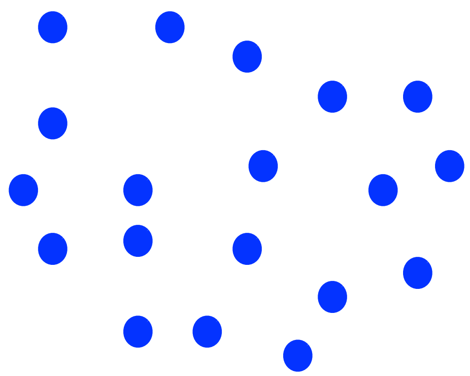
Towards a holographic description of hydro with spin

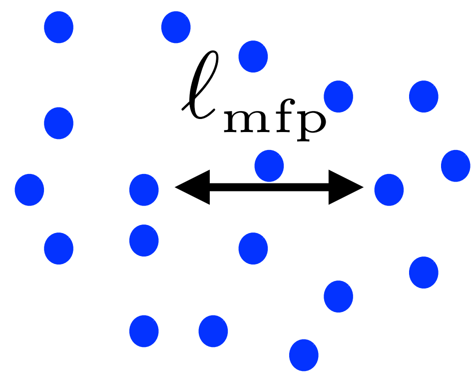
A. Yarom

Together with C. Cartwright, A. D. Gallegos, U. Gursoy and R. Klein

Simple hydrodynamics

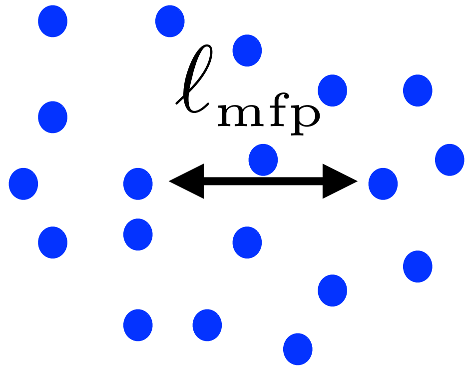


Simple hydrodynamics

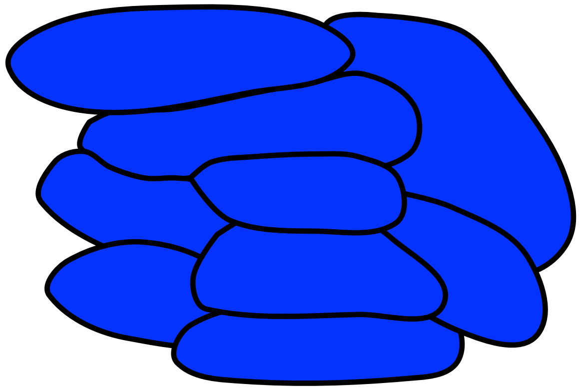


Simple hydrodynamics

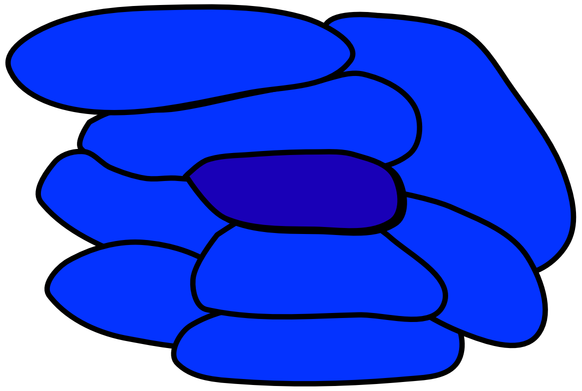
$$L \gg \ell_{\rm mfp}$$



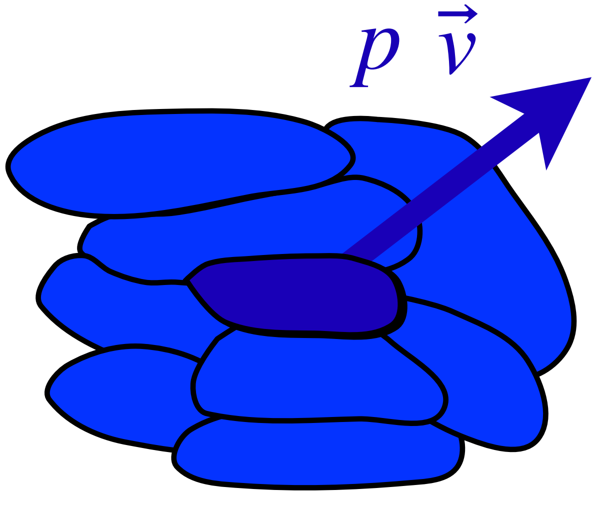
Simple hydrodynamics



Simple hydrodynamics



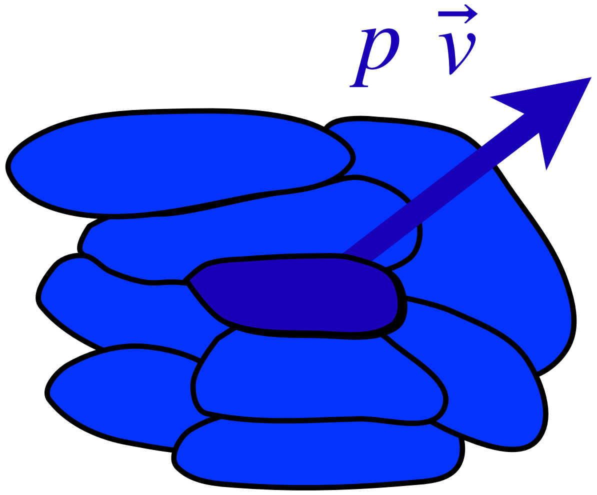
Simple hydrodynamics



Simple hydrodynamics

$$\dot{\vec{v}} + \vec{v} \cdot \overrightarrow{\nabla} \vec{v} = - \overrightarrow{\nabla} p + \eta \nabla^2 \vec{v}$$

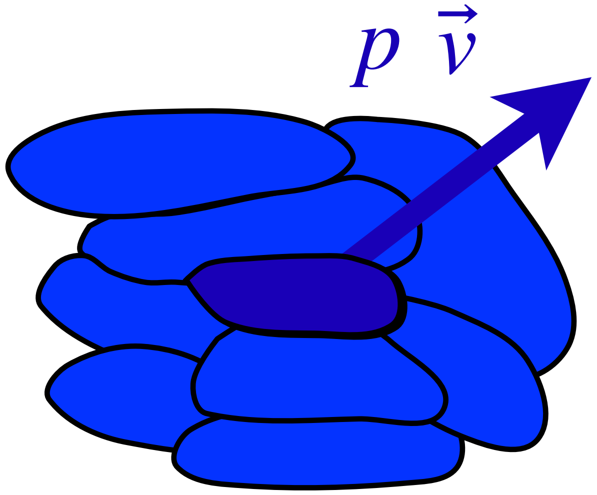
$$\overrightarrow{\nabla} \cdot \vec{v} = 0$$



Simple hydrodynamics

$$\dot{\vec{v}} + \vec{v} \cdot \vec{\nabla} \vec{v} = - \vec{\nabla} p + \eta \nabla^2 \vec{v}$$

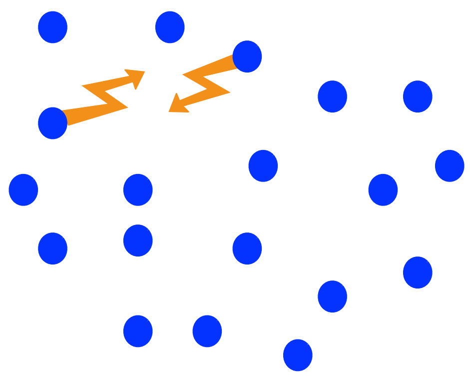
$$\vec{\nabla} \cdot \vec{v} = 0$$



Simple hydrodynamics

$$\dot{\vec{v}} + \vec{v} \cdot \overrightarrow{\nabla} \vec{v} = - \overrightarrow{\nabla} p + \eta \nabla^2 \vec{v}$$

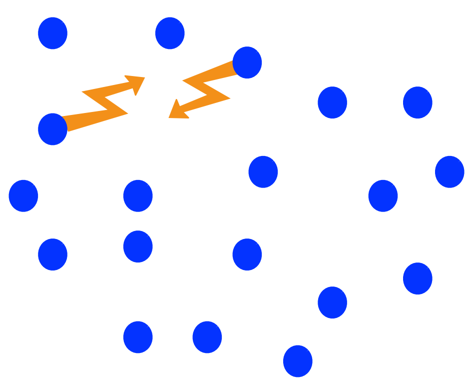
$$\overrightarrow{\nabla} \cdot \vec{v} = 0$$



Simple hydrodynamics

$$\dot{\vec{v}} + \vec{v} \cdot \vec{\nabla} \vec{v} = - \vec{\nabla} p + \eta \nabla^2 \vec{v}$$

$$\vec{\nabla} \cdot \vec{v} = 0$$

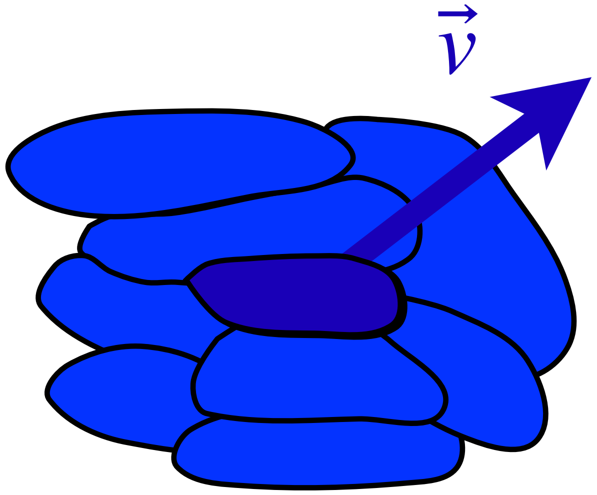


	Viscosity (mPa s)
Water	1
Whole milk	2
Olive oil	56
Pitch	10^{11}

Simple hydrodynamics

$$\dot{\vec{v}} + \vec{v} \cdot \overrightarrow{\nabla} \vec{v} = - \overrightarrow{\nabla} p + \eta \nabla^2 \vec{v}$$

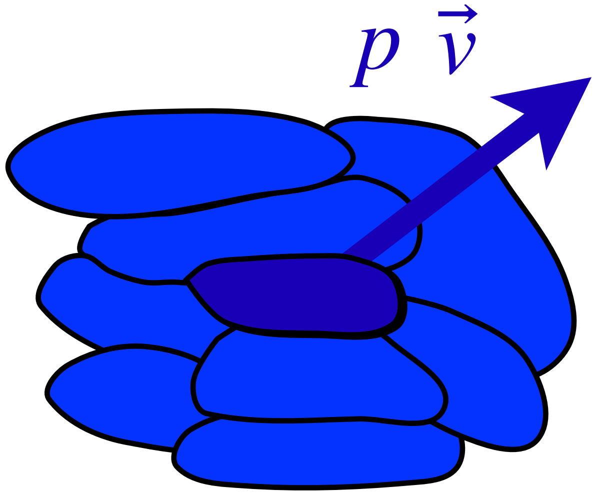
$$\overrightarrow{\nabla} \cdot \vec{v} = 0$$



Simple hydrodynamics

$$\dot{\vec{v}} + \vec{v} \cdot \overrightarrow{\nabla} \vec{v} = - \overrightarrow{\nabla} p + \eta \nabla^2 \vec{v}$$

$$\overrightarrow{\nabla} \cdot \vec{v} = 0$$

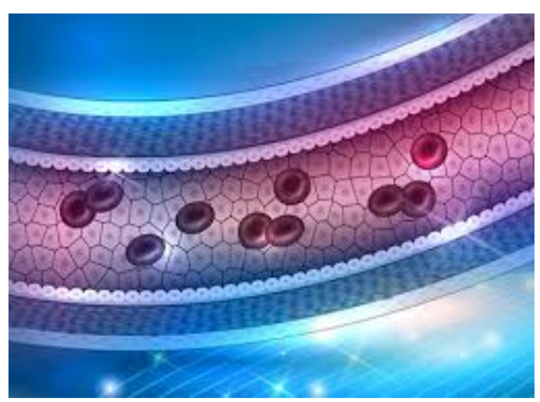


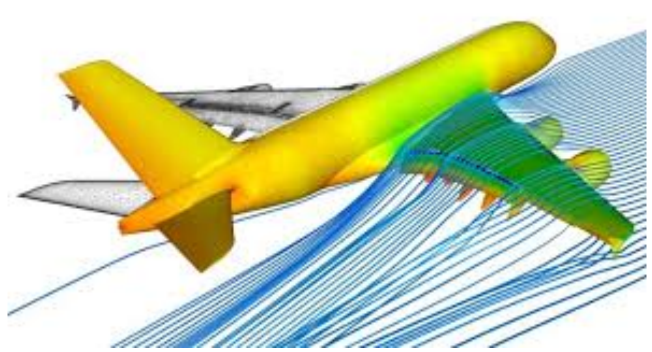
Simple hydrodynamics

$$\dot{\vec{v}} + \vec{v} \cdot \vec{\nabla} \vec{v} = -\vec{\nabla} p + \eta \nabla^2 \vec{v}$$

$$\vec{\nabla} \cdot \vec{v} = 0$$

It works!



