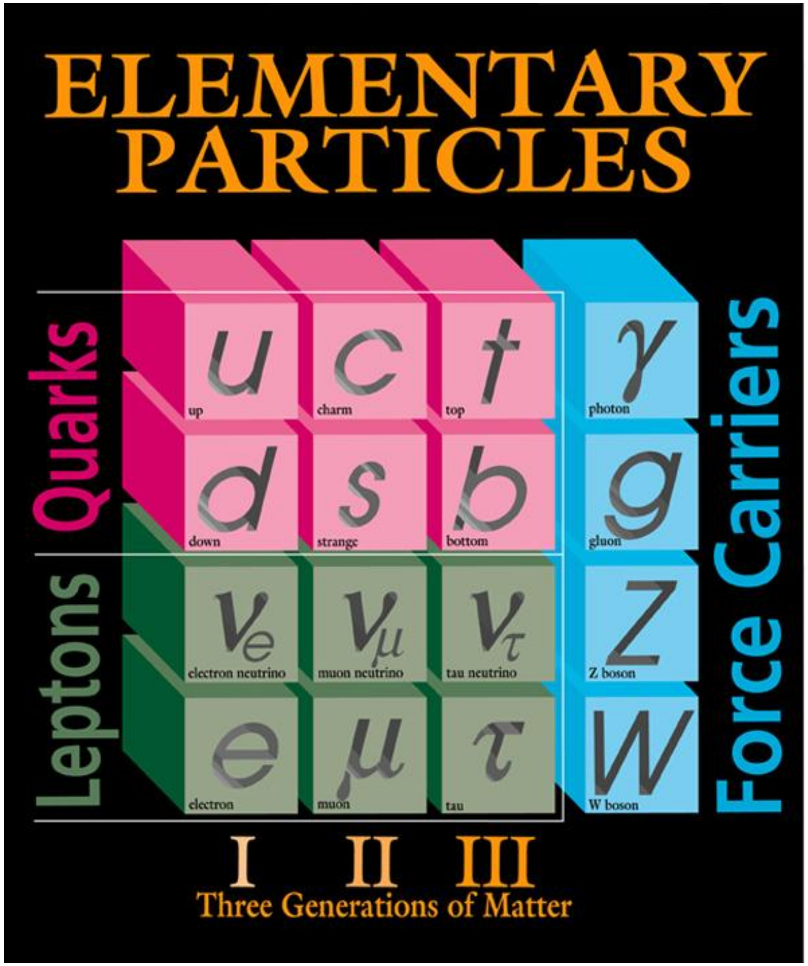
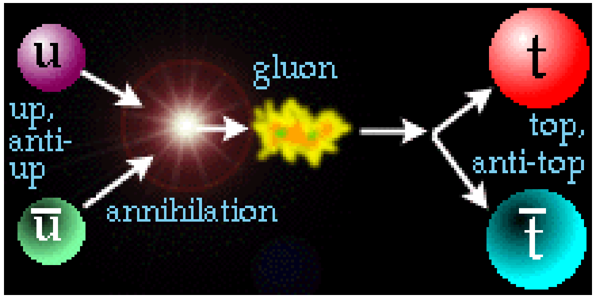


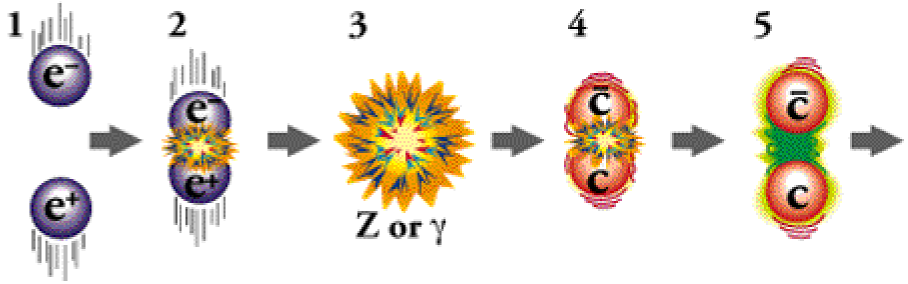
The cloverleaf of matter ….



High energy physics: elementary particles.



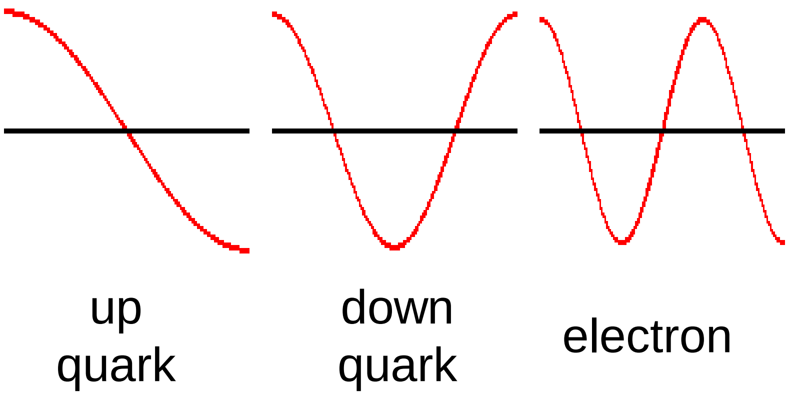


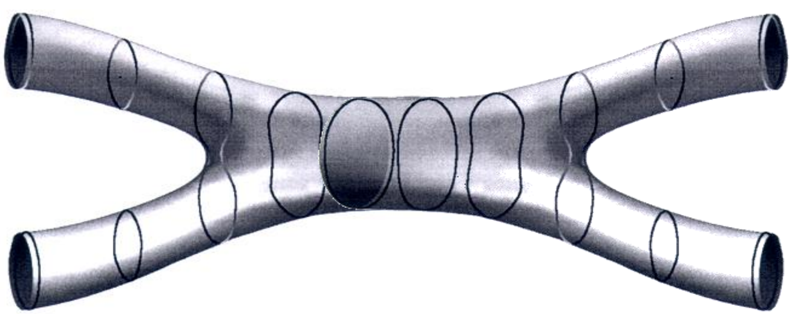


Particles as string vibrations (1980’s)

String vibration modes→ Different particles

Morphing strings → Particle interactions

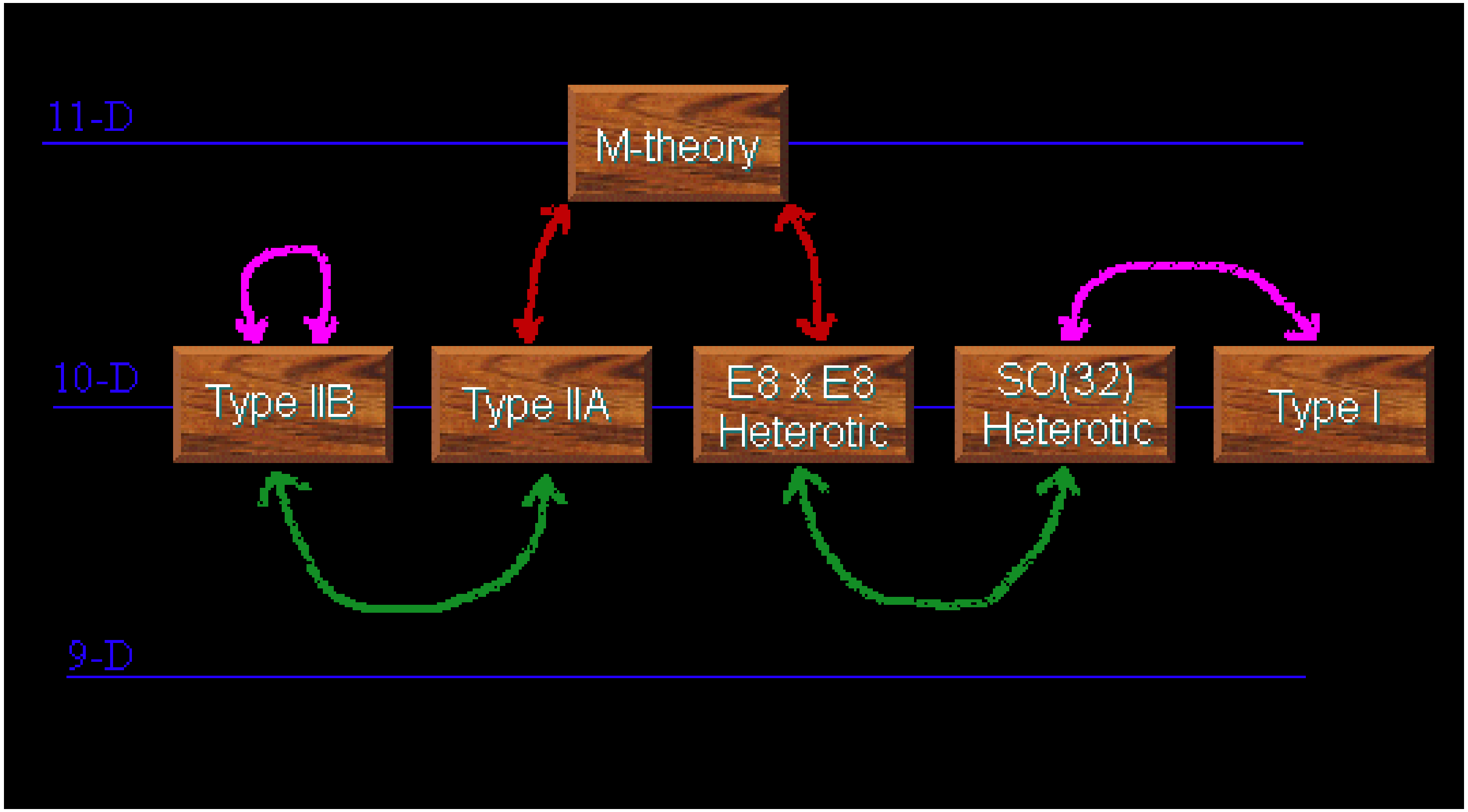




=>Unified theory: one string = all particles

=> Vibrations of “closed strings” describe gravitons (quantum particles carrying gravitational force).

