Simulations of BH Collisions in AdS Spacetimes

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CU Boulder & CTQM & JET Collaboration

Based on arXiv: 1410.4799 with Hans Bantilan

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University of Colorado Boulder

JET Collaboration

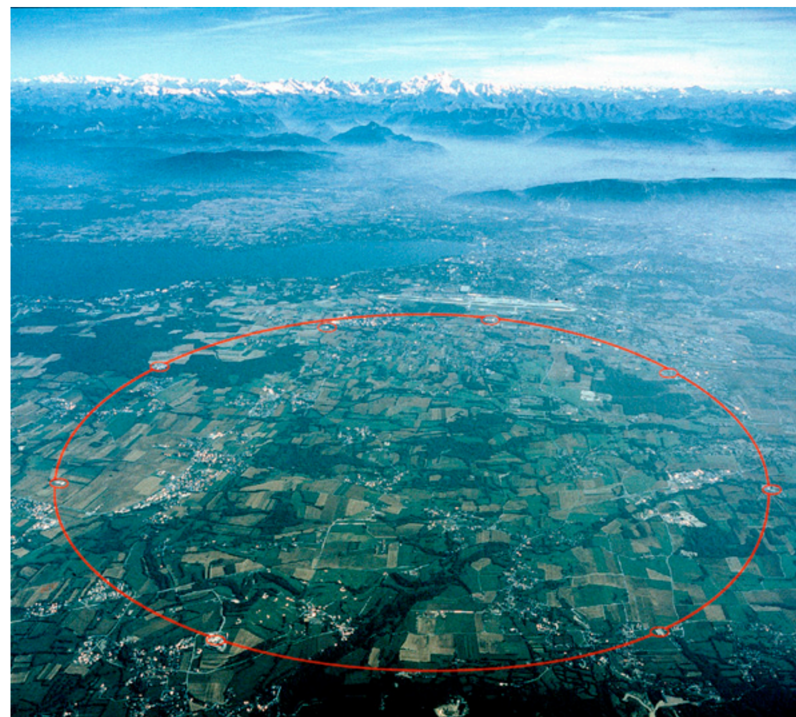
Outline

- Motivation
- Simulating BH Collisions
- Conclusions

Motivation
Relativistic Ion Collisions

RHIC

LHC

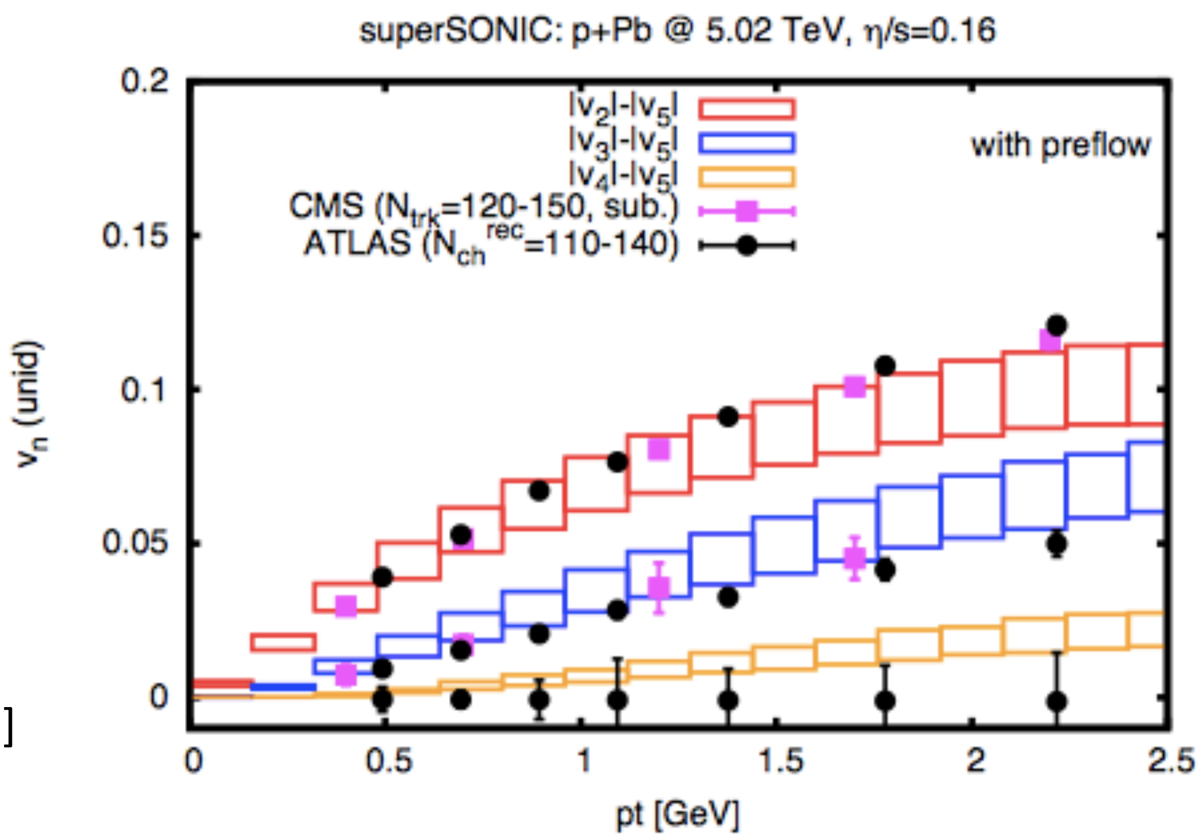


Heavy-Ion Collisions

- 2003-present: QCD matter behaves fluid-like, not gas-like (despite asymptotic freedom)
- Large “flow” signals, e.g. v_2, v_3, v_4, v_5 in Pb+Pb collisions at LHC (correspond to l=2..5 in CMB Background)
- Hydrodynamic models correctly describe 99% of particles registered in experimental detectors

Light-on-Heavy-Ion Collisions

- Large "flow" signals, e.g. v_2, v_3 also found in d+Au, p+Pb collisions



[PR, 1502.04745]

QGP: Matter @ 4 Trillion K

- Temperature: 4×10^{12} K
- Lifetime: 10^{-23} sec
- Size: 10^{-14} m

Gradients are large!

Why does hydrodynamics apply at all?

Even for small systems (p+Pb)?

Can we understand equilibration?

Motivation

Understand equilibration in relativistic ion collisions using AdS/CFT

Goal

Solve dynamical Einstein Equations (w/ or w/o additional fields) in asymptotic AdS for strong gravity situations (BH formation, BH collisions, etc.)

Want: general purpose tool to study far-from equilibrium strongly coupled systems!

Einstein Field Equations in GH

$$
\begin{aligned}
0 &= R_{\mu\nu} + \frac{2\Lambda}{2-d} g_{\mu\nu} - 8\pi \left(T_{\mu\nu} - \frac{1}{d-2} T^{\alpha}{}_{\alpha} g_{\mu\nu} \right) \\
&\quad - \kappa \left(2 n_{(\mu} C_{\nu)} - (1+P) g_{\mu\nu} n^{\alpha} C_{\alpha} \right) - \nabla_{(\mu} C_{\nu)}
\end{aligned}
$$

$$C^{\mu} \equiv H^{\mu} - \Box x^{\mu}$$

(physical solutions satisfy $C^{\mu} = 0$)

Slides from Hans Bantilan, CU Boulder, Oct 2014

Einstein Field Equations in GH

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& - \kappa \left(2 n_{(\mu} C_{\nu)} - (1+P) g_{\mu\nu} n^{\alpha} C_{\alpha} \right) - \nabla_{(\mu} H_{\nu)} + \cancel{\nabla_{(\mu} \Box x_{\nu)}} \\
& - \frac{1}{2} g^{\alpha\beta} g_{\mu\nu,\alpha\beta} + \cancel{g^{\alpha\beta} g_{\beta(\mu,\nu)\alpha}} + \cancel{\frac{1}{2} g^{\alpha\beta}{}_{,\alpha} \left(g_{\alpha\beta,\nu} - g_{\nu\mu,\beta} + g_{\beta\nu,\mu} \right)} \\
& - \cancel{\left(\log\sqrt{-g} \right)_{,\mu\nu}} + \cancel{\left(\log\sqrt{-g} \right)_{,\beta} \Gamma^{\beta}{}_{\mu\nu}} - \Gamma^{\alpha}{}_{\nu\beta} \Gamma^{\beta}{}_{\alpha\nu} - g^{\alpha\beta}{}_{,(\mu} g_{\nu)\alpha,\beta}
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\end{aligned}
$$

+evolution eq's for H^{μ}

$$C^{\mu} \equiv H^{\mu} - \Box x^{\mu}$$

(physical solutions satisfy $C^{\mu} = 0$)

We solve these numerically

Slides from Hans Bantilan, CU Boulder, Oct 2014

Evolution Equations:

$$
\begin{aligned}
0 &= -\frac{1}{2} g^{\alpha\beta} g_{\mu\nu,\alpha\beta} - g^{\alpha\beta}{}_{,(\mu} g_{\nu)\alpha,\beta} \\
&\quad - H_{(\mu,\nu)} + H_\alpha \Gamma^\alpha{}_{\mu\nu} - \Gamma^\alpha{}_{\beta\mu} \Gamma^\beta{}_{\alpha\nu} \\
&\quad - \kappa \left(2 n_{(\mu} C_{\nu)} - (1+P) g_{\mu\nu} n^\alpha C_\alpha \right) \\
&\quad - \frac{2}{3} \Lambda_5 g_{\mu\nu} - 8\pi \left(T_{\mu\nu} - \frac{1}{3} T^\alpha{}_\alpha g_{\mu\nu} \right) \\
&\quad \downarrow \\
0 &= \mathcal{L}_f \big|^n_{ij} \qquad \text{(15 such equations, one for each } \mu\nu\text{)}
\end{aligned}
$$

Use second-order differencing to discretize these

Coordinate Choice near the AdS Boundary

- Coordinate choice in asymptotically AdS spacetimes
  - not enough to simply demand b.c.s for $\bar{g}_{\mu\nu}$, $\bar{H}_\mu$, $\bar{\phi}$
    $g_{\mu\nu} = g_{\mu\nu}^{AdS} + (1-\rho)^{\#}\bar{g}_{\mu\nu}$
    $H_\mu = H_\mu^{AdS} + (1-\rho)^{\#}\bar{H}_\mu$
    $\varphi = (1-\rho)^{\#}\bar{\varphi}$
  - how to choose H_μ so that b.c.s are preserved by evolution?

- Example: tt component of field equations near $\rho = 1$

$$\tilde{\Box}\bar{g}_{(1)tt} = (-8\bar{g}_{(1)\rho\rho} + 4\bar{H}_{(1)\rho})(1-\rho)^{-2} + ...$$

  - regularity requires a delicate cancellation between terms in the near-boundary limit
  - smart coordinate choice: $\bar{H}_{(1)\rho} = 2\bar{g}_{(1)\rho\rho}$

Numerics/Hardware

- C,C++, Fully parallel (openMPI)
- Hardware used:

Eridanus cluster (CU Boulder, 192 cores @ 2 GHz/core), Infiniband interconnections

Orbital cluster (Princeton, ~3700 cores @ 3.5 GHz/core), Infiniband interconnections

Simulations of BH Collisions in Global AdS_5

- Head-on Collisions
- Global AdS rather than Poincare patch
- Initial Data: pure AdS + massless scalar field (Coulomb branch), quickly collapsing to form BHs (non-planar horizon!)
- Use excision to simulate space-times with BHs

Heavy Ion Collisions as BH Collisions in AdS_5

'nuclear collisions' in 3+1d as shock wave collisions in AdS_5:

$$T_{++} \propto \rho(x_\perp)\delta(x^+)$$

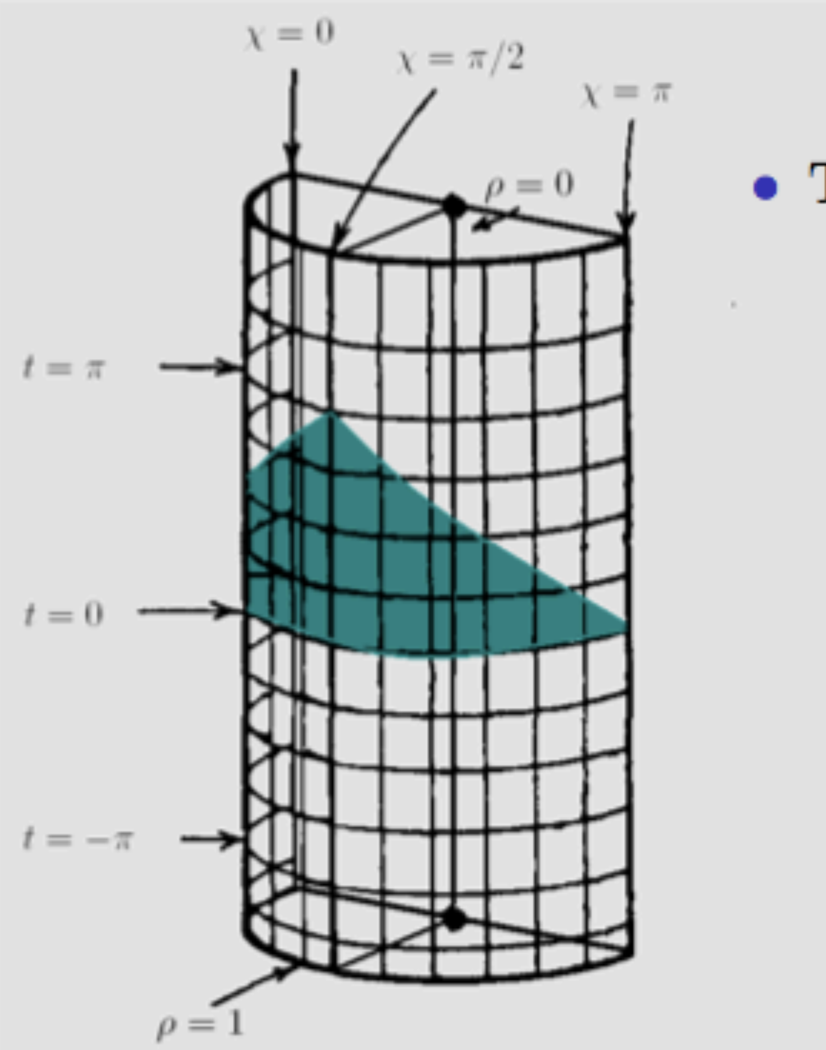
$$ds^2 = \frac{-2dx^+dx^- + dx_\perp^2 + dz^2 + dx^{+2}\Phi(x_\perp, z)\delta(x^+)}{z^2}$$

$$\boxed{\lim_{z\to 0} \frac{\Phi(x_\perp, z)}{z^4} = \frac{\rho(x_\perp)}{\kappa}}$$