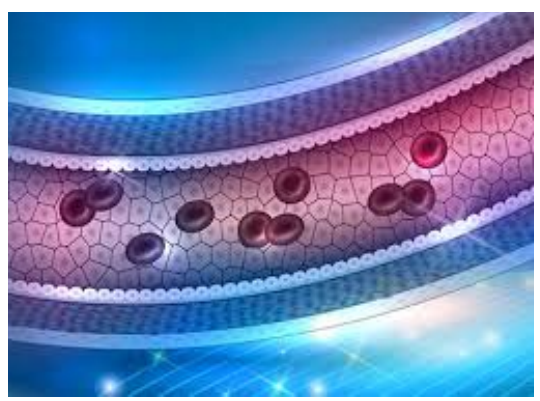


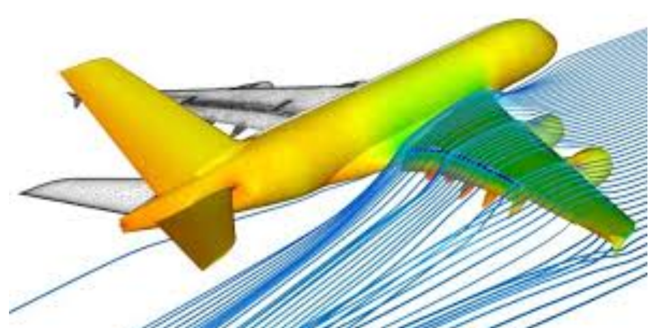
Simple hydrodynamics

$$\dot{\vec{v}} + \vec{v} \cdot \vec{\nabla}\vec{v} = -\vec{\nabla}p + \eta\nabla^2\vec{v}$$

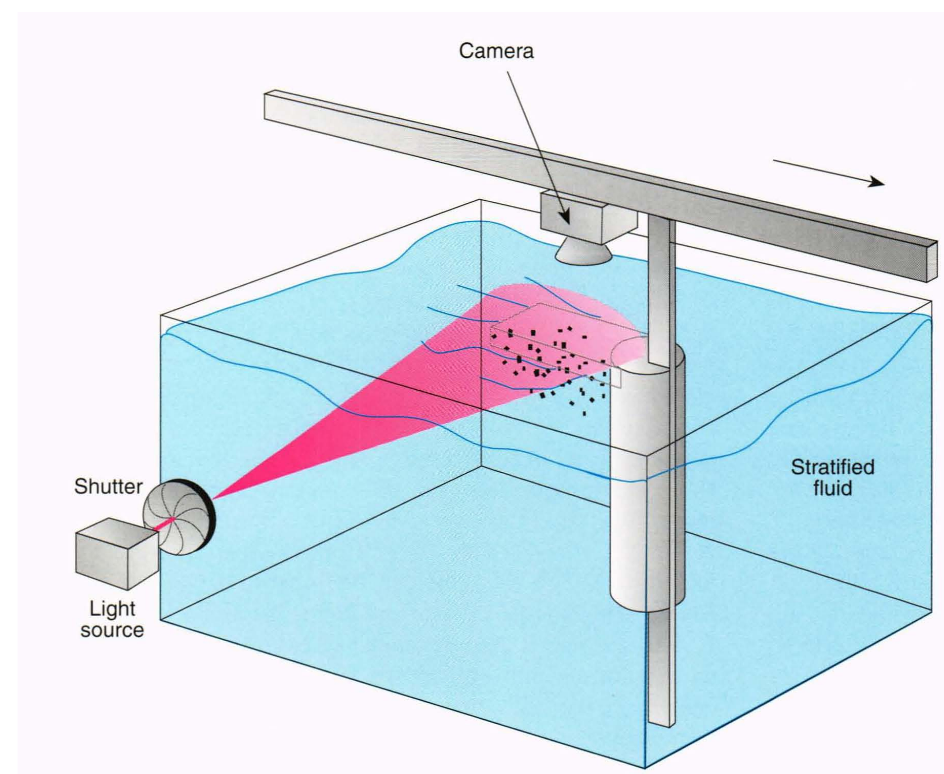
$$\vec{\nabla} \cdot \vec{v} = 0$$

It works!





Can be verified!



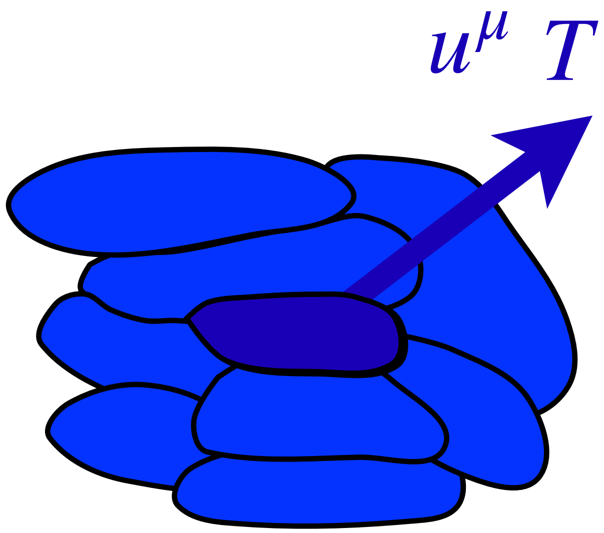
(S. Diamond, 1994)

Relativistic hydrodynamics

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

where

$$T^{\mu\nu} = \epsilon(T) u^\mu u^\nu + P(T)\left(\eta^{\mu\nu} + u^\mu u^\nu\right) - 2\eta(T)\sigma_{\mu\nu} + \ldots$$

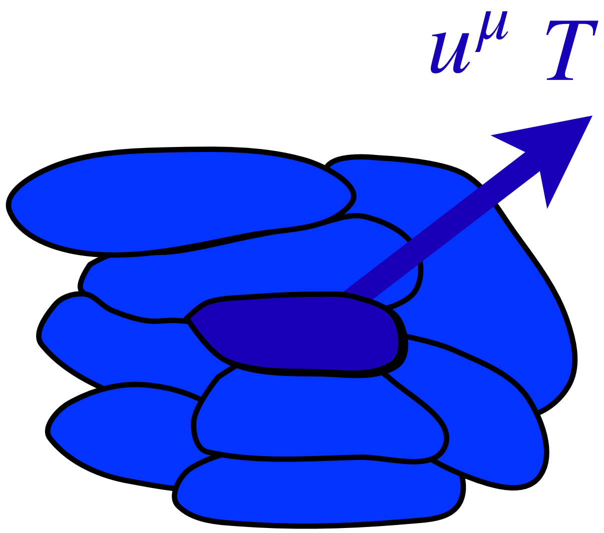


Relativistic hydrodynamics

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

where

$$T^{\mu\nu} = \epsilon(T)u^\mu u^\nu + P(T)\left(\eta^{\mu\nu} + u^\mu u^\nu\right) - 2\eta(T)\sigma_{\mu\nu} + \ldots$$

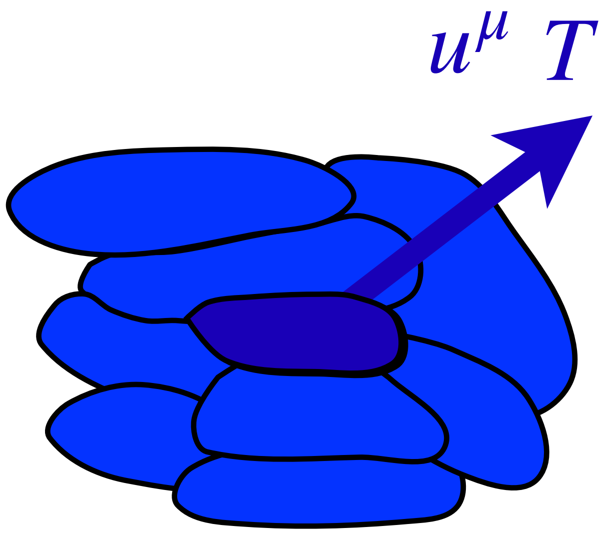


Relativistic hydrodynamics

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

where

$$T^{\mu\nu} = \epsilon(T)u^\mu u^\nu + P(T)\left(\eta^{\mu\nu} + u^\mu u^\nu\right) - 2\eta(T)\sigma_{\mu\nu} + \ldots$$

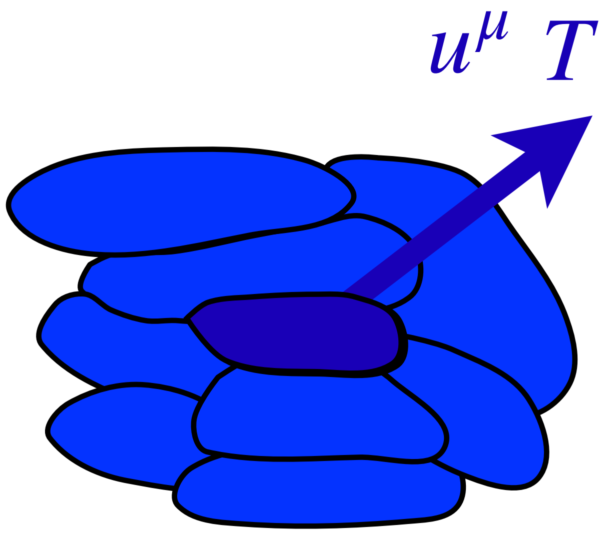


Relativistic hydrodynamics

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

where

$$T^{\mu\nu} = \epsilon(T) u^\mu u^\nu + P(T)\left(\eta^{\mu\nu} + u^\mu u^\nu\right) - 2\eta(T)\sigma_{\mu\nu} + \ldots$$



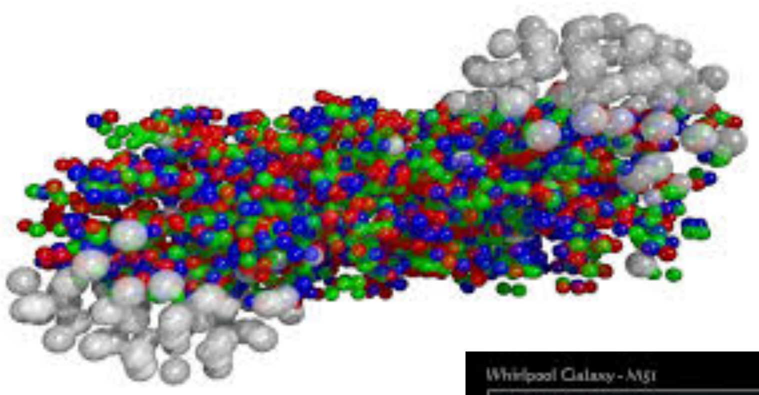
Relativistic hydrodynamics

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

where

$$T^{\mu\nu} = \epsilon(T)u^\mu u^\nu + P(T)\left(\eta^{\mu\nu} + u^\mu u^\nu\right) - 2\eta(T)\sigma_{\mu\nu} + \ldots$$

It works.



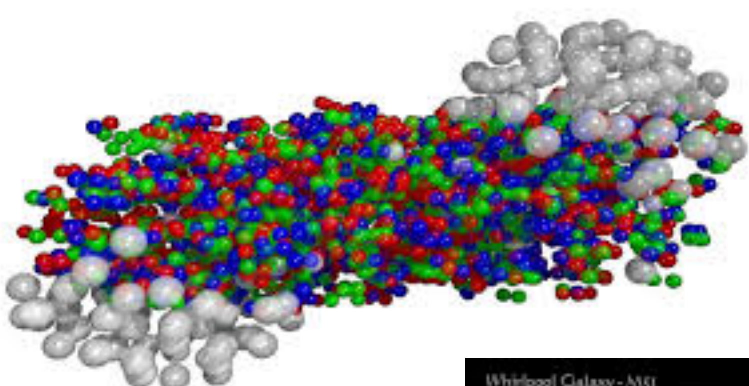
Relativistic hydrodynamics

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

where

$$T^{\mu\nu} = \epsilon(T) u^\mu u^\nu + P(T)\left(\eta^{\mu\nu} + u^\mu u^\nu\right) - 2\eta(T)\sigma_{\mu\nu} + \dots$$

It works.



Can be verified.

?

Holographic hydrodynamics

$$\mathscr{L} = \text{tr}\left(\frac{1}{2g} F_{\mu\nu} F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \begin{matrix}\text{Yukawa} \\ \text{interactions}\end{matrix} \right)$$

Holographic hydrodynamics

$$\mathscr{L} = \text{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \begin{array}{c}\text{Yukawa} \\ \text{interactions}\end{array} \right)$$

SU(N)

Holographic hydrodynamics

$$\mathscr{L} = \mathrm{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \text{Yukawa interactions} \right)$$

SU(N)

$$X^1 = \begin{pmatrix} \phi^1_{11} & \phi^1_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

Holographic hydrodynamics

$$\mathscr{L} = \mathrm{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \text{Yukawa interactions} \right)$$

SU(N)

$$X^1 = \begin{pmatrix} \phi^1_{11} & \phi^1_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$$X^2 = \begin{pmatrix} \phi^2_{11} & \phi^2_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

Holographic hydrodynamics

$$\mathscr{L} = \text{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \text{Yukawa interactions} \right)$$

SU(N)

$$X^1 = \begin{pmatrix} \phi^1_{11} & \phi^1_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$$X^2 = \begin{pmatrix} \phi^2_{11} & \phi^2_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$$\vdots$$

Holographic hydrodynamics

$$\mathscr{L} = \mathrm{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \text{Yukawa interactions} \right)$$

SU(N)

$$X^1 = \begin{pmatrix} \phi^1_{11} & \phi^1_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$$X^2 = \begin{pmatrix} \phi^2_{11} & \phi^2_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$\vdots$

$$\bar{\psi}^1 = \begin{pmatrix} \bar{\psi}^1_{11} & \bar{\psi}^1_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$\vdots$

Holographic hydrodynamics

$\sim \phi^4$

$$\mathscr{L} = \mathrm{tr}\left(\frac{1}{2g}F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i\sum_{A=1}^{4}\bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2}\sum_{I,J}[X^I, X^J][X^I, X^J] + \text{Yukawa interactions}\right)$$

SU(N)

$$X^1 = \begin{pmatrix} \phi^1_{11} & \phi^1_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$$X^2 = \begin{pmatrix} \phi^2_{11} & \phi^2_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$\vdots$

$$\bar{\psi}^1 = \begin{pmatrix} \bar{\psi}^1_{11} & \bar{\psi}^1_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$\vdots$

Holographic hydrodynamics

$\sim \phi^4$

$$\mathscr{L} = \mathrm{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \text{Yukawa interactions} \right)$$

SU(N)

$$X^1 = \begin{pmatrix} \phi^1_{11} & \phi^1_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$$\bar{\psi}^1 = \begin{pmatrix} \bar{\psi}^1_{11} & \bar{\psi}^1_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$\sim \phi \bar{\psi} \psi$

$$X^2 = \begin{pmatrix} \phi^2_{11} & \phi^2_{12} & \cdots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$\vdots$

Holographic hydrodynamics

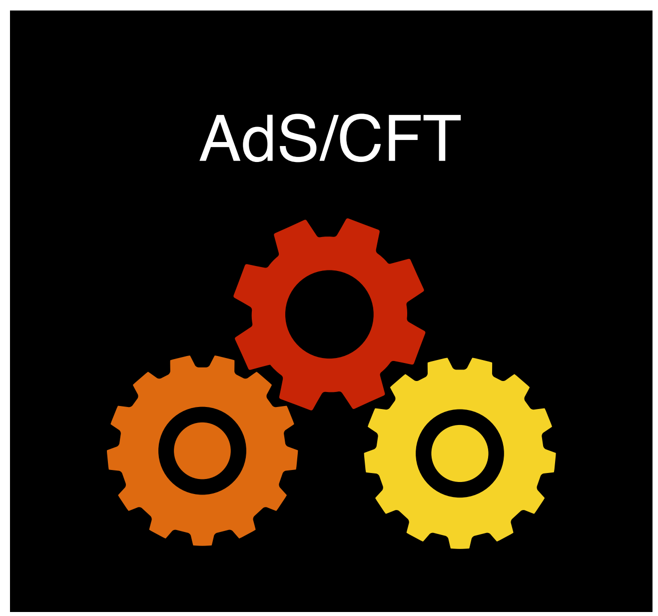
$$\mathscr{L} = \text{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \begin{array}{c}\text{Yukawa}\\ \text{interactions}\end{array} \right)$$

What is $\langle T^{\mu\nu} \rangle$ in a hydrodynamic configuration? (For large N and large g)

Holographic hydrodynamics

$$\mathscr{L} = \text{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \text{Yukawa interactions} \right)$$

