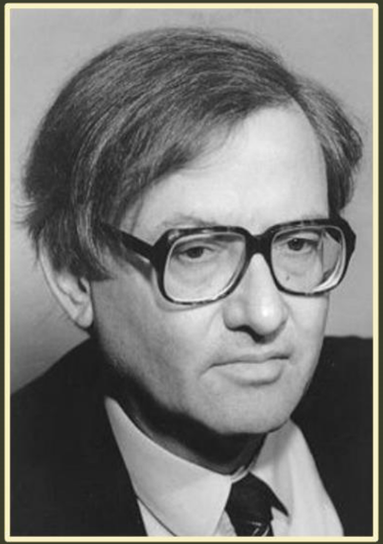

Lifetime estimation from RHIC Au+Au data

arXiv:1811.09990

Gábor Kasza, Tamás Csörgő

Zimányi School'18

3rd - 7th of December 2018, Budapest

Outline

- New, exact solution of relativistic perfect fluid hydro arXiv:1805.01427
- Observables – dN/dη arXiv:1806.06794
- Observables – R_{long} arXiv:1810.00154
- Inverse slope fits
- *dN/dη* fits
- R_L fits
- Exact result of initial energy density arXiv:1806.11309
- Method is submitted for a publication in the MDPI Journal Universe (Zimányi School + analytic hydro special volume): arXiv:1811.09990

Perfect fluid hydrodynamics

- Energy and momentum conservation:

$$\partial_\nu T^{\mu\nu} = 0$$

- Energy-momentum tensor (perfect fluid):

$$T^{\mu\nu} = (\varepsilon + p)\, u^\mu u^\nu - p g^{\mu\nu}$$

- Continuity equation:

$$\partial_\mu \left(\sigma u^\mu\right) = 0$$

- Equation of state (EoS): closes the equation system

$$\varepsilon = \kappa p \qquad \kappa = c_s^{-2}$$

- In this work κ is constant and the speed of sound (c_s) as well

New, exact solutions of perfect hydro

- Rindler coordinates, velocity field:

$$(\tau, \eta_x) = \left(\sqrt{t^2 - r_z^2}\,, \frac{1}{2}\ln\left[\frac{t + r_z}{t - r_z}\right] \right)$$

$$u^\mu = (\cosh(\Omega), \sinh(\Omega))$$

- 1+1 dimensional, parametric solution (in κ→1 limit: CNC):

$$\eta_x(H) = \Omega(H) - H,$$

$$\Omega(H) = \frac{\lambda}{\sqrt{\lambda - 1}\sqrt{\kappa - \lambda}} \arctan\left(\sqrt{\frac{\kappa - \lambda}{\lambda - 1}} \tanh(H) \right)$$

$$\sigma(\tau, H) = \sigma_0 \left(\frac{\tau_0}{\tau}\right)^{\lambda} \mathcal{V}_\sigma(s) \left[1 + \frac{\kappa - 1}{\lambda - 1}\sinh^2(H)\right]^{-\frac{\lambda}{2}},$$

$$T(\tau, H) = T_0 \left(\frac{\tau_0}{\tau}\right)^{\frac{\lambda}{\kappa}} \mathcal{T}(s) \left[1 + \frac{\kappa - 1}{\lambda - 1}\sinh^2(H)\right]^{-\frac{\lambda}{2\kappa}},$$

$$\mathcal{T}(s) = \frac{1}{\mathcal{V}_\sigma(s)},$$

$$s(\tau, H) = \left(\frac{\tau_0}{\tau}\right)^{\lambda - 1} \sinh(H) \left[1 + \frac{\kappa - 1}{\lambda - 1}\sinh^2(H)\right]^{-\lambda/2}$$