Heavy Ion Collisions as BH Collisions in AdS5

- Two infinitely boosted ‘nuclei’ superimposed become two shock waves in gravity
- Extremely high-energy analogue of black-hole collisions (Aichelburg-Sexl shock waves)
- Hard to treat collision process via numerical relativity
- Some insight may be gained analytically

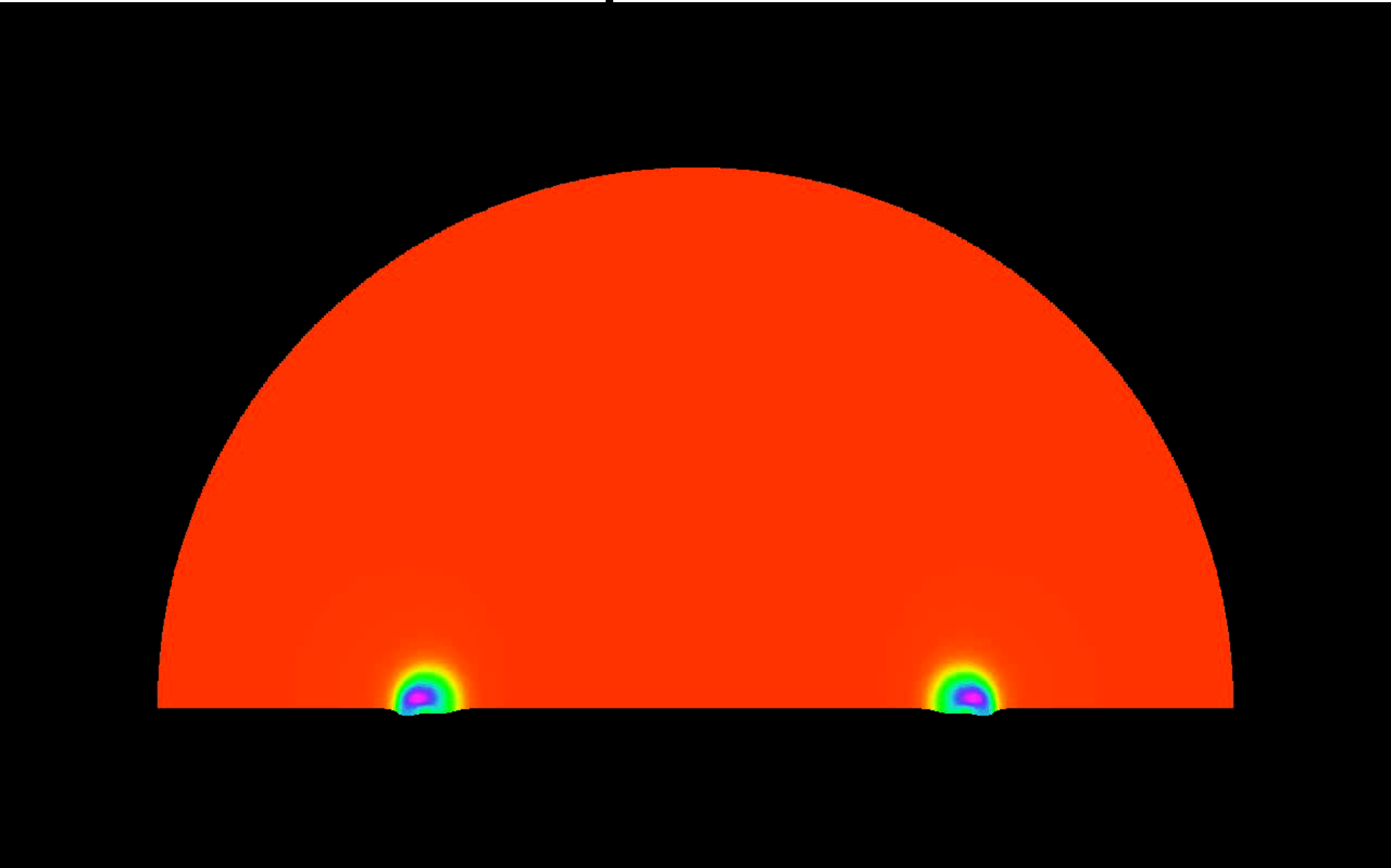
The anti-de Sitter Spacetime



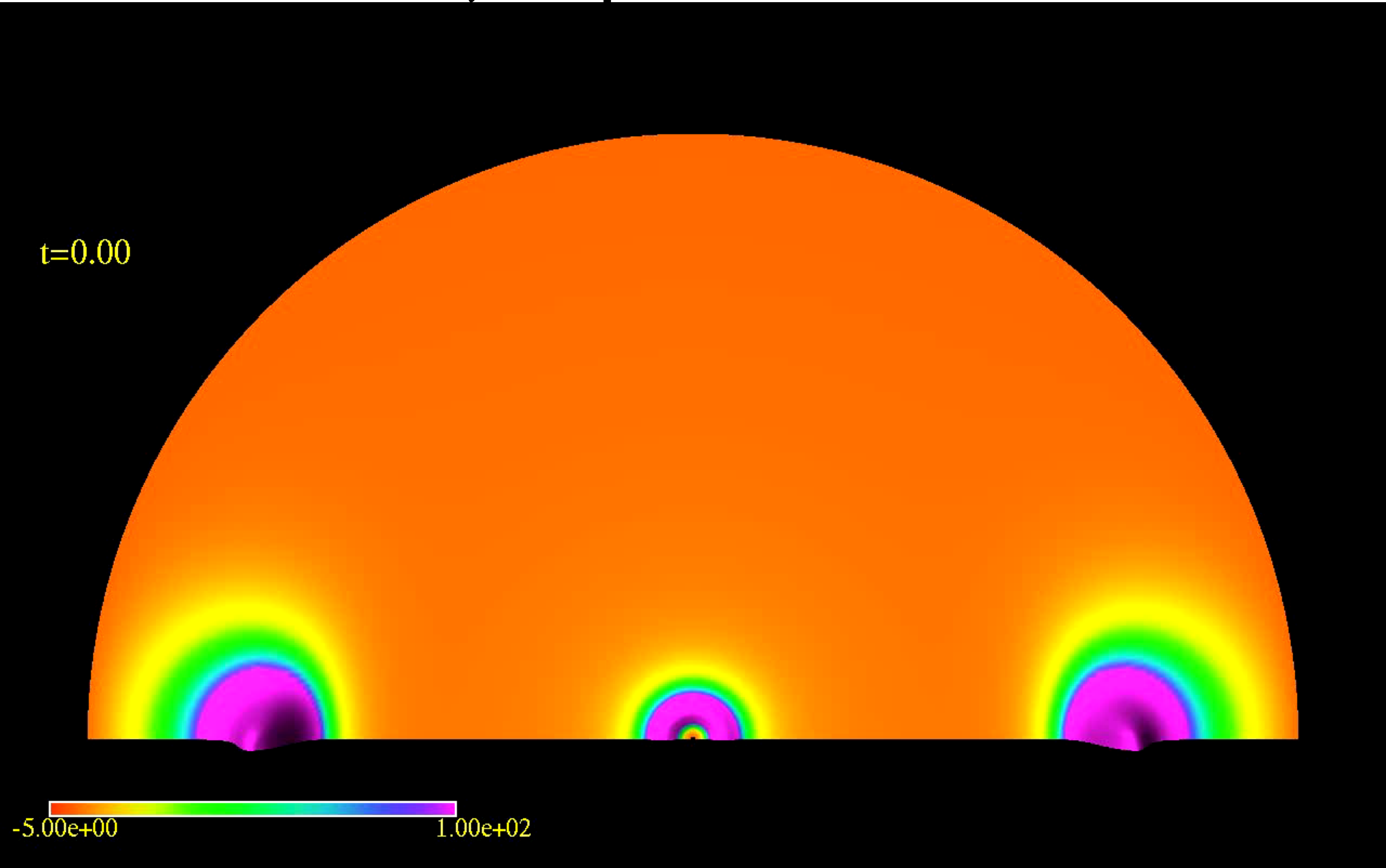
- The AdS_5 spacetime
  - its boundary is causally connected to its interior
    - spacelike infinity $\cup$ null infinity
    - forms a timelike 4-surface
    - identified with $\mathbb{R} \times S^3$

FIGURE: Conformal sketch of the AdS_5 spacetime; there is an internal 2-sphere geometry at each point of this sketch.

Metric, separation D=0.5



Metric, separation D=0.7



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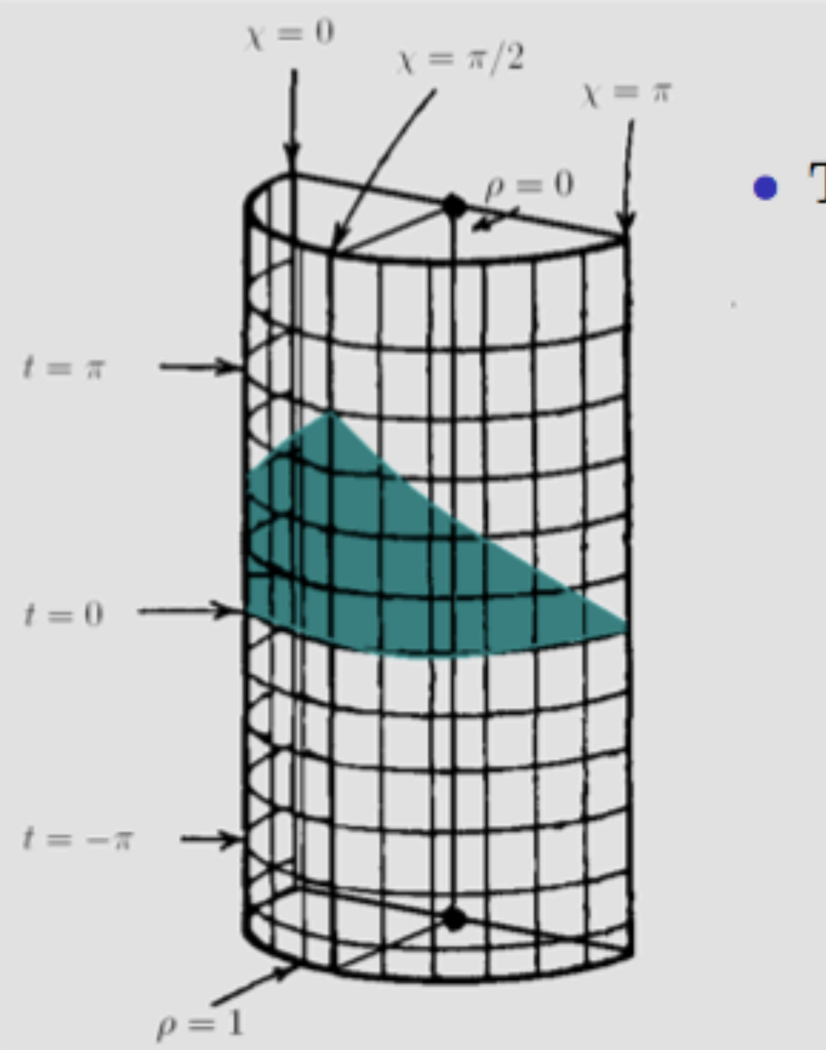