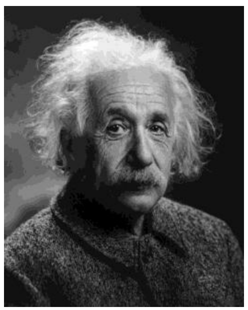
The “second string revolution” (1995)

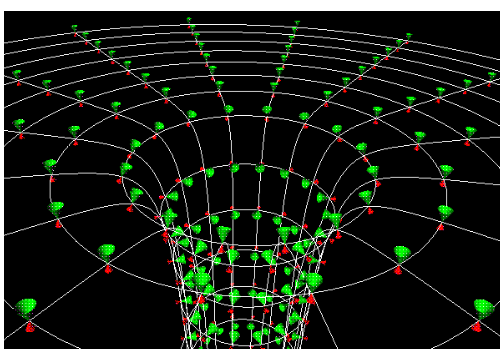


Dualities

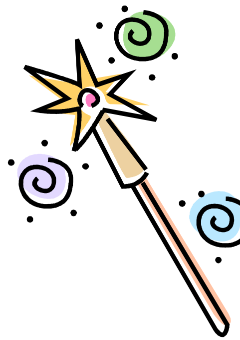
General relativity "=" quantum field theory

General relativity





'AdS/CFT'



Maldacena 1997

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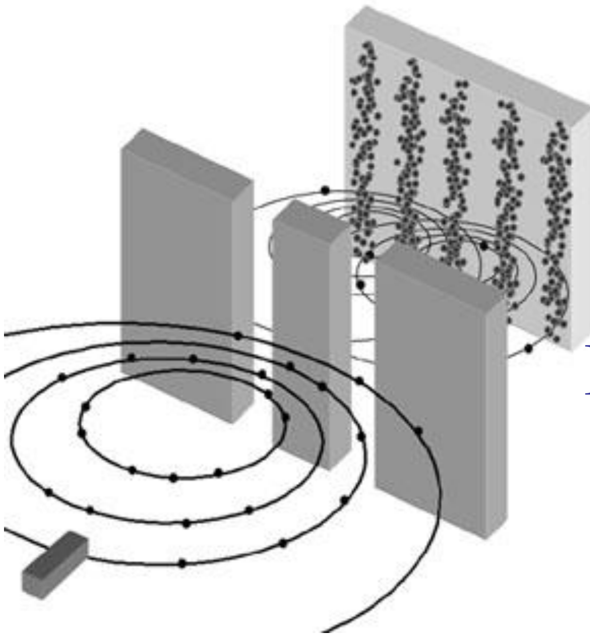
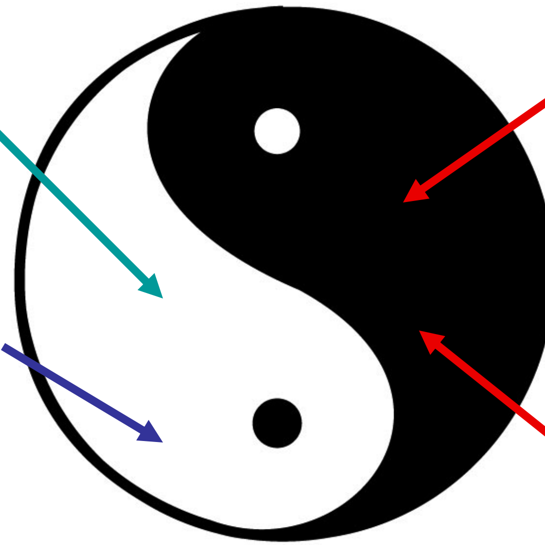
Quantum fields

Particle-wave duality.





“The exact opposites form an indivisable whole”

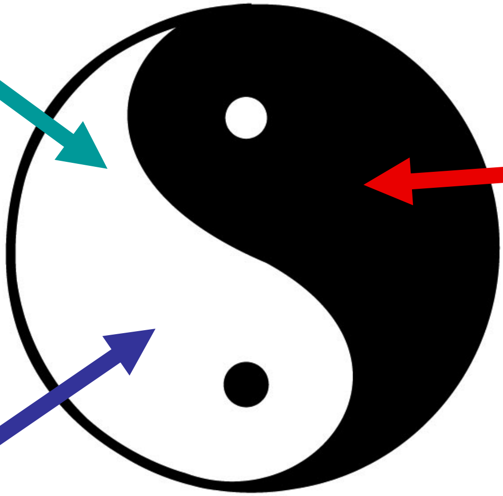
Heisenberg uncertainty relation: $\Delta p \times \Delta x \geq \hbar$

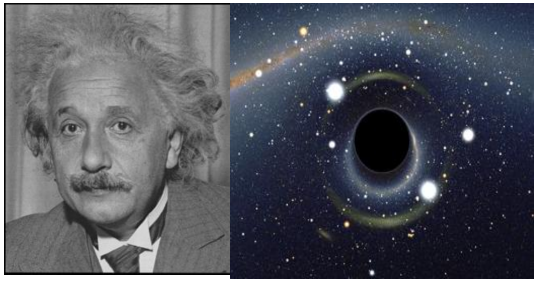
The Grand Unified "holographic" duality.

"AdS/CFT"

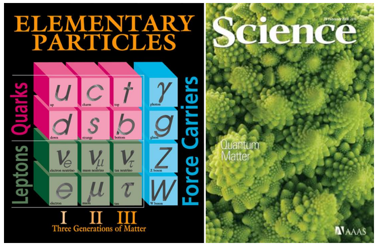
the exact opposites form an indivisible whole

Thermal matter, dissipation





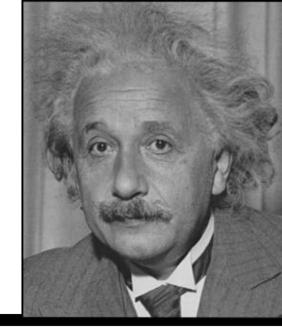
General relativity



Kramers/Wannier-, Local-gobal duality.

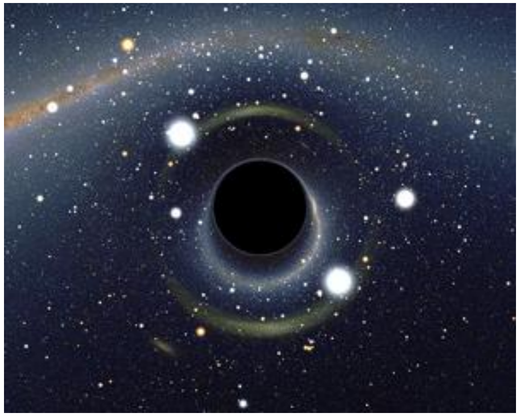
Quantum fields- Quantum matter

Einstein

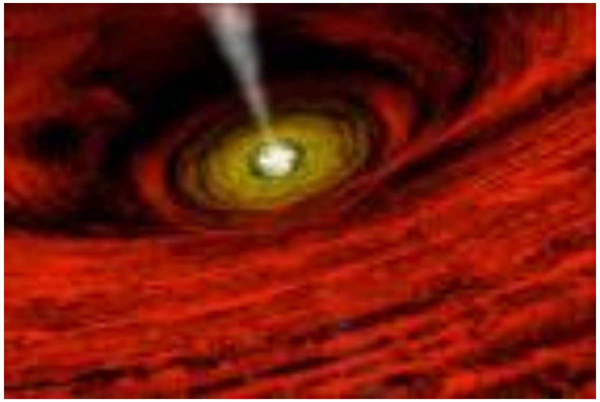


Einstein equations (theory of general relativity):

