About the Unruh temperature

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November 4, 2018

Talk by T.S.Biró at University of Szeged, Hungary Nov. 8, 2018.

Outline of this talk

Hawking: **"The greatest enemy of knowledge is not ignorance, but the illusion of knowledge."**

- Acceleration and energy variance
- Rindler trajectories in imaginary time
- Accelerated Doppler $\rightarrow$ Planck spectrum
- Other radiation and other effects

Planck scale

from natural constants

We have **four** natural constants: $G, c, k, \hbar$.

They connect:

1. c: length with time, and mass with energy
2. G: mass and length with energy
3. k: temperature with energy
4. $\hbar$: action scale: energy with time, momentum with length

try and catch: $M_P = \sqrt{\hbar c/G}, \quad L_P = \sqrt{\hbar G/c^3}$

Planck scale

in a physical situation

In a Compton wavelength distance from source the Newton potential equals to the rest mass energy.

From this follows

$$\frac{GMm}{r} = mc^2 \qquad \text{and} \qquad r = \frac{\hbar}{Mc} \tag{1}$$

This concludes again as

$$\frac{GM^2c}{\hbar} = c^2. \tag{2}$$

solution: $M = M_P = \sqrt{\hbar c/G}, \quad r = L_P = \sqrt{\hbar G/c^3}$

Planck's natural system of units

M. Planck, Über irreversible Strahlungsvorgänge, Sitz.Ber.Preuss.Akad.Wiss. 449-476 (1898)

Wiens'law: $w = \frac{8\pi\nu^2}{c^3} b\nu\, \mathrm{e}^{-a\nu/T}$. From Planck's law limit: $b = h = 6.626 \times 10^{-27}$ erg sec, and $a = h/k = 4.798 \times 10^{-11}$ cm K.

1. length: $L_P = \sqrt{\hbar G/c^3} = 1.616 \times 10^{-33}$ cm
2. mass: $M_P = \sqrt{\hbar c/G} = 2.176 \times 10^{-5}$ g
3. time: $t_P = L_P/c = 5.392 \times 10^{-44}$ s
4. temperature: $T_P = M_P c^2/k = 1.417 \times 10^{32}$ K.

"These quantities preserve their natural meaning as long as the laws of gravitation, propagation of light in vacuum and both the two laws of heat theory remain valid, that is, being measured by most various intelligent beings unsing most different methods, they must always give the same value."

Uncertainty relations

Hermitic operators

and their combinations

Let $A = A^\dagger$, $B = B^\dagger$ (be hermitic operators). For the sake of simplicity: $\langle A \rangle = \langle B \rangle = 0$.
Now $\Delta A^2 = \left\langle A^2 \right\rangle$ and $\Delta B^2 = \left\langle B^2 \right\rangle$.

We construct a combined (not hermitic) operator:

$$C \equiv \lambda A + \frac{i}{\lambda^*} B. \tag{3}$$

From this $C^\dagger = \lambda^* A - \frac{i}{\lambda} B$.

$$\begin{aligned} CC^\dagger &= |\lambda|^2 A^2 + iBA - iAB + \frac{1}{|\lambda|^2} B^2 \\ C^\dagger C &= |\lambda|^2 A^2 - iBA + iAB + \frac{1}{|\lambda|^2} B^2 \end{aligned} \tag{4}$$

$\left\langle CC^\dagger \right\rangle \geq 0$ **and** $\left\langle C^\dagger C \right\rangle \geq 0$.

An inequality

following from $\langle CC^\dagger \rangle \geq 0$ and $\langle C^\dagger C \rangle \geq 0$

A consequence of eq.(4)

$$\frac{1}{2}\left(|\lambda|^2 \left\langle A^2 \right\rangle + \frac{1}{|\lambda|^2} \left\langle B^2 \right\rangle \right) \geq \left| \left\langle \frac{i}{2}[A,B] \right\rangle \right| \tag{5}$$

The minimum of the arithmetic mean is just the geometric one!

$$\Delta A \cdot \Delta B = \sqrt{\left\langle A^2 \right\rangle \left\langle B^2 \right\rangle} \geq \left| \left\langle \frac{i}{2}[A,B] \right\rangle \right| . \tag{6}$$

Minimal variance relations

Not "insecurity"

Note: $A_2 = A + a1$ and $B_2 = B + b1$ imply $[A_2, B_2] = [A, B]$ and $\Delta A_2^2 = \langle A_2^2 \rangle - \langle A_2 \rangle^2 = \langle A^2 \rangle$, same for B_2.