λ: acceleration parameter

↓

accelerating solution

Csörgő, Nagy, Csanád solution
arXiv:0709.3677

arXiv:1805.01427

arXiv:1806.06794

New, exact solutions of perfect hydro

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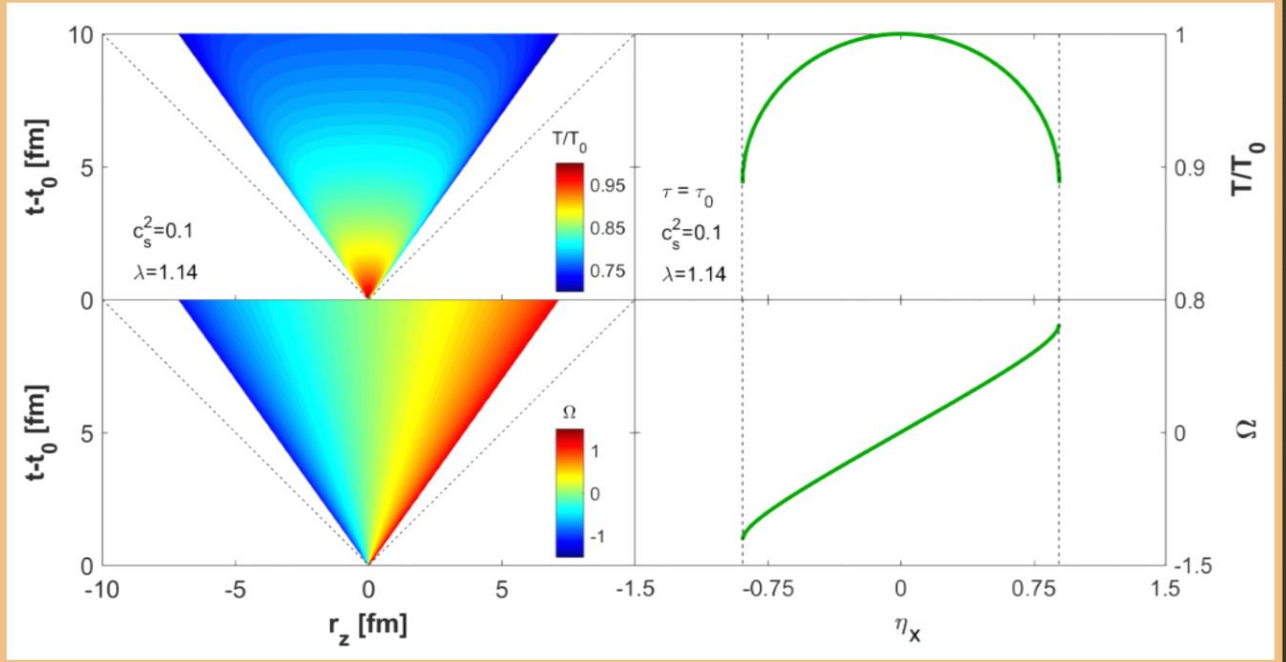

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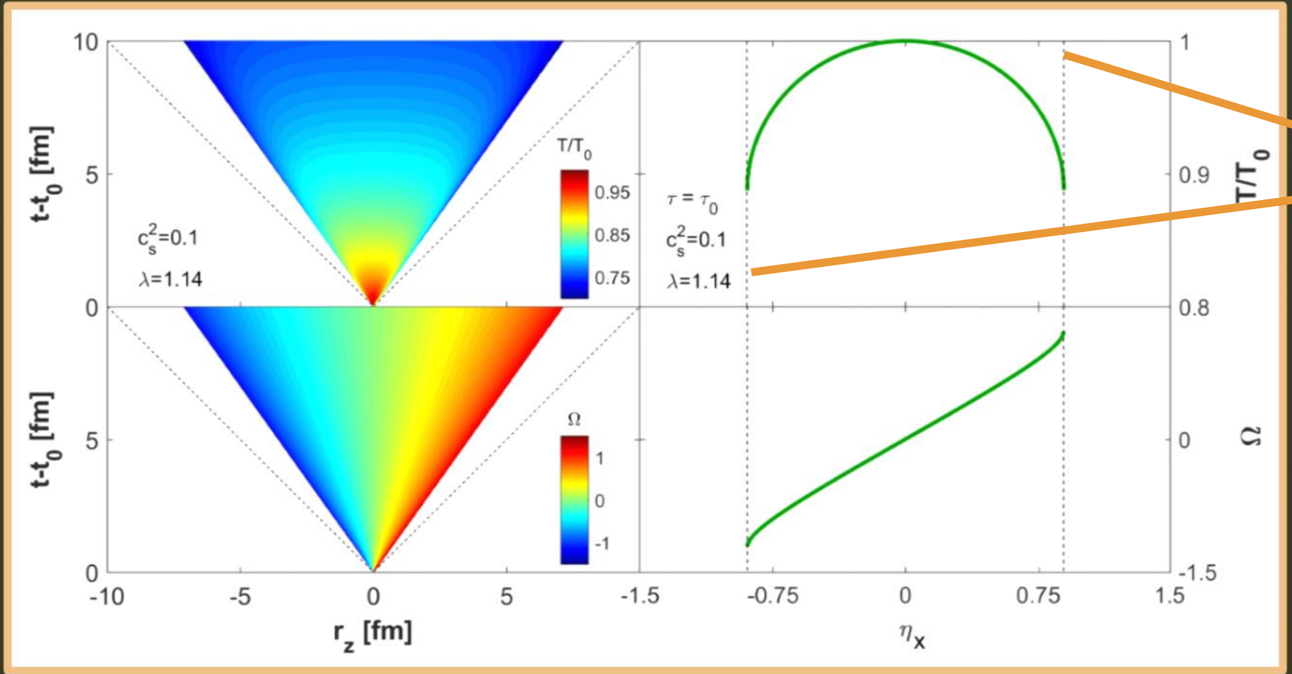

Finite solution, should be extended with shockwaves

arXiv:1805.01427

arXiv:1806.06794

Observables – Pseudorapidity density

- Rapidity density (embedded to 1+3 d space):

$$\frac{dn}{dy} \approx \left.\frac{dn}{dy}\right|_{y=0} \cosh^{-\frac{1}{2}\alpha(\kappa)-1}\left(\frac{y}{\alpha(1)}\right) \exp\left(-\frac{m}{T_{\rm eff}}\left[\cosh^{\alpha(\kappa)}\left(\frac{y}{\alpha(1)}\right)-1\right]\right)$$

T_{eff}: effective temperature, $\alpha(\kappa)=\frac{2\lambda-\kappa}{\lambda-\kappa}$