$$R_{mn} - \frac{1}{2} R g_{mn} = \frac{8pG}{c^{4}} T_{mn}$$

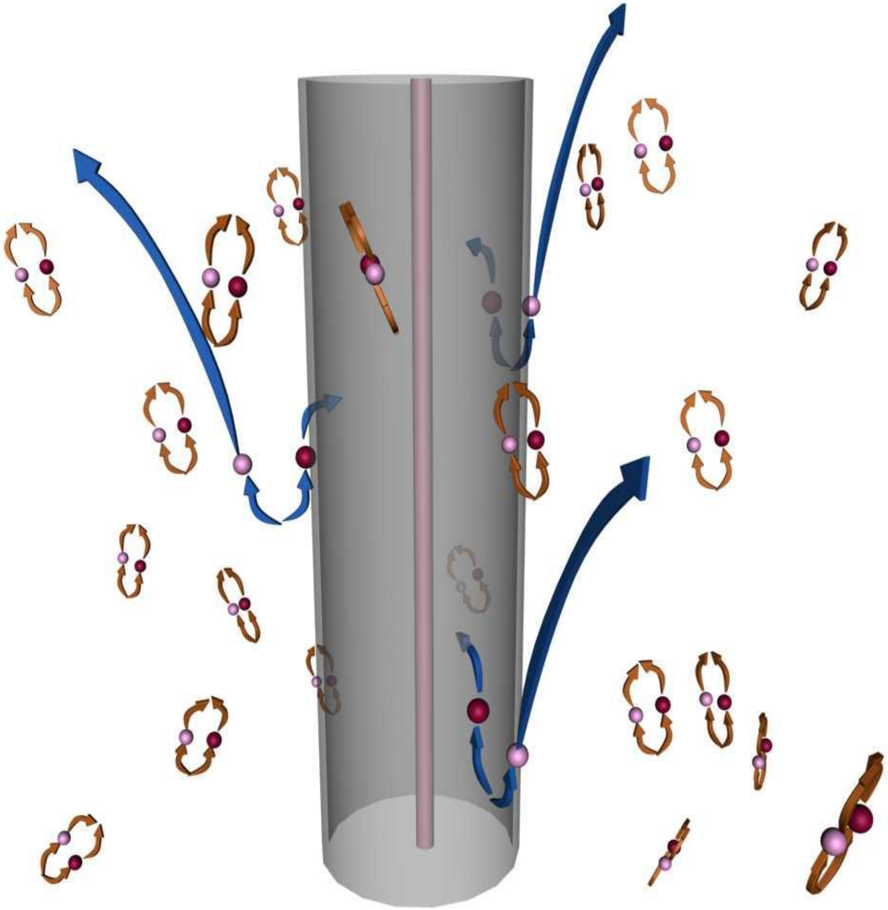


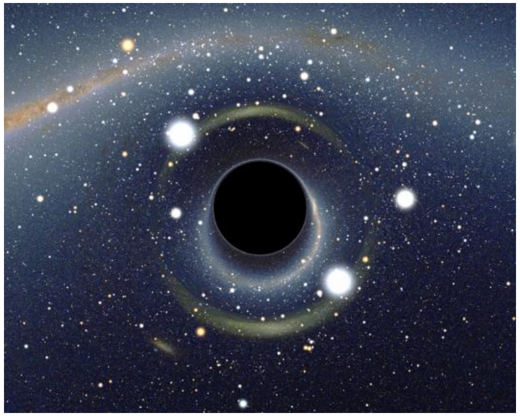
Space time as ‘fabric’

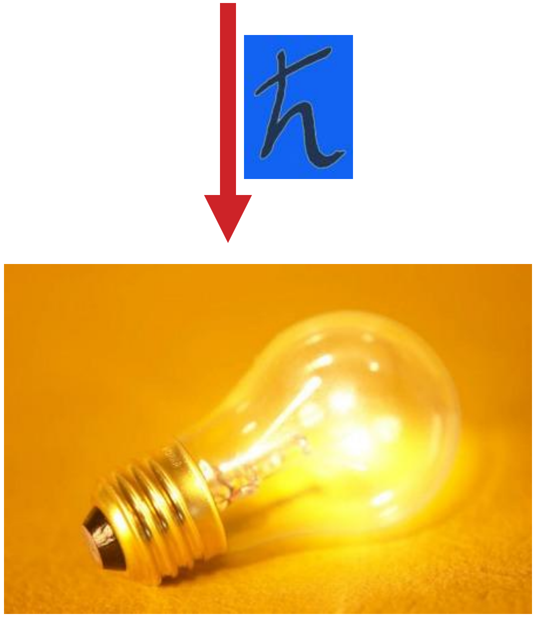


Matter and energy

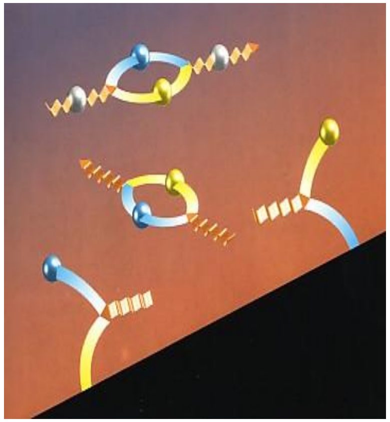
Hawking radiation: space-time turns into material stuff …





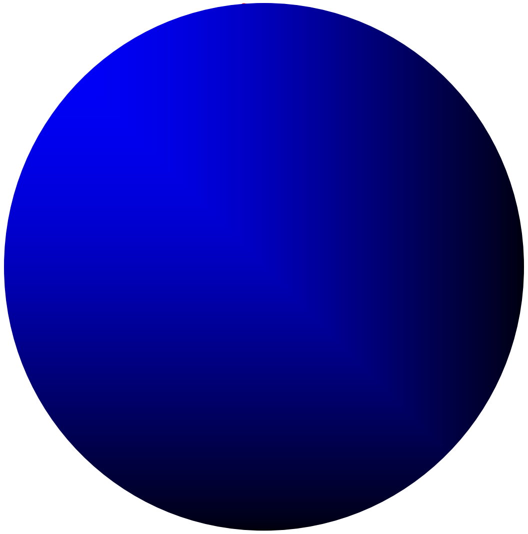


‘t Hooft - Susskind holographic principle



Hawking Temperature: $T = \frac{\hbar g}{2\pi k c}$

g = acceleration at horizon

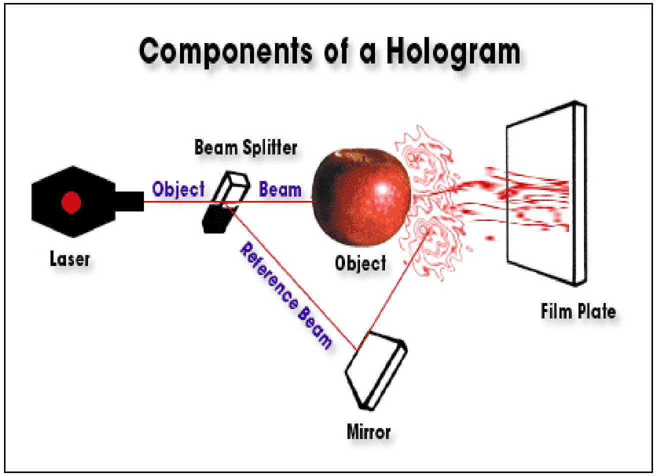


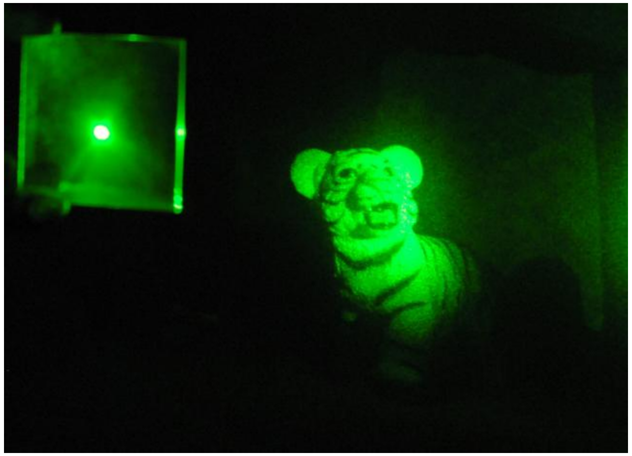
BH entropy: $S = \frac{k c^3 A}{4 \hbar G}$

***A* = area of horizon**

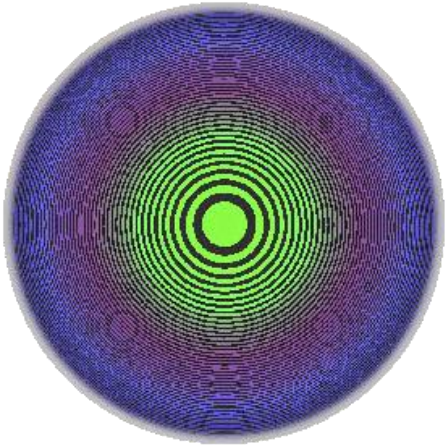
Number of degrees of freedom (field theory) scales with the area and not with the volume (gravity)