☺ **The general result** ☻

$$\Delta A \cdot \Delta B \geq \left| \left\langle \frac{i}{2} [A, B] \right\rangle \right| \tag{7}$$

- $\Delta x \cdot \Delta p \geq \left| \left\langle \frac{i}{2} \frac{\hbar}{i} \right\rangle \right| = \frac{\hbar}{2}.$ **Heisenberg**
- $\Delta E \cdot \Delta p \geq \left| \left\langle \frac{i}{2} [H, P] \right\rangle \right| = \frac{\hbar}{2} |\langle F \rangle|.$ **Force**
- $\Delta E \cdot \Delta x \geq \left| \left\langle \frac{i}{2} [H, Q] \right\rangle \right| = \frac{\hbar}{2} |\langle v \rangle|.$ **Velocity**

Variance-bounds beyond Heisenberg

Clock-operator

In closed systems $\frac{\mathrm{d}A}{\mathrm{d}t} = \frac{i}{\hbar}[H, A]$. The inequality says

$$\Delta E \cdot \Delta A \geq \left| \frac{i}{2}[H, A] \right| = \frac{\hbar}{2} \left| \left\langle \frac{\mathrm{d}A}{\mathrm{d}t} \right\rangle \right| . \tag{8}$$

Rearranged somewhat

$$\Delta E \cdot \frac{\Delta A}{\left| \left\langle \frac{\mathrm{d}A}{\mathrm{d}t} \right\rangle \right|} \equiv \Delta E \cdot \Delta t_A \geq \frac{\hbar}{2} . \tag{9}$$

All time elapse variances defined by such operators do have a lower bound!

Variance-bounds beyond Heisenberg

Gravitational red-shift

Energy of a radially moving photon in SChwarzschild metric, in weak grav. field:

$$E \;=\; \hbar\omega\sqrt{1-\frac{2GM}{c^2 r}} \;\approx\; \hbar\omega \;-\; \frac{GM}{r}\,\frac{\hbar\omega}{c^2}. \tag{10}$$

$\langle E\rangle \approx \hbar\omega$, and due to the dispersion formula $\Delta E = c\Delta p$. Expectation value of the force $\langle F\rangle \;=\; \frac{GM}{r^2}\frac{\hbar\omega}{c^2} \;=\; g\frac{\hbar\omega}{c^2}$.

Let us apply here the result "product of enbergy and momentum variances $\geq \hbar/2$ times the exp. value of the force":

$$\Delta E\cdot\frac{\Delta E}{c} \;\geq\; \frac{\hbar}{2}\,\frac{\langle E\rangle}{c^2}\,g. \tag{11}$$

Photon uncertainty

$$\frac{\Delta E^2}{\langle E\rangle} \;\geq\; \frac{\hbar g}{2c} \;=\; \pi k T_{\mathrm{Unruh}}. \tag{12}$$

For the Boltzmann distribution $\Delta E^2/\langle E\rangle = kT$ is exact!

Constant acceleration on a line

in the comoving frame using $c = 1$ units

Velocity four-vector:

$$u^{\mu} = (\cosh\eta, \sinh\eta, 0, 0)\,. \tag{13}$$

Acceleration four-vector:

$$\frac{\mathrm{d}u^{\mu}}{\mathrm{d}\tau} = \frac{\mathrm{d}\eta}{\mathrm{d}\tau}\,(\sinh\eta, \cosh\eta, 0, 0)\,. \tag{14}$$

Its constant Minkowski-length be

$$\left\|\frac{\mathrm{d}u^{\mu}}{\mathrm{d}\tau}\right\|^2 = -\left(\frac{\mathrm{d}\eta}{\mathrm{d}\tau}\right)^2 = -g^2. \tag{15}$$

solution: $\eta = g\,\tau$.

Rindler trajectories

defined by constant comoving acceleration

One obtains

$$u^\mu = (\cosh(g\tau),\, \sinh(g\tau),\, 0,\, 0) \tag{16}$$

The Rindler trajectories are given in the $x^\mu(\tau)$ parametrization:

$$x^\mu = \left(\frac{1}{g} \sinh(g\tau),\, \frac{1}{g}(\cosh(g\tau) - 1),\, 0,\, 0 \right). \tag{17}$$

In the low acceleration limit we obtain **Galilei's** result:

$$x^\mu \approx \left(\tau,\, g\frac{\tau^2}{2},\, 0,\, 0 \right). \tag{18}$$

Rindler trajectories in imaginary time

are periodic!