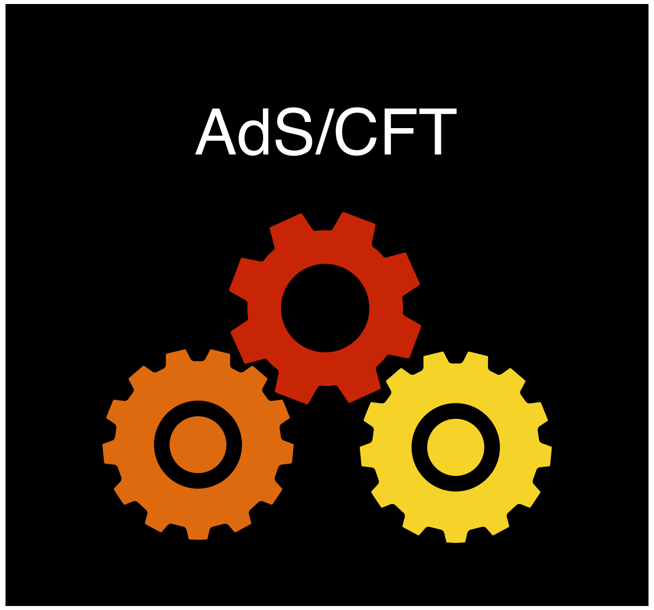
What is $\langle T^{\mu\nu} \rangle$ in a hydrodynamic configuration? (For large N and large g)



Holographic hydrodynamics

$$\mathscr{L} = \text{tr}\left(\frac{1}{2g}F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i\sum_{A=1}^{4}\bar{\psi}^A\bar{\sigma}D_\mu\psi_A + \frac{g^2}{2}\sum_{I,J}[X^I,X^J][X^I,X^J] + \text{Yukawa interactions}\right)$$

What is $\langle T^{\mu\nu}\rangle$ in a hydrodynamic configuration? (For large N and large g)

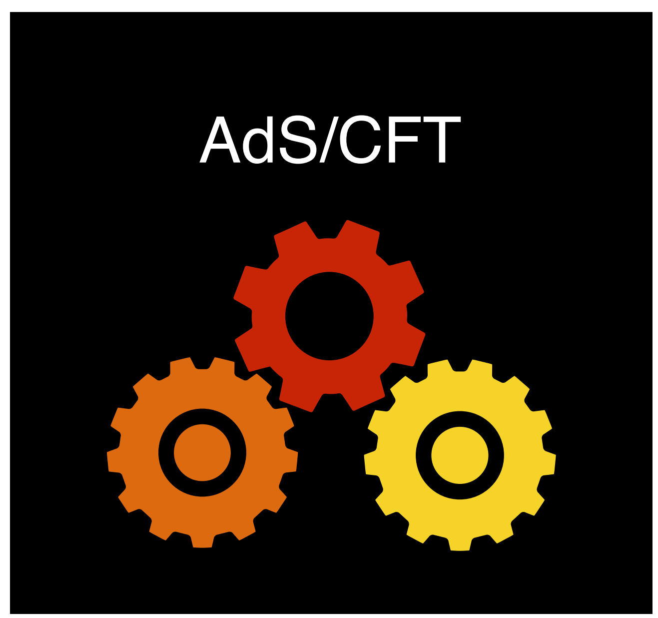


$$\langle T^{\mu\nu}\rangle = \epsilon u^\mu u^\nu + P(\eta^{\mu\nu} + u^\mu u^\nu) - 2\eta\sigma_{\mu\nu} + \ldots$$

Holographic hydrodynamics

$$\mathscr{L} = \text{tr}\left(\frac{1}{2g}F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i\sum_{A=1}^{4}\bar{\psi}^A\bar{\sigma}D_\mu\psi_A + \frac{g^2}{2}\sum_{I,J}[X^I,X^J][X^I,X^J] + \begin{array}{c}\text{Yukawa}\\ \text{interactions}\end{array}\right)$$

What is $\langle T^{\mu\nu}\rangle$ in a hydrodynamic configuration? (For large N and large g)



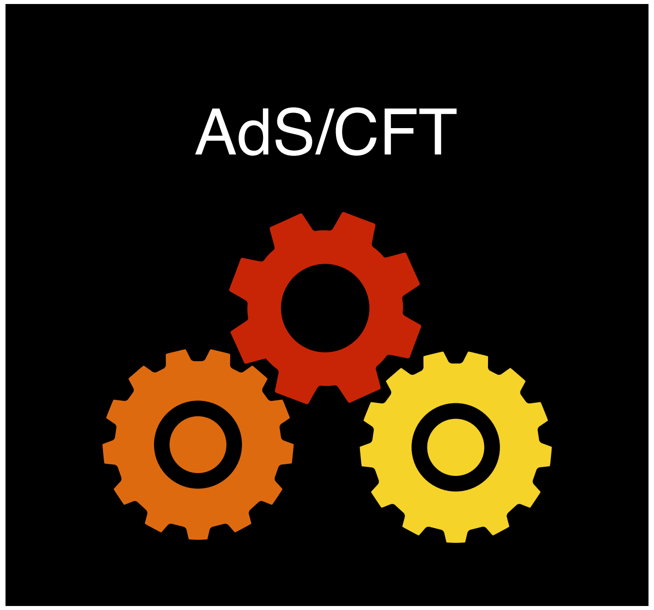
$$\langle T^{\mu\nu}\rangle = \epsilon u^\mu u^\nu + P(\eta^{\mu\nu} + u^\mu u^\nu) - 2\eta\sigma_{\mu\nu} + \ldots$$

$$\epsilon = \frac{3\pi^2 N^2}{8}T^4$$

Holographic hydrodynamics

$$\mathscr{L} = \text{tr}\left(\frac{1}{2g}F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i\sum_{A=1}^{4}\bar{\psi}^A\bar{\sigma}D_\mu\psi_A + \frac{g^2}{2}\sum_{I,J}[X^I,X^J][X^I,X^J] + \text{Yukawa interactions}\right)$$

What is $\langle T^{\mu\nu}\rangle$ in a hydrodynamic configuration? (For large N and large g)



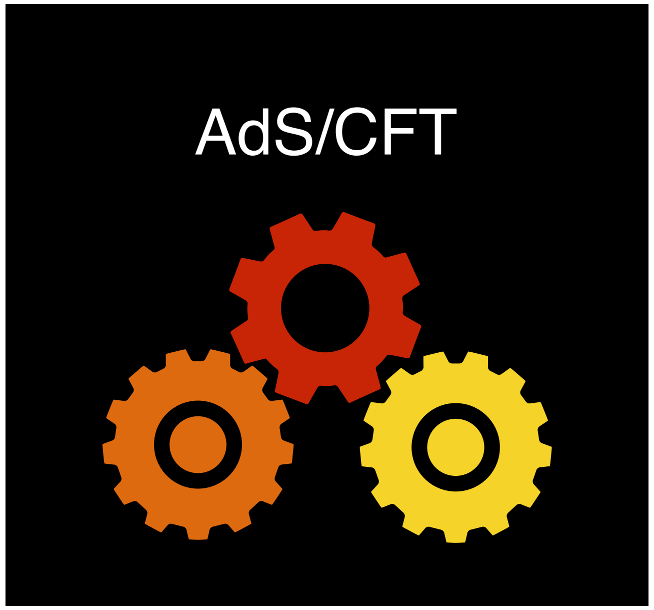
$$\langle T^{\mu\nu}\rangle = \epsilon u^\mu u^\nu + P(\eta^{\mu\nu} + u^\mu u^\nu) - 2\eta\sigma_{\mu\nu} + \ldots$$

$$\epsilon = \frac{3\pi^2 N^2}{8}T^4 \qquad P = \frac{1}{3}\epsilon$$

Holographic hydrodynamics

$$\mathscr{L} = \mathrm{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} D_\mu X^I D^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \begin{matrix}\text{Yukawa} \\ \text{interactions}\end{matrix} \right)$$

What is $\langle T^{\mu\nu} \rangle$ in a hydrodynamic configuration? (For large N and large g)



$$\langle T^{\mu\nu} \rangle = \epsilon u^\mu u^\nu + P(\eta^{\mu\nu} + u^\mu u^\nu) - 2\eta\sigma_{\mu\nu} + \dots$$

$$\epsilon = \frac{3\pi^2 N^2}{8} T^4 \qquad P = \frac{1}{3}\epsilon \qquad \eta = \frac{\frac{\partial P}{\partial T}}{4\pi} = \frac{s}{4\pi}$$

AdS/CFT

AdS/CFT

$$ds^2 = g_{mn}dx^m dx^n$$

AdS/CFT

$$ds^2 = g_{mn} dx^m dx^n$$

Solve

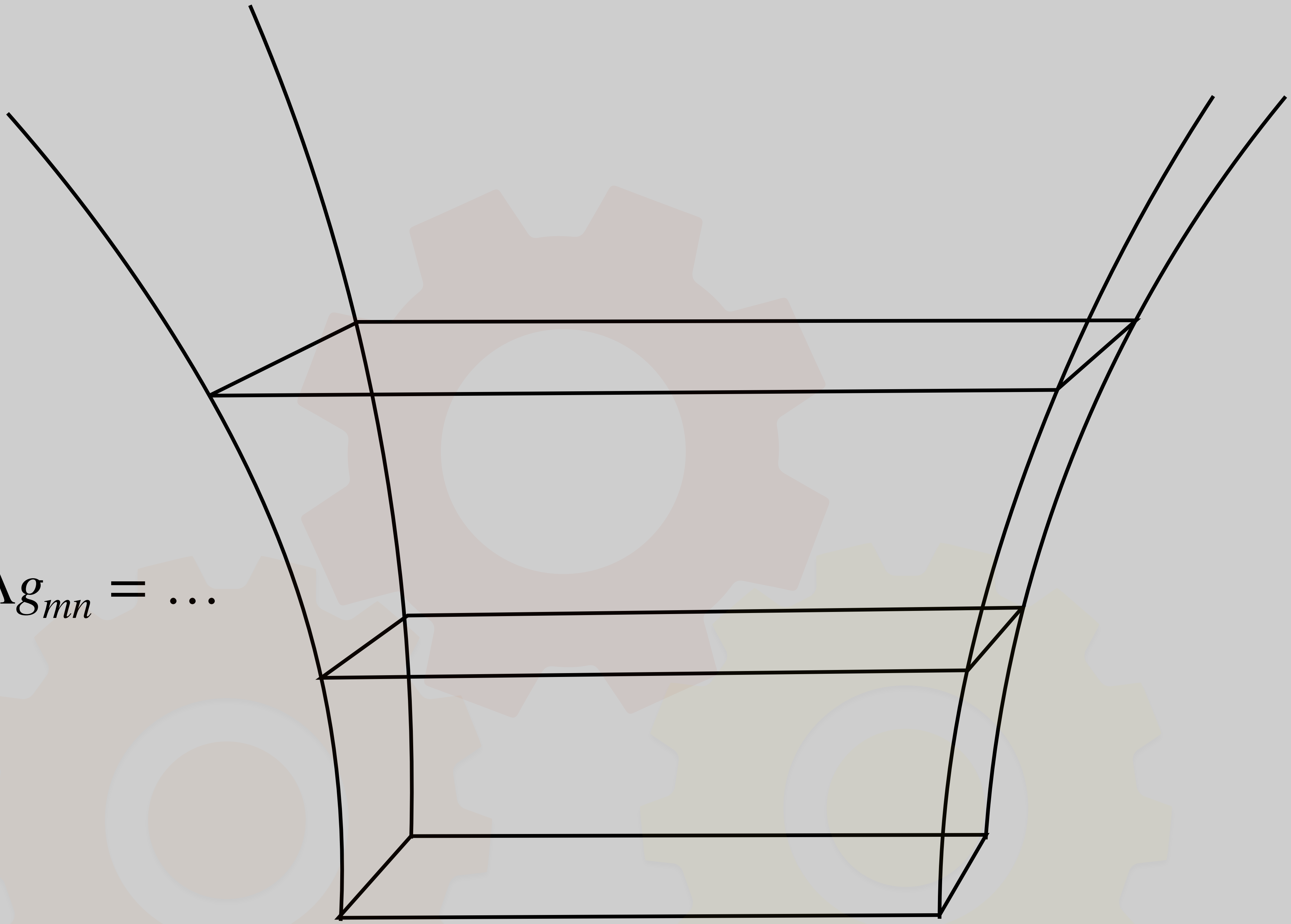
$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \dots$$