Holography with lasers





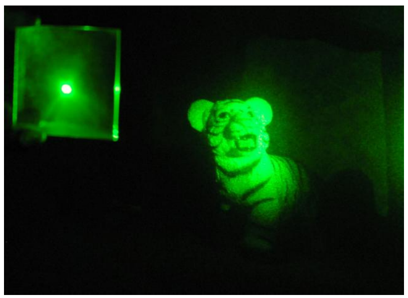
Three dimensional image

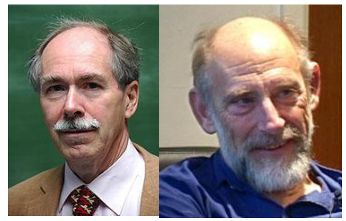


Encoded on a two dimensional photographic plate

Holographic gauge-gravity duality

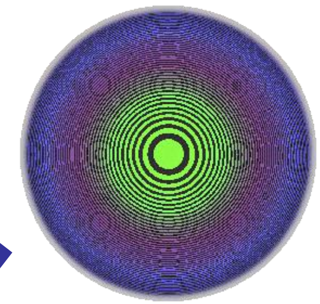
Einstein Universe "AdS"

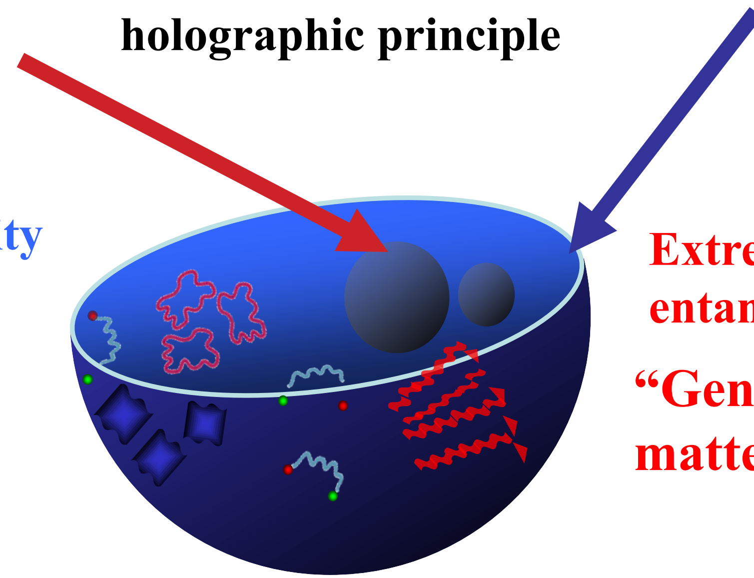




't Hooft-Susskind holographic principle

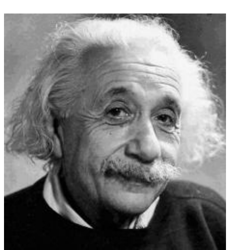
Quantum field world "CFT"





Classical general relativity

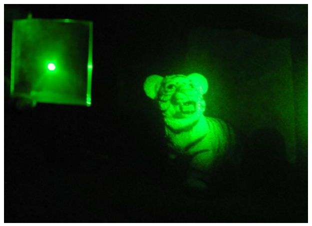
Uniqueness of GR solutions

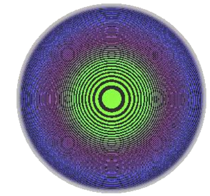


Extremely strongly entangled quantum matter

"Generating functional of matter emergence principle"

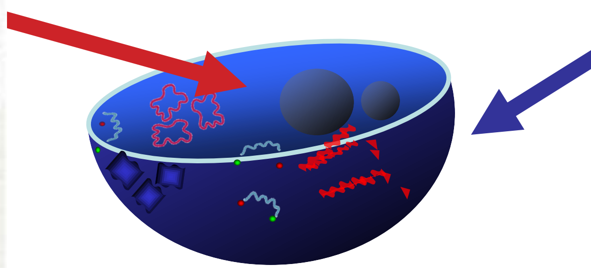
Holography and scale invariance.

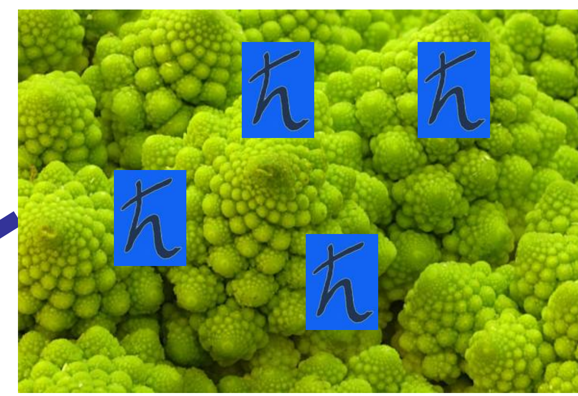




Einstein universe "AdS" =
Anti de Sitter universe

Quantum field theory
"CFT"= quantum critical





General Relativity = Renormalization Group

Extra radial dimension of the bulk <=> **scaling "dimension" in the field theory**

Bulk AdS geometry = **scale invariance of the field theory**

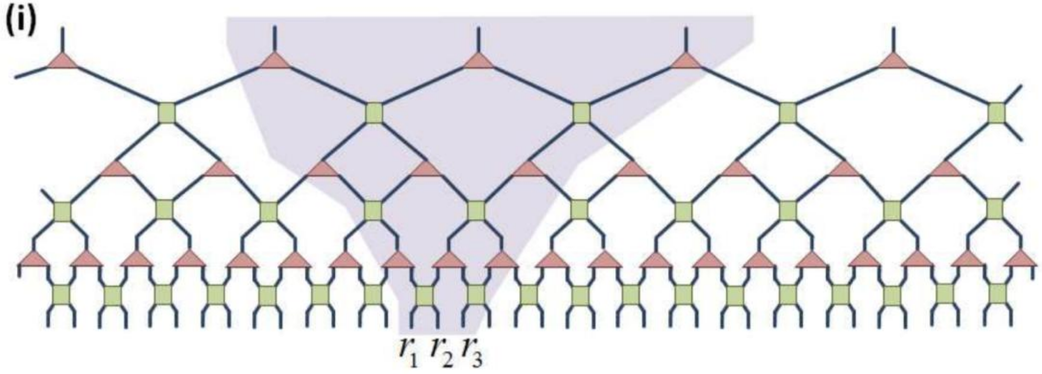
$$dr^2 = -F(r)dt^2 + \frac{dr^2}{F(r)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$F(r) = -\Lambda r^2 + 1, \qquad \Lambda < 0$$

Central charge and quantum complexity of CFT's

Vidal

Hierarchical tensor networks (MERA): pragmatic approximation scheme "stitching together" the vacuum entanglement CFT's in terms of local tensors. For a non-integrable CFT this becomes exact only when the bond dimension of the local tensors becomes "2^N".



Evenbly and Vidal (arXiv:1109.5334): to maintain the same accuracy the bond dimension has to increase by e^c with the central charge $c = N^2$. In this sense the large N limit CFT's are maximally entangled.

Many body/bit Hilbert space.

Two qubits: Hilbert space dimension $2^2 = 4$

$$|00\rangle, |01\rangle, |10\rangle, |11\rangle$$

Three qubits: Hilbert space dimension $2^3 = 8$

$$|000\rangle, |001\rangle, |010\rangle, |011\rangle, |100\rangle, |101\rangle, |110\rangle, |111\rangle,$$

Physical world 10^{23} "qubits": Hilbert space dimension $2^{10^{23}}$

$$|\Psi_n\rangle = \sum_{config.i} C_i^n |config.i\rangle$$

Overwhelming amount of quantum information.

Eigenstate Thermalization hypothesis (Srednicki, Deutscher, 90's)

"Any local observer gets overwhelmed by the enormous amount of quantum info in the physical world to such an extent that he/she does not know better than that everything becomes a thermal state at long times."

Precise formulation:

$$|\Psi(0)\rangle = \sum_n c_n |E_n\rangle$$

$$|\Psi(t)\rangle = \sum_n c_n e^{-iE_n t/\hbar} |E_n\rangle$$

$$\langle\Psi(t)|A|\Psi(t)\rangle = \sum_{n,n'} c_n c_{n'} e^{-i(E_{n'}-E_n)t/\hbar} A_{n,n'} \to Tr\left[\rho_T A\right]$$

$$\rho_T = \sum e^{-E_n/(k_B T)} |E_n\rangle\langle E_n|$$

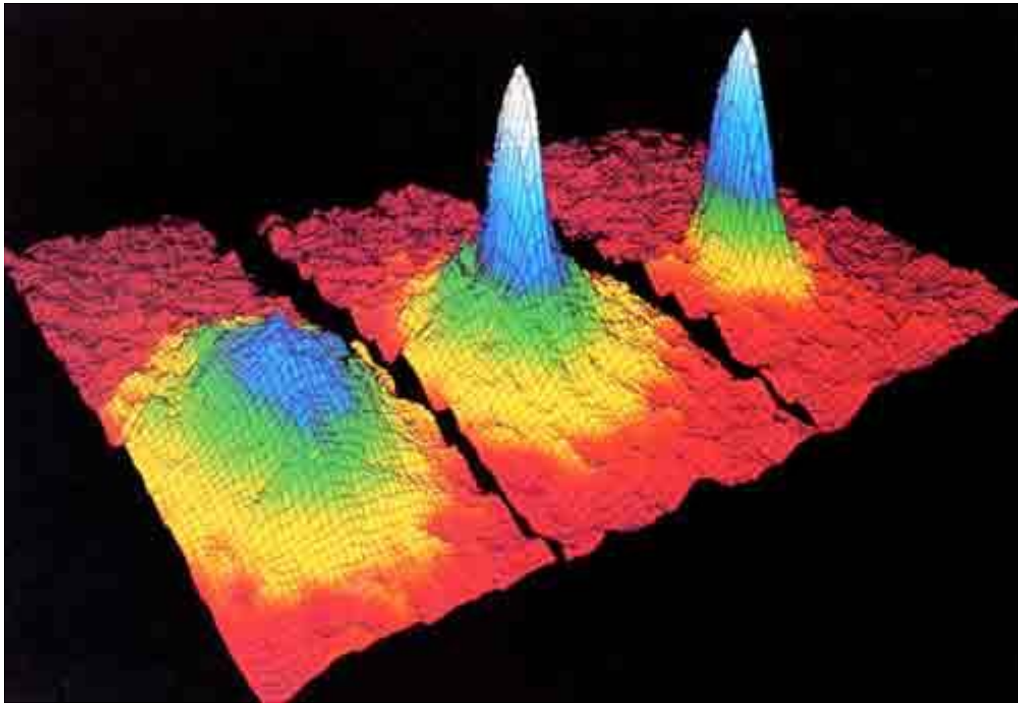
We keep moving because of hbar ..