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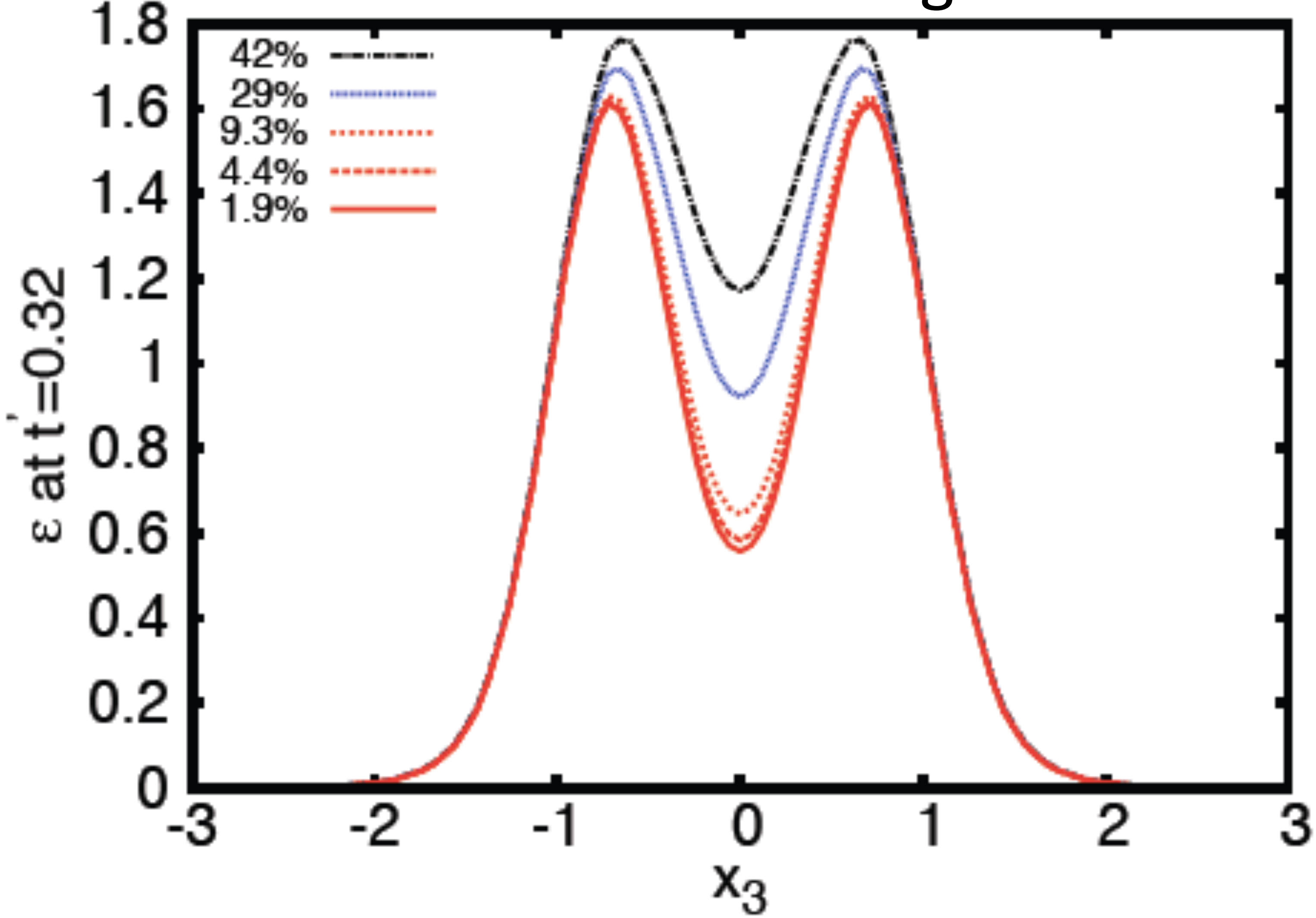
Space-time Diagram of the Bulk

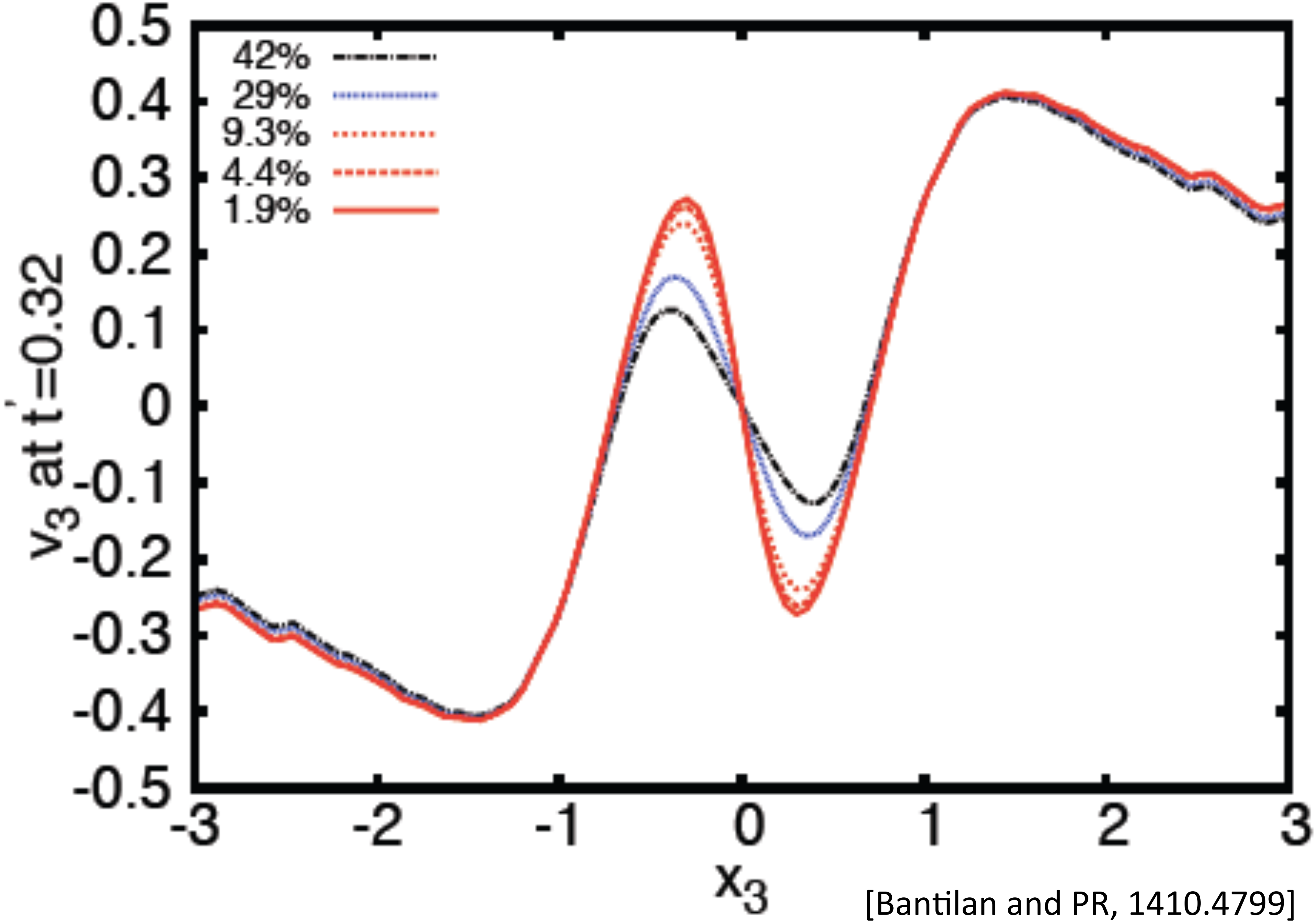
[Bantilan and PR, 1410.4799]

Relevance of the regulator BH



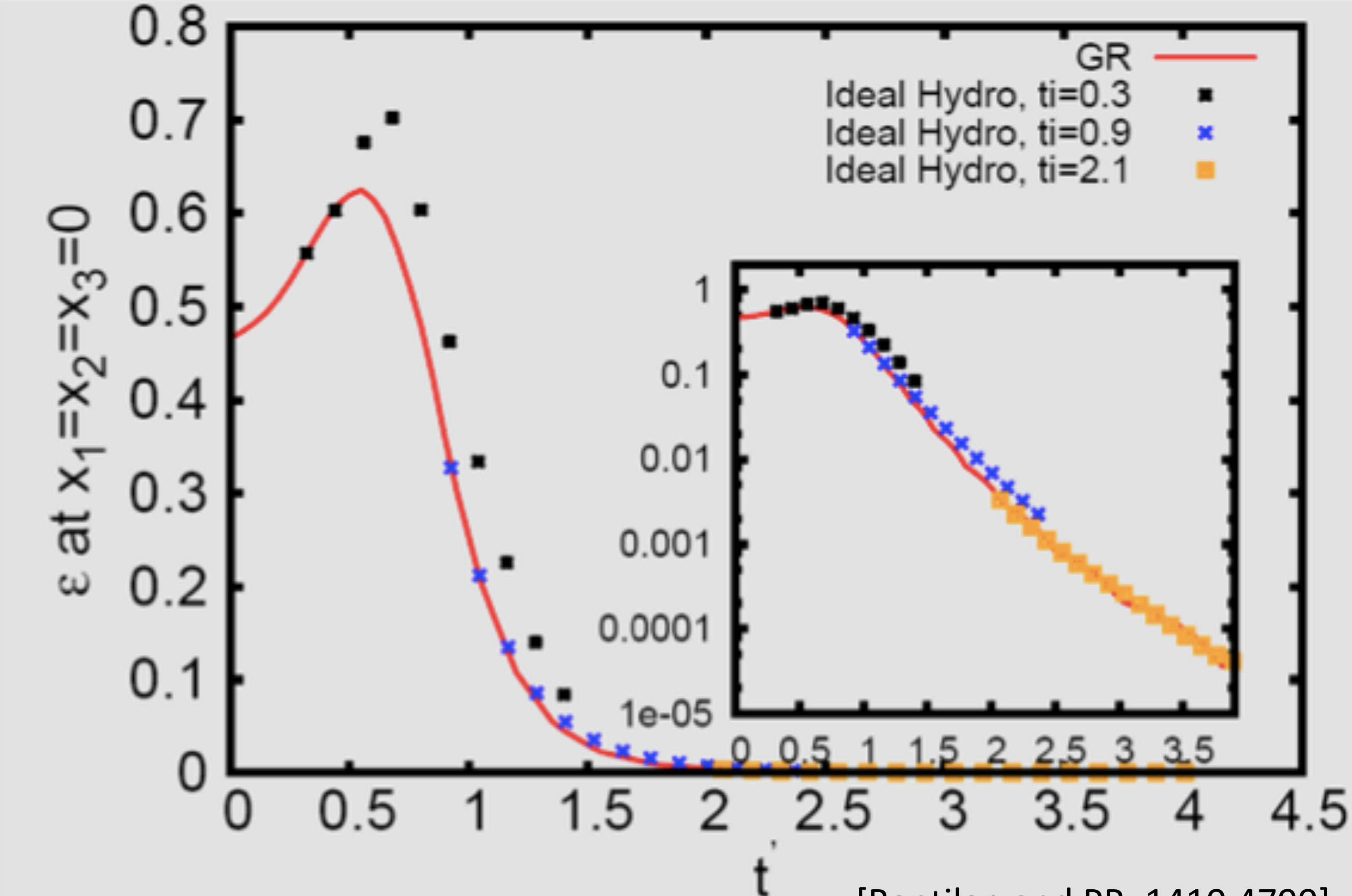
[Bantilan and PR, 1410.4799]

“Collision” velocities

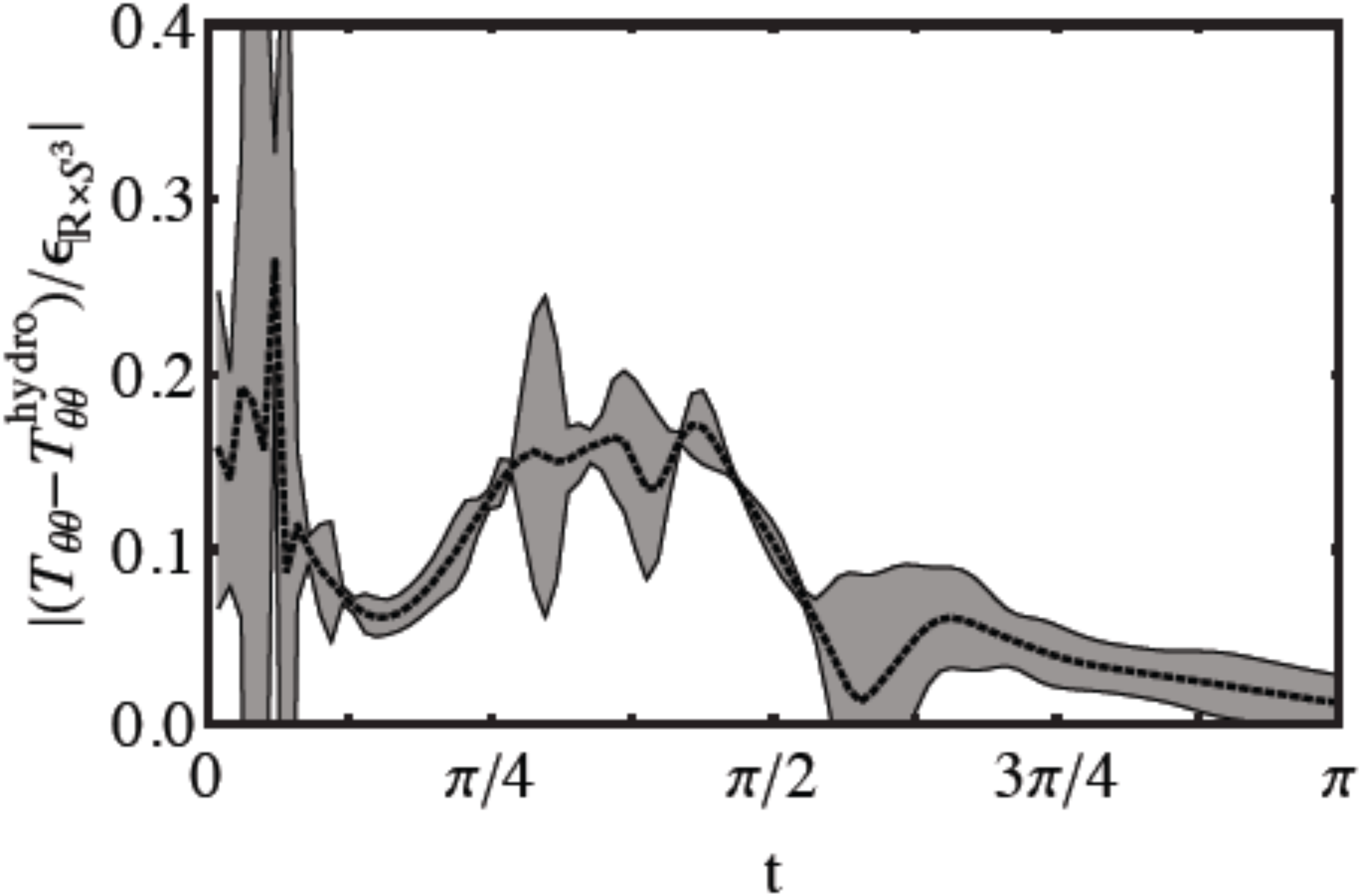


[Bantilan and PR, 1410.4799]