- Explicit relation between the average p_T, T_{eff} and m:

$$\bar{p}_T(y) \approx \sqrt{T_{\rm eff}^2 + 2mT_{\rm eff}}\left(1+\frac{\alpha(\kappa)}{2\alpha(1)^2}\frac{T_{\rm eff}+m}{T_{\rm eff}+2m}y^2\right)^{-1}$$

- Pseudorapidity density: parametric curve

$$\left(\eta_p(y)\,,\,\frac{dn}{d\eta_p}(y)\right) = \left(\frac{1}{2}\log\left[\frac{\bar{p}(y)+\bar{p}_z(y)}{\bar{p}(y)-\bar{p}_z(y)}\right]\,,\,\frac{\bar{p}(y)}{\bar{E}(y)}\frac{dn}{dy}\right)$$

- Four fit parameters: κ, λ, T_{eff}, $dn/dy|_{y=0}$

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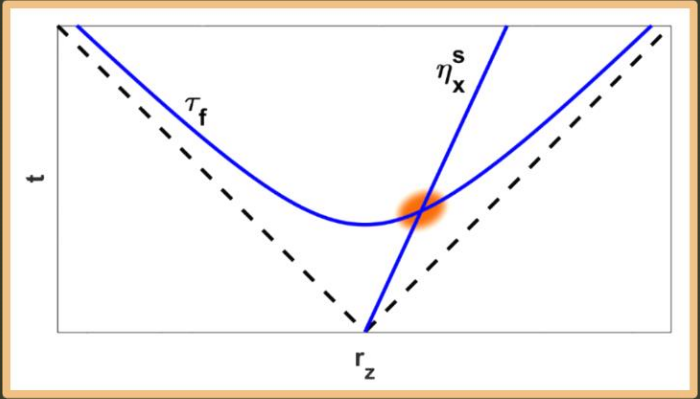
Observables – R_L

- For a 1+1 d relativistic source (LCMS):

$$R_L^2 = \cosh^2(\eta_x^s)\tau_f^2\Delta\eta_x^2 + \sinh^2(\eta_x^s)\Delta\tau^2$$



- (η_x^s, τ_f): saddle point
- CKCJ solutions limited to a narrow rapidity interval around $\eta_x \approx 0$
- At midrapidity:

$$R_L = \tau_f \Delta\eta_x$$

with the new solution →

$$R_L = \tau_f \Delta\eta_x \approx \frac{\tau_f}{\sqrt{\lambda(2\lambda - 1)}}\sqrt{\frac{T_f}{m_T}}$$

- $\Delta\eta_x$: gaussian width of rapidity distribution

hep-ph/9411307

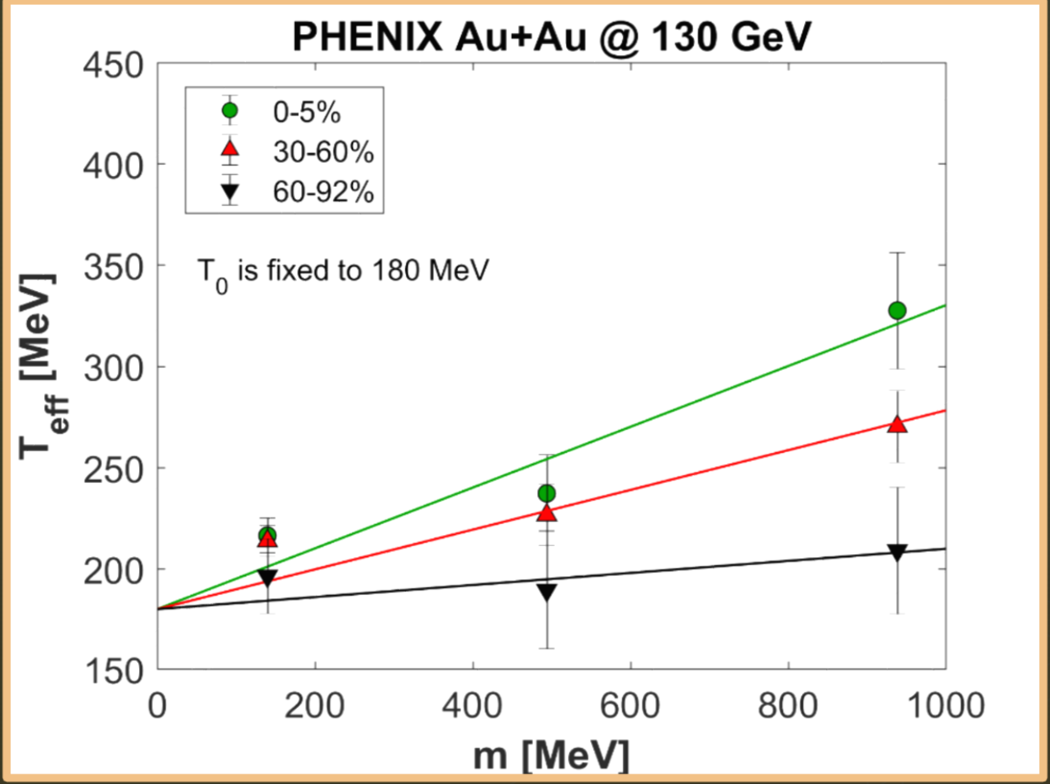
Inverse slope fits – Au+Au @ 130 GeV

- Effective temperature: need centrality dependence
- Linear model is fitted to m_0 vs T_{eff} PHENIX data
- T_f is fixed to 180 MeV