$$\rho_T = \sum_n e^{-E_n/(k_B T)} |E_n\rangle\langle E_n|$$

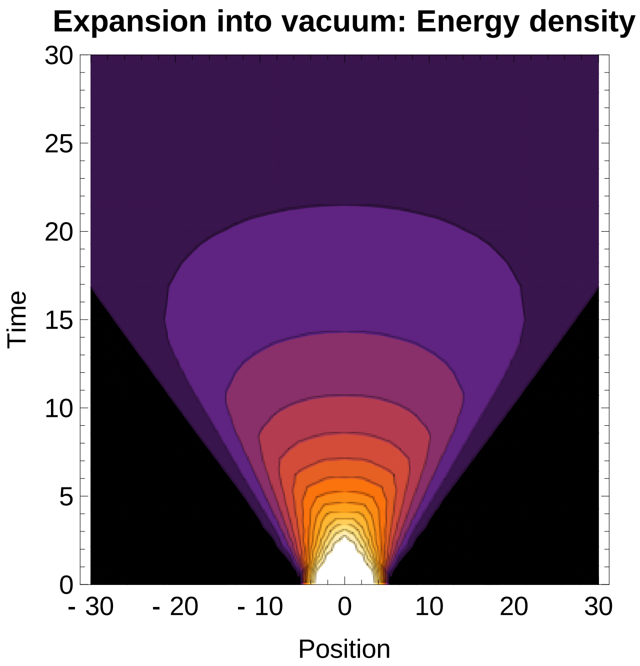
But every highy excited energy state is a hugely entangled "quantum-field computer" !? The thermal world of humans falls prey to the ultimate information overload!

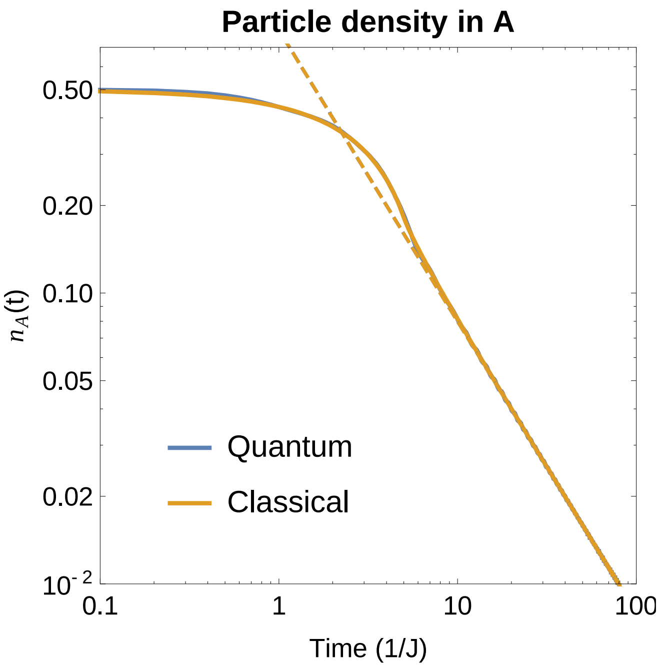
Quantum thermalization and the expansion of atomic clouds…

Louk Rademaker, JZ, Scientific Reports 7, 6118 (2017) (arXiv:1703.02489)



Expansion and the initial momentum distribution.





Louk's tric: evolve the modular hamiltonian …

Modular Hamiltonian is the log of the density matrix: $\mathcal{M} = -\log\rho.$

Initial density matrix: "A" = reservoir, "B" = bath $\rho_0 = \frac{1}{Z_A Z_B} e^{-\beta_A \mathcal{H}_A} \otimes e^{-\beta_B \mathcal{H}_B}$

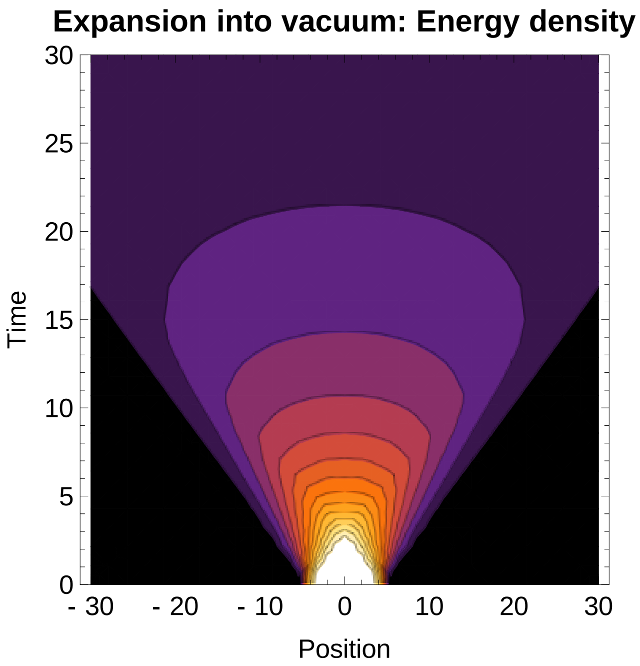
Time evolution: $\mathcal{M}(t) = e^{-i\mathcal{H}t}\mathcal{M}_0 e^{i\mathcal{H}t}.$ Free system: $\mathcal{H} = \sum_k \xi_k n_k$

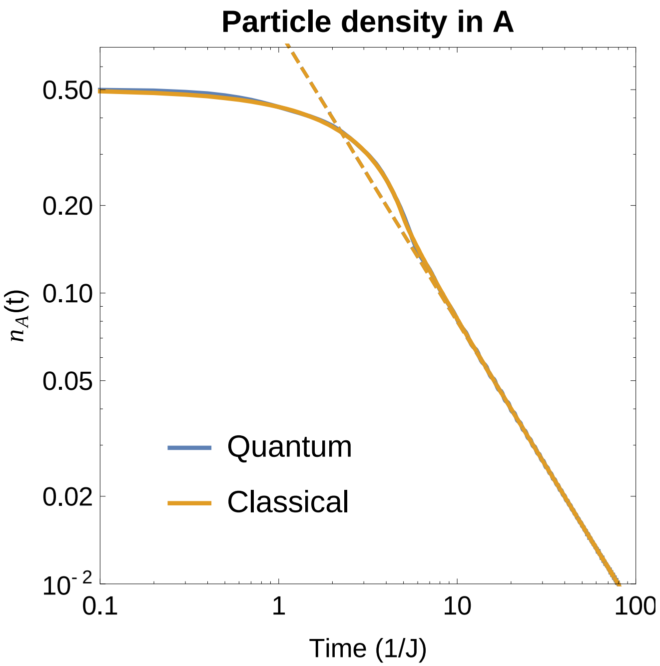
General form: $\mathcal{M}(t) = \sum_{kk'} m_{kk'}(t)\ \hat{c}_k^\dagger \hat{c}_{k'} + \log Z$

$$m_{jl}(t) = \beta_B \delta_{|j-l|=1} + (\beta_A - \beta_B) \int \frac{d^d\mathbf{k} d^d\mathbf{k}'}{(2\pi)^{2d}} e^{-i\mathbf{k}\mathbf{r}_j + i\mathbf{k}'\mathbf{r}_l} \left(\sum_{i=1}^{d} e^{ik_i} + e^{-ik_i'} \right) \left(\prod_{i=1}^{d} \frac{e^{i(k_i - k_i')(L_A - 1)} - 1}{e^{i(k_i - k_i')} - 1} \right) e^{i(\epsilon_{\mathbf{k}} - \epsilon_{\mathbf{k}'})\,t}$$

Observables: $G_{ij}(t) = \mathrm{Tr}\left[\ \hat{c}_i^\dagger \hat{c}_j \rho(t)\right]$ $\hat{G}(t) = \left[e^{\hat{m}(t)} - \eta\right]^{-1}.$

Expansion and the initial momentum distribution.