Consider $\tau = i\hbar\beta$ with $\beta = 1/kT$.

The Rindler trajectory becomes

$$x^\mu = \left(\frac{i}{g} \sin(\hbar\beta g), \frac{1}{g}(\cos(\hbar\beta g) - 1), 0, 0 \right). \tag{19}$$

Taken at the period, $g\tau = g(i\hbar\beta) = 2i\pi$, we determine the **Unruh** temperature:

Unruh temperature as an imaginary-time period *c* restored ☺

$$kT = \frac{\hbar g}{2\pi c}. \tag{20}$$

Doppler effect

signals from moving source

Spectrum of a monochromatic source: $\delta(\nu-\omega)$

Spectrum of an inertially moving mono source: $\delta\left(\nu-\gamma(\omega-k\cdot v)\right)$

Spectrum of a free falling source on a line?

$$S(\nu) \sim \left|\mathcal{F}_{\tau}^{-1}\left(e^{i(\omega t(\tau)-kx(\tau))}\right)\right|^{2}. \tag{21}$$

Doppler effect

phase and amplitude along Rindler trajectories

The phase in the Fourier back-transformation: $\varphi = \omega(t - x)$ in $c = 1$ units.

On a Rindler trajectory the retarded time:

$$t - x \; = \; \frac{1}{g} \left[1 - e^{-g\tau} \right] \tag{22}$$

Here $g \to g/c$ is a frequency...

The dimensionless Fourier amplitude becomes

$$A(\nu) \; = \; e^{i\omega/g} \int_{-\infty}^{+\infty} e^{-i\frac{\omega}{g} e^{-g\tau}} \, e^{i\nu\tau} \, g d\tau. \tag{23}$$

Doppler effect

integral over red-shift factor

The red-shift factor, $z = \frac{d}{d\tau}(t-x) = e^{-g\tau}$ is a good variable.

Its limiting values are: $z(-\infty) = +\infty$ and $z(+\infty) = 0$. Differentials: $gd\tau = -dz/z$.

The complex amplitude becomes

$$A(\nu) = e^{i\omega/g} \int_0^\infty \frac{dz}{z} e^{-i\omega z/g} e^{i\nu(-\frac{1}{g}\ln z)} = e^{i\omega/g} \left(i\frac{\omega}{g}\right)^{i\nu/g} \Gamma\left(-i\frac{\nu}{g}\right). \qquad (24)$$

Important: $i^{i\frac{\nu}{g}} = e^{i\frac{\pi}{2}\cdot\frac{i\nu}{g}} = e^{-\frac{\pi\nu}{2g}}$

Doppler effect

the observed intensity

With fixed sign of g there is **no time reversal**: $A(-\nu) \neq A(\nu)^*$.

The intensity:

$$|A(\nu)|^2 = e^{-\pi\frac{\nu}{g}}\,\Gamma\left(i\frac{\nu}{g}\right)\,\Gamma\left(-i\frac{\nu}{g}\right). \tag{25}$$

A property of Gamma functions:

$$\Gamma(ix)\,\Gamma(-ix) = \frac{1}{(-ix)}\,\Gamma(ix)\,\Gamma(1-ix) = \frac{i}{x}\,\frac{\pi}{i\sinh(\pi x)} = \frac{\pi}{x\sinh(\pi x)}. \tag{26}$$

leads to

$$N(\nu) \equiv \frac{\nu}{2\pi g}\,|A(\nu)|^2 = \frac{1}{e^{2\pi\nu/g}-1}. \tag{27}$$

Compare with Planck's law: $kT = g\hbar/(2\pi c)$.

Time reversal

KMS relation

What about negative frequencies ("heated vacuum")?

$$\frac{|A(-\nu)|^2}{|A(+\nu)|^2} = \mathrm{e}^{\frac{2\pi\nu c}{g}} \tag{28}$$

Kubo-Martin-Schwinger for the numbers:

$$\frac{-N(-\nu)}{N(\nu)} = \mathrm{e}^{\frac{2\pi\nu c}{g}} = 1 + \frac{1}{N(\nu)}. \tag{29}$$

KMS interpretation ☺

$$-N(-\nu) = 1 + N(\nu). \tag{30}$$

Pseudo-thermalization? Pseudo-Hydro?

