# Shear Viscosities of Strongly Coupled Anisotropic Plasma

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Institute for Theoretical Physics
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  - Shear viscosity and heavy ion collisions
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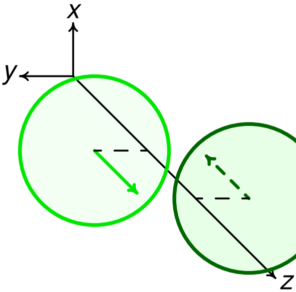
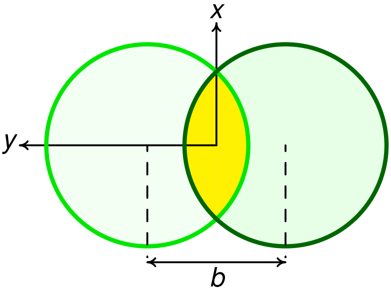
- Model of anisotropic plasma
- Calculation of the shear viscosities at strong coupling
- Conclusion

# A phenomenologist's view



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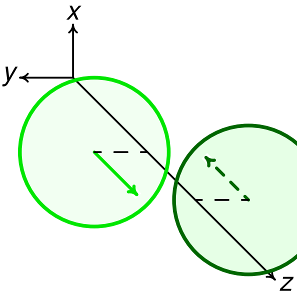


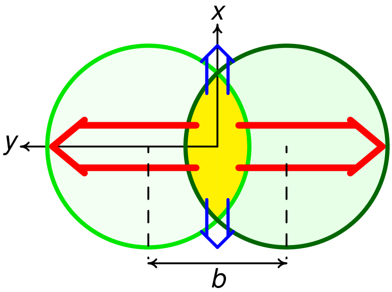


$$v_n = \frac{\int \frac{dN}{d^3p} e^{in(\phi - \phi_R)} d^3p}{\int \frac{dN}{d^3p} d^3p}$$

elliptic flow $\rightarrow n = 2$

$\phi_R$ ... orientation of reaction plane

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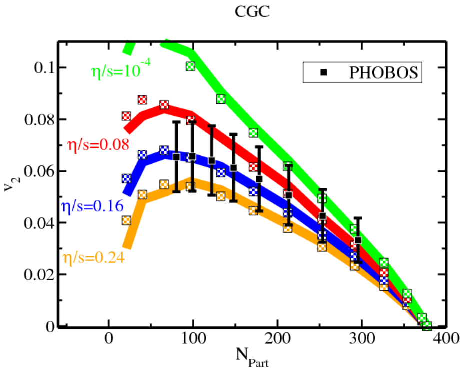


[Luzum, Romatschke '08]

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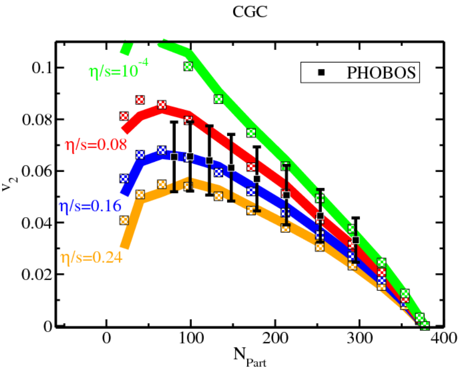


[Luzum, Romatschke '08]


"RHIC serves the perfect fluid" (2005)

**large $v_2 \Rightarrow$ small $\eta/s$!**

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$\eta/s \lesssim O(1) \Rightarrow$ **Strong coupling effect!**

# The challenge of strong coupling

- **Lattice QCD**
    - powerful non-perturbative tool
    - not suited for real time phenomena (transport coefficients)
      (see however [Meyer '09] )

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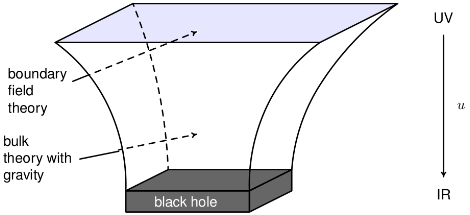
- **Gauge/gravity duality**
  - string theory inspired method to study large N gauge theories at strong coupling
  - not (yet ?) established for QCD
    $\Rightarrow$ Need to study "wrong" theory!