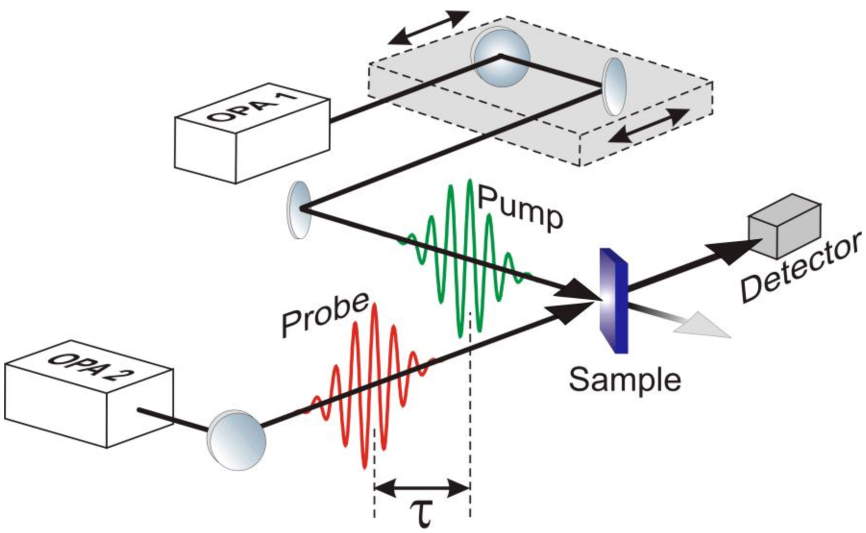


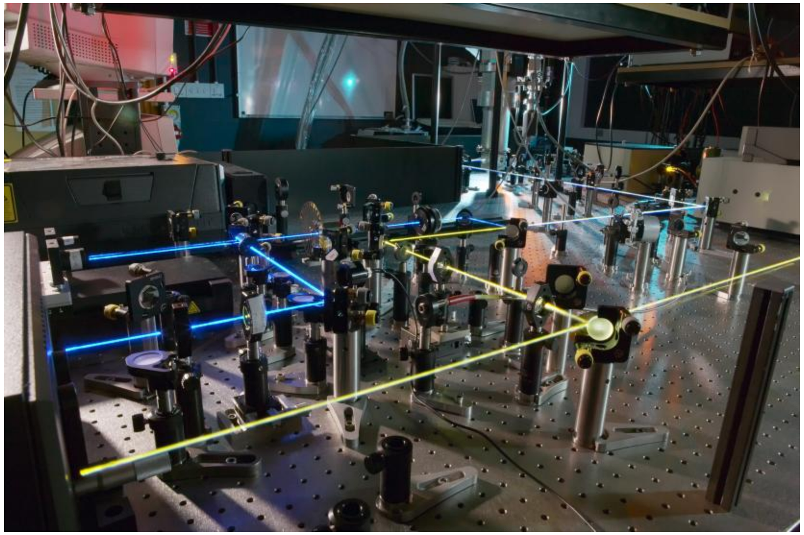
Observing quantum thermalization.

Established wisdom: given the eigenstate thermalization principle, invariably a classical dynamical analogue system can be identified that represents perfectly the knowledge of a 'classical' observer regarding the full many body unitary time evolution.

Can circumstances be identified where it is impossible to construct such a classical analogue of the quantum thermalization?

Pump probe spectroscopy.





- Pump with very short intense laser pulse.

- Measure the time evolution of e.g. the optical conductivity with small "probe" light pulses on a femtosecond time scale.

Strange metal optical pump-probe spectroscopy arXiv:1708.08279

Holography and thermalization in optical pump-probe spectroscopy

A. Bagrov,[a] B. Craps,[b] F. Galli,[c] V. Keränen,[d] E. Keski-Vakkuri,[d] J. Zaanen[e]

Einstein-Maxwell + linear axion: RN strange metal + momentum dissipation:

$$S = \frac{1}{2\kappa_4^2}\int d^4x\,\sqrt{-g}\Big[R - 2\Lambda - \frac{1}{2}\sum_{I=1}^{2}(\partial\phi_I)^2 - \frac{1}{4}F^2\Big]$$

Finite density: solve numerically for a homogeneous pulse using the Ansatz

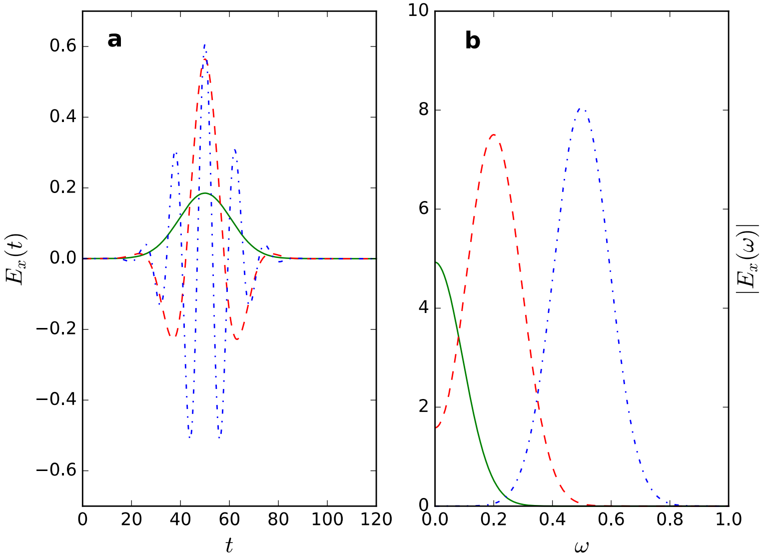
$$ds^2 = -F_z(z,v)dv^2 - \frac{2}{z^2}dvdz + 2F_x(z,v)dxdv + \Sigma(z,v)^2(e^{-B(z,v)}dx^2 + e^{B(z,v)}dy^2)$$
$$A = (E_x(v)x + a_v(z,v))dv + a_x(z,v)dx$$
$$\phi_1 = kx + \Phi(z,v)\,, \quad \phi_2 = ky$$

For a given electrical field profile in the boundary: $E_x(v=t, z=0)$

Holographic pump-probe spectroscopy (II).

Pump pulse (in units of chemical potential):

$$E_x(t) = A\cos(\omega_P t)e^{-\frac{(t-t_0)^2}{(\Delta t)^2}}\frac{1-\tanh\frac{t-t_0-3\Delta t}{\delta}}{2}$$



This is surely unitary …

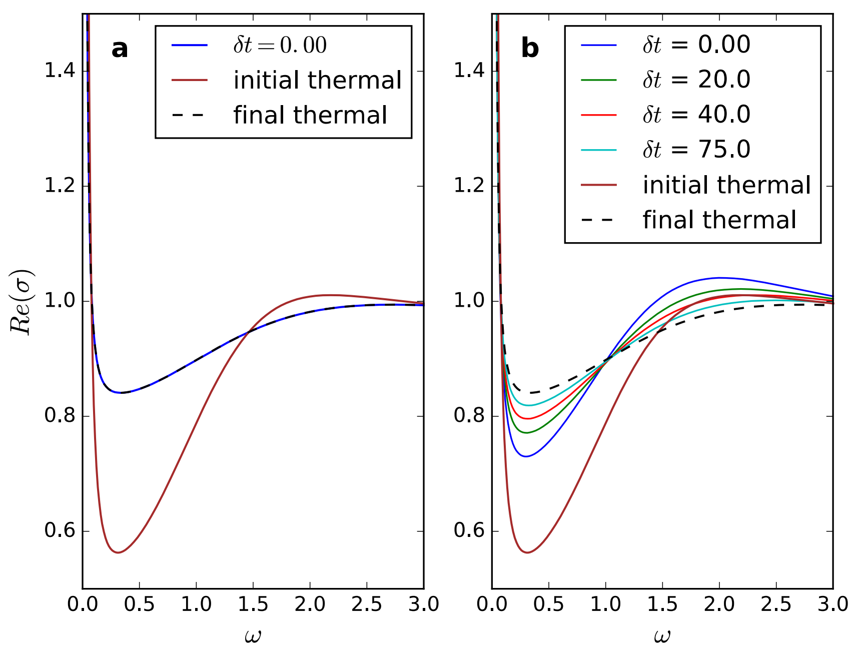
Probe optical conductivity, the two times taken after the termination of the pulse:

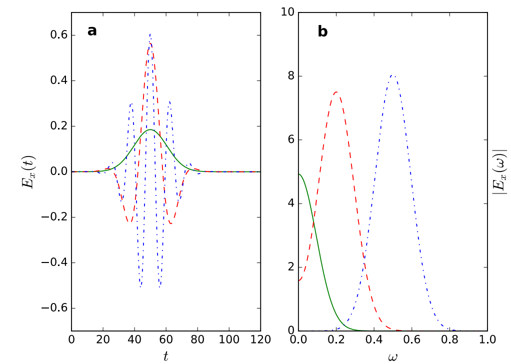
$$\delta\langle J_i(t)\rangle = \int_{t_i}^{t} dt'\sigma_{ij}(t,t')\delta E_j(t') \qquad \sigma(\omega,t) = \int_t^{t_m} dt' e^{i\omega(t'-t)}\sigma_{xx}(t',t)$$

Holographic pump-probe spectroscopy (III).