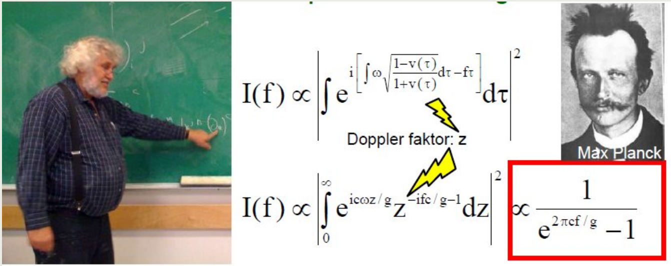
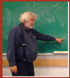


Figure: Unruh effect (1975), Hawking radiation (1975)

$$v = \tanh\xi, \quad u_i = (\cosh\xi, \sinh\xi), \quad a_i = (\sinh\xi, \cosh\xi)\frac{d\xi}{d\tau}$$

$$a_i a^i = -g^2, \qquad \xi = \xi_0 - g\tau; \qquad z = e^{-\xi}, \qquad g\, d\tau = \frac{dz}{z}.$$



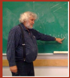
Is the Unruh temperature measurable?

Unruh temperature in Planck units: $\boxed{T = \frac{g}{2\pi}}$

Unruh temperature in ordinary units: $\boxed{k_B T = \frac{\hbar}{c} \frac{g}{2\pi}}$

Small for Newtonian gravity: $g = GM/R^2$, therefore $k_B T = Mc^2/2\pi \cdot L_P^2/R^2$. On Earth' surface we have $k_B T \approx 10^{-19}$ eV ($10^{-16}\times$ room temperature) .

Perceivable for heavy ion collisions: $g = c^2/L = mc^3/\hbar$ for stopping in a Compton wavelength. For a proton of mass $m = 940$ MeV we have $k_B T = mc^2/2\pi \approx 150$ MeV.



Photon Spectrum from Linear Acceleration

Photon number:

$$d^3N = \frac{1}{2k_0}\frac{d^3k}{(2\pi)^3}\sum\left|\epsilon^{(a)}\cdot J(k)\right|^2$$

Source:

$$J^i(k) = q\int e^{ik\cdot x(\tau)}u^i(\tau)\,d\tau.$$

After partial integration only the acceleration related term kept:

$$\epsilon\cdot J(k) = q\int_{\tau_1}^{\tau_2} e^{ik\cdot x(\tau)}\,\frac{d}{d\tau}\left(\frac{\epsilon\cdot u}{k\cdot u}\right)\,d\tau$$

Relativistic Kinematics

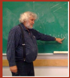
Photon $k_i = k_\perp(\cosh\eta, \sinh\eta, \cos\psi, \sin\psi)$
Source velocity: $u_i = (\cosh\xi, \sinh\xi, 0, 0)$
Integration parameter: $v_i = \tanh(\xi - \eta)$, $\qquad g = d\xi/d\tau$.
Amplitude

$$\mathcal{A} = \frac{e^{i\phi_0}}{k_\perp} \int_{v_1}^{v_2} e^{ik_\perp \gamma v/g}\, dv$$

Photon Yield

$$k_\perp^2 \frac{dN}{k_\perp dk_\perp d\eta} = 2\alpha \left| \int_{\xi_1-\eta}^{\xi_2-\eta} e^{i\,(k_\perp/g)\,\sinh\xi} \frac{d\xi}{\cosh^2\xi} \right|^2$$

Relation to Unruh



Photon Yield for infinitely long path ($\xi_1 = -\infty$, $\xi_2 = +\infty$):

$$k_\perp^2 \frac{dN}{k_\perp \, dk_\perp \, d\eta} = 8\alpha \frac{k_\perp^2}{g^2} K_1^2 \left(k_\perp / g \right)$$

Asymptotics of the Bessel K-function is **exponential**!

$$\frac{dN}{k_\perp \, dk_\perp \, d\eta} \longrightarrow \frac{8\alpha}{g^2} \frac{\pi g}{2k_\perp} \, \mathrm{e}^{-2k_\perp / g}$$

$$\boxed{T_{\text{spectral}} = \pi \, T_{\text{Unruh}} = \text{min. of } \frac{\Delta E^2}{\langle E \rangle}.}$$

Nonrelativistic approximation ($\gamma = 1$)

$$k_{\perp}^{2} \frac{dN}{k_{\perp}\, dk_{\perp}\, d\eta} = \frac{8\alpha g^{2}}{k_{\perp}^{2}} \sin^{2}\left(\frac{k_{\perp}}{2g} (v_{2} - v_{1}) \right)$$

This gives an invariant yield smaller than $1/k_{\perp}^{4}$, and shows interference effects.