$$T_{eff}(m) = T_f + m\langle u_T \rangle^2$$

arXiv:1801.05716

arXiv:1811.09990



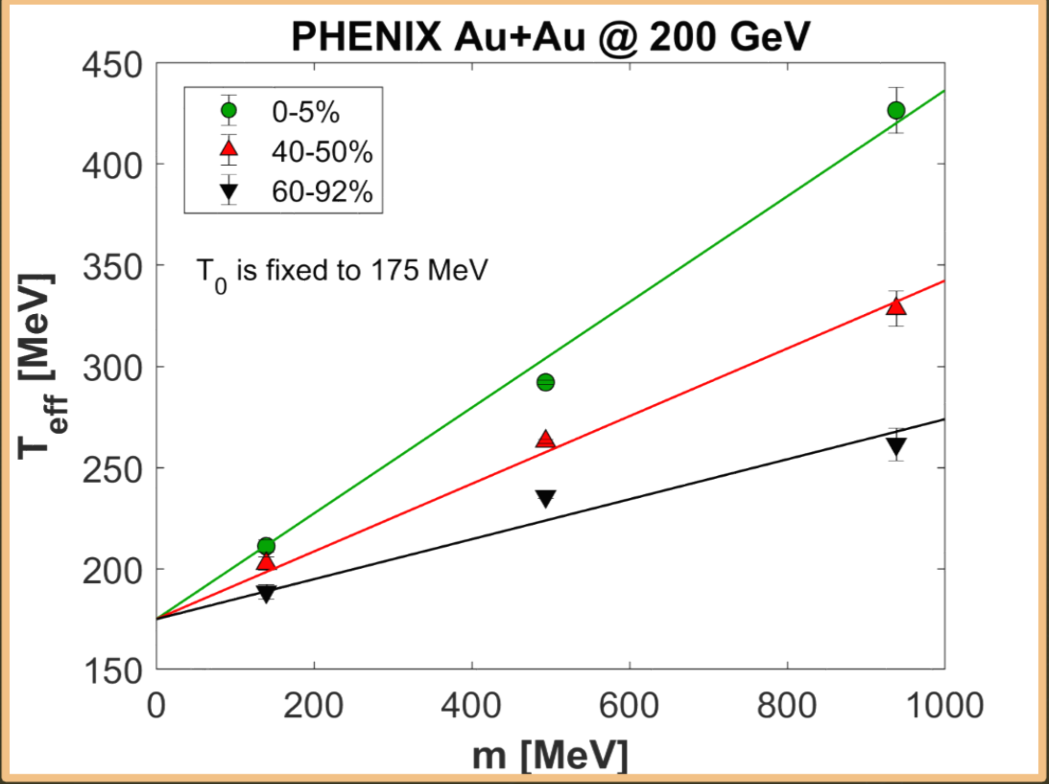
Inverse slope fits – Au+Au @ 200 GeV

- Effective temperature: need centrality dependence
- Linear model is fitted to m_0 vs T_{eff} PHENIX data
- T_f is fixed to 175 MeV

$$T_{eff}(m) = T_f + m\langle u_T \rangle^2$$

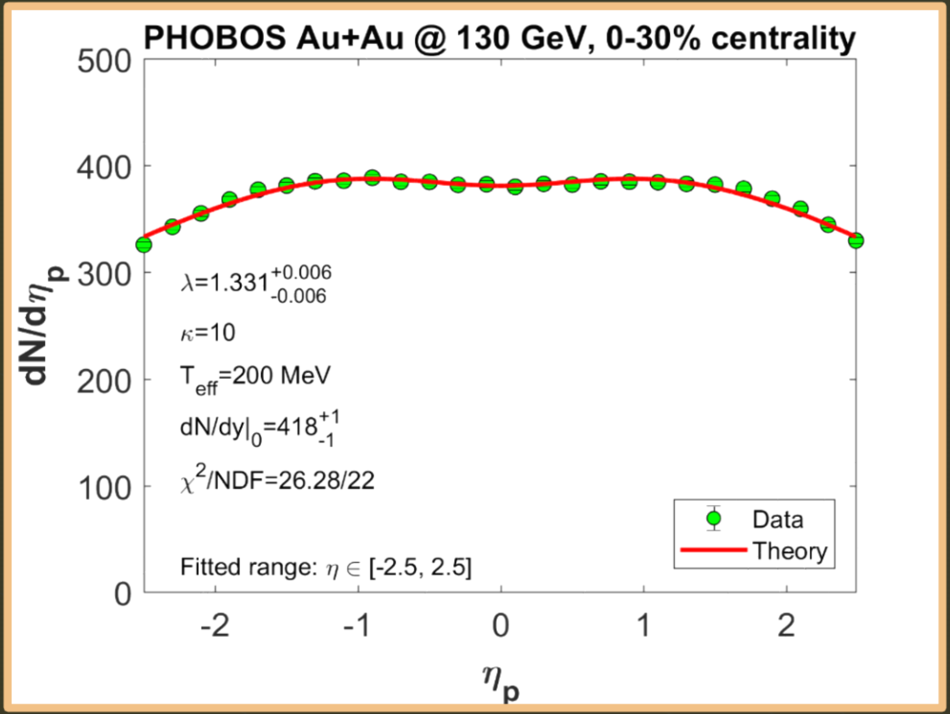
arXiv:1801.05716

arXiv:1811.09990



dN/dη fits – Au+Au @ 130 GeV

- Fit the CKCJ model to *dN/dη* PHOBOS data
- Fit range limited
  (because of the finiteness CKCJ model)
- c_s^2 is fixed to 0.1 (κ=10)
- R_L datas of 130 GeV Au+Au are published with 0-30% centrality
- No T_{eff} data with 0-30% centrality → fit to *dN/dη,* result seems consistent with the centrality dependence