AdS/CFT

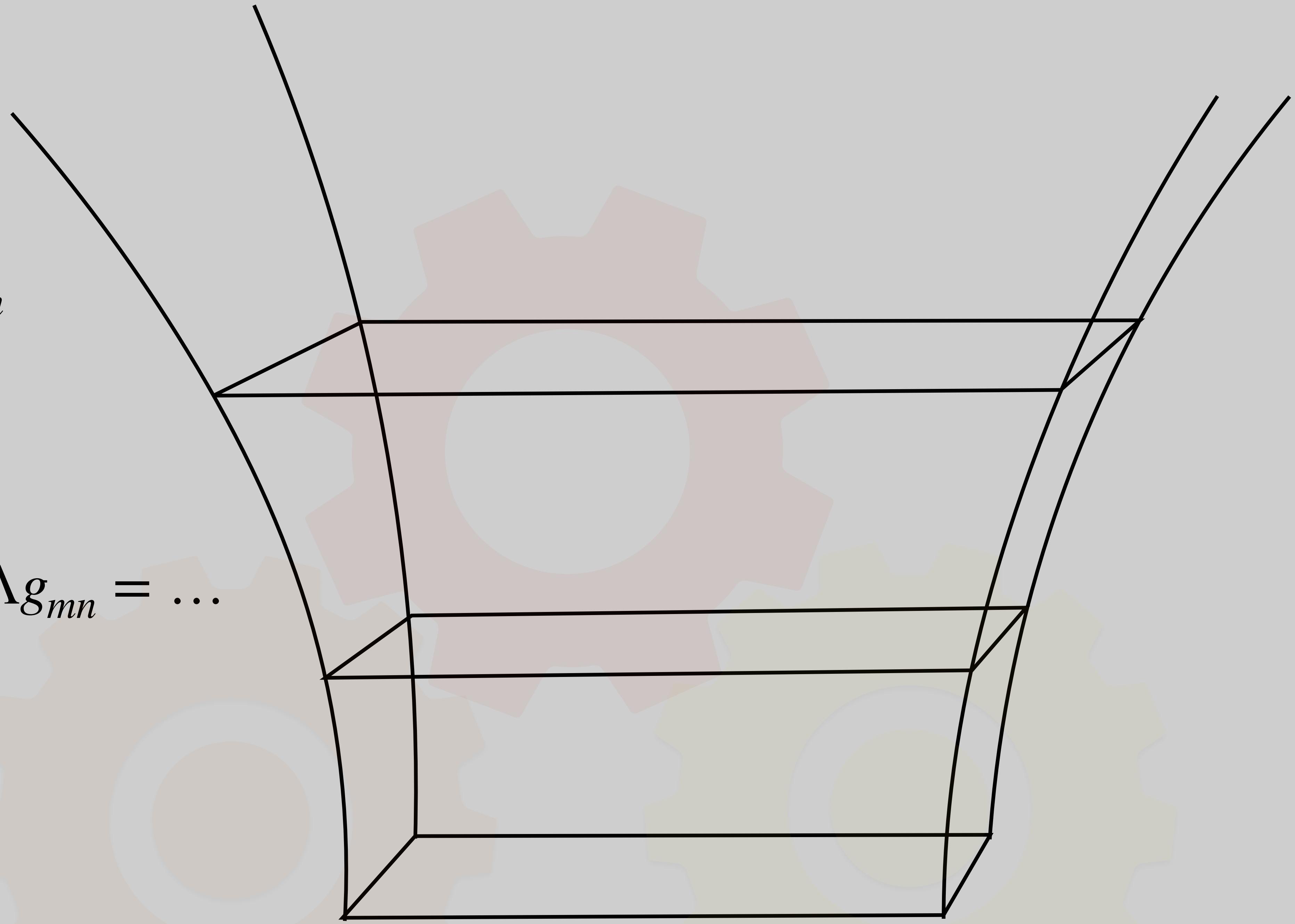
$$ds^2 = g_{mn}dx^m dx^n$$

Solve

$$R_{mn} - \frac{1}{2}g_{mn}R + \Lambda g_{mn} = \ldots$$



AdS/CFT



$$ds^2 = g_{mn}dx^m dx^n$$

Solve

$$R_{mn} - \frac{1}{2}g_{mn}R + \Lambda g_{mn} = \ldots$$

Evaluate

$$\lim g^{mn} \sim \langle T^{\mu\nu} \rangle$$

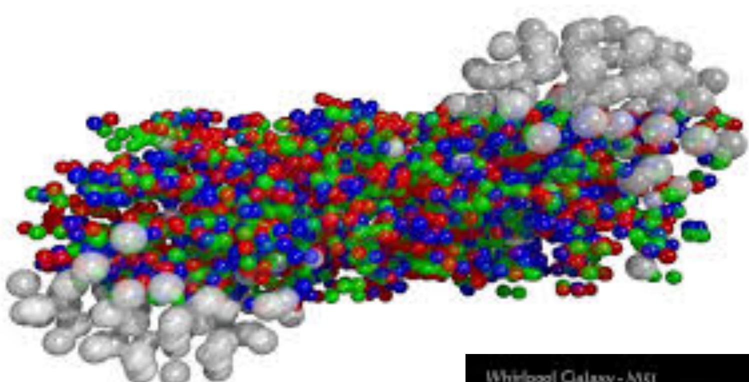
Relativistic hydrodynamics

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

where

$$T^{\mu\nu} = \epsilon(T)u^\mu u^\nu + P(T)\left(\eta^{\mu\nu} + u^\mu u^\nu\right) - 2\eta(T)\sigma_{\mu\nu} + \dots$$

It works.



Can be verified.

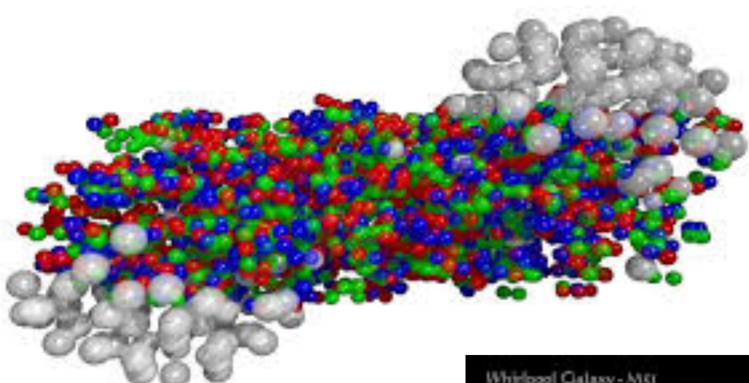
Relativistic hydrodynamics

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

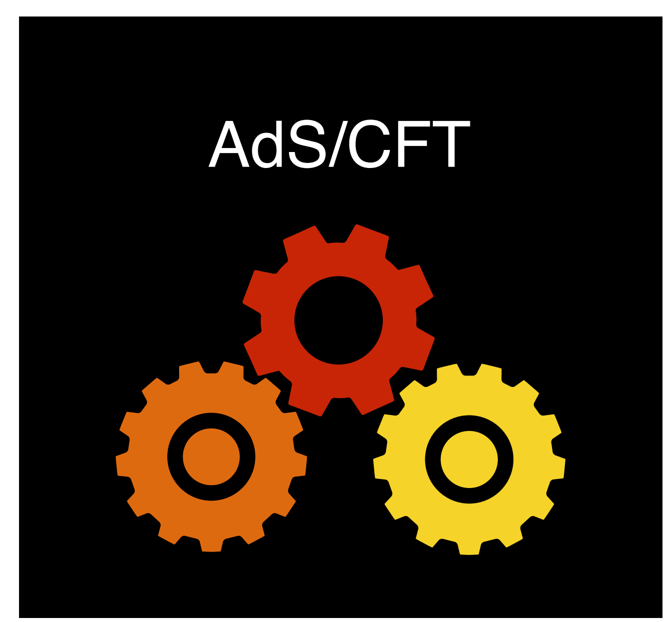
where

$$T^{\mu\nu} = \epsilon(T) u^\mu u^\nu + P(T)\left(\eta^{\mu\nu} + u^\mu u^\nu\right) - 2\eta(T)\sigma_{\mu\nu} + \ldots$$

It works.



Can be verified(?)

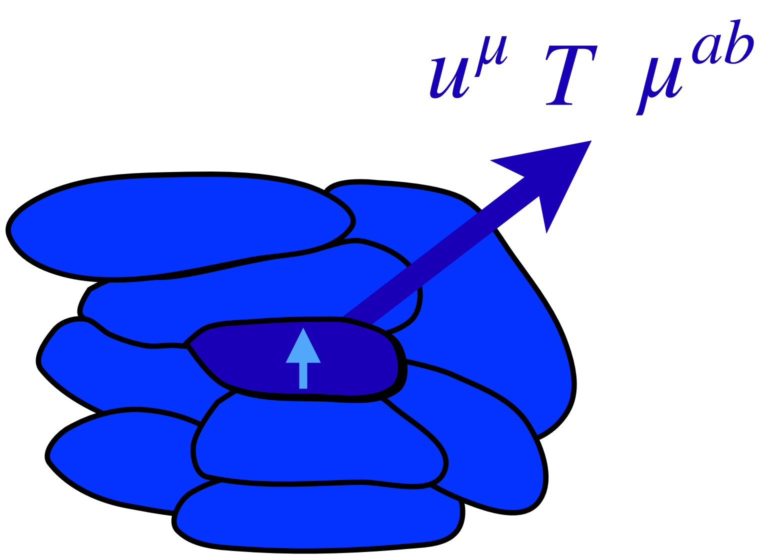


Spin hydrodynamics

$$\nabla_\mu T^{\mu\nu} = 0 \qquad \nabla_\mu J^{\mu\nu\rho} = 0$$

$$J^{\mu\nu\rho} = x^\nu T^{\mu\rho} - x^\rho T^{\mu\nu} + S^{\mu\nu\rho}$$

$$S^{\mu\nu\rho} = S^{\mu\nu\rho}[u, T, \mu^{\alpha\beta}] \qquad T^{\mu\nu} = T^{\mu\nu}[u, T, \mu^{\alpha\beta}]$$



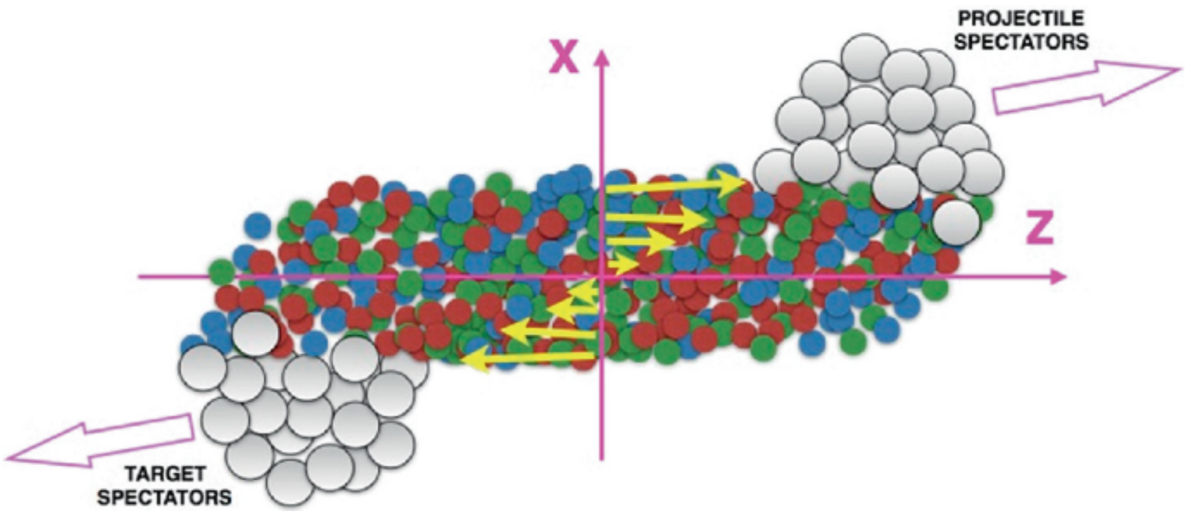
Spin hydrodynamics

$$\nabla_\mu T^{\mu\nu} = 0 \qquad \nabla_\mu J^{\mu\nu\rho} = 0$$

$$J^{\mu\nu\rho} = x^\nu T^{\mu\rho} - x^\rho T^{\mu\nu} + S^{\mu\nu\rho}$$

$$S^{\mu\nu\rho} = S^{\mu\nu\rho}[u, T, \mu^{\alpha\beta}] \qquad T^{\mu\nu} = T^{\mu\nu}[u, T, \mu^{\alpha\beta}]$$

It works?



Spin hydrodynamics

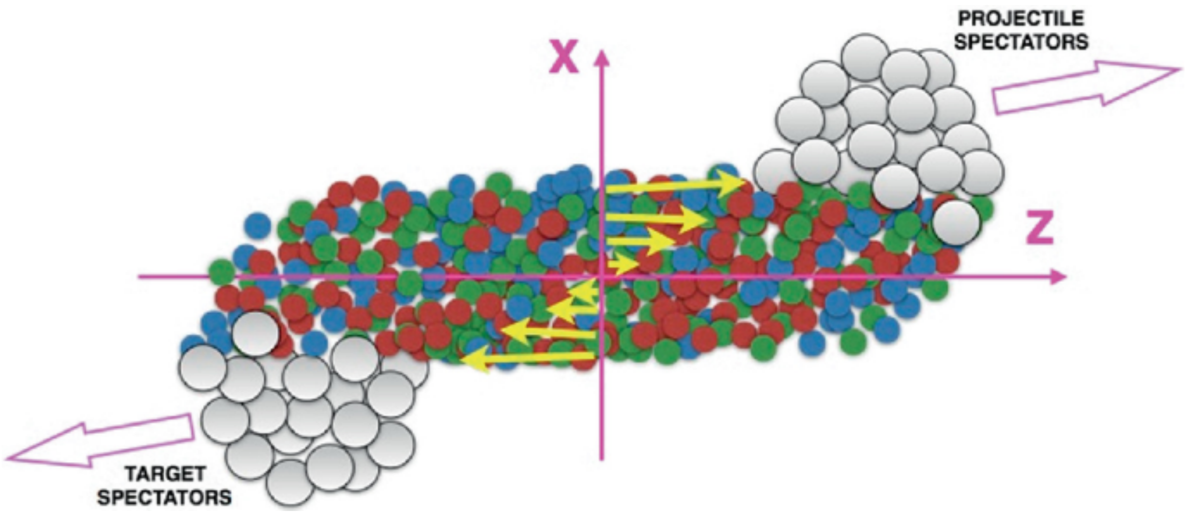
$$\nabla_\mu T^{\mu\nu} = 0 \qquad \nabla_\mu J^{\mu\nu\rho} = 0$$

$$J^{\mu\nu\rho} = x^\nu T^{\mu\rho} - x^\rho T^{\mu\nu} + S^{\mu\nu\rho}$$

$$S^{\mu\nu\rho} = S^{\mu\nu\rho}[u, T, \mu^{\alpha\beta}] \qquad T^{\mu\nu} = T^{\mu\nu}[u, T, \mu^{\alpha\beta}]$$

It works?

Can be verified?



Holographic hydrodynamics

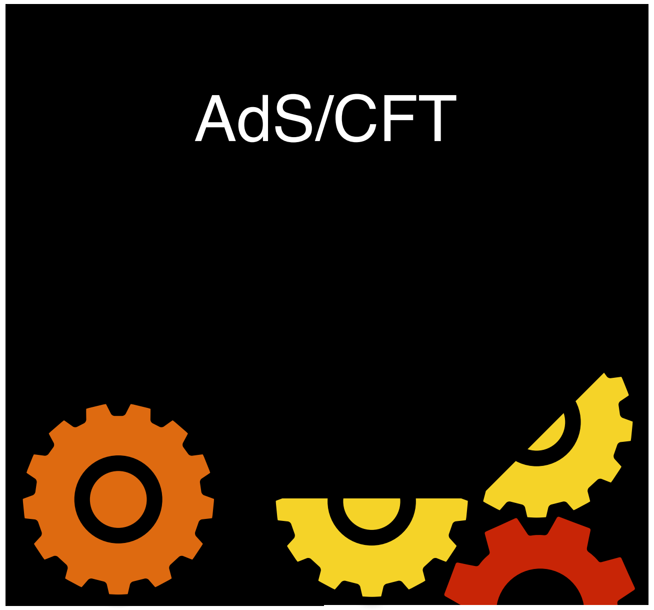
$$\mathscr{L} = \text{tr}\left(\frac{1}{2g}F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6}\partial_\mu X^I \partial^\mu X^I + i\sum_{A=1}^{4}\bar{\psi}^A\bar{\sigma}D_\mu\psi_A + \frac{g^2}{2}\sum_{I,J}[X^I, X^J][X^I, X^J] + \begin{array}{c}\text{Yukawa}\\\text{interactions}\end{array}\right)$$

What is $\langle S^{\mu\nu\rho}\rangle$ in a hydrodynamic configuration? (For large N and large g)

Holographic hydrodynamics

$$\mathscr{L} = \mathrm{tr}\left(\frac{1}{2g}F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6}\partial_\mu X^I \partial^\mu X^I + i\sum_{A=1}^{4}\bar{\psi}^A\bar{\sigma}D_\mu\psi_A + \frac{g^2}{2}\sum_{I,J}[X^I,X^J][X^I,X^J] + \text{Yukawa interactions}\right)$$