Comparison to Hydrodynamics on $\mathbb{R}^{3,1}$

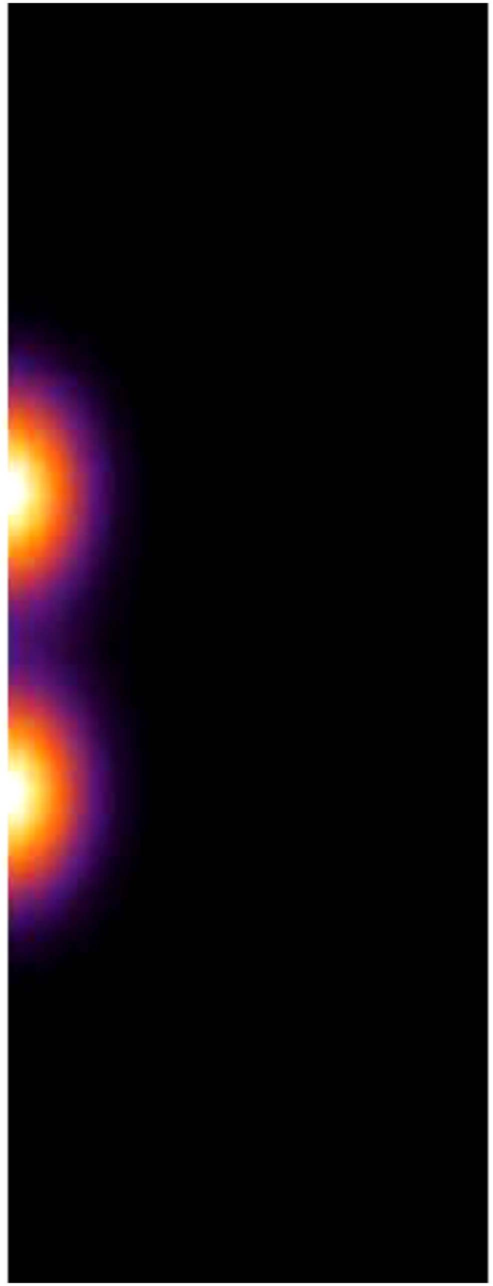


[Bantilan and PR, 1410.4799]



[Bantilan and PR, 1410.4799]

Boundary Energy Density



[Bantilan and PR, 1410.4799]

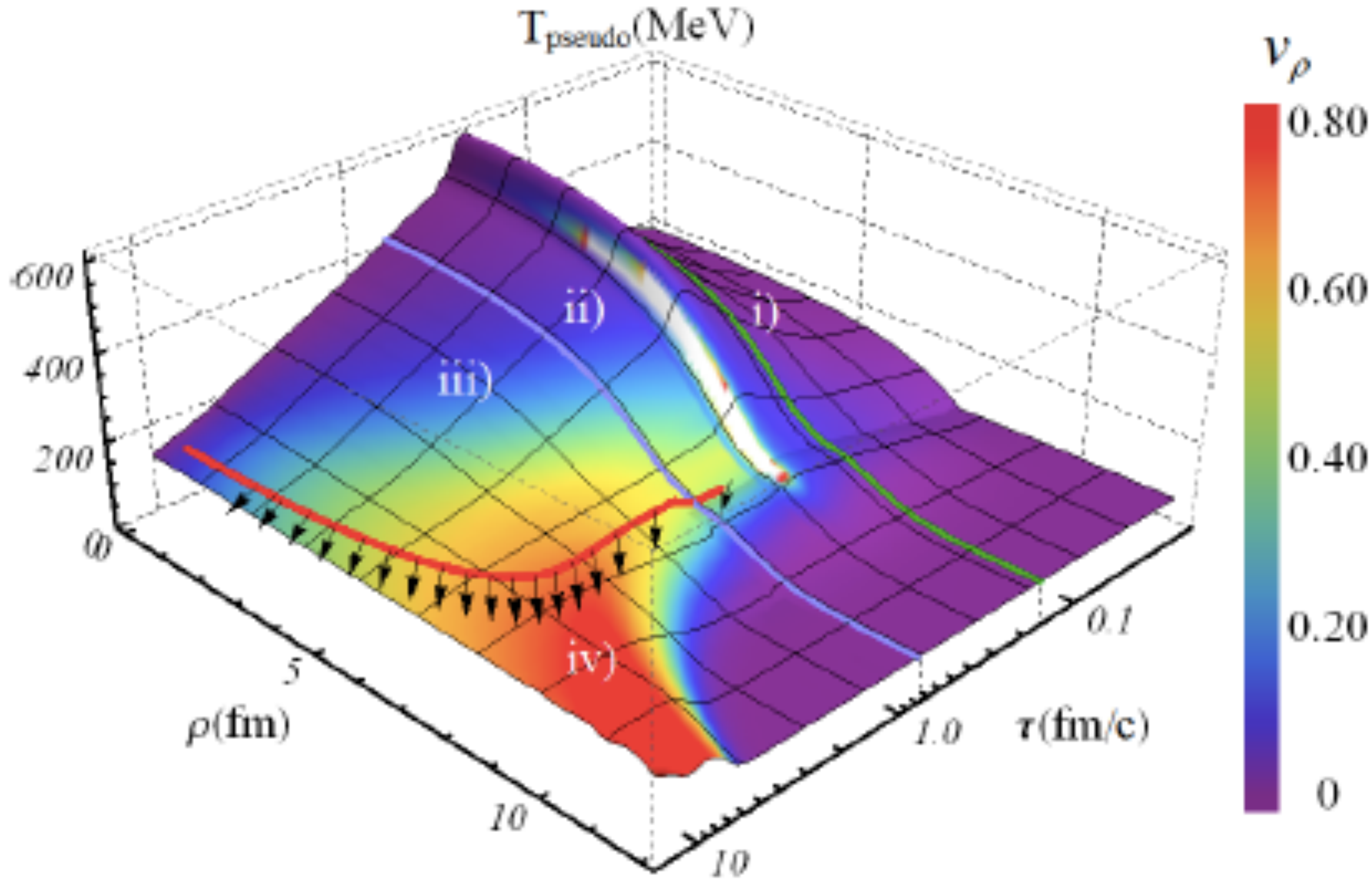
Simulations of BH collisions

- We have numerical results for metric in all of space-time, including boundary data
- We have metric data (a bit) inside trapped surfaces: could be useful for entanglement entropy calculations (?)
- Metric data/boundary data could be used for comparison to analytic results
- This data is publicly available. If you can’t find something on our website, just ask!

AdS/CFT Phenomenology

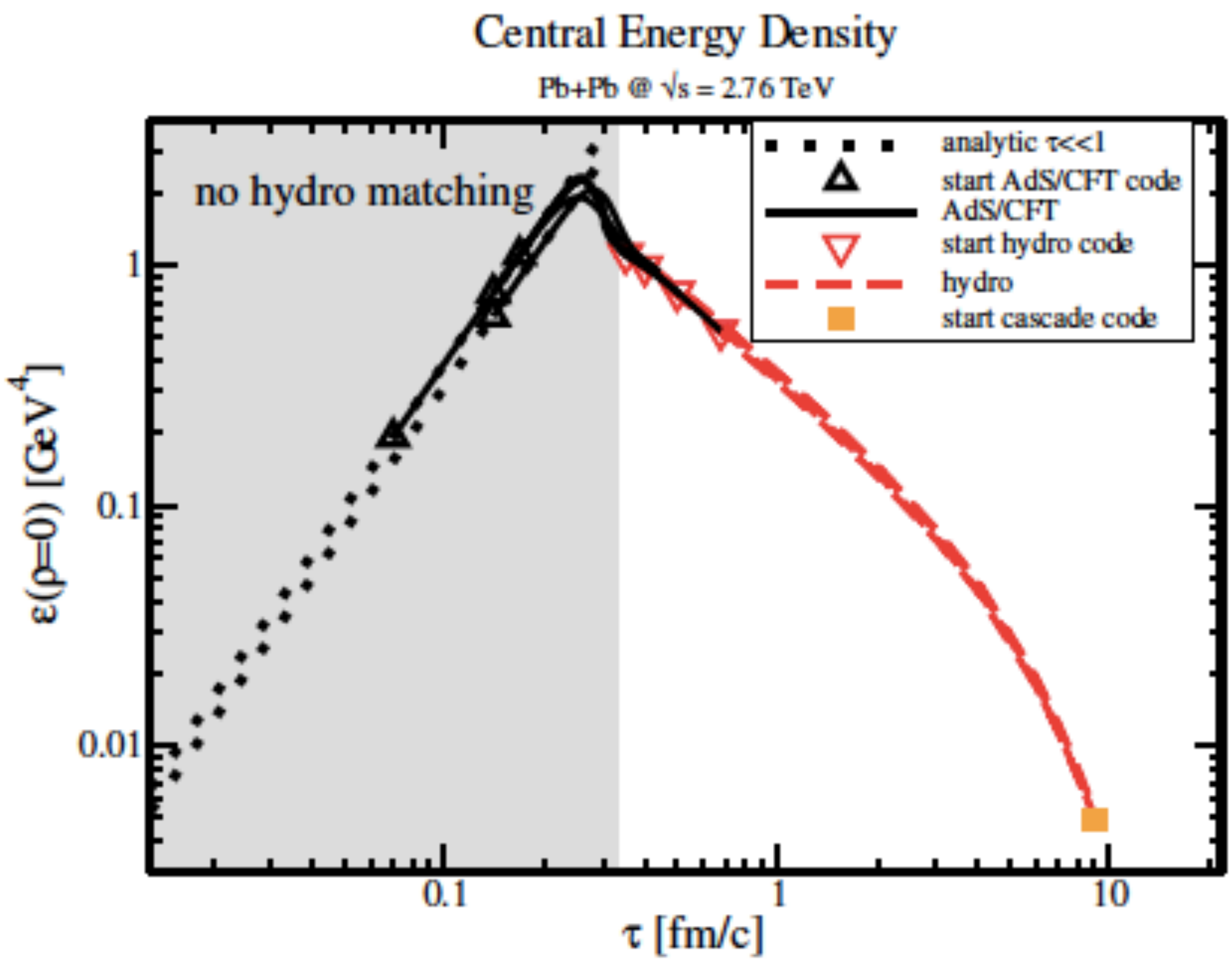
Can AdS/CFT dynamics be experimentally probed in relativistic ion collisions?