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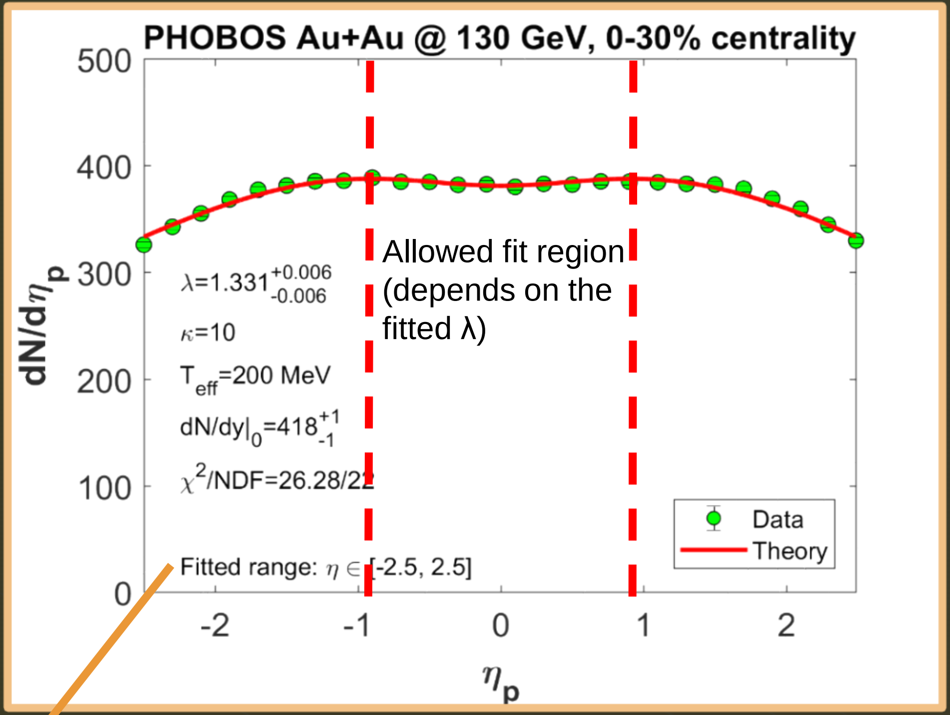

Fit range is *λ* dependent, but *λ* determined by the fit → iteration is needed (postponed)

arXiv:1811.09990

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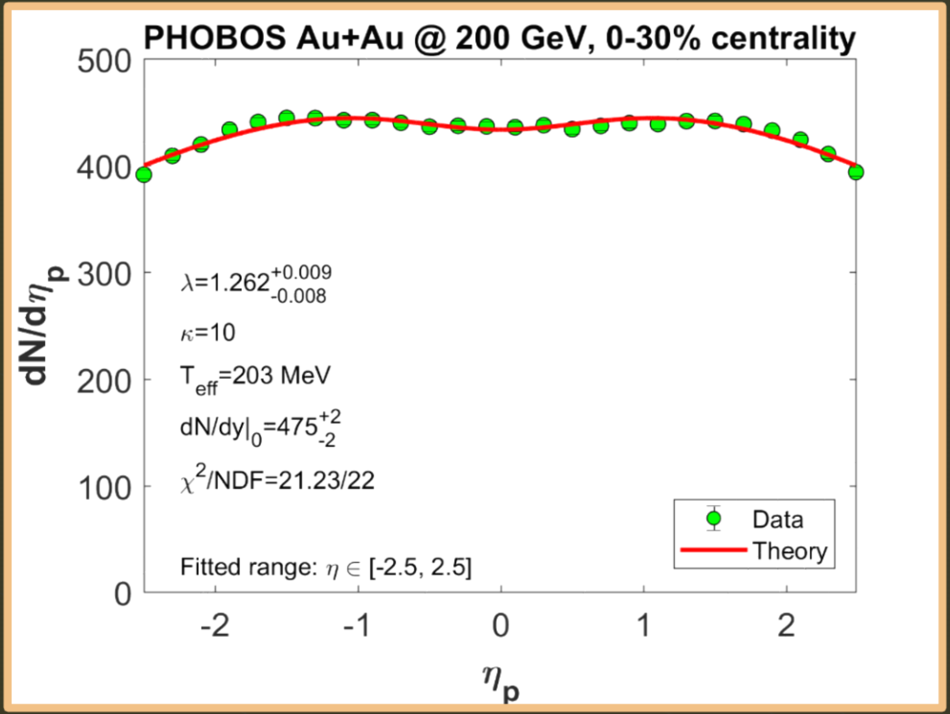

