Kinetic freeze out from a local anisotropic fluid

Hot Quarks 2016

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Content

- Reminder on Cooper-Frye freeze out
- Motivation for local anisotropy
- Effects of the local anisotropy on:
	- 1. transverse particle spectra
	- 2. flow coefficients
	- 3. HBT radii (time permitting)
- Conclusion

Need for kinetic freeze out

- Inside QGP fluid-like behavior with small $l_{mfp} \rightarrow$ hydrodynamics works
- Expanding fireball of conserved global quantities
- Particles reaching the detector do not interact with each other, large/infinite $l_{mfp} \rightarrow$ kinetic theory works

r t Hadrons \rightarrow kinetic theory Hadrons \rightarrow Hydro QGP \rightarrow ideal Hydro QGP \rightarrow aniso. / dissipative Hydro early stages \rightarrow pre-equilibrium kinetic freeze out here

Need to glue two very different types of theoretical models

Cooper-Frye freeze out

- Description of the medium turns suddenly from fluid to a kinetic one, while passing through a hypersurface Σ
- On-shell phase space distribution $f(x^{\mu}, \vec{p})$
- Particles inside a fluid element: $dN = dV \int_{-\infty}^{\infty} d^3 \vec{p} f(E_p)$ $-\infty$
- Lorentz invariant particle spectrum:

$$
E_p \frac{d^3 N}{d^3 \vec{p}} = \frac{1}{(2\pi)^3} \int_{\Sigma} f(x^{\mu}, \vec{p}) p^{\mu} d^3 \sigma_{\mu}(x^{\mu})
$$

Problems of (naive) Cooper-Frye freeze out

- Negative contributions to the particle spectrum due to Σ regions where $d\sigma_{\mu}d\sigma^{\mu} < 0$ (see talk by Oliinychenko)
- Computed observables depend on choice of freeze out parameter

Not physical, Nature performs a "smooth" transition between the two asymptotic models

But Cooper-Frye recipe is much too attractive to be discarded

$$
E_p \frac{d^3 N}{d^3 \vec{p}} = \frac{1}{(2\pi)^3} \int_{\Sigma} f(x^{\mu}, \vec{p}) p^{\mu} d^3 \sigma_{\mu}(x^{\mu})
$$

Motivation for an anisotropic distribution function

- Nonrelativistic studies show:
	- Hypersonic flow through a nozzle into vacuum will end in an anisotropic distribution function
	- Characterized by two effective temperatures T_{\parallel} and T_{\perp}
- Anisotropic hydrodynamics can improve transition from pre-equilibrium to hydrodynamics (see talk by Bazow)
- Generalization to relativistic HIC case …

technical details coming soon

Anisotropic freeze pout $f(\cdot, \cdot, \mathbf{p}) = f_{\text{eq}}(\mathbf{p} | T(\tau, \mathbf{x})) + \delta f$

- Idea: implement an anisotropy along the radial direction in the phase space distribution $f(\tau,\mathbf{x},\mathbf{p})=f_\text{aniso}(\mathbf{p},\Lambda(\tau,\mathbf{x}),\xi)$ $\overline{}$ and $\overline{}$ a
- Tool: Romatschke-Strickland distribution

$$
f_{aniso}^{LRF}(x^{\mu},\vec{p},\Lambda,\xi) \propto exp\left(-\frac{\sqrt{(p\cdot u)^2\sqrt{4\pi k_0^2}(\pi k_0)(p^2\pi)^2\zeta(x,\tau)p_z^2}}{\Lambda(x^{\mu})}\right)
$$

 \overline{T} T_{\perp}

 \sum_{nic} anis

Matter Official Conduction of the Conducti Taken from: Michael Strickland's Quark Matter 2015 Talk

 $\frac{\Delta P}{2\langle p_L^2 \rangle} - 1$

 \setminus

Consequence: additional parameter ξ

• Boost into lab-frame

- In order to generate higher effective temperature/pressure in radial direction, need to choose $\xi < 0$
- Next step: insert into Cooper-Frye Integral

Technical details

- Cylindrical lab-frame coordinates
- Blast-wave like fluid velocity profile:

$$
u^{\phi} = u^{\eta} = 0 \quad ; u^{r} = \bar{u}_{max} \frac{r}{R} \left(1 + 2 \sum_{n} V_{n} \cos(n\phi) \right)
$$

•
$$
R = 10 fm
$$
, $\tau_{fo} = 7.5 \frac{fm}{c}$, $V_2 = V_3 = 0.05$

- Particle mass: 140 MeV
- Anisotropic temperature $\Lambda(x^{\mu})$, anisotropy parameter $\xi(x^{\mu})$

Transverse momentum spectrum for to deviations from the almost exponential shape valid in the reflects the growing radial pressure—or equivalently the ϵ . More precisely, the spectrum becomes harder precisely, the spectrum becomes harder precisely. effective radial temperature"*/* (ϵ) poiro different:

 ζ values. The ζ values. The ζ

ξ values (Λ,ξ)-pairs

- particles, due to higher • ξ decreasing \longrightarrow more fast effective pressure ϵ explanation describing all its details. Ellective pressure
- radius *R*side with varying ξ seen in the upper right panel of **+** r_1 + r_2 nearly same spectrum Λ at freeze out, but anisotropic flow coefficients *vn*. The results shown in Figs. 3 neglect this ingredient. • Varying "temperatures"

Anisotropic flow coefficients

Fourier series in azimuthal angle ϕ_p *d*²*N* $d^2\vec{p}_t$ = 1 2π *dN* $p_t dp_t$ $\sqrt{ }$ $1 + \sum$ ∞ *n*=1 $2v_n \cos(n(\phi_p - \psi_n))$

Fourier coefficients:

$$
v_n = \frac{\int_0^{2\pi} d\phi_p \cos(n\phi_p) \frac{d^2 N^{aniso}}{dp_t^2}}{\int_0^{2\pi} d\phi_p \frac{d^2 N^{aniso}}{dp_t^2}}
$$

Elliptic flow v_2 for different

 ξ values (A,ξ) -pairs

- smaller anisotropic flow Fig. 2 is more involved, and we did not find a satisfactory $\mathcal{L}^{\mathcal{L}}$ • Higher anisotropy leads to
- explanation describing all its details. • v_3 and v_4 follow same trend
- Variation of parameters gives nearly the same observables out [24]. Secondly, this could help diminish the sensitivity of **Fig. 4** Transverse spectra for various choices of \mathcal{L} case, there will be such a dependence, which will affect the and *r*_n. The results show consider α

Hanbury-Brown Twiss radii *vlong* den Wellenhum Index Korrel rimentell gemessen werden kann. Fur die HBT-Radien-Bestimmung betrachten wir die ¨

• Computation of HBT radii: $R_{out}^2 = \langle (\tilde{x} - v_{out} \tilde{t}) \rangle$ 2 M_{\odot} Computation utation of HBT radii: $R_{out}^2 = \langle (\tilde{x} - v_{out} \tilde{t})^2 \rangle$

$$
\begin{array}{ccc} R_{side}^2&=&\langle (\tilde{y})^2\rangle\\ R_{long}^2&=&\langle (\tilde{z})^2\rangle\end{array}
$$

• Averaging:
$$
\langle X \rangle = \frac{\int d^4x \, X \, S(x^{\mu}, \vec{k})}{\int d^4x \, S(x^{\mu}, \vec{k})}
$$

, kann man die Korrelationsfunktion *C*(*k,* ~ *q*) weiter umschreiben. Letztendlich sollte man auch de Soul die Tatsache, das Mal die $\mathcal{P}(x, p) = \int p^r a^r \mu f(p, x^r) e^{i\lambda t} (x^r - x^r)$ • Source-function: $S(x^{\mu}, \vec{p}) = \int p^{\mu} d\Sigma_{\mu} f(\vec{p}, x'^{\mu}) \delta^{(4)}(x'^{\mu} - x^{\mu})$

HBT radii for different anisotropy parameter values \blacksquare ξ = 0.15 $\mathbf{1}$ **Fig. 1** Transverse spectra for fixed " and varying anisotropy parame- $\mathsf C$ larger *R*out, as observed in the upper left panel, as well as to a larger ratio *R*out*/R*side (lower right panel) In turn, the <u>UL UIIIUIUII</u> τ is a large extent unaffected by τ ; this could be anticipated by τ since the longitudinal part of the occupation factor remains γ om γ tok γ unchanged. On the other hand, the behaviour of the side of the side γ dilittle valuts *K*T (GeV) \mathcal{L}

- R_{out} varies due to higher radial thermal motion ϵ_{out} varies due to ring \sim $n J \perp$ R_{out} varies due to higher radial
- R_{long} nearly constant 6

HBT radii for different (Λ,ξ) pairs **275** Page 6 of 7 Eur. Phys. J. C (2015) 75 :275 Λ = 130 MeV, ξ = --0.5, --*u* Ω and Ω is a set of Ω \mathbf{I}

- Small variation of R_{out} *Rout*
- \bullet R_{side} very sensitive to parameter pair out 24 , this could help diminish the sensitivity of the sensitivit R_{side} very sensitive to parameter pair All in all, the results for transverse-momentum distribuparameter opens a much wider range for the "freeze-out tem-

Conclusion

Introduce an anisotropic phase space distribution

Get additional parameter ξ

- Lower sensitivity of observables on parameters at freeze out
- Option for a smoother transition from hydro to kinetic theory
- Further reading:
	- 1. N. Borghini, SF, C. Lang; [Eur. Phys. J. C 75 \(2015\) 275](http://dx.doi.org/10.1140/epjc/s10052-015-3489-3)
	- 2. Work in preparation

Thank you for your attention