What is $\langle S^{\mu\nu\rho}\rangle$ in a hydrodynamic configuration? (For large N and large g)



AdS/CFT

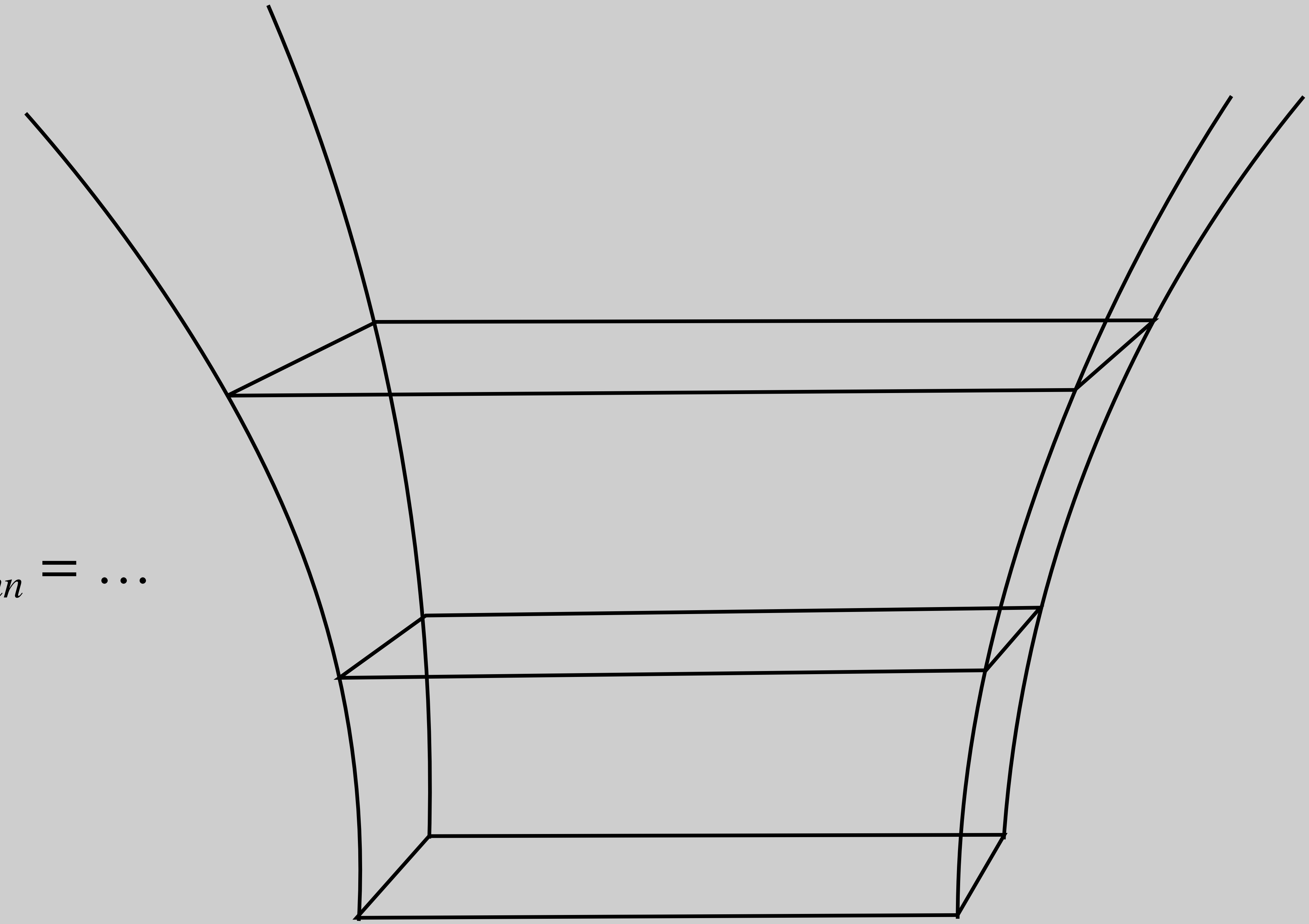
$$ds^2 = g_{mn} dx^m dx^n$$

Solve

$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \ldots$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$



AdS/CFT

$$ds^2 = g_{mn} dx^m dx^n$$

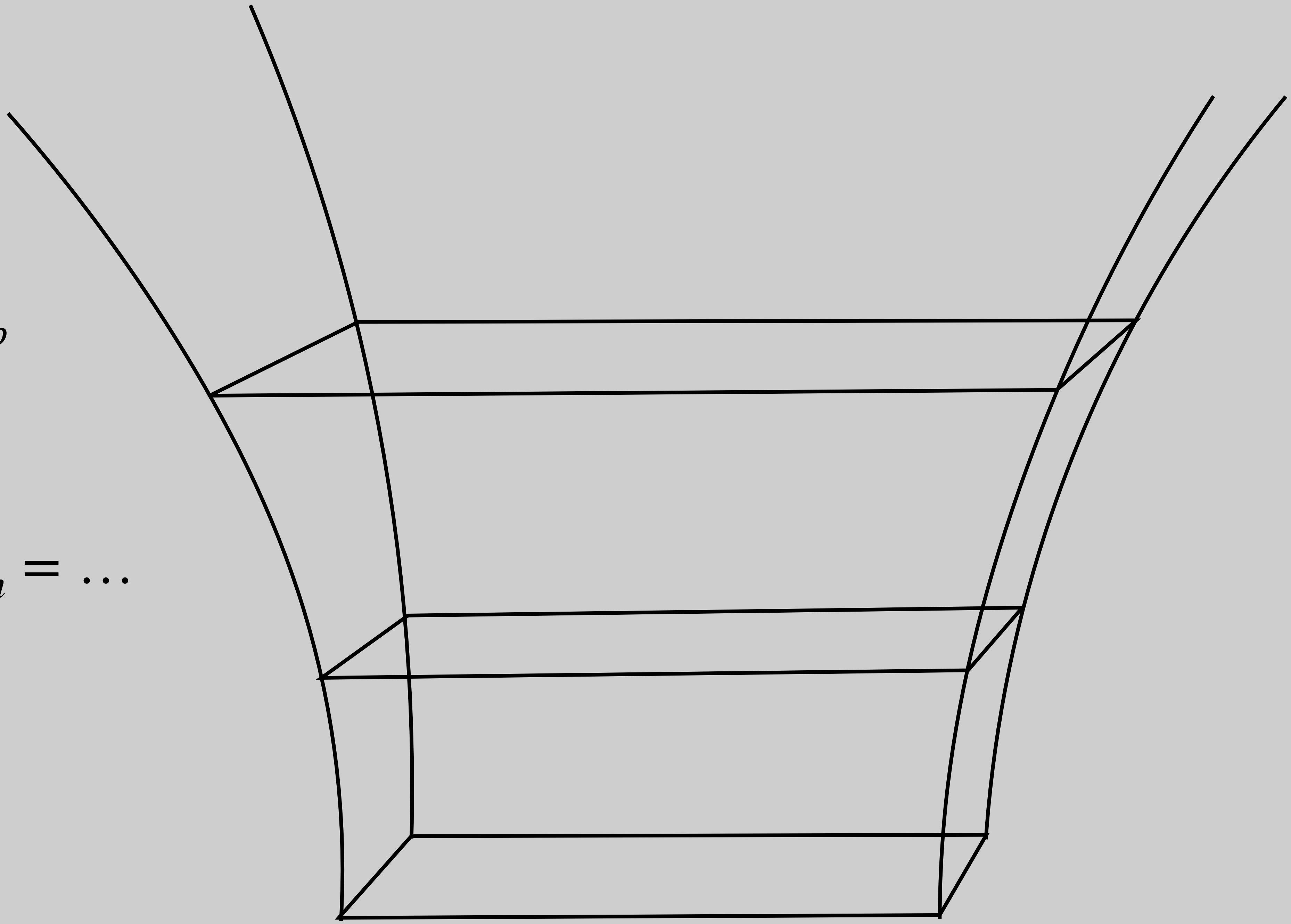
$$\Gamma^m_{np} = \left\{ \begin{matrix} m \\ np \end{matrix} \right\} + K^m{}_{np}$$

Solve

$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \ldots$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$



AdS/CFT

$$ds^2 = g_{mn} dx^m dx^n$$

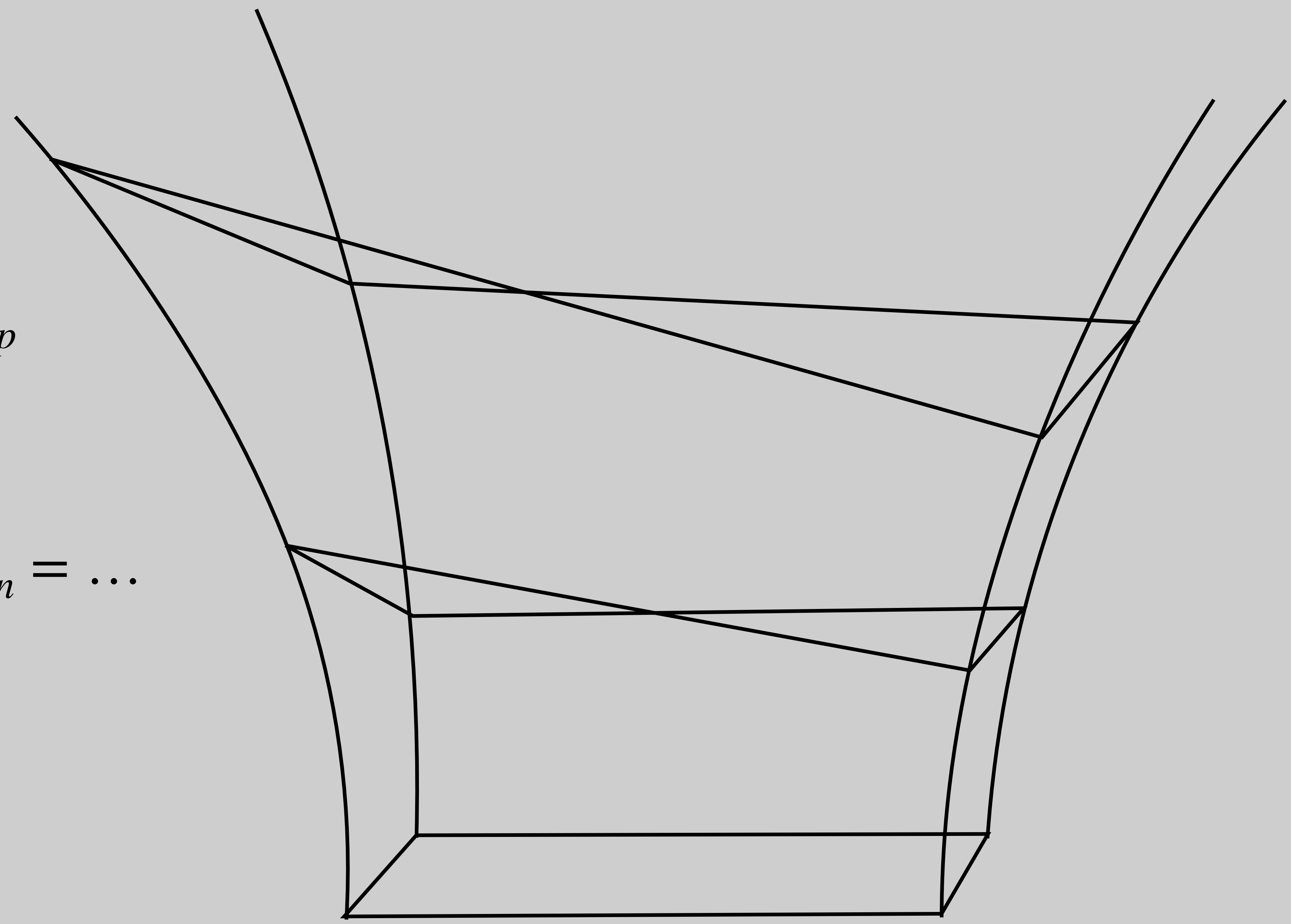
$$\Gamma^m_{np} = \left\{ \begin{matrix} m \\ np \end{matrix} \right\} + K^m{}_{np}$$

Solve

$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \ldots$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$



AdS/CFT

$$ds^2 = g_{mn}dx^m dx^n$$

$$\Gamma^m_{np} = \left\{ \begin{matrix} m \\ np \end{matrix} \right\} + K^m{}_{np}$$

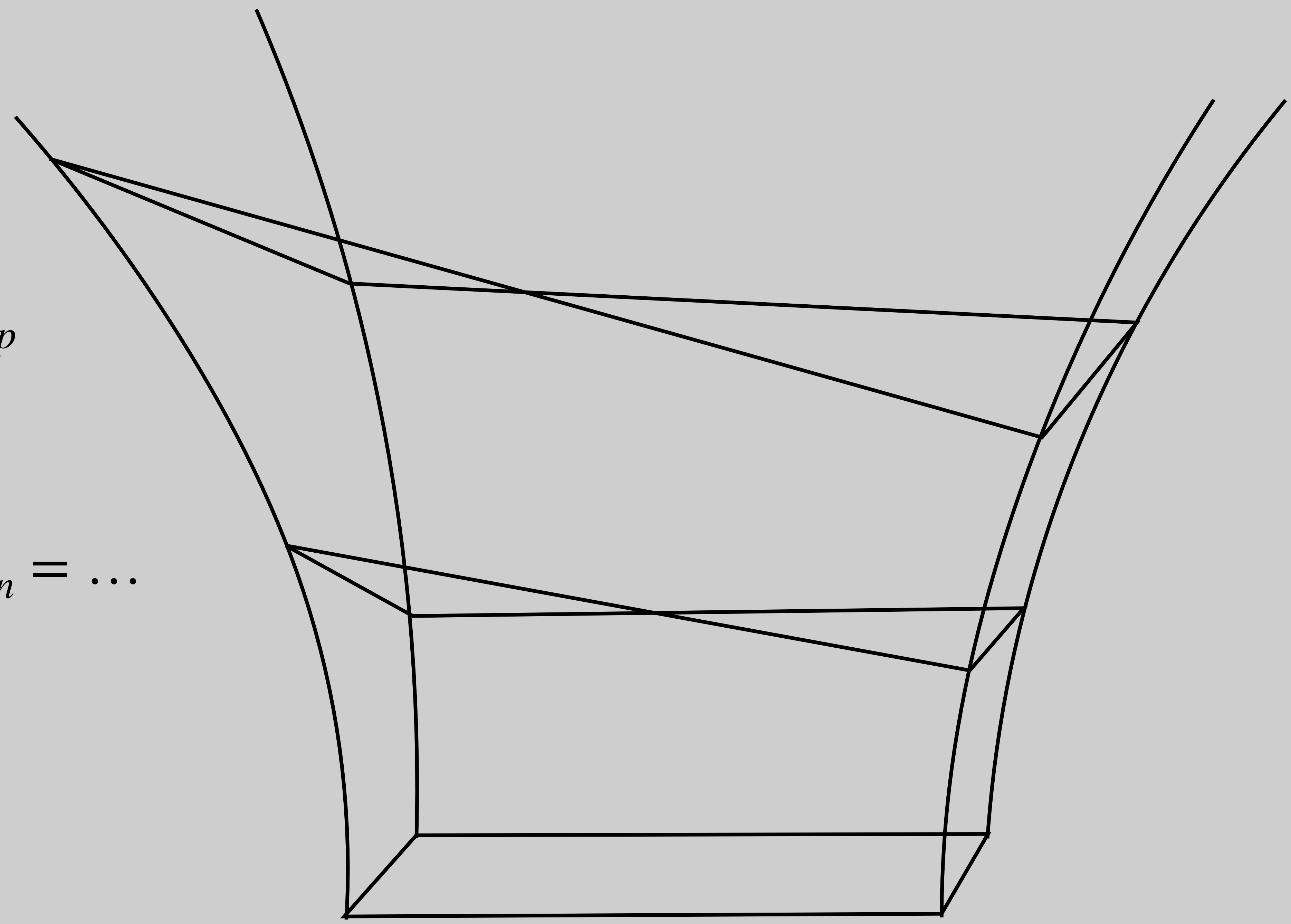
Solve

$$R_{mn} - \frac{1}{2}g_{mn}R + \Lambda g_{mn} = \ldots$$

$$\partial^2 K = \ldots$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$



AdS/CFT

$$ds^2 = g_{mn} dx^m dx^n$$

$$\Gamma^m_{np} = \left\{ \begin{matrix} m \\ np \end{matrix} \right\} + K^m{}_{np}$$