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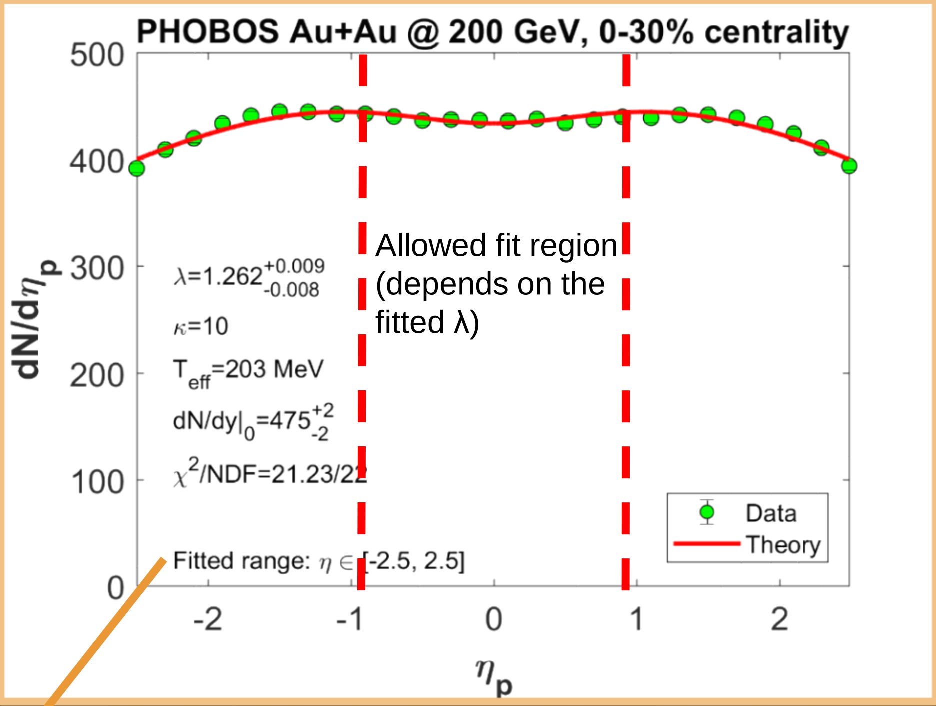

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arXiv:1811.09990

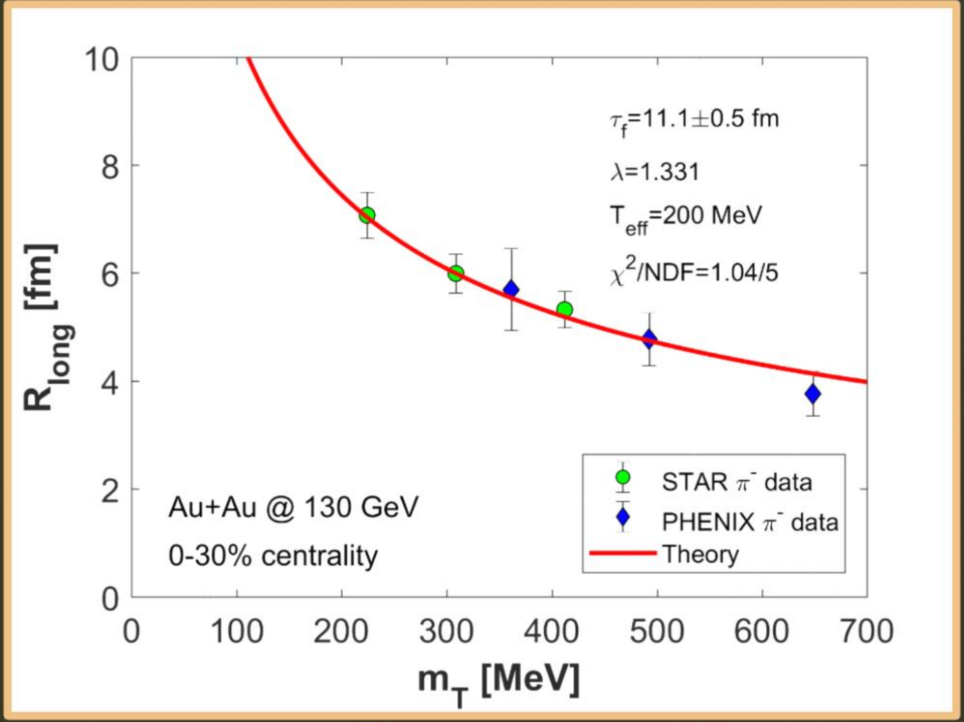
R_L fits – Au+Au @ 130 GeV

- The new formula is fitted to PHENIX and STAR R_L data
- From fits to *dN/dη:* λ=1.33, T_{eff}=200 MeV
- τ_f is fit parameter

arXiv:1811.09990

arXiv:nucl-ex/0201008

$$R_L = \tau_f \Delta\eta_x \approx \frac{\tau_f}{\sqrt{\lambda(2\lambda-1)}}\sqrt{\frac{T_f}{m_T}}$$