AdS+hydro+cascade ("SONIC")



[van der Schee, PR & Pratt, PRL111 (2013)]

AdS+hydro+cascade



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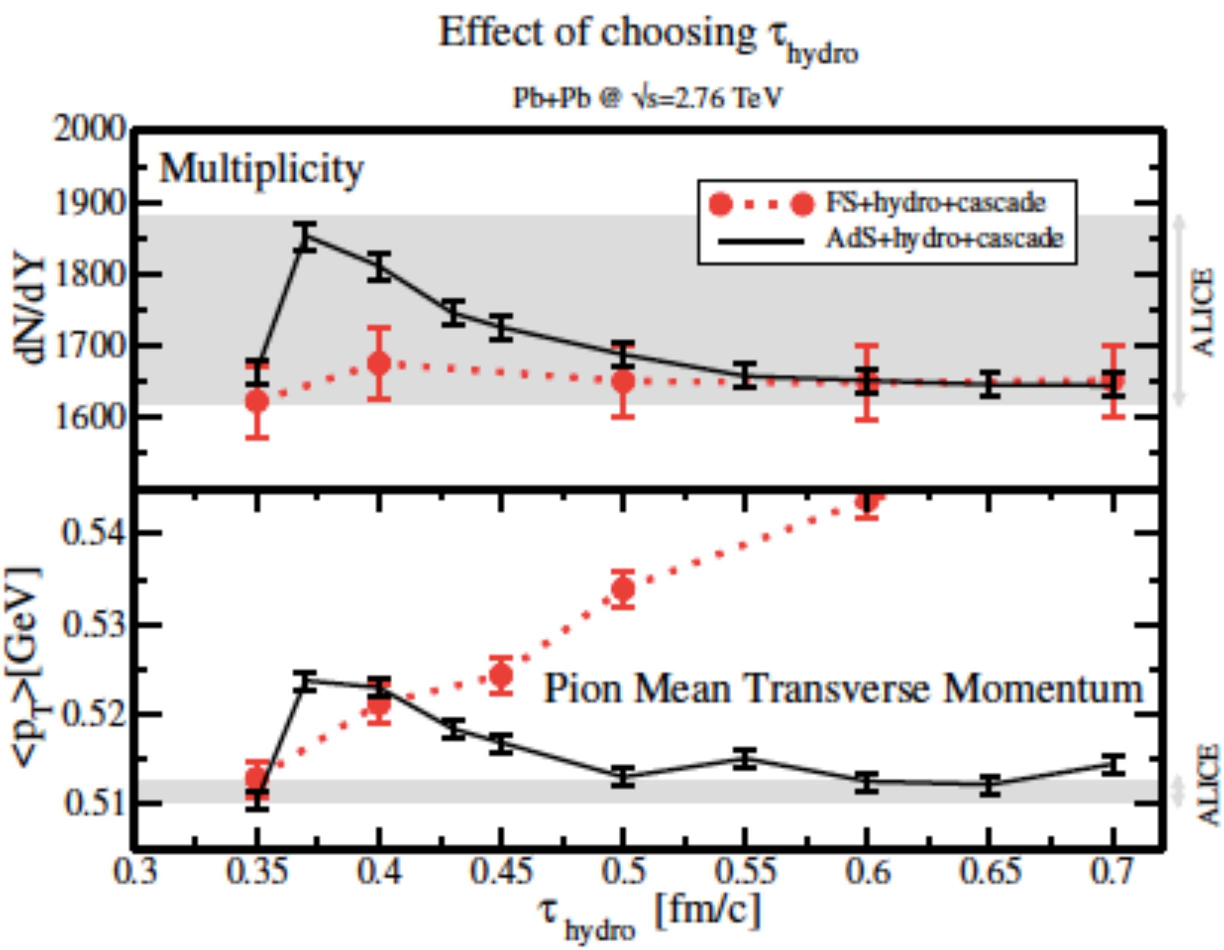


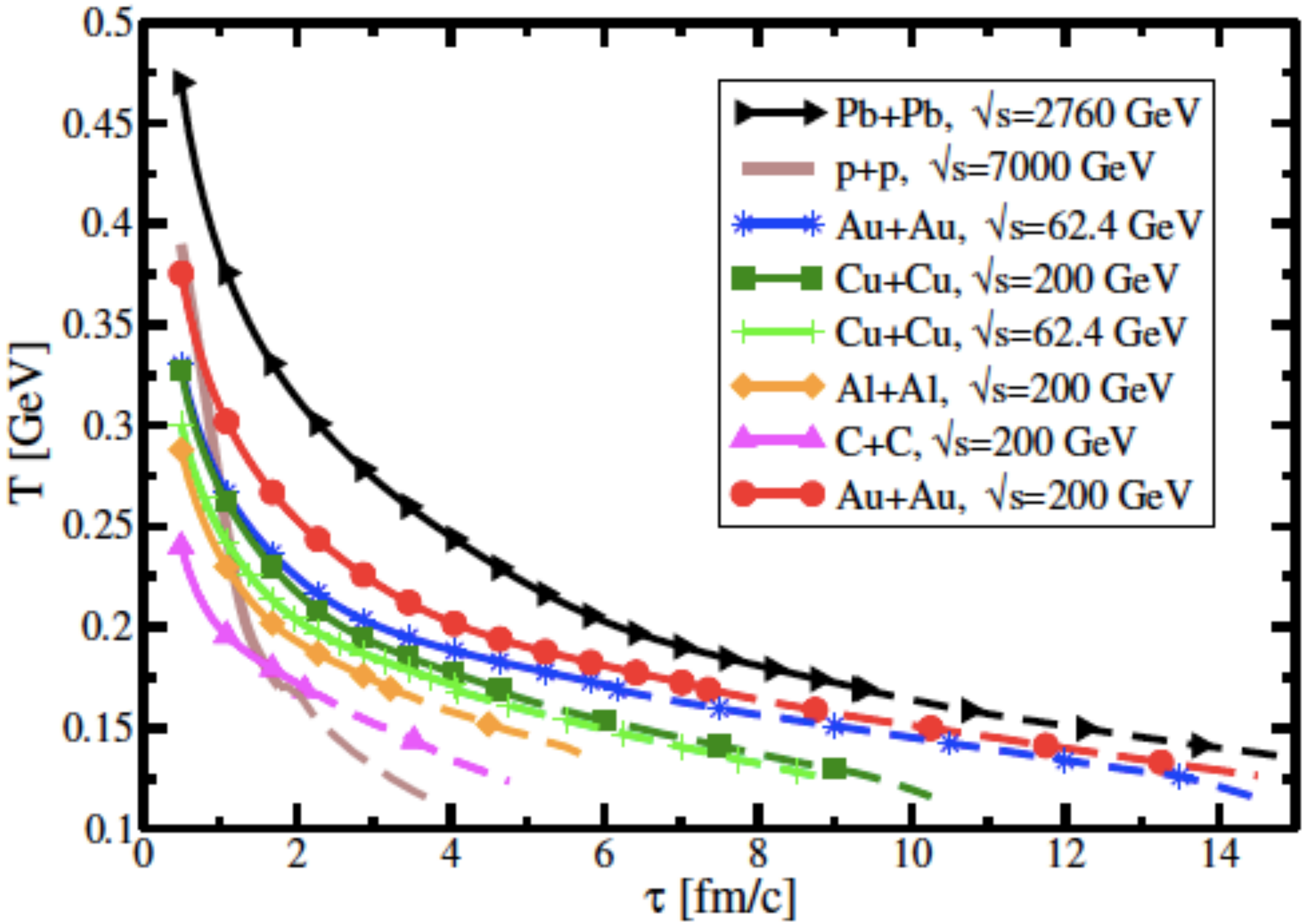
[van der Schee, PR & Pratt, 2013]

AdS+hydro+cascade

AdS/CFT+hydro results are independent of choice of switching time

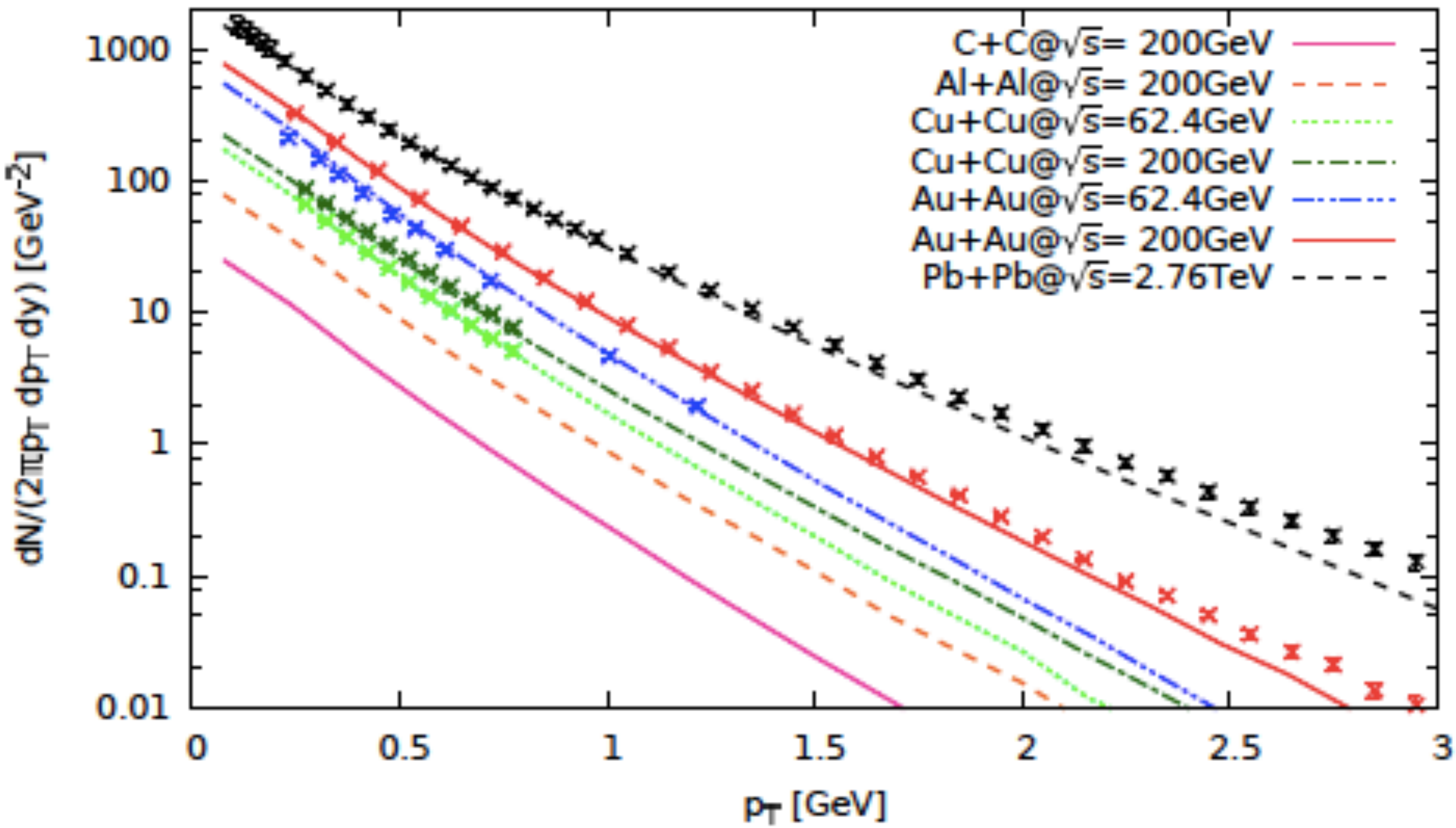
You get what you get.
No ‘tuning’

Central Temperature Evolution



[Habich, Nagle and PR, 1409.0040]

SONIC works well for describing exp' data in AA



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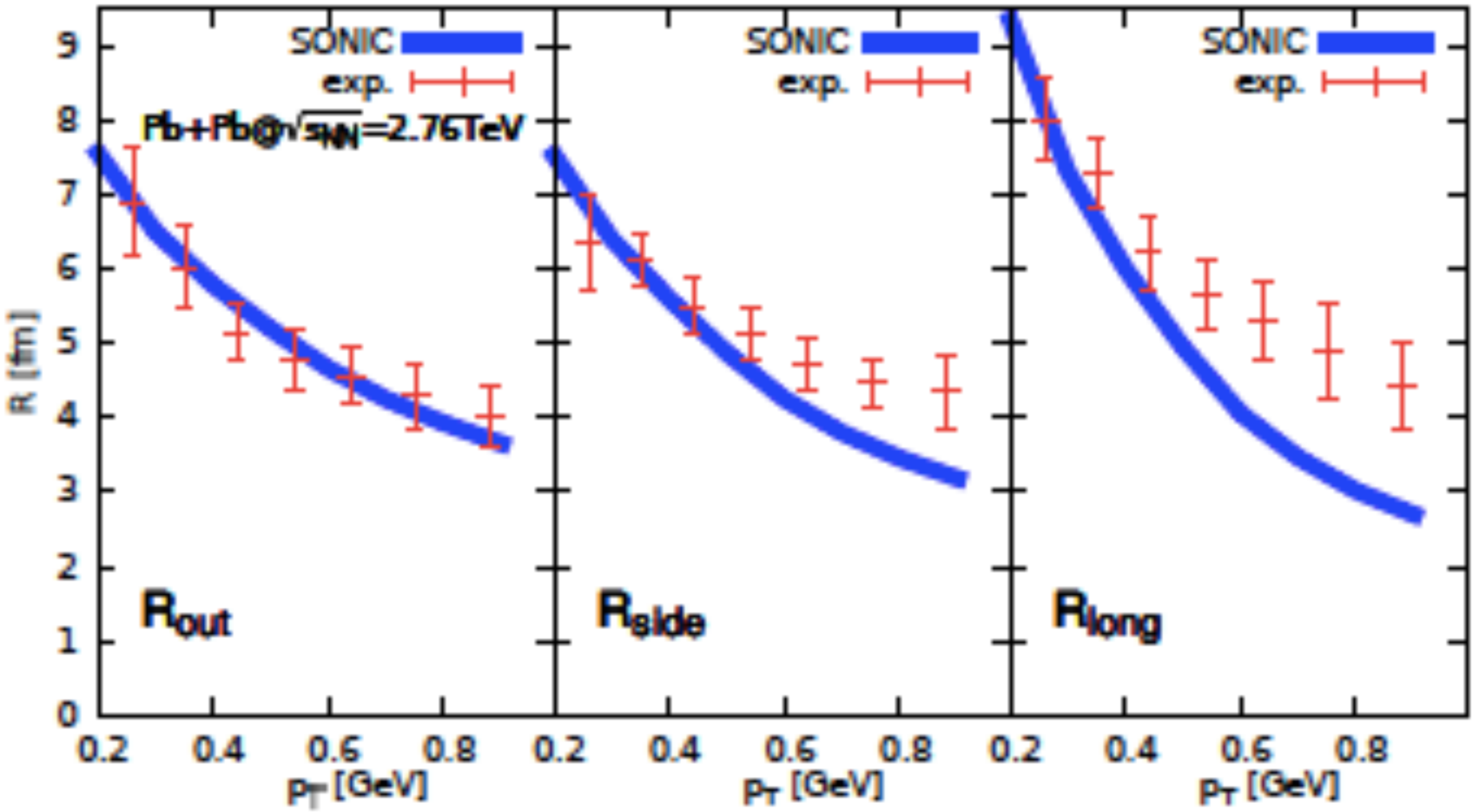
SONIC: AdS+Hydro (eta/s=0.08)+Hadron Cascade