Solve

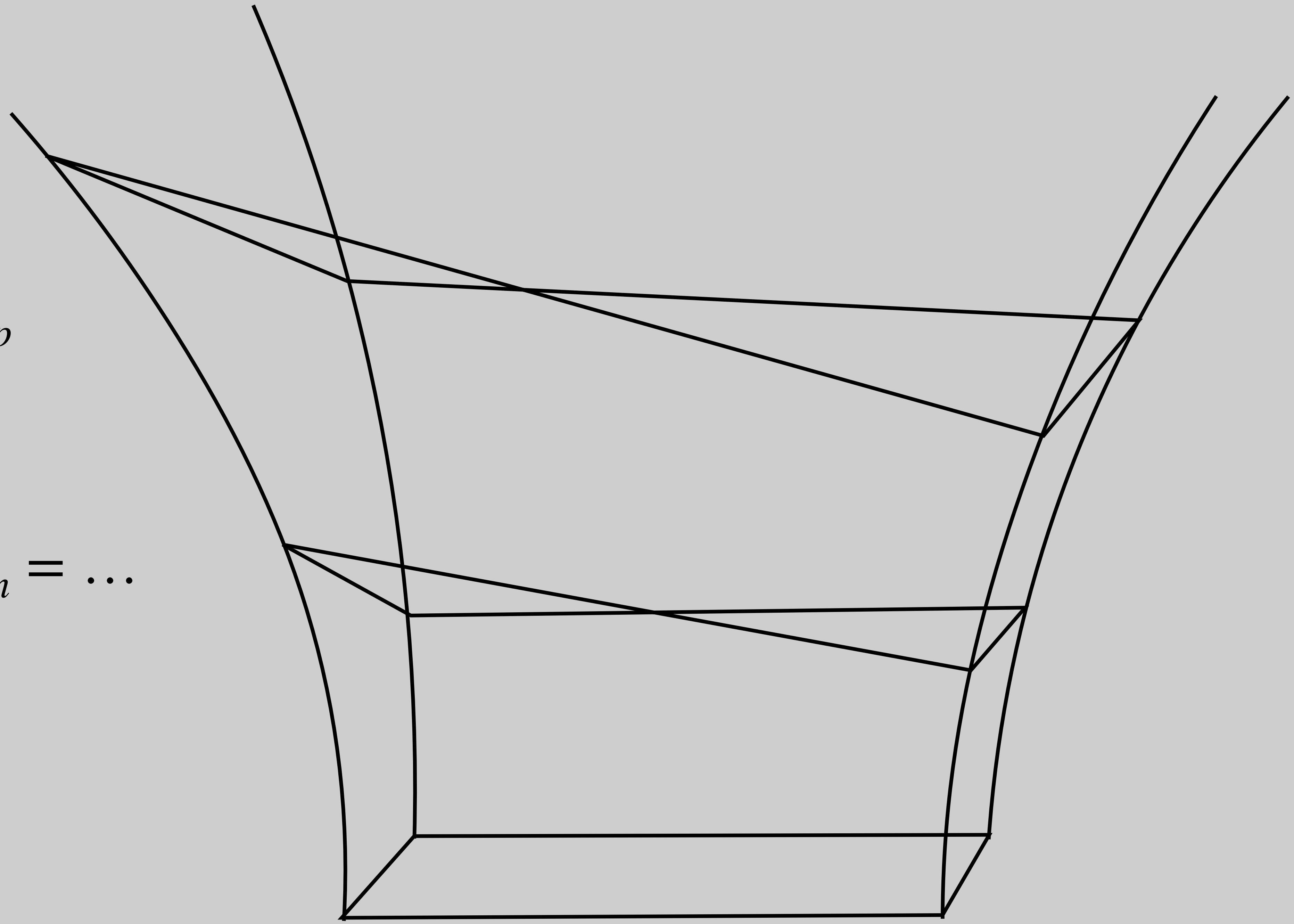
$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \ldots$$

$$\partial^2 K = \ldots$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$

$$\lim K^m{}_{np} \sim \langle S^\mu{}_{\nu\rho} \rangle$$



AdS/CFT

$$ds^2 = g_{mn} dx^m dx^n$$

$$\Gamma^m_{np} = \left\{ \begin{matrix} m \\ np \end{matrix} \right\} + K^m{}_{np}$$

Solve

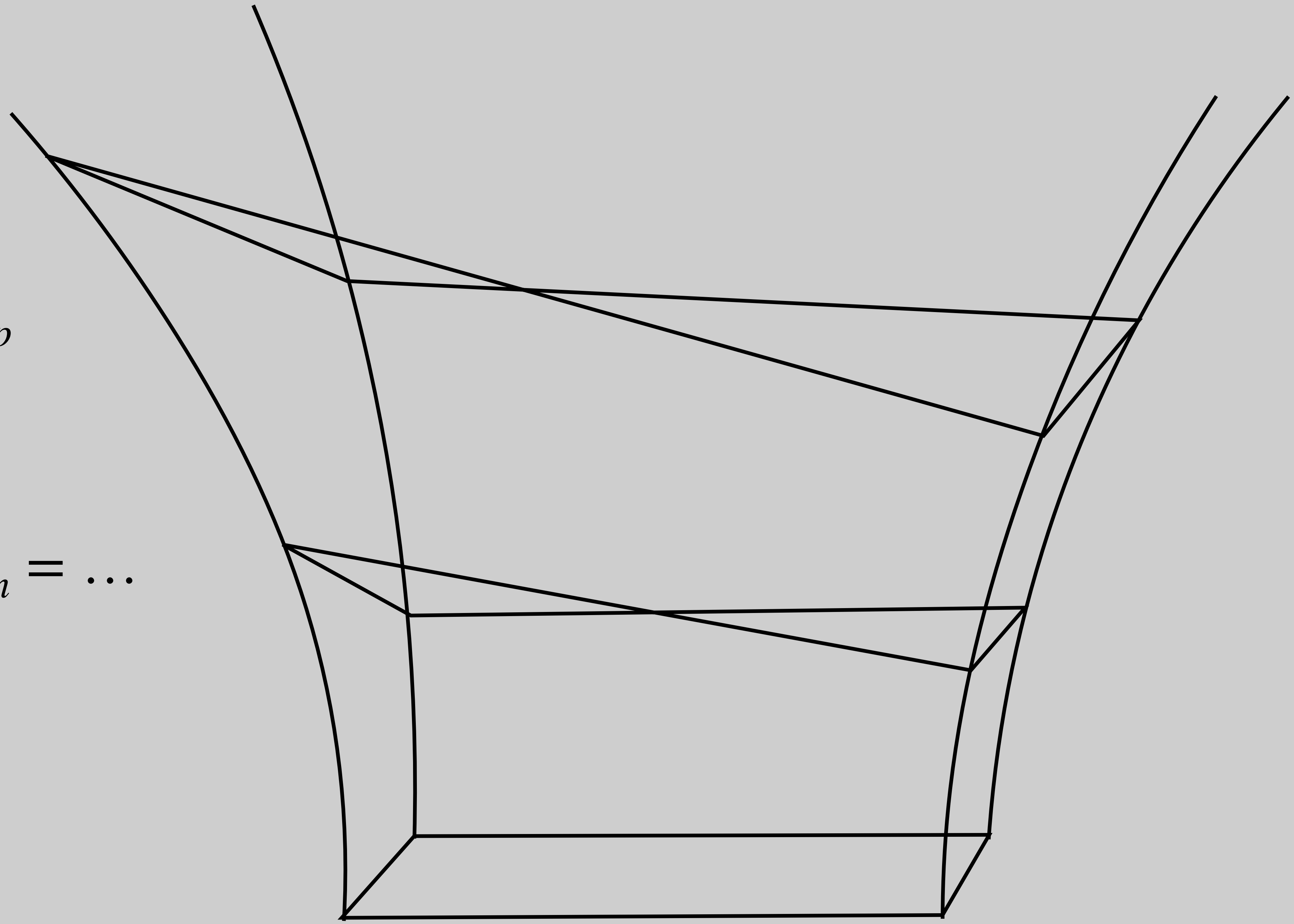
$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \ldots$$

$$\partial^2 K = ?$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$

$$\lim K^m{}_{np} \sim \langle S^\mu{}_{\nu\rho} \rangle$$



Organizing multiplets

Organizing multiplets

Consider the x^i component of a vector, V^i. Under a rotation we have, e.g.,

$$V^1 \to V^1 \cos\theta + V^2 \sin\theta$$

Organizing multiplets

Consider the x^i component of a vector, V^i. Under a rotation we have, e.g.,

$$V^1 \to V^1 \cos\theta + V^2 \sin\theta$$

So it makes sense to organize the components of a vector in a multiplet:

$$V = \begin{pmatrix} V^1 & V^2 \end{pmatrix}$$

Organizing multiplets

Consider the x^i component of a vector, V^i. Under a rotation we have, e.g.,

$$V^1 \rightarrow V^1 \cos\theta + V^2 \sin\theta$$

So it makes sense to organize the components of a vector in a multiplet:

$$V = \begin{pmatrix} V^1 & V^2 \end{pmatrix}$$

Consider the energy, E. Under a Lorentz transformation,

$$E \rightarrow \gamma \left(E - \beta p^x \right)$$

Thus,

$$P^\mu = \begin{pmatrix} E & p^x & p^y & p^z \end{pmatrix}$$

Organizing multiplets

Consider the x^i component of a vector, V^i. Under a rotation we have, e.g.,

$$V^1 \rightarrow V^1 \cos\theta + V^2 \sin\theta$$

So it makes sense to organize the components of a vector in a multiplet:

$$V = \begin{pmatrix} V^1 & V^2 \end{pmatrix}$$

Consider the energy, E. Under a Lorentz transformation,

$$E \rightarrow \gamma \left(E - \beta p^x \right)$$

Thus,

$$P^\mu = \begin{pmatrix} E & p^x & p^y & p^z \end{pmatrix}$$

Likewise,

$$T^{\mu\nu} = \begin{pmatrix} \epsilon & \cdots \\ \vdots & \ddots \end{pmatrix}$$

SUSY multiplets

SUSY is a symmetry that mixes bosons and fermions, schematically,

$$\phi \to \phi + \bar{\theta}\psi$$

SUSY multiplets

SUSY is a symmetry that mixes bosons and fermions, schematically,

$$\phi \to \phi + \bar{\theta}\psi$$

$$\mathscr{L} = \text{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} \partial_\mu X^I \partial^\mu X^I + i \sum_{A=1}^{4} \bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2} \sum_{I,J} [X^I, X^J][X^I, X^J] + \text{Yukawa interactions} \right)$$

SUSY multiplets

SUSY is a symmetry that mixes bosons and fermions, schematically,

$$\phi \to \phi + \bar{\theta}\psi$$

Composite operators will also transform, schematically,

$$T^{\mu\nu} \to T^{\mu\nu} + \bar{\theta}^{\mu} J^{\nu}$$

SUSY multiplets

SUSY is a symmetry that mixes bosons and fermions, schematically,

$$\phi \rightarrow \phi + \bar{\theta}\psi$$

Composite operators will also transform, schematically,

$$T^{\mu\nu} \rightarrow T^{\mu\nu} + \bar{\theta}^{\mu} J^{\nu}$$

Thus,

$$\mathbf{T}^{\mu} = \begin{pmatrix} T^{\mu\nu} & J^{\mu}_{\alpha} & R^{\mu} \end{pmatrix}$$

SUSY multiplets

SUSY is a symmetry that mixes bosons and fermions, schematically,

$$\phi \to \phi + \bar{\theta}\psi$$

Composite operators will also transform, schematically,

$$T^{\mu\nu} \to T^{\mu\nu} + \bar{\theta}^{\mu} J^{\nu}$$

Thus,

$$\mathbf{T}^{\mu} = \begin{pmatrix} T^{\mu\nu} & J^{\mu}_{\alpha} & R^{\mu} \end{pmatrix}$$

Our main result is that

$$S^{\mu\nu\rho} = \epsilon^{\mu\nu\rho\sigma} R_{\sigma}$$

for a large (infinite) class of supersymmetric theories.

SUSY multiplets

SUSY is a symmetry that mixes bosons and fermions, schematically,

$$\phi \to \phi + \bar{\theta}\psi$$

Composite operators will also transform, schematically,

$$T^{\mu\nu} \to T^{\mu\nu} + \bar{\theta}^{\mu} J^{\nu}$$

Thus,

$$\mathbf{T}^{\mu} = \begin{pmatrix} T^{\mu\nu} & J^{\mu}_{\alpha} & R^{\mu} \end{pmatrix}$$

$$\mathscr{L} = \mathrm{tr}\left(\frac{1}{2g} F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6} \partial_{\mu}X^{I}\partial^{\mu}X^{I} + i\sum_{A=1}^{4} \bar{\psi}^{A}\bar{\sigma}D_{\mu}\psi_{A} + \frac{g^{2}}{2}\sum_{I,J}[X^{I},X^{J}][X^{I},X^{J}] + \text{Yukawa interactions} \right)$$

Our main result is that

$$S^{\mu\nu\rho} = \epsilon^{\mu\nu\rho\sigma} R_{\sigma}$$

for a large (infinite) class of supersymmetric theories.