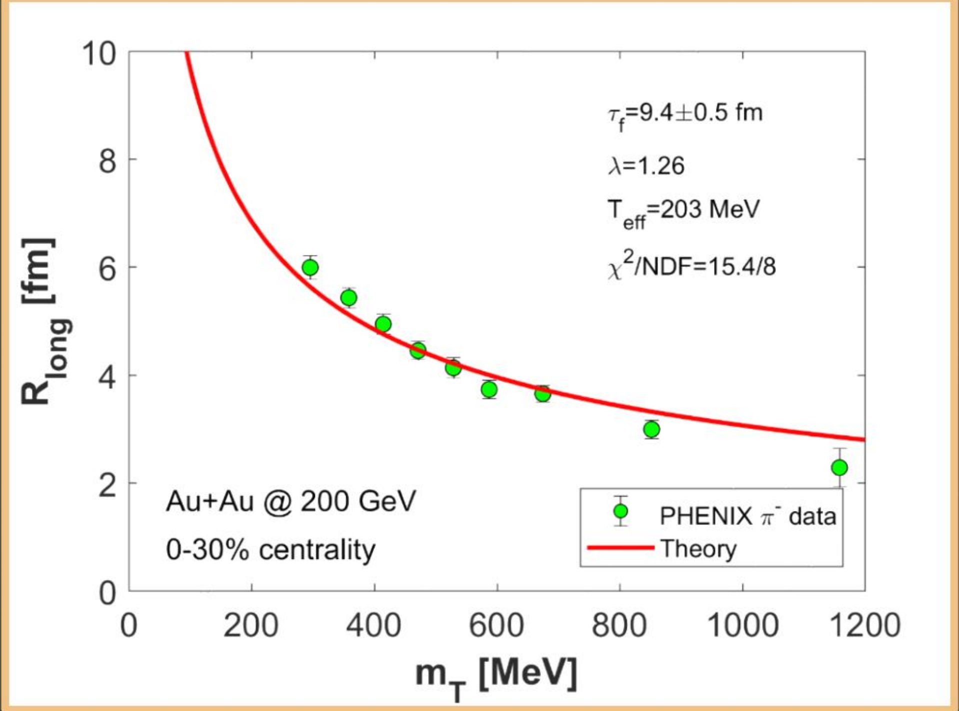


R_L fits – Au+Au @ 200 GeV

- The new formula is fitted to PHENIX R_L data
- From fits to *dN/dη:* λ=1.26, T_{eff}=203 MeV
- τ_f is fit parameter

arXiv:1811.09990

arXiv:nucl-ex/0401003



$$R_L = \tau_f \Delta\eta_x \approx \frac{\tau_f}{\sqrt{\lambda\left(2\lambda-1\right)}}\sqrt{\frac{T_f}{m_T}}$$

Exact result of initial energy density

- From the CKCJ model the ε_0 is exactly calculated:

$$\varepsilon_0(\kappa, \lambda) = \varepsilon_0^{Bj} (2\lambda - 1) \left(\frac{\tau_f}{\tau_0}\right)^{\lambda\left(1+\frac{1}{\kappa}\right)-1}$$

- $\lambda \to 1$ limit: EoS dependence is not vanishing
- Bjorken's formula can be reobtained only in the case of dust (thus we find the fundamental correction to Bjorken's initial energy estimate)
- The new, EoS dependent correction takes into account the work of the pressure
- λ and τ_f are obtained by $dN/d\eta$ and R_L fits → τ_0 dependence

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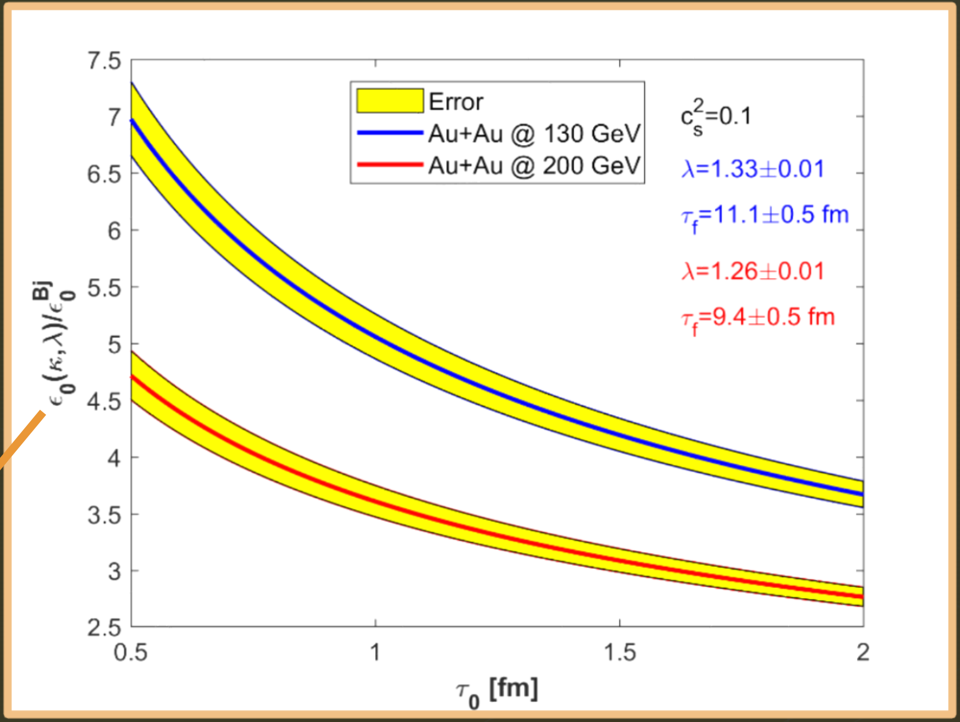
arXiv:1806.11309