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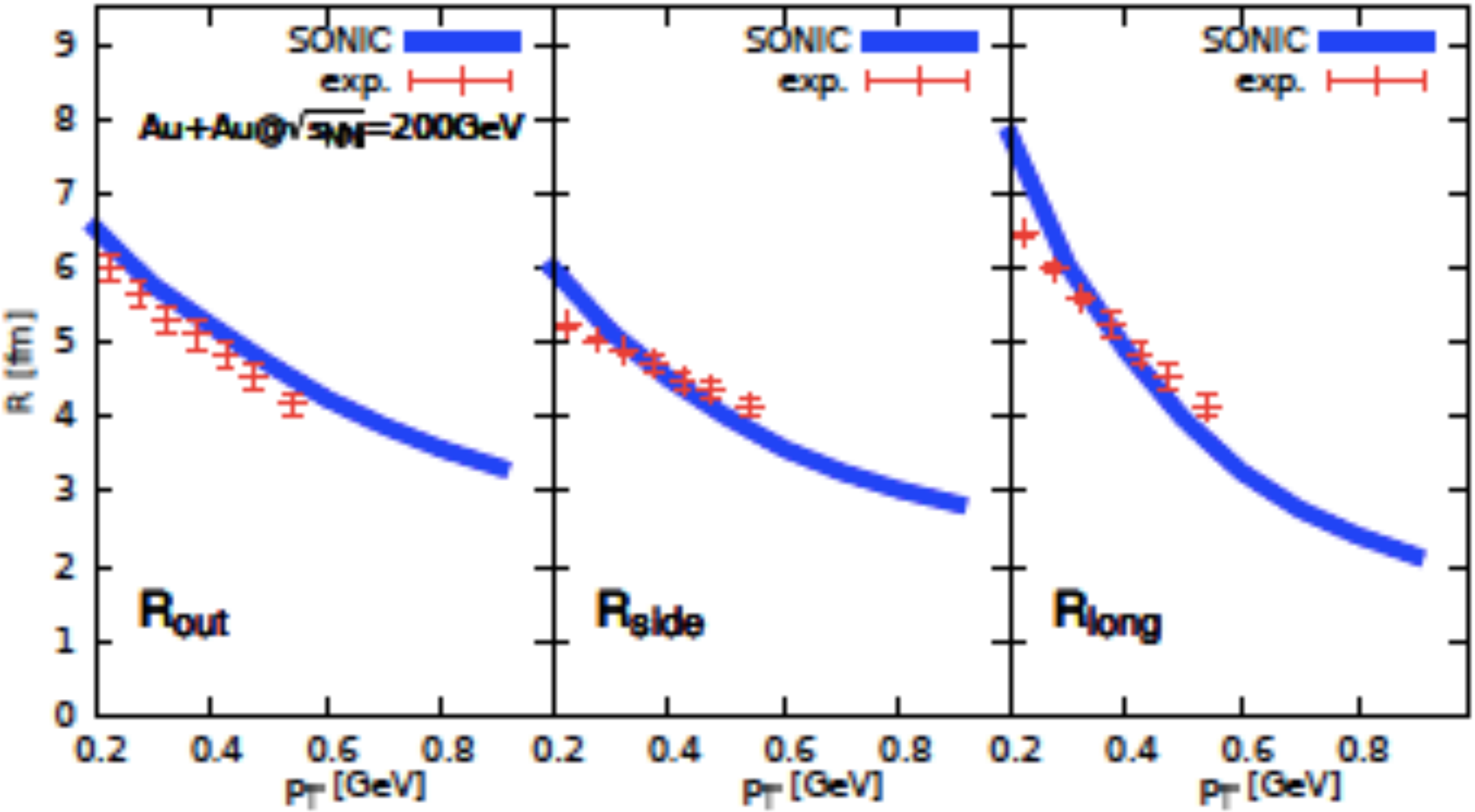

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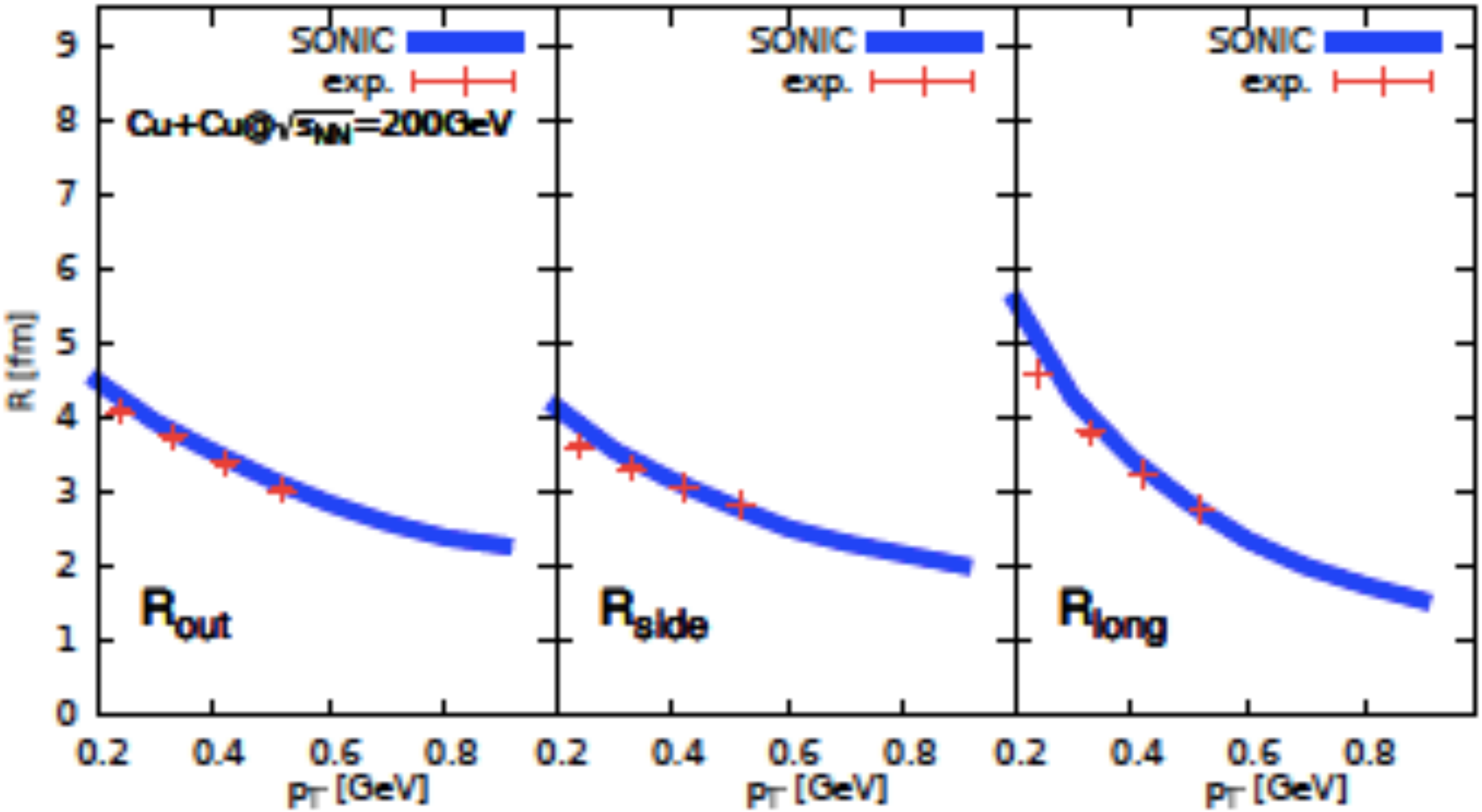

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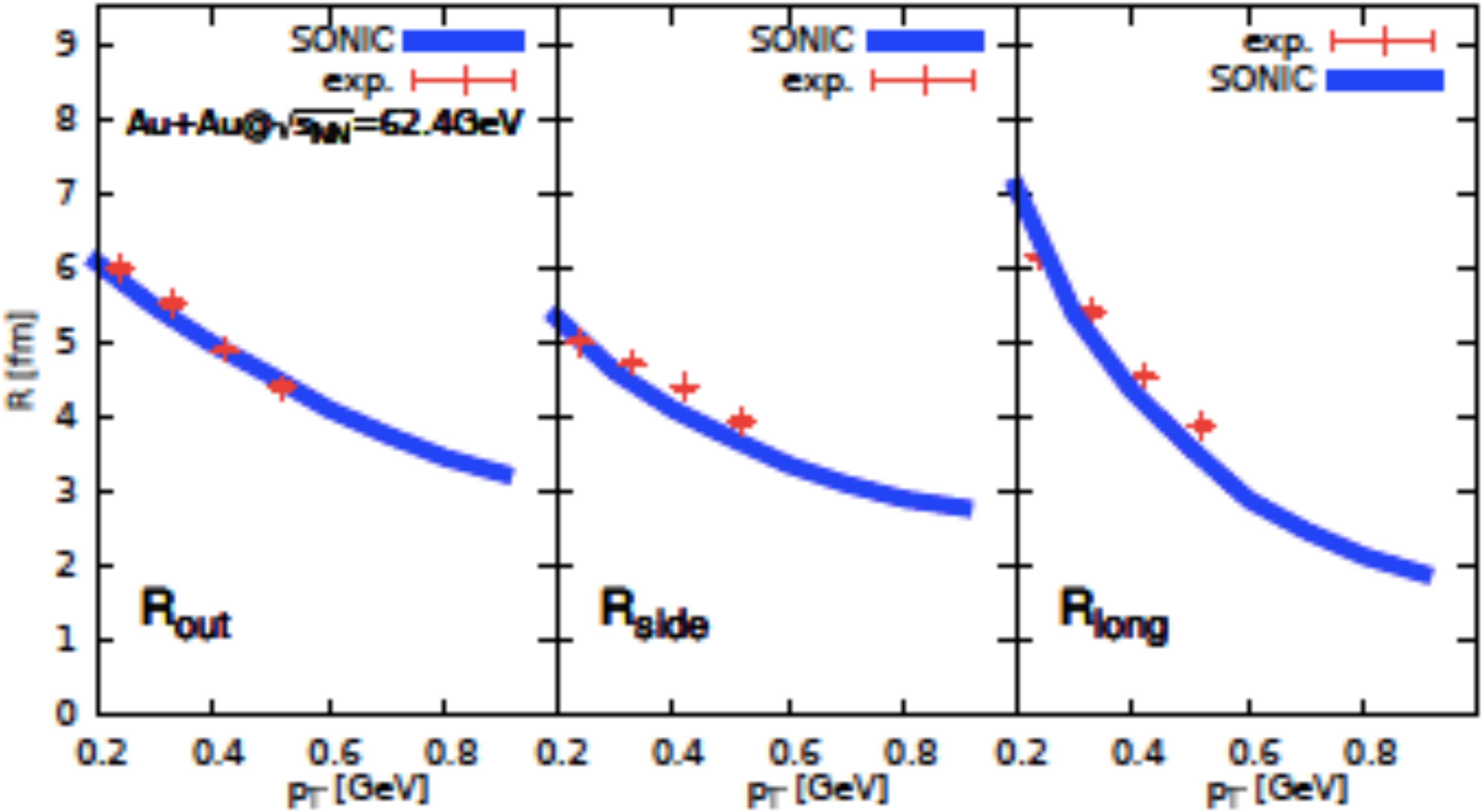