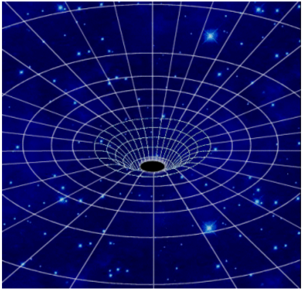

thermal state in boundary theory

$\Updownarrow$

black hole geometry

# Holographic view [Policastro, Son, Starinets '01]

absorbtion of transverse gravitons $\psi = h^j_i$ ($\sim T^i_j$)



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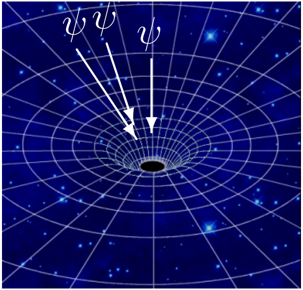


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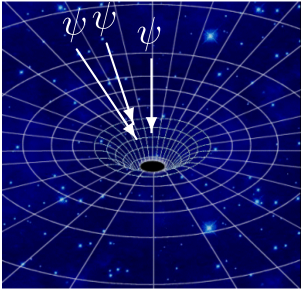


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Einstein eqs. to linear order in $\psi$

$$\Box\psi = 0 \qquad \text{massless scalar}$$

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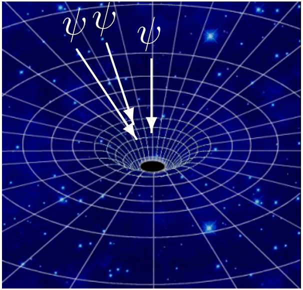


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Only assumptions: 2 derivative gravity and isotropy

[Kovtun, Son, Starinets '03; Buchel, Liu '03; Kovtun, Son, Starinets '04]

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conjectured **lower (quantum) bound for any fluid in nature**

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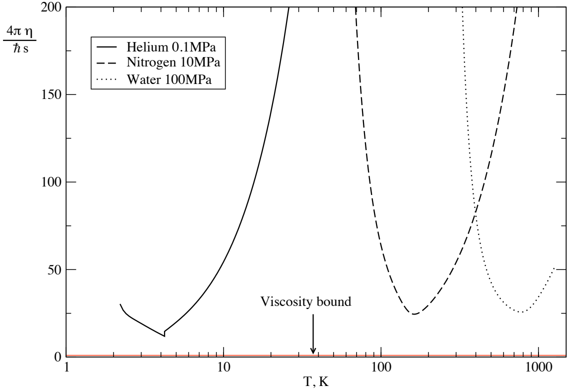

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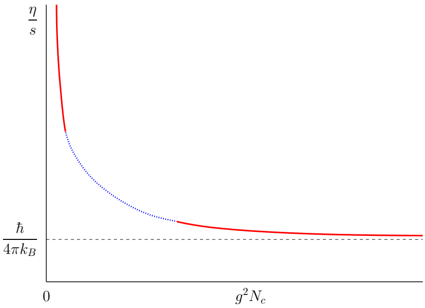

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**spatial anisotropies important in early stages of heavy ion collisions**

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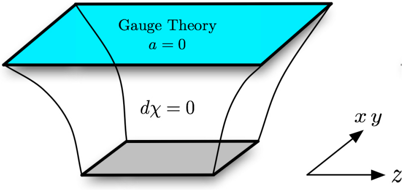
$$S_{bulk} = \frac{1}{2\kappa^2} \int \sqrt{-g} \Big( \mathcal{R} + 12 \qquad \Big)$$



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with $\theta(z) = 2\pi\chi/g_s = 2\pi n_{D7}\, z$

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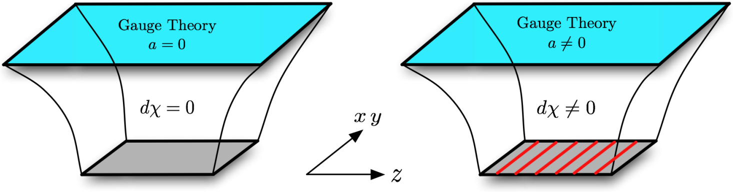
$$S_{bulk} = \frac{1}{2\kappa^2}\int \sqrt{-g}\left(\mathcal{R} + 12 - \frac{(\partial\phi)^2}{2} - \frac{e^{2\phi}(\partial\chi)^2}{2}\right)$$

with $\chi = az$



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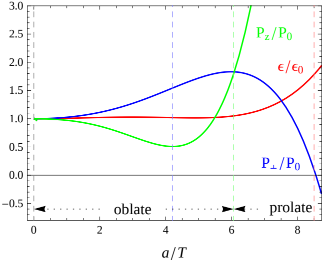