Panel a: “blue pulse”, **no zero frequency component = instantaneous thermalization**

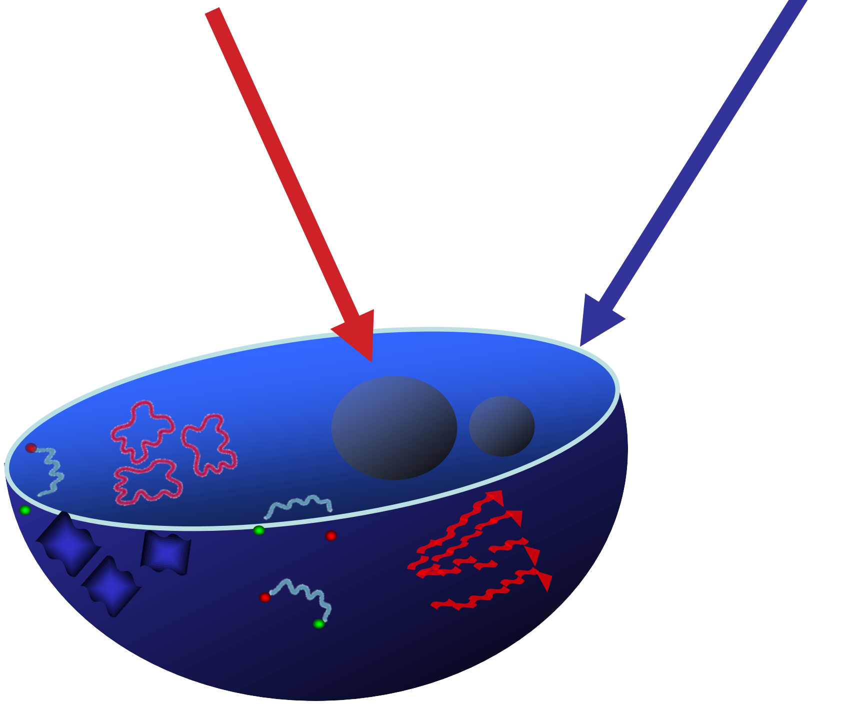
Panel b: “green/red” pulse, **zero frequency component = finite thermalization time.**





The triumph: gravitational encoding of all thermal physics!

Schwarzschild black hole
in the bulk



Boundary: the emergence theories of finite temperature matter.

- **All of thermodynamics! Caveat: phase transitions are mean field (large N limit).**

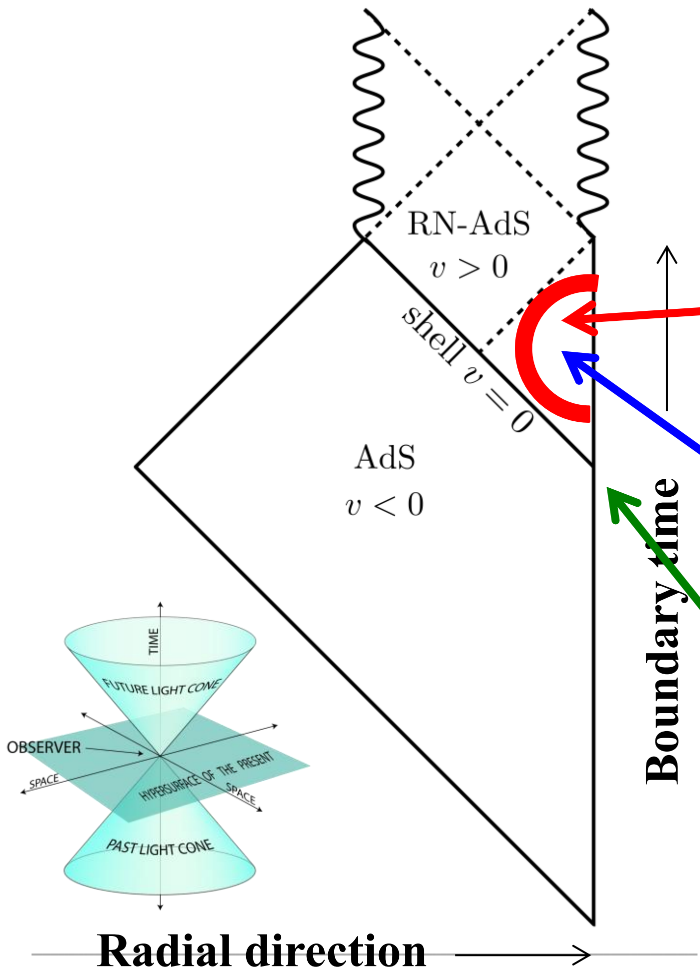
- **Precise encoding of Navier-Stokes hydrodynamics! Right now used to debug complicated hydrodynamics (e.g. anomalies).**

- **For special "Planckian dissipation" values of parameters (quantum criticality):**

$$\tau_\hbar = const.\frac{\hbar}{k_B T}, \quad const. = O(1)$$

Vaidya = holographic pump probe.

Minwalla



Equal time propagators, non-local operators (entanglement entropy) show finite thermalization time.

Causal two point propagators reveal instanteneous thermalization

Black hole space time forms immediately after the pulse

Null shell is released = pulse of transversal electric field in the CFT

Reaching the ETH speed limit …

The instantaneous thermalization of "Vaidya holography" reveals the limiting behaviour of ETH:

- Vaidya initial state literally the one of ETH: width of shell = distribution over energy eigenstates, etc.

- Homogeneous quench, single velocity: no further light cone structure.

- "Maximally strongly interacting CFT" = a quantum critical state characterized by maximally dense entanglement of excited states (large N, 't Hooft coupling).

- UV cutoff at infinity: in real systems the thermalization time will be bounded from below by the "particle physics" at the lattice scale (t-J model, etc.).

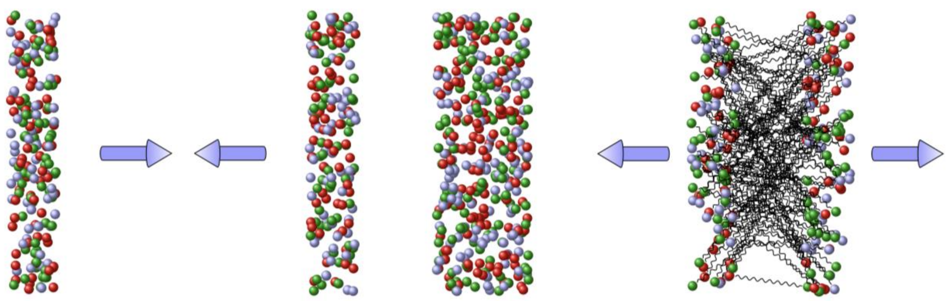
Quantum non-equilibrium tour de force.

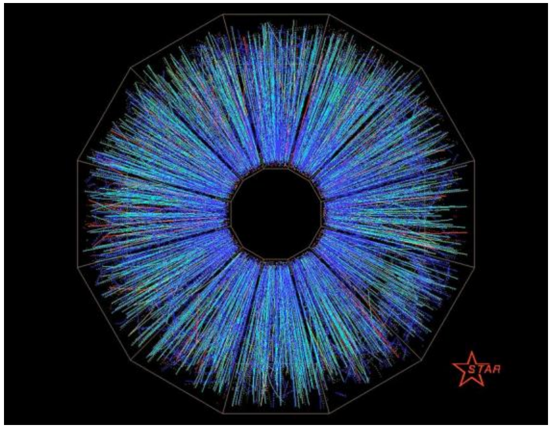
Instantaneous thermalization of causal responses reproduced in explicit quantum time evolution of densely entangled systems:

arXiv:1603.04856, Sonner et al.: homogeneous quench in large c zero density CFT.

arXiv:1706.07803, Sachdev et al.: homogeneous quench in the SYK model.

Inspiration: the quark gluon plasma.





- "Fast hydrodynamization": within the time it takes a quark to traverse half a proton radius local quark-gluon equilibrium is established.