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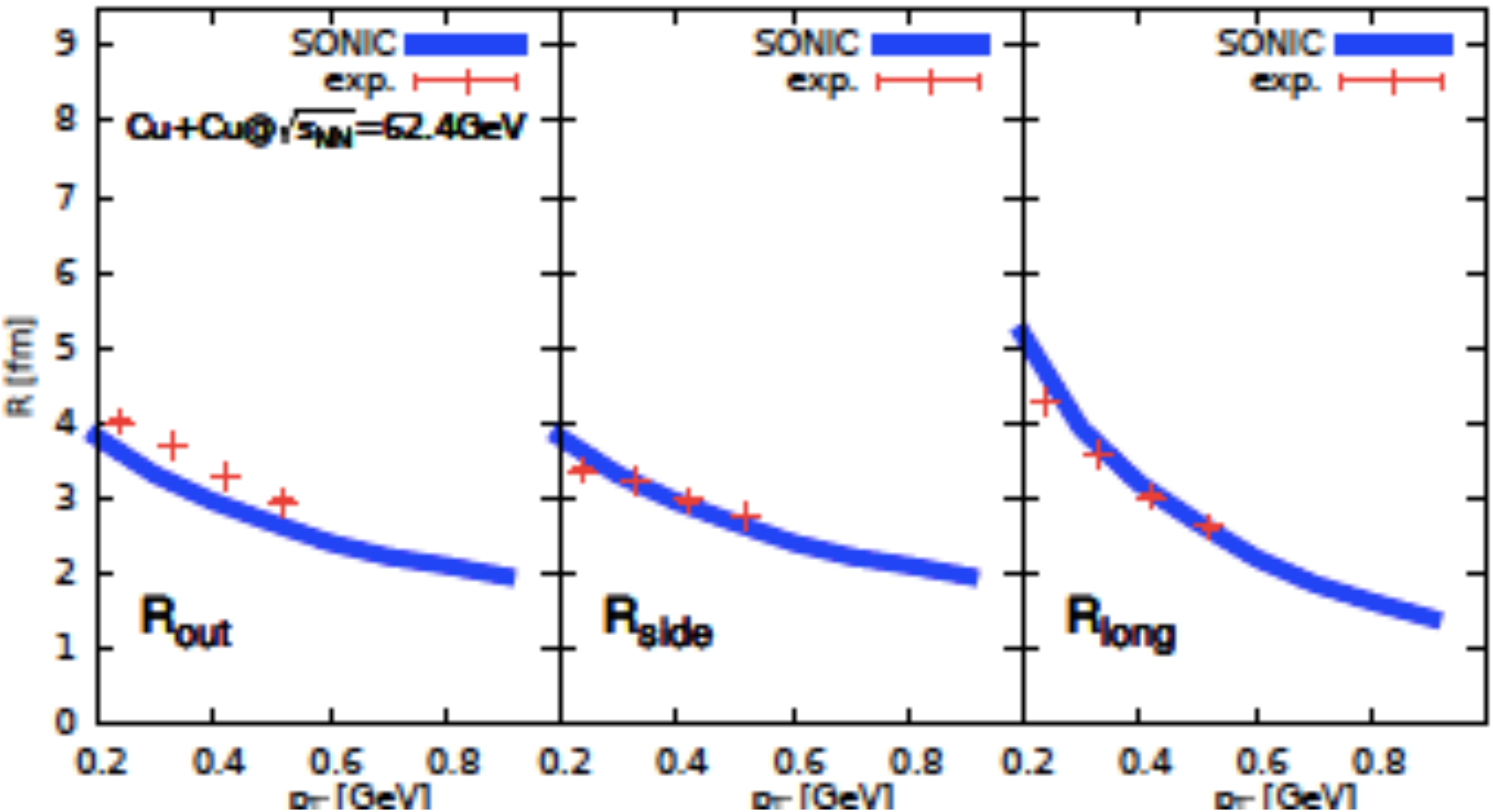

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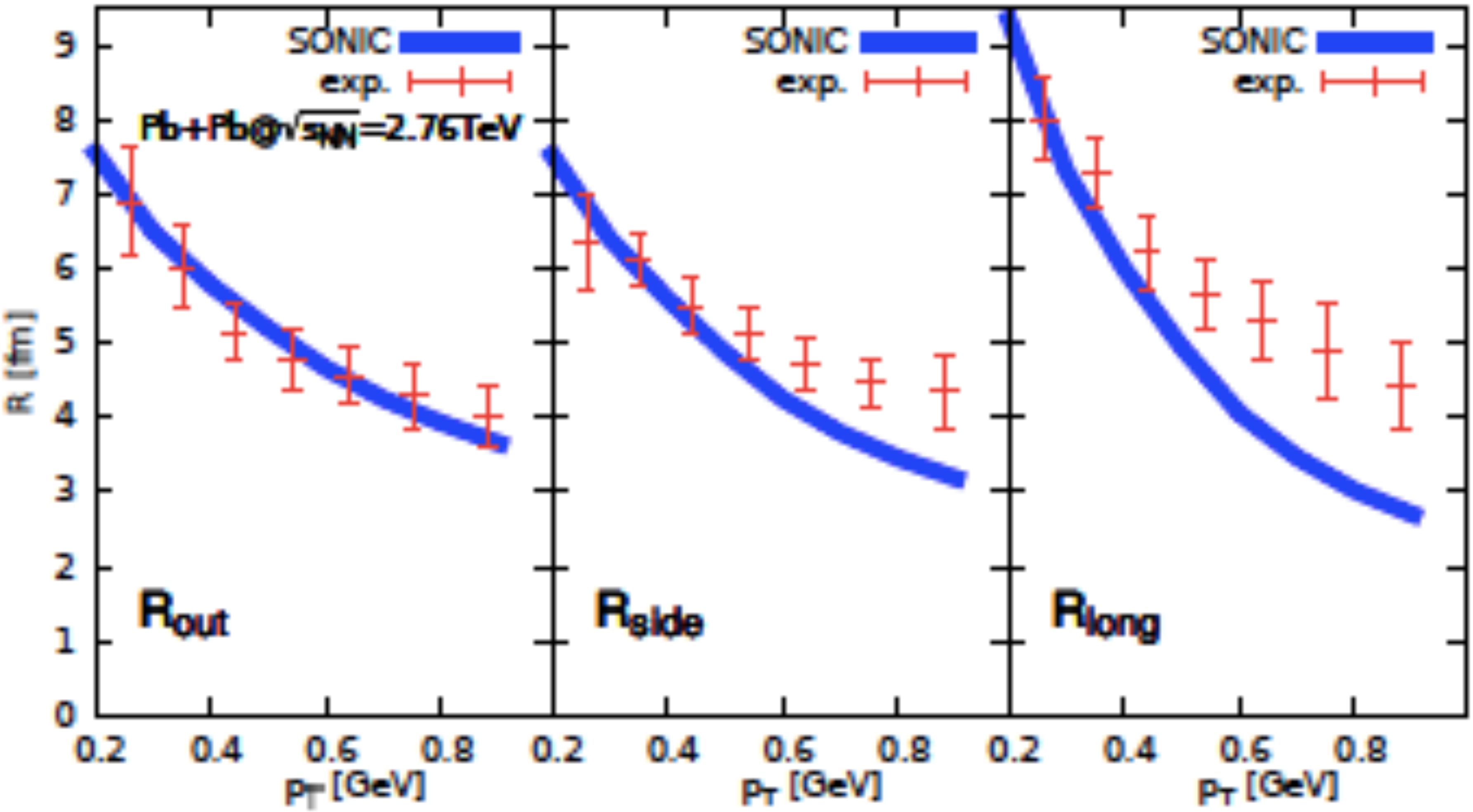
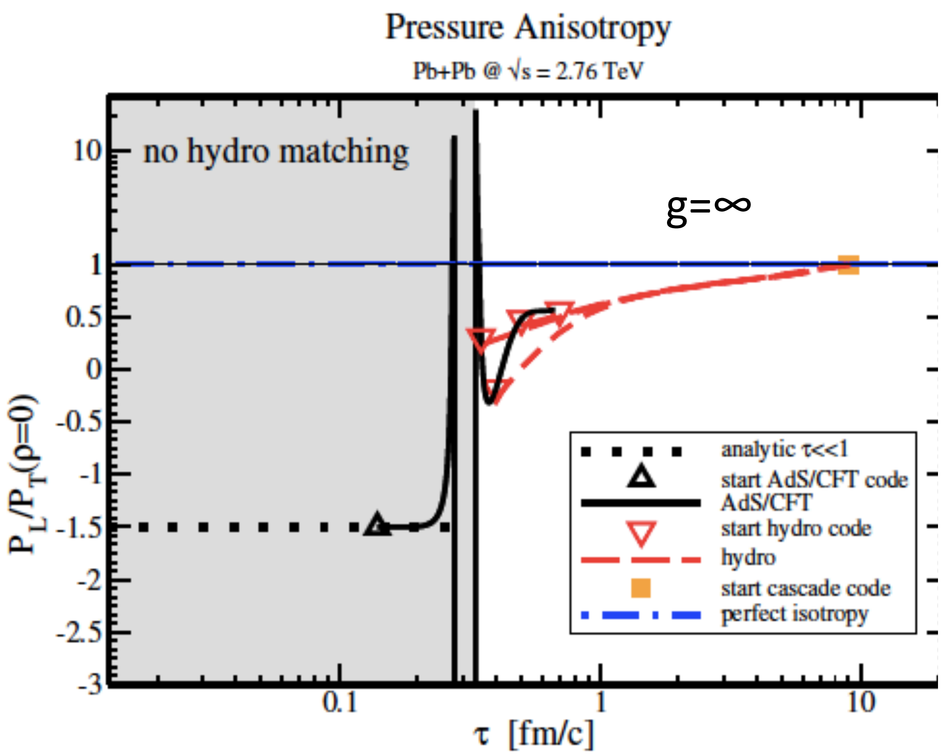
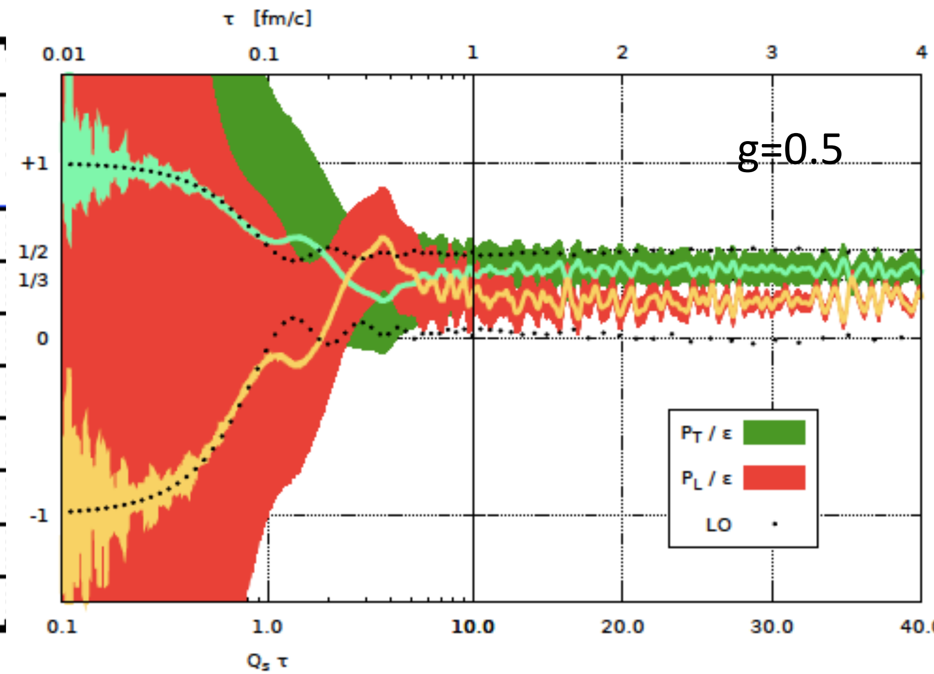


[Habich, Nagle and PR, 1409.0040]

Strong vs. Weak Coupling

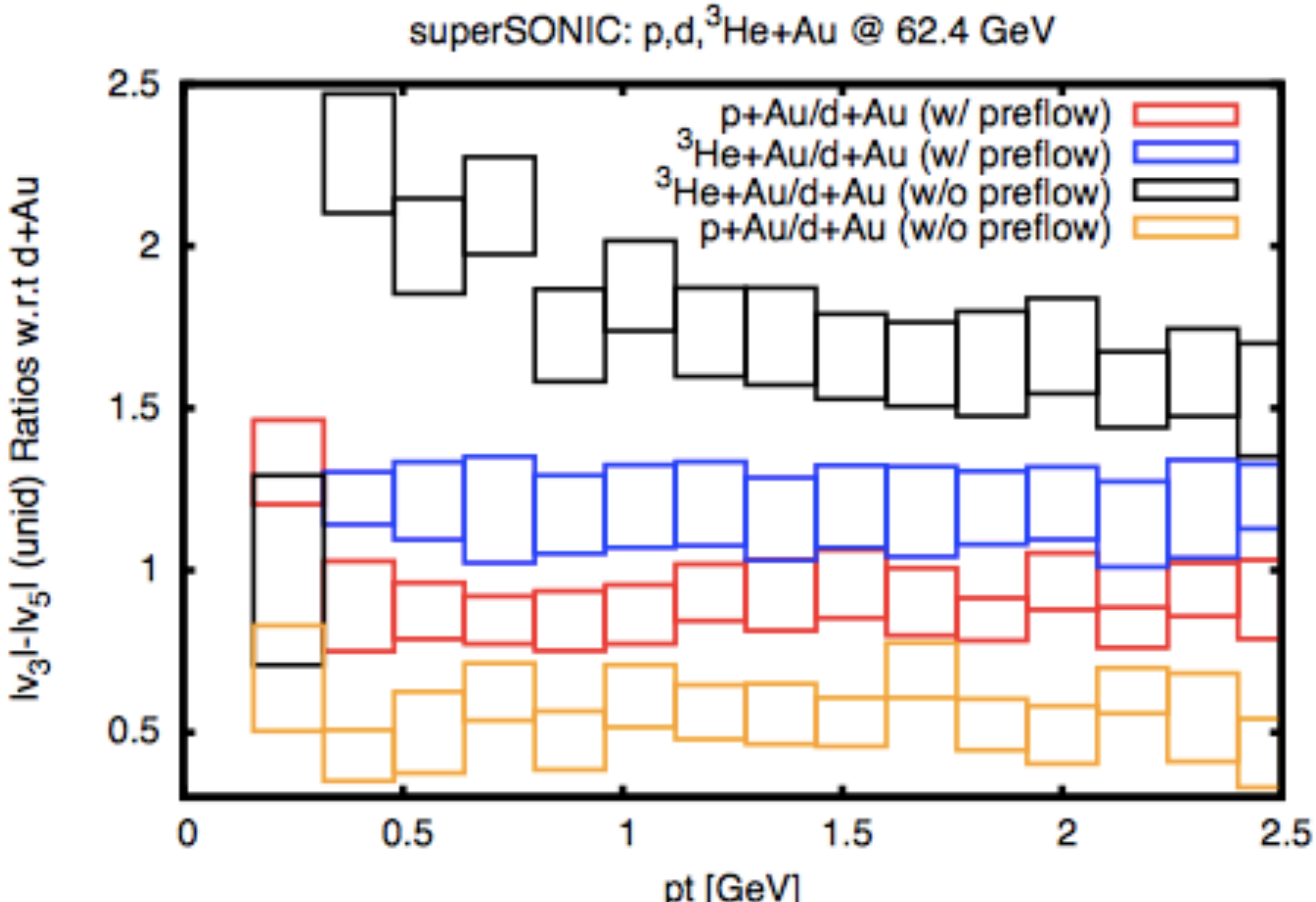




[van der Schee, PR & Pratt, 2013] [Epelbaum, Gelis, 2013]