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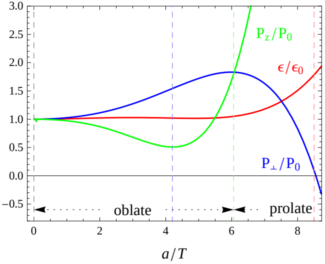


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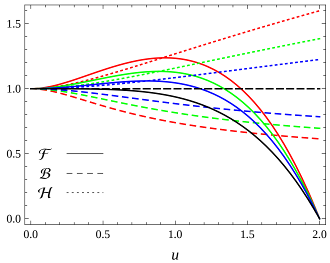

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$$s = \frac{(\epsilon + P_\perp)}{T}$$

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$$s = \frac{A_h}{4GV_3}$$

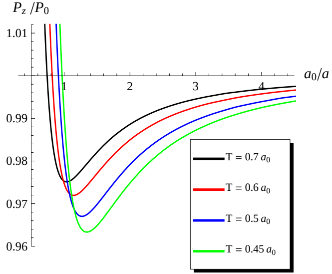
# Thermodynamics at infinite coupling

[Mateos, Trancanelli '11; Gynther, Rebhan, DS '12]

Note: anisotropic system is in thermodynamic equilibrium

thermodynamically **unstable** (wrt. redistribution of D7 branes):

$$\left(\frac{\partial P_z}{\partial L_z}\right)_{T,N} > 0 \quad \Rightarrow \quad \left(\frac{\partial P_z}{\partial (1/a)}\right)_{T,N} > 0$$



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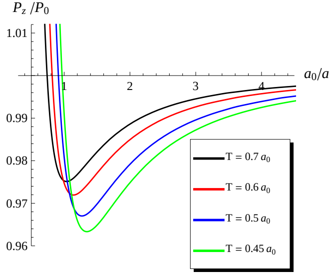


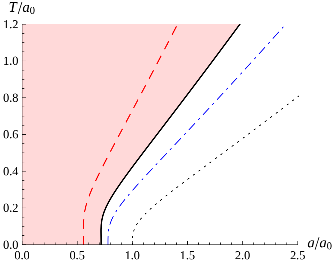

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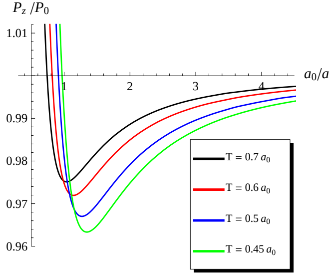


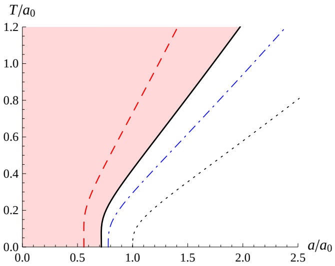


(thermodynamics at zero coupling → [Gynther, Rebhan, DS '12])

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**effective action**

$$S^{(2)}_{eff} = \frac{1}{16\pi G} \int \frac{d^4K}{(2\pi)^4} du \Big( \psi'_n \mathcal{C}^1_n(K,u) \psi'_n + \psi_n \mathcal{C}^0_n(K,u) \psi_n \Big)$$

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**retarded correlator**

$$G^R_n(K) = -\lim_{u\to 0}\frac{\Pi_n(K,u)}{\psi_n(K,u)} \qquad \text{with } \Pi_n = \frac{\partial \mathcal{L}^{(2)}}{\partial(\partial_u \psi_n)} \propto \partial_u \psi_n$$

retarded correlator $\leftrightarrow$ infalling boundary conditions at horizon

# Shear viscosities

**Membrane paradigm** [Iqbal, Liu '08]

generic transport coefficient of boundary theory

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|---|---|---|

at the horizon

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# Shear viscosities

**Membrane paradigm** [Iqbal, Liu '08]

| generic transport coefficient of boundary theory | $\Rightarrow$ | geometric quantities evaluated at horizon |
|---|---|---|

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shear viscosity

$$\eta_n = \frac{\Pi_n(K, u_h)}{i\omega\psi_n(K, u_h)} \qquad \text{with } \Pi_n(u_h, q) \propto i\omega\psi_n$$

# Shear viscosities [Rebhan, DS '11]

In the anisotropic plasma we find

- purely transverse $\psi_\perp = h^x_y$

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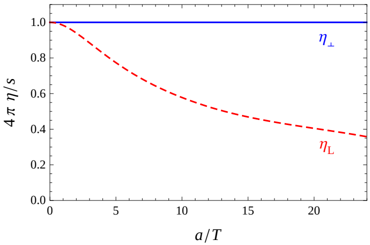