Exact result of initial energy density

- Indication for an increasing initial energy density with decreasing colliding energy?
- Suggest a non-monotonic behaviour of the initial energy density with $\sqrt{s}$.
- Need to extend the studies to lower energies (RHIC BES I, BES II, SPS and LHC data)
- Need to extend the CKCJ solution to 1+3 dimensions
- Need to investigate the fit range iteration



the corrections to Bjorken's initial energy estimate

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Summary

- New, exact solutions of hydrodynamics: CKCJ model
- Initial energy density is calculated exactly → Bjorken's estimate ignores the first law of thermodynamics (except for dust, $p=0$)
- Fit to PHOBOS $dN/d\eta$ data: obtain λ
- Fit to PHENIX and STAR R_L data: obtain τ_f
- τ_0 dependence of ε_0 can be calculated → surprising result
- Further investigations are needed: lower energies, 1+3 dimensional extension of CKCJ model, fit range iteration

Summary

- New, exact solutions of hydrodynamics: CKCJ model
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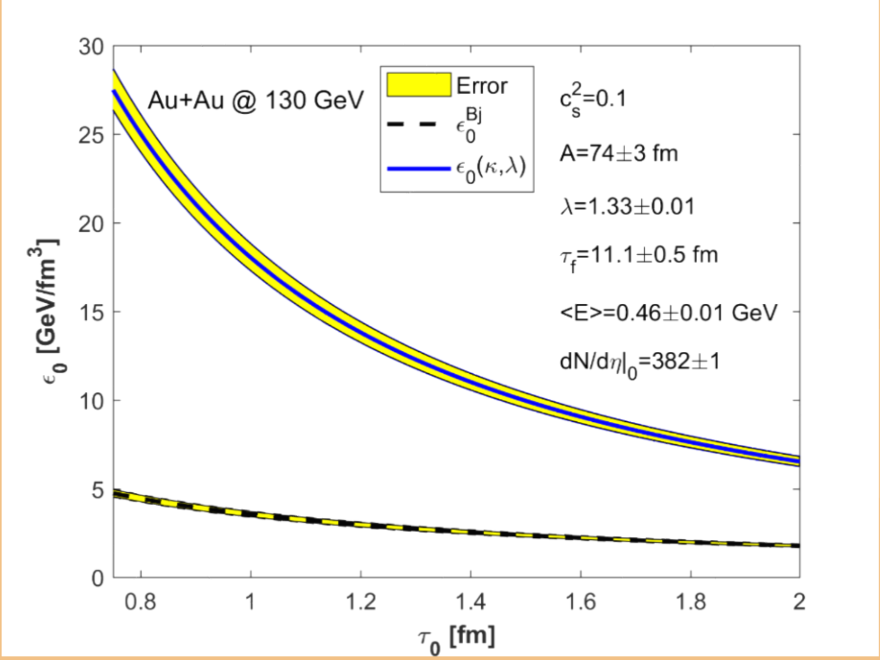
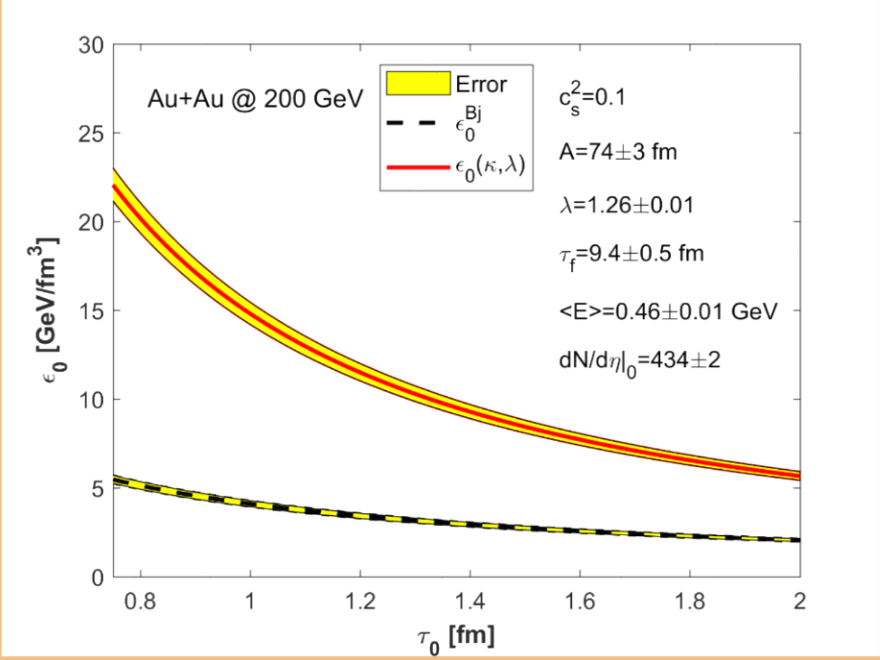
Thank you for your attention!

Backup slide

Exact result of initial energy density

- At both collision energies the correction is significant
- Only the thermalized energy is included
- Greater energy density on lower collision energy??





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