AdS/CFT

$$ds^2 = g_{mn} dx^m dx^n$$

$$\Gamma^m_{np} = \left\{ \begin{matrix} m \\ np \end{matrix} \right\} + K^m{}_{np}$$

Solve

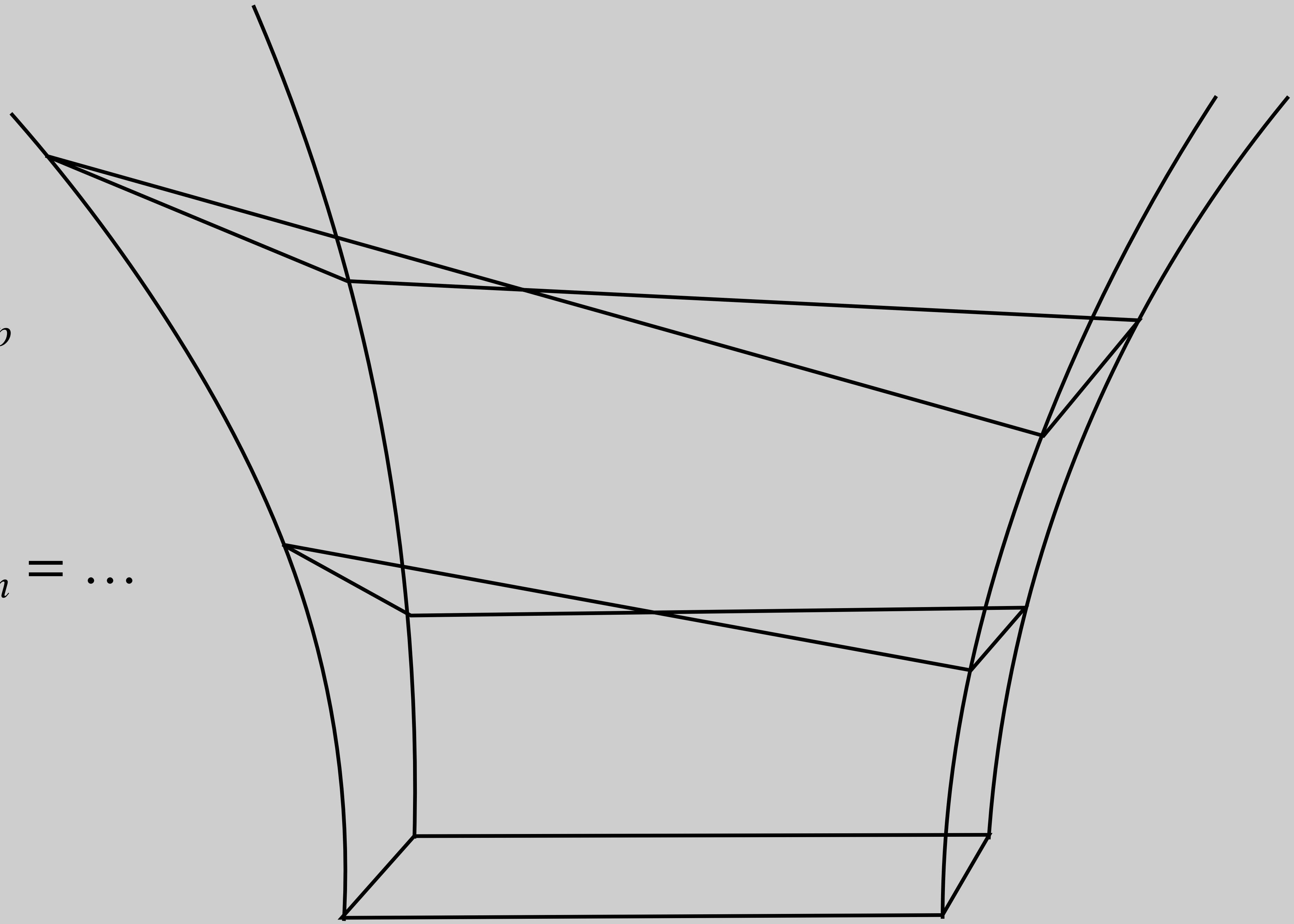
$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \ldots$$

$$\partial^2 K = ?$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$

$$\lim K^m{}_{np} \sim \langle S^\mu{}_{\nu\rho} \rangle$$



AdS/CFT

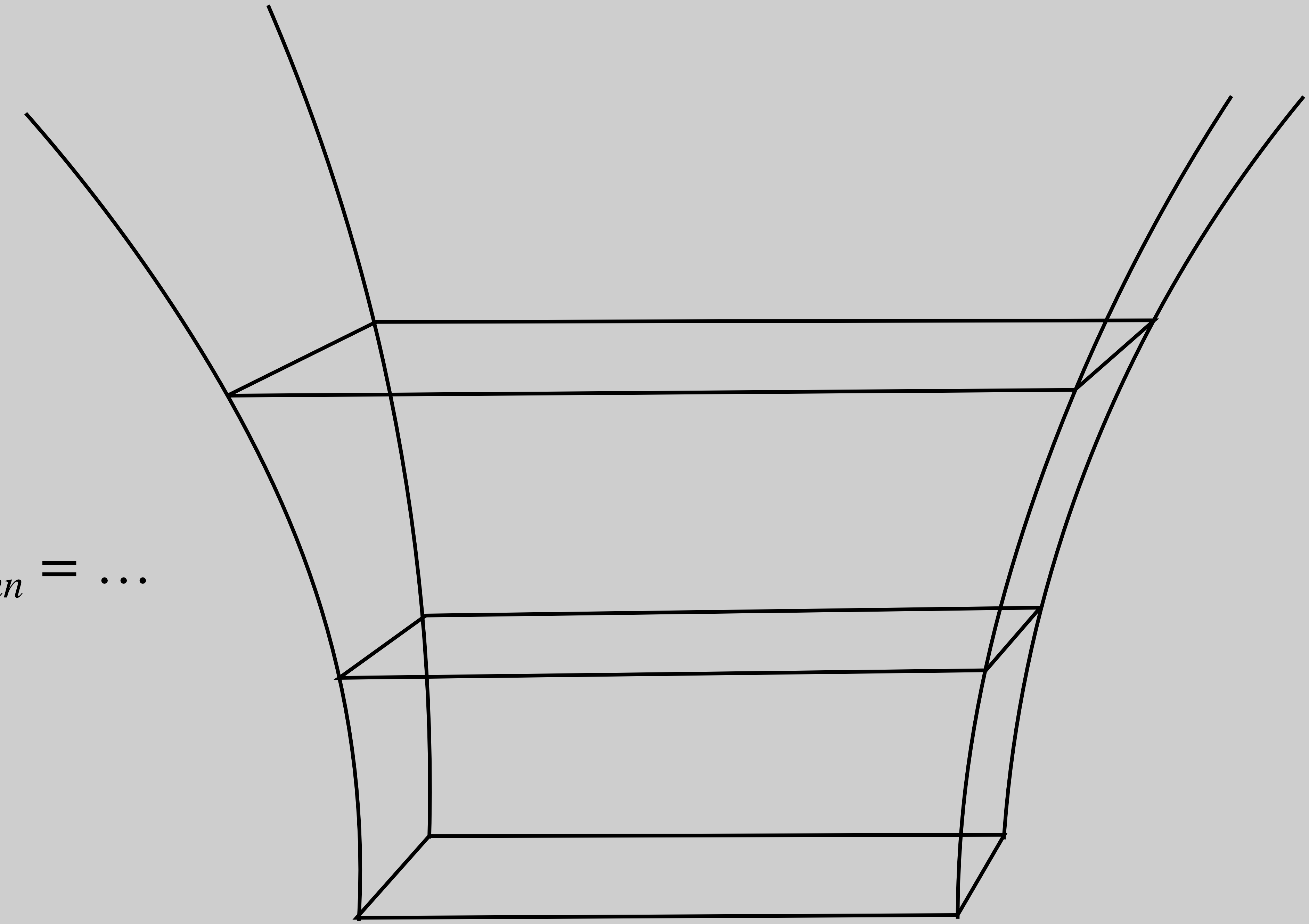
$$ds^2 = g_{mn} dx^m dx^n$$

Solve

$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \ldots$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$



AdS/CFT

$$ds^2 = g_{mn} dx^m dx^n$$

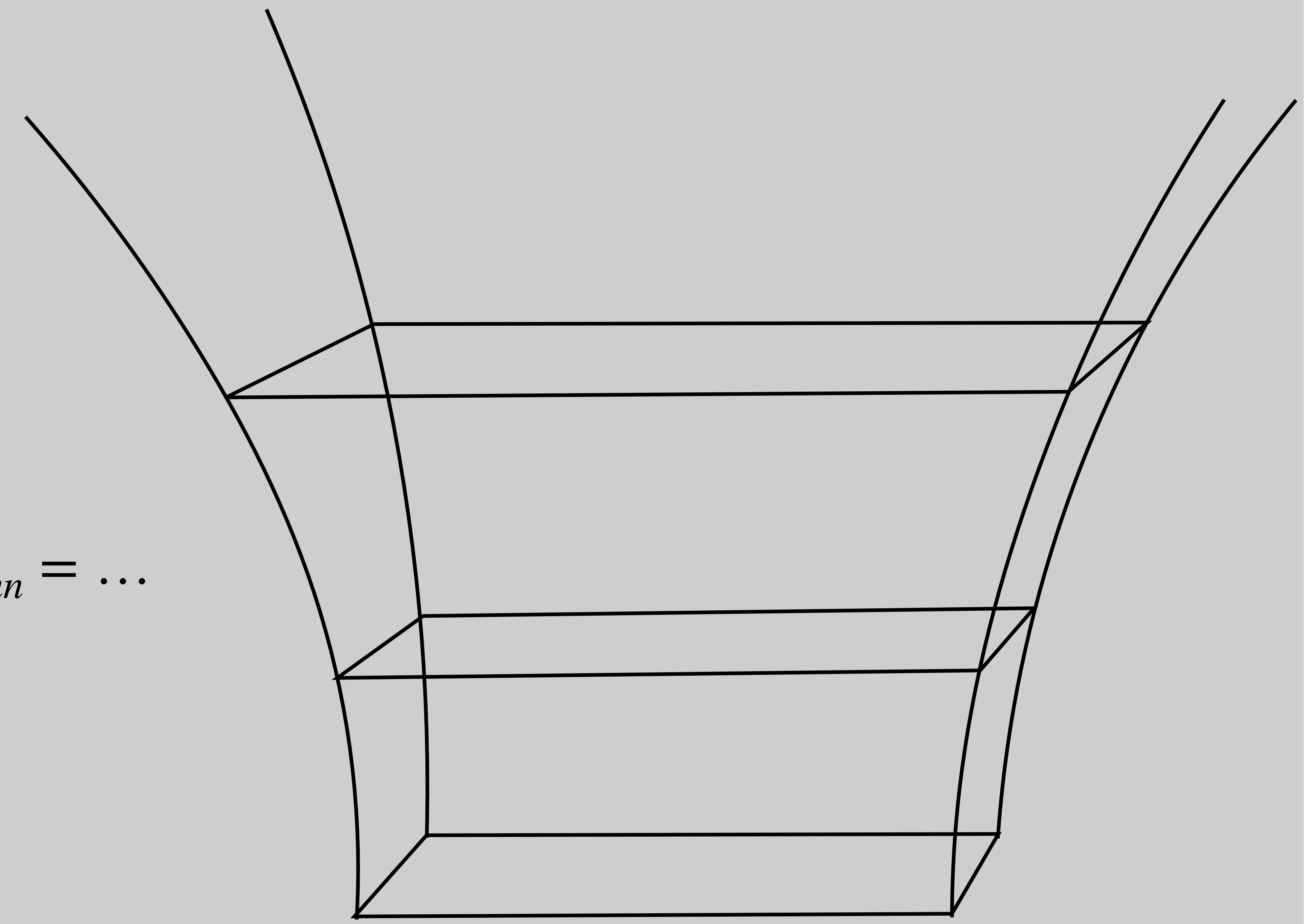
$$A = A_\mu dx^\mu$$

Solve

$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \ldots$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$