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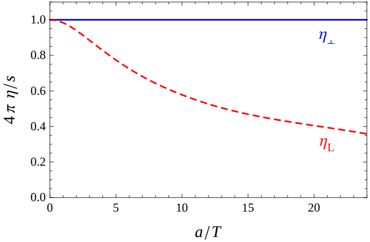


**Violation of the viscosity bound!**

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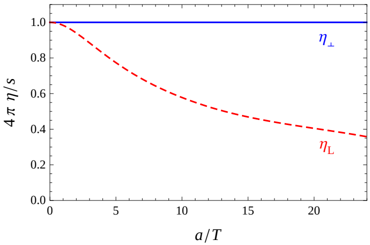


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- 3rd shear viscosity $\psi_{\tilde{L}} = h^z_x$

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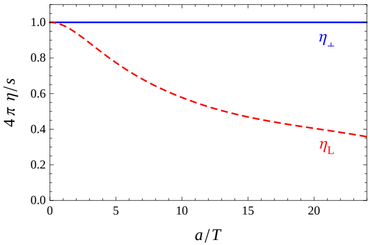


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**3 is 1 too much in boundary theory $\Rightarrow$ symmetry**

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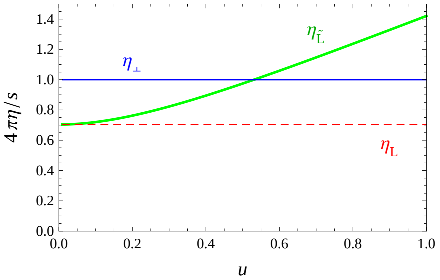

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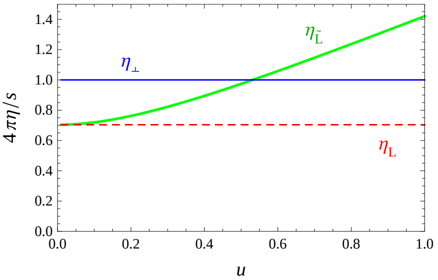

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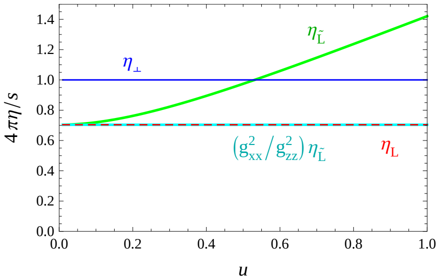


Furthermore

$$\eta_{\tilde{L}}(u) = \eta^{x\ x}_{\ z\ z}(u) = \left(\frac{g_{zz}(u)}{g_{xx}(u)}\right)^2 \eta_{x\ x}^{\ z\ z} = \left(\frac{g_{zz}(u)}{g_{xx}(u)}\right)^2 \eta_L$$

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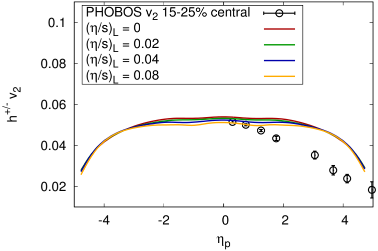


[Schenke, private communication]

Larger

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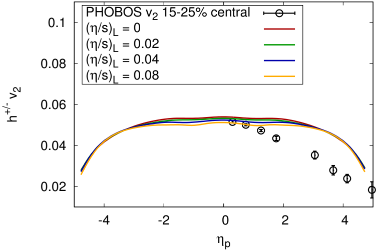


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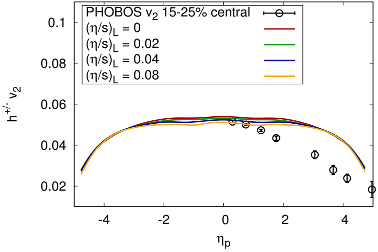


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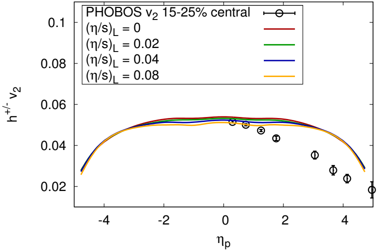