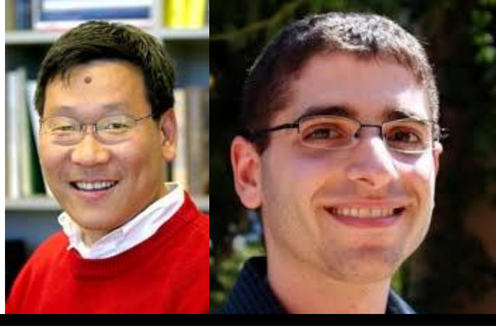
-"Minimal viscosity":

$$\frac{\eta}{s} \simeq \frac{1}{4\pi}\frac{\hbar}{k_B}$$

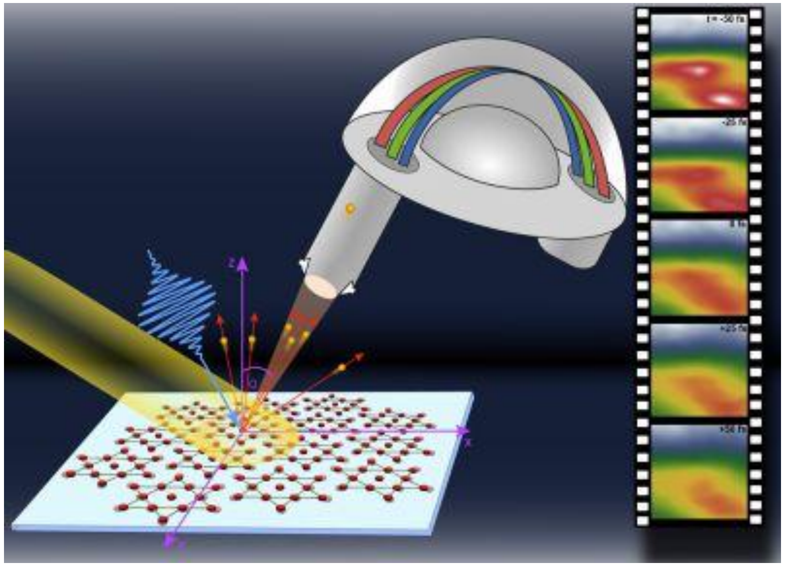
associated with "Planckian relaxation time":

$$\tau_\hbar \simeq \frac{\hbar}{k_B T}$$

Time resolved ARPES.



Z.X. Shen Sobota



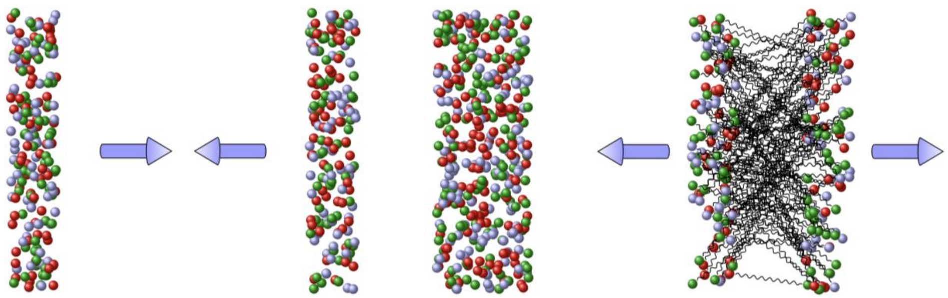
Electrons even in normal metals are very fast: thermal equilibrium in 200 femtoseconds.

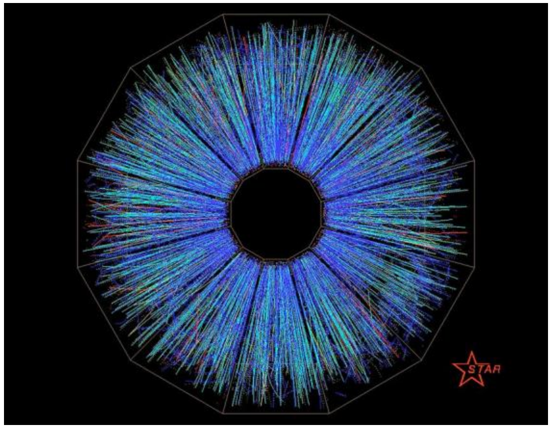
State of the art time resolution: 50 femtoseconds.

Non-equilibrium distributions have been detected in simple metals.

The Stanford group is presently looking for signs of ultra-rapid equilibration in Cuprate strange metals.

Inspiration: the quark gluon plasma.





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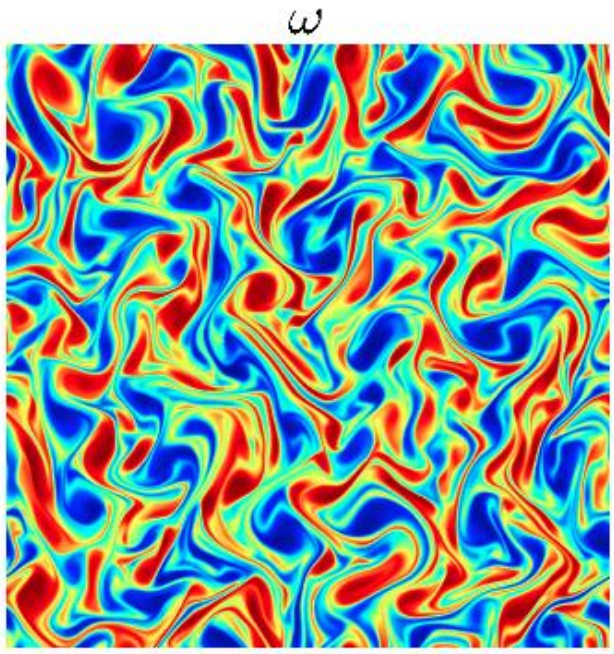
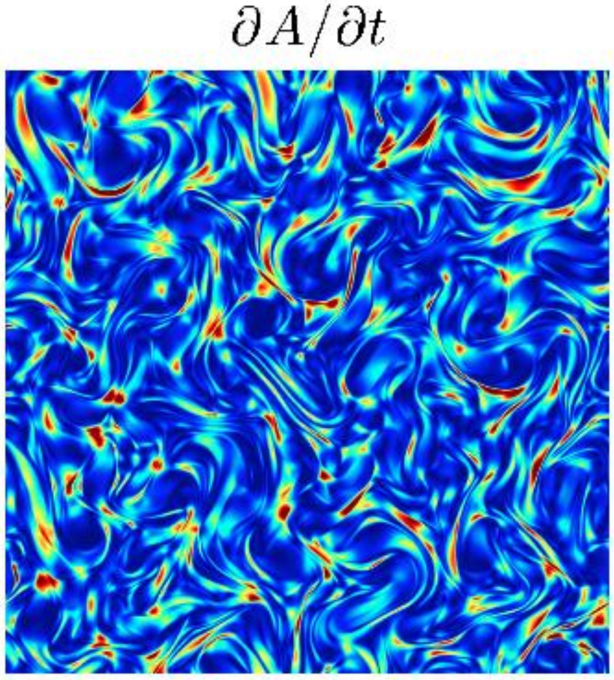
Fluid-gravity duality and the turbulent black hole hair.

Chesler Yaffe

Holography and numerical GR

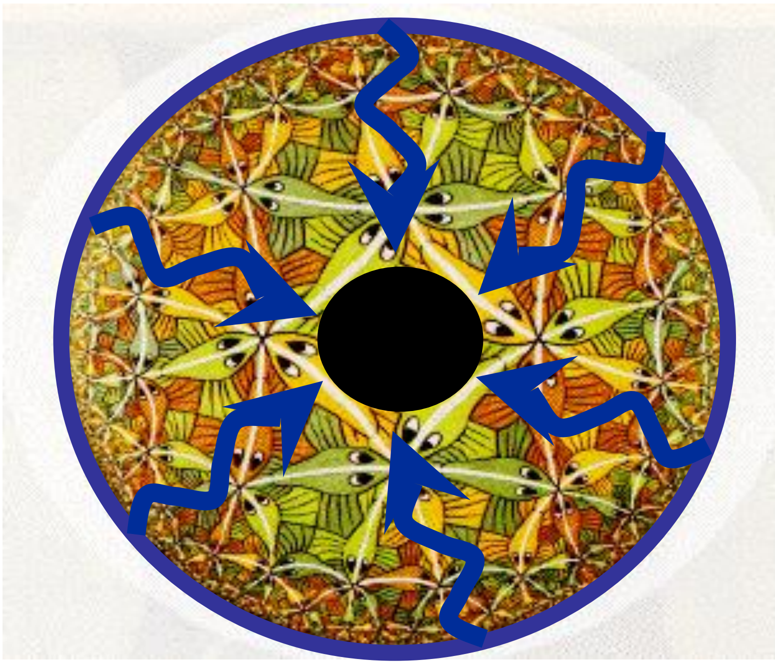


Vorticity in the liquid (Kolmagorov scaling)



Near horizon geometry (fractal)

Dissipation = absorption of classical waves by Black hole!



Policastro-Son-Starinets (2002):

Viscosity: absorption cross section of gravitons by black hole

$$\eta = \frac{\sigma_{abs}(0)}{16\pi G}$$

= area of horizon (GR theorems)

Entropy density s: Bekenstein-Hawking BH entropy = area of horizon

Universal viscosity-entropy ratio for CFT's with gravitational dual limited in large N by:

$$\frac{\eta}{s} = \frac{1}{4\pi}\frac{\hbar}{k_B}$$

Planckian dissipation: the origin.

- In a classical system relaxation times are determined by many "collisions" that all take a finite time.

- This is invariably a complicated business: the viscosity of water is still very hard to compute reliably!

- In the finite temperature densely entangled compressible quantum fluids it becomes extremely simple: "Planckian dissipation"

$$\tau_K = A \frac{\hbar}{k_B T}$$

This is Eigenstate Thermalization at work near equilibrium!

Take home message

Quantum Many body entanglement makes the difference!

The matter explained in physics books (including standard model): "short range entangled product" = ruled by the principles of classical physics on the macroscopic scale.

"Quantum supreme matter" = "stuff that quantum computes all by itself", "everything is entangled with everything on the macroscopic scale".

Ruled by "physical laws" of an entirely new kind, believing the black holes …