Infrared ($k_\perp \to 0$) limit

even relativistic!

$$\lim_{k_\perp \to 0} k_\perp^2 \frac{dN}{k_\perp \, dk_\perp \, d\eta} = 2\alpha \left| v_2 - v_1 \right|^2$$

In terms of rapidities

$$\lim_{k_\perp \to 0} k_\perp^2 \frac{dN}{k_\perp \, dk_\perp \, d\eta} = 2\alpha \left| \frac{2 \, \sinh \xi_{\text{rel}} \, \cosh \xi_{\text{rel}}}{\cosh^2(\eta - \xi_{\text{mid}}) \, + \, \sinh^2(\xi_{\text{rel}})} \right|^2$$

rel: half difference, mid: half sum.

Short Time and Long Time Acceleration

Short time –> small $|\xi_{\rm rel}|$ Landau-like bell shape

$$\lim_{k_\perp \to 0} k_\perp^2 \frac{dN}{k_\perp dk_\perp d\eta} = 8\alpha \frac{\xi_{\rm rel}^2}{\cosh^4(\eta - \xi_{\rm mid})}$$

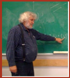
Long time –> large $|\xi_{\rm rel}|$ Bjorken-Hwa-like plateau

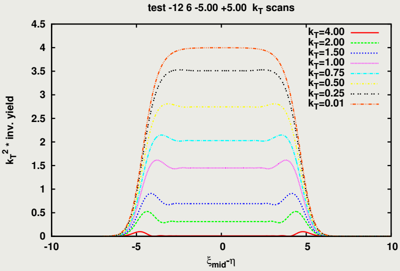
$$\lim_{k_\perp \to 0} k_\perp^2 \frac{dN}{k_\perp dk_\perp d\eta} = 8\alpha \frac{1}{\left(1 + 4\, e^{-2|\xi_{\rm rel}|} \sinh^2(\eta - \xi_{\rm mid})\right)^2}$$

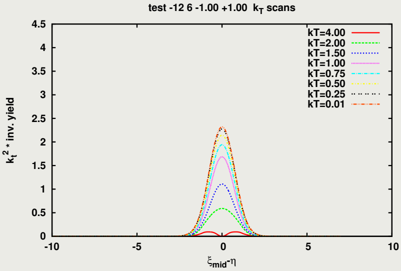
Infinite time: Biró + Gyulassy + Schram: PLB 708: 276 (2012)

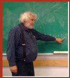
(Semi)classical Photon Rapidity Spectra

T. S. Biro, Z. Schram, Z. Szendi: EPJ A 50 (2014) 62

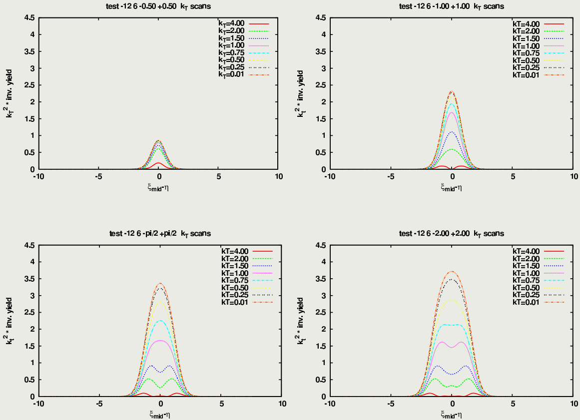








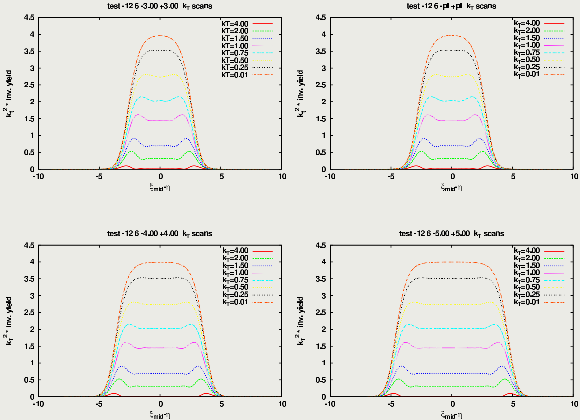
Differential Photon Rapidity Distributions