AdS/CFT

$$ds^2 = g_{mn} dx^m dx^n$$

$$A = A_\mu dx^\mu$$

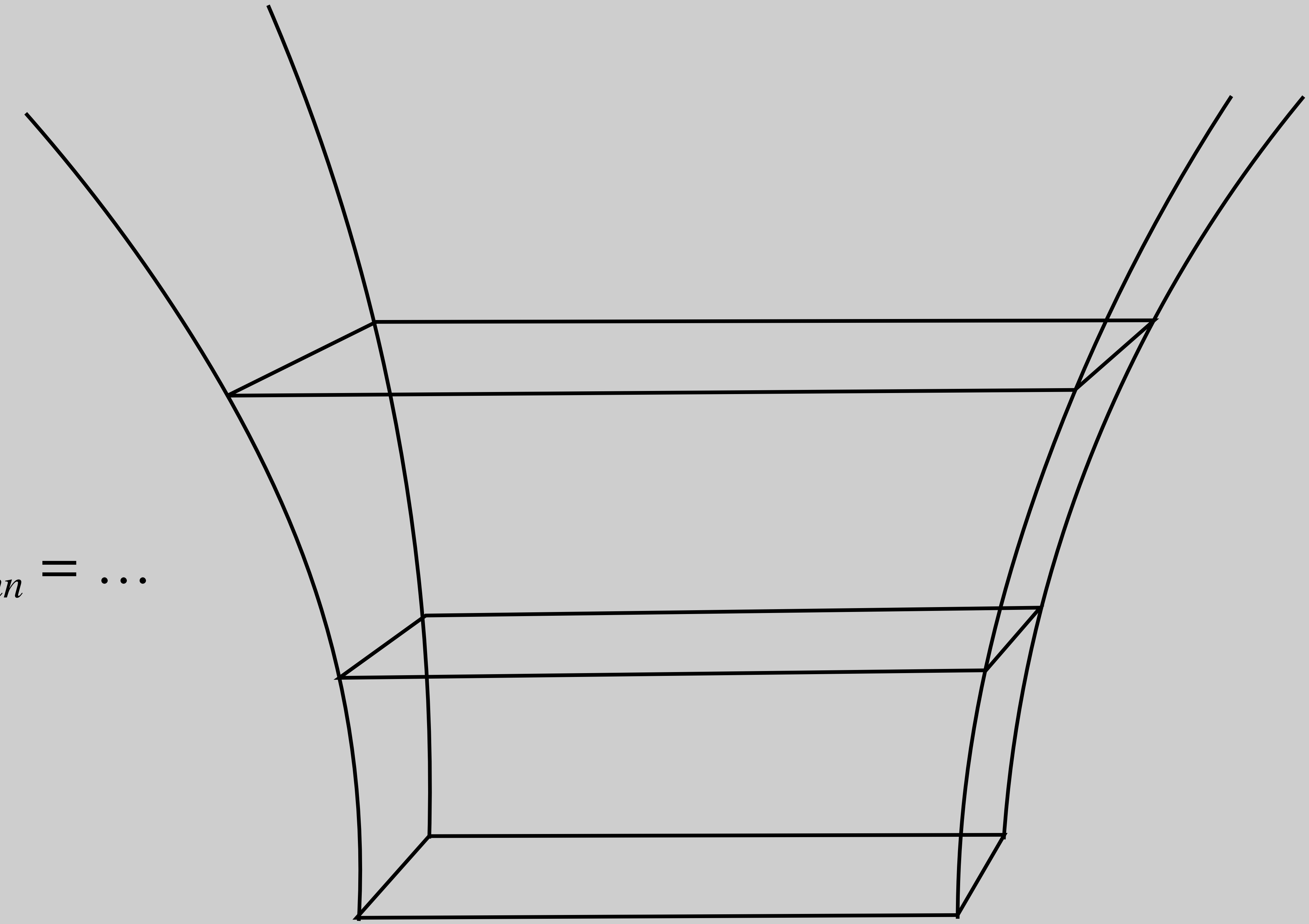
Solve

$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \dots$$

$$\nabla_m F^{mn} = \dots$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$



AdS/CFT

$$ds^2 = g_{mn} dx^m dx^n$$

$$A = A_\mu dx^\mu$$

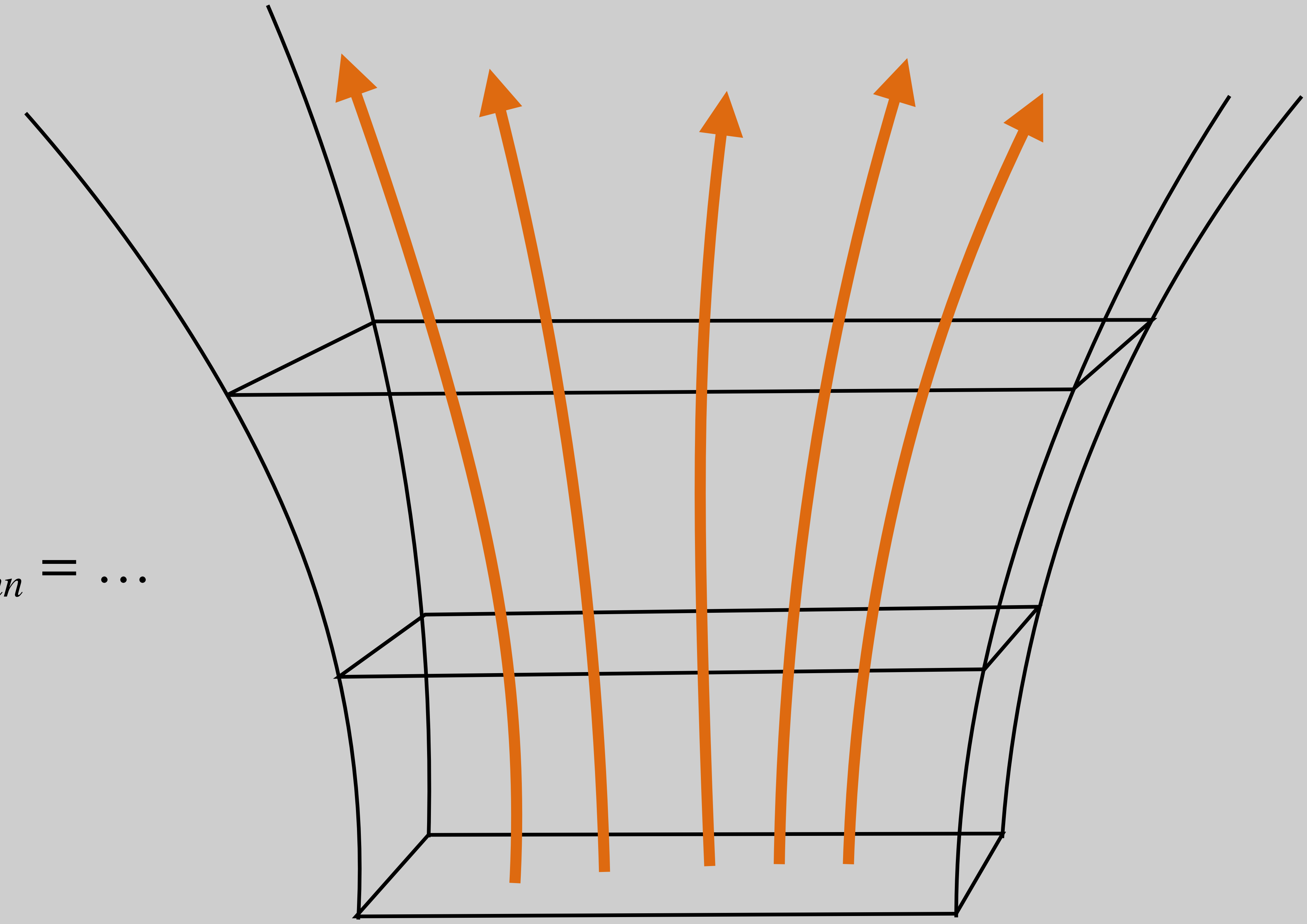
Solve

$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \ldots$$

$$\nabla_m F^{mn} = \ldots$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$



AdS/CFT

$$ds^2 = g_{mn} dx^m dx^n$$

$$A = A_\mu dx^\mu$$

Solve

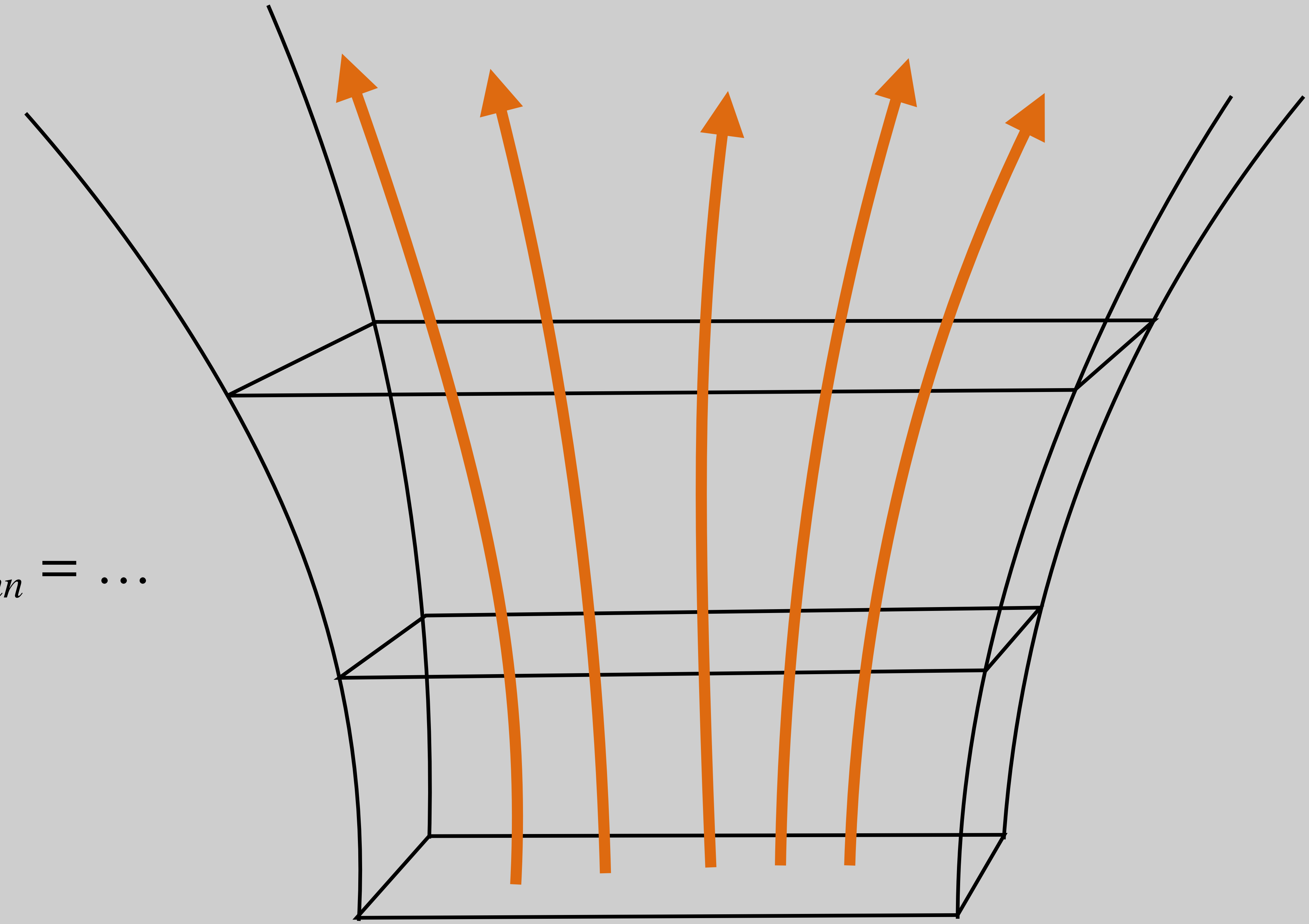
$$R_{mn} - \frac{1}{2} g_{mn} R + \Lambda g_{mn} = \ldots$$

$$\nabla_m F^{mn} = \ldots$$

Evaluate

$$\lim g_{mn} \sim \langle T^{\mu\nu} \rangle$$

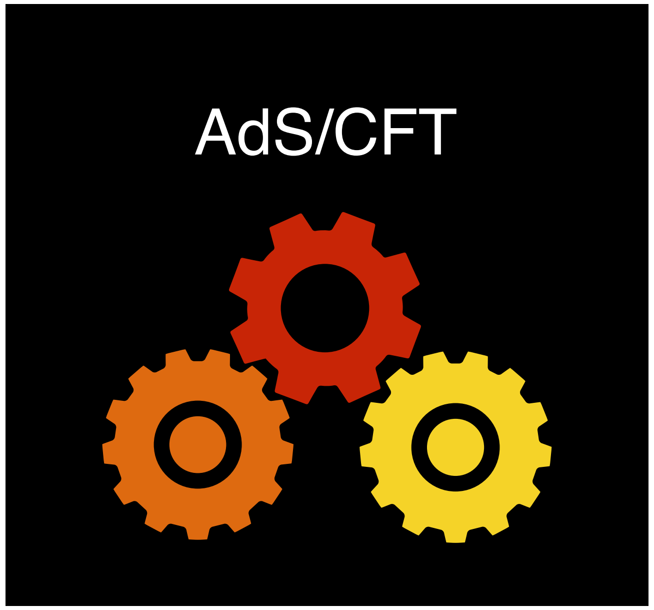
$$\lim A^m \sim \langle \epsilon^{\mu\nu\rho\sigma} S_{\nu\rho\sigma} \rangle$$



Holographic hydrodynamics

$$\mathscr{L} = \text{tr}\left(\frac{1}{2g}F_{\mu\nu}F^{\mu\nu} + \sum_{I=1}^{6}\partial_\mu X^I \partial^\mu X^I + i\sum_{A=1}^{4}\bar{\psi}^A \bar{\sigma} D_\mu \psi_A + \frac{g^2}{2}\sum_{I,J}[X^I, X^J][X^I, X^J] + \text{Yukawa interactions}\right)$$

What is $\langle S^{\mu\nu\rho} \rangle$ in a hydrodynamic configuration? (For large N and large g)



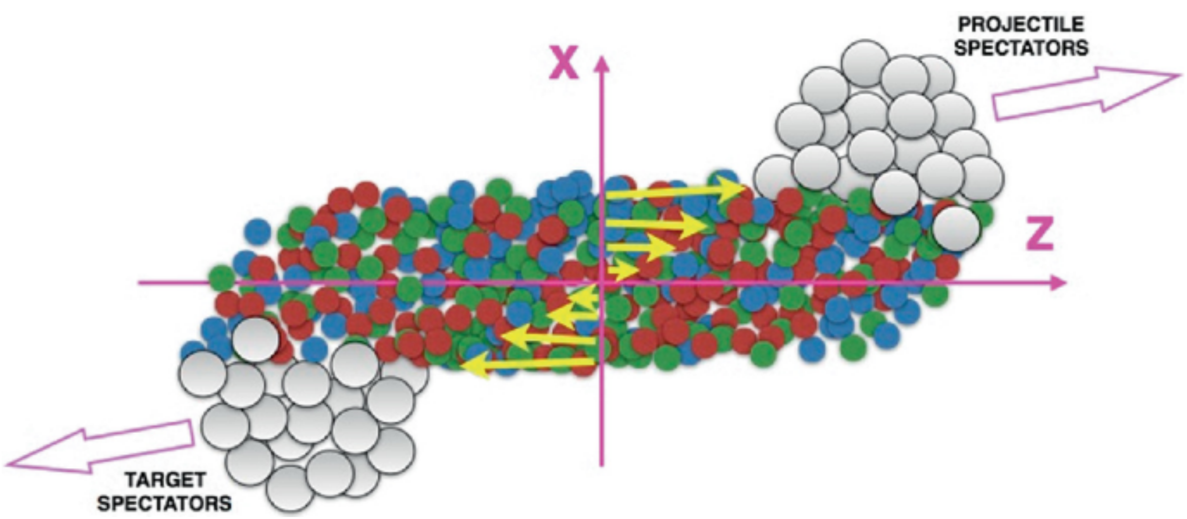
Spin hydrodynamics

$$\nabla_\mu T^{\mu\nu} = 0 \qquad \nabla_\mu J^{\mu\nu\rho} = 0$$

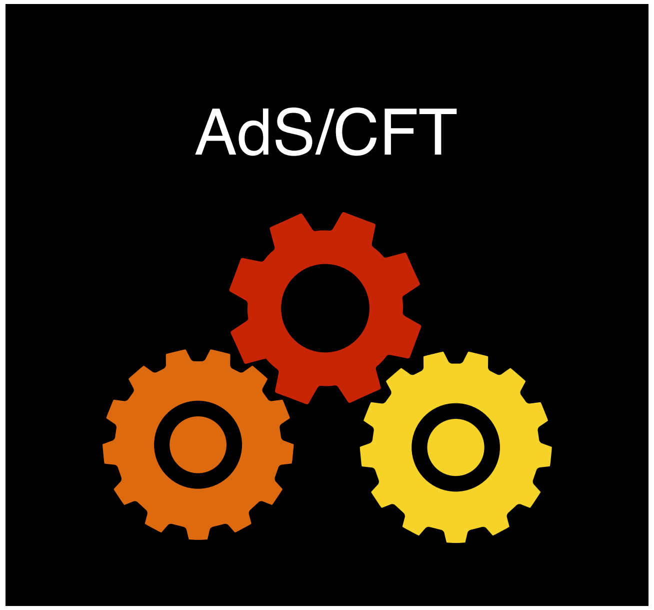
$$J^{\mu\nu\rho} = x^\nu T^{\mu\rho} - x^\rho T^{\mu\nu} + S^{\mu\nu\rho}$$

$$S^{\mu\nu\rho} = S^{\mu\nu\rho}[u, T, \mu^{\alpha\beta}] \qquad T^{\mu\nu} = T^{\mu\nu}[u, T, \mu^{\alpha\beta}]$$

It works?



It can be verified



Thank you