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Larger

**Thank you!**

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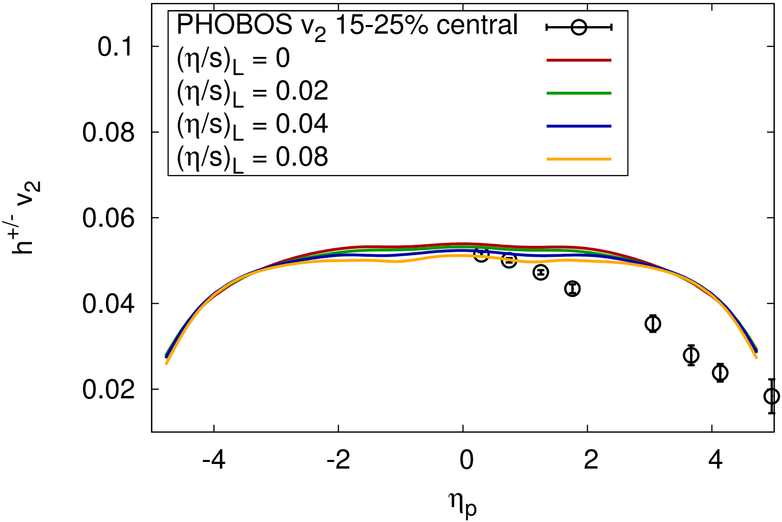
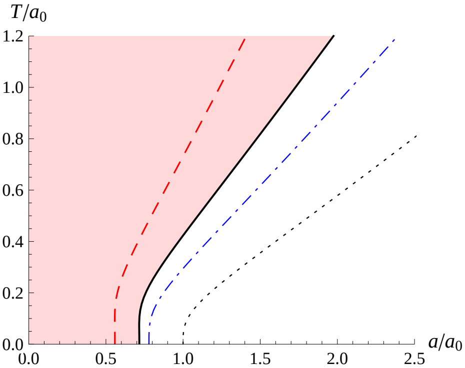



Back

# The issue of instabilities [Mateos, Trancanelli '11; Rebhan, DS '11]



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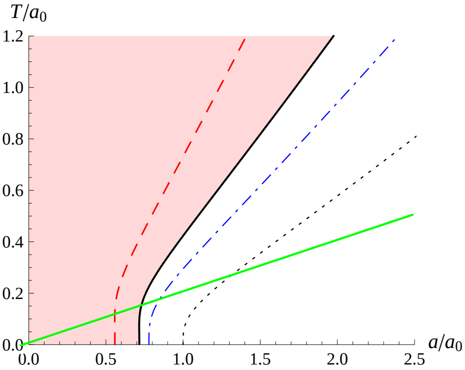


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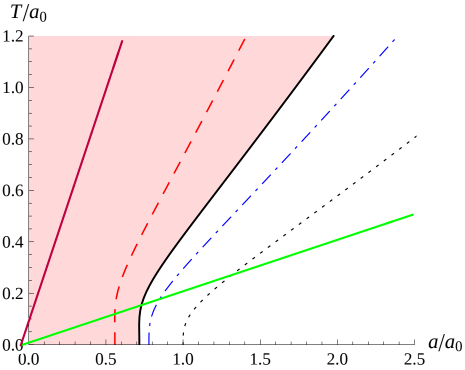


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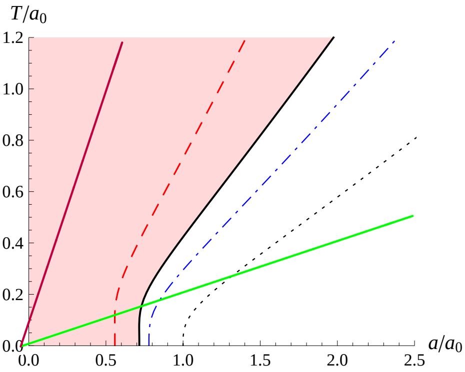


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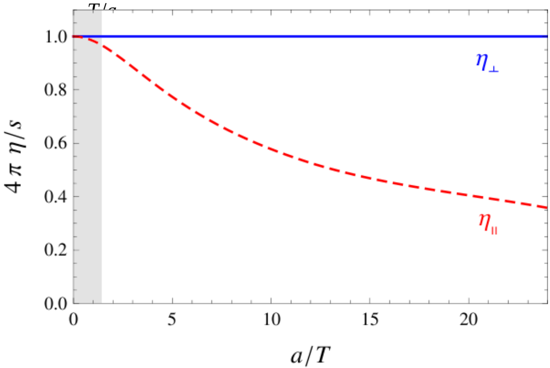


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