Short time

small ξ_{rel}

Differential Photon Rapidity Distributions



Long time

large ξ_{rel}

Elliptic Flow

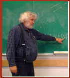
T. S. Biro, M. Horvath, Z. Schram: EPJ A 51 (2015) 75

- Illusory Flow by Unruh type radiation in $dN/d\eta$
  - (1401.1987 –> EPJ A 2014)
- Exponential Tails in $k_\perp$ envelop interference
  - (1111.4817 –> PLB 708 (2012) 276)
- This section: Jacobi-Anger Formula delivers Elliptic Flow –> EPJ A 2015

Fourier Spectrum of Phase Difference in $k_\perp$-space

Jacobi-Anger Formula

$$e^{ix\cos\Theta} = J_0(x) + 2\sum_{n=1}^{\infty} i^n J_n(x)\cos(n\Theta). \tag{31}$$



Interference Term in 1-Photon Yield

The yield is proportional to

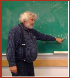
$$Y \propto \left| A_1 e^{ik\cdot x_1} + A_2 e^{ik\cdot x_2} \right|^2 \tag{32}$$

Detector angle α, distance angle ψ, distance d result in

$$Y \propto \left| A_1 e^{ik_\perp \frac{d}{2} \cos(\alpha-\psi)} + A_2 e^{-ik_\perp \frac{d}{2} \cos(\alpha-\psi)} \right|^2 \tag{33}$$

Expanding the square we arrive at (real and positive):

$$Y \propto |A_1|^2 + |A_1|^2 + A_1 A_2^* e^{ik_\perp d \cos(\alpha-\psi)} + A_1^* A_2 e^{-ik_\perp d \cos(\alpha-\psi)} \tag{34}$$



Higher Flow coefficients

$\Theta = \alpha - \psi$

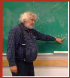
Flow coefficients are defined by relative amplitudes of $\cos(n\Theta)$ terms to the zeroth order term.

$$v_n = \frac{2 R_n \, J_n(k_\perp d)}{|A_1|^2 + |A_2|^2 + R_0 \, J_0(k_\perp d)} \tag{35}$$

with

$$R_n := 2 \, \mathrm{Re} \left(i^n A_1 A_2^* \right) = 2 \, |A_1| \, |A_2| \, \cos \left(\Delta\varphi + n \frac{\pi}{2} \right).$$

In relative ratios of this *Young* interference $k_\perp$ powers cancel in the ratio of A-squares!!!



Higher Flow coefficients

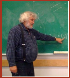
The complex amplitudes may differ in a further phase $\Delta\varphi$ due to longitudinal and time positions at the start and at the end of deceleration.

We define the interference ratio :

$$r_n := \frac{2\,|A_1|\,|A_2|}{|A_1|^2 + |A_2|^2}\,\cos\left(\Delta\varphi + \frac{n\pi}{2}\right). \tag{36}$$

We get

$$v_n = \frac{2 r_n\, J_n(k_\perp d)}{1 + r_0\, J_0(k_\perp d)} \tag{37}$$



v2 behavior

For $n = 2$ the (in)famous v_2 is

$$v_2 = \frac{-2\,\varepsilon\, J_2(k_\perp d)\, cos(\Delta\varphi)}{1 + \varepsilon\, J_0(k_\perp d)\, cos(\Delta\varphi)} \tag{38}$$

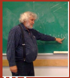
with

$$\varepsilon = \frac{2\,|A_1|\,|A_2|}{|A_1|^2 + |A_2|^2} \leq 1. \tag{39}$$

For small $k_\perp d$ the J-Bessel behave like power, so v_2 would go like $k_\perp^2$.

Longitudinal Phase averaged v_2

formula



Considering a longitudinal phase difference $\Delta\varphi$

$$v_n = \frac{2\varepsilon J_n \cos\left(\Delta\varphi + n\frac{\pi}{2}\right)}{1 + \varepsilon J_0 \ \cos(\Delta\varphi)}. \tag{40}$$

Integrating over $\Delta\varphi$ uniformly we obtain

$$\langle v_n \rangle = 2\cos(n\frac{\pi}{2})\,\frac{J_n}{J_0}\left(1 - \frac{1}{\sqrt{1-\varepsilon^2 J_0^2}}\right) \tag{41}$$

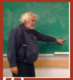
In particular for $|A_1| = |A_2|$ it is $\varepsilon = 1$ and one obtains

$$\langle v_2 \rangle = 2\frac{J_2}{J_0}\left(\frac{1}{\sqrt{1-J_0^2}} - 1\right) \tag{42}$$

This result starts **linearly** for small $k_\perp d$.

Longitudinal Phase averaged v_2

picture



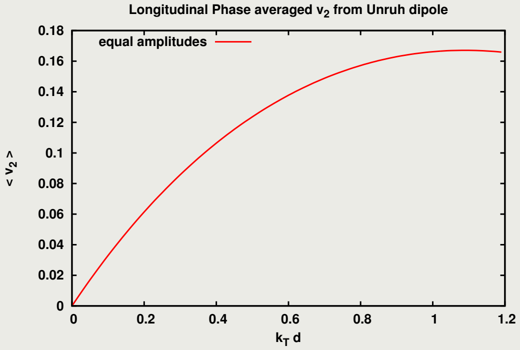
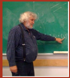


Figure: It starts linear, then levels, then falls again.



v_2 vs amplitudes

formulas

v_2 coefficient expressed by the amplitude ratio:

$$v_2 = F_2 \frac{2J_2(x)}{J_0(x)} \left(\frac{1}{\sqrt{1-\varepsilon^2 J_0^2(x)}} - 1 \right) \tag{43}$$

with $x = k_\perp d$,

$$\varepsilon = \frac{2\,|A_1|\,|A_2|}{|A_1|^2 + |A_2|^2} \tag{44}$$

and F_2 depending on centrality, but not on $k_\perp$.

v_2 dependence on amplitude ratio $|A_1|/|A_2|$ picture

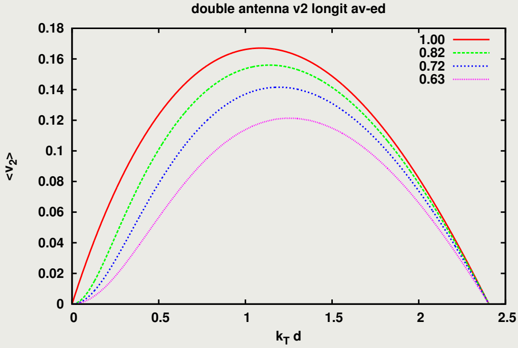


Figure: It starts linear only for equal amplitudes, otherwise quadratic. For all curves $F_2 = 1$.

v_2 (de-)magnified by centrality factors

picture

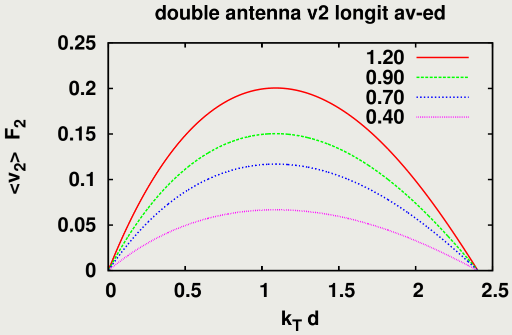
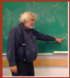


Figure: It copies the same core function with $k_\perp$-independent factors.



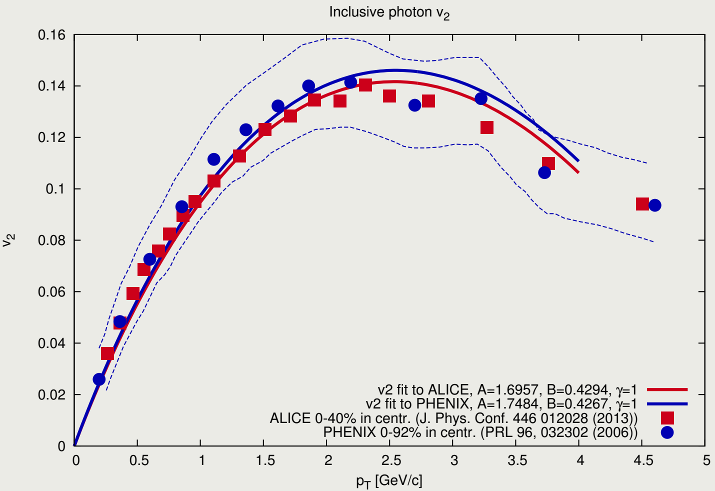
Fit parameters

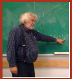
In the simplest (two-antenna arrays) scenario we fit:

- $\varepsilon = \frac{2\gamma}{1+\gamma^2}, \quad \gamma = |A_1|/|A_2|$ magnitude ratio parameter
- $B = d$ antenna distance parameter
- $A = F_2$ geometric form factor

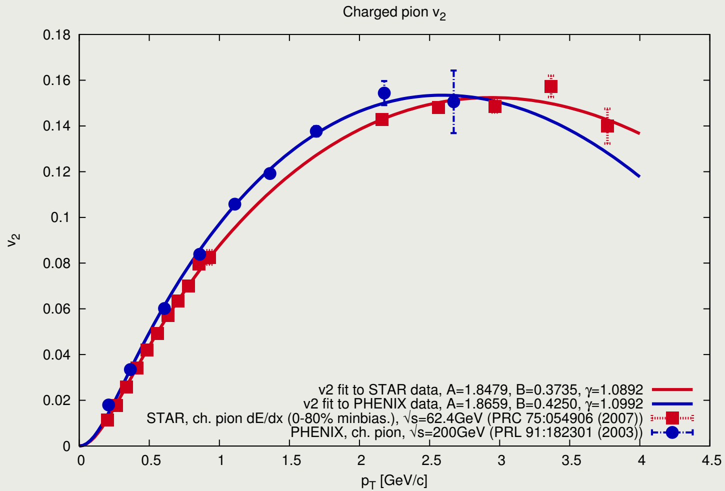
We assume that F_2 depends on centrality, but not on the momentum $k_\perp$.

Photon v_2

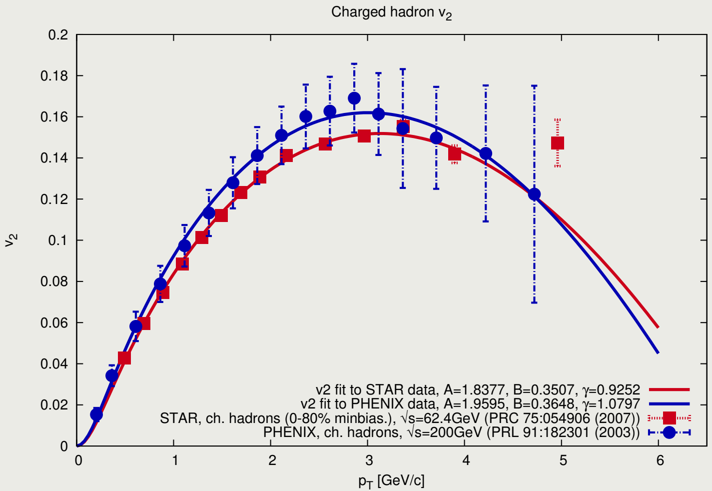

Inclusive photon v2
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
v2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
pT [GeV/c]
v2 fit to ALICE, A=1.6957, B=0.4294, γ=1
v2 fit to PHENIX, A=1.7484, B=0.4267, γ=1
ALICE 0-40% in centr. (J. Phys. Conf. 446 012028 (2013))
PHENIX 0-92% in centr. (PRL 96, 032302 (2006))

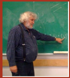


Pion


Charged pion v2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
v2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
pT [GeV/c]
v2 fit to STAR data, A=1.8479, B=0.3735, γ=1.0892
v2 fit to PHENIX data, A=1.8659, B=0.4250, γ=1.0992
STAR, ch. pion dE/dx (0-80% minbias.), √s=62.4GeV (PRC 75:054906 (2007))
PHENIX, ch. pion, √s=200GeV (PRL 91:182301 (2003))

Charged hadrons

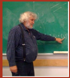




Fit conclusions

- Even a simple model comes close to data
- No need for hydrodynamics or initial state fluctuations
- Fits to amplitude ratio and characteristic distance are stable
- Fits to the centrality factor scatter

The shape of v_2 vs $k_\perp$ is explained well!



Summary of heavy-ion related studies

- Spectral temperature can be a ”deceleration effect”
- Bell-shaped and Plateau-shaped Rapidity Distributions from ”relativistic Doppler”
- Azimuthal coefficients from ”dipole interference”
- Local Equilibrium (Thermal and Flow Models) appear but they are not there
- Quantum (Wave) behavior can only be trapped by observing interference patterns
- Independent and uniformly random filling of phase space always looks at the end as a ”thermalized” distribution of energy

Summary of Planck scale occurrence

- Planck scale is physical
- Occurs in energy uncertainty for accelerated photons
- Sets the imaginary time period in BH physics
- Occurs as ”temperature” due to smeared Doppler effect