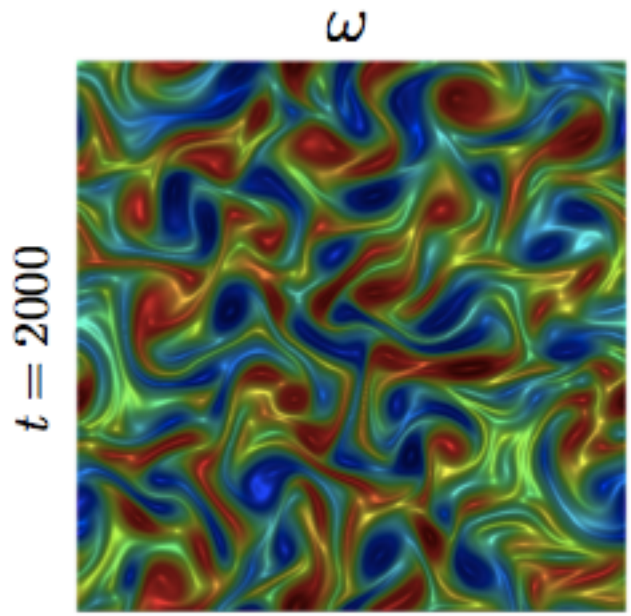
How about making more comparisons like these???

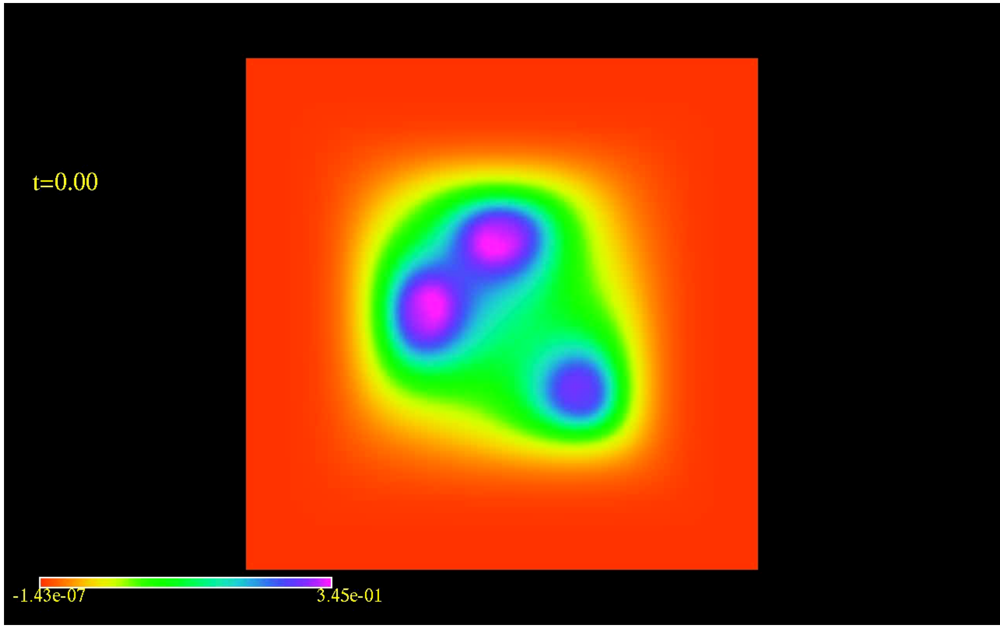
A way to probe QCD pre-eq flow?



[PR, 1502.04745]

Turbulent Gravity





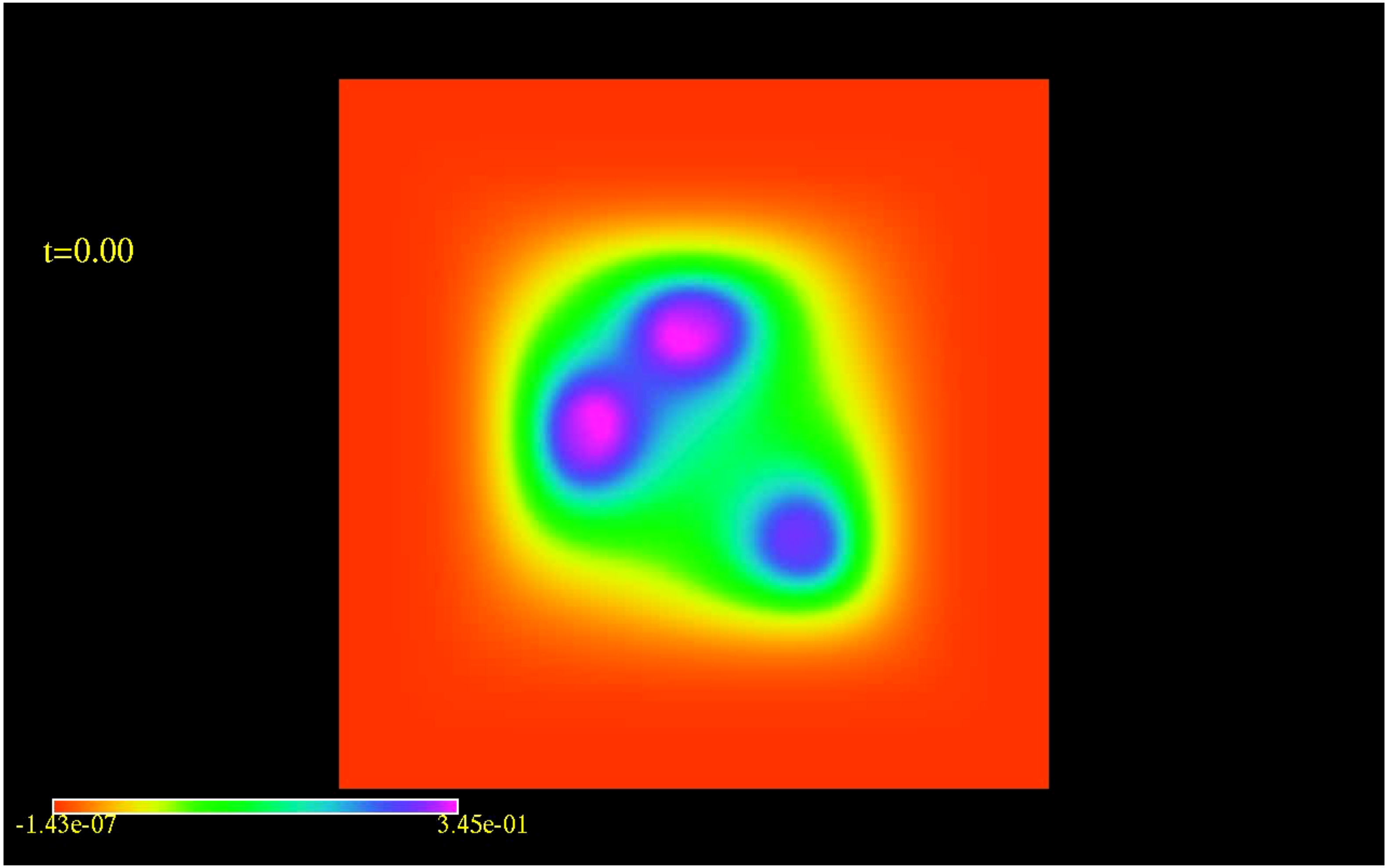
[Adams, Chesler, Liu 2013]

[Gorda & Bantilan, unpublished]

Planar Horizon (Black Brane)

No/Poincare Horizon

Turbulent Gravity



[Gorda & Bantilan, unpublished]

Summary/Conclusions

- General Purpose numeric solutions to Einstein Equations in asymptotic AdS using GH
- Successful numerical solutions for BH collisions in global AdS_5
- AdS (preeq)+Hydro(eq)+Hadron Cascade works surprisingly well in describing experimental data
- More results (e.g. AdS stability) coming soon!

Bonus Material

Numerical Relativity

Evolution Equations:

$$
\begin{aligned}
0 &= -\frac{1}{2} g^{\alpha\beta} g_{\mu\nu,\alpha\beta} - g^{\alpha\beta}{}_{,(\mu} g_{\nu)\alpha,\beta} \\
&\quad - H_{(\mu,\nu)} + H_\alpha \Gamma^\alpha{}_{\mu\nu} - \Gamma^\alpha{}_{\beta\mu} \Gamma^\beta{}_{\alpha\nu} \\
&\quad - \kappa \left(2 n_{(\mu} C_{\nu)} - (1+P) g_{\mu\nu} n^\alpha C_\alpha \right) \\
&\quad - \frac{2}{3} \Lambda_5 g_{\mu\nu} - 8\pi \left(T_{\mu\nu} - \frac{1}{3} T^\alpha{}_\alpha g_{\mu\nu} \right) \\
&\downarrow \\
0 &= \mathcal{L}_f |^n_{ij} \qquad \text{(15 such equations, one for each } \mu\nu\text{)}
\end{aligned}
$$

Use second-order differencing to discretize these

Numerical Relativity

Evolution Equations:

$$0 = \mathcal{L}_f|^n_{ij} \qquad \text{(15 such equations, one for each } \mu\nu\text{)}$$

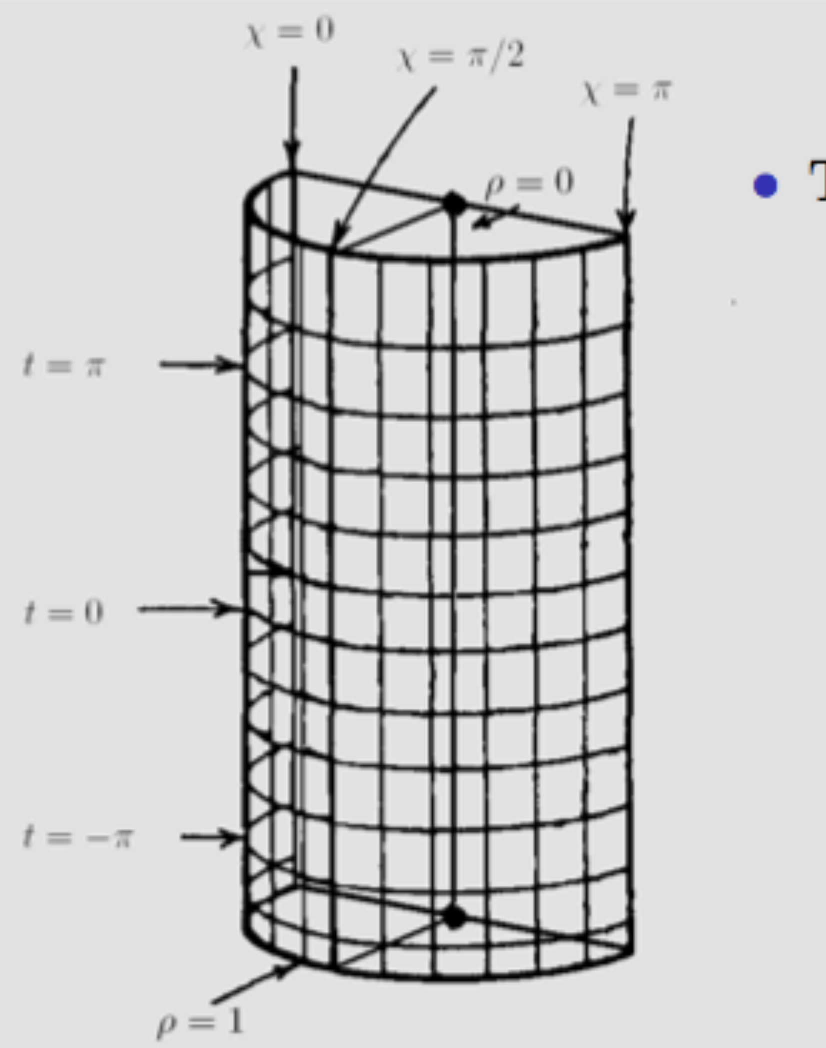
Solve by a Newton-Gauss-Seidel iterative scheme:

- three-level scheme at time levels t^{n+1}, t^n, t^{n-1}
- knowns: f^n_{ij}, f^{n-1}_{ij}, unknowns: f^{n+1}_{ij}
- the f^n_{ij} are used as an initial guess for the f^{n+1}_{ij}
- one iteration step:

  $$\tilde{f}^{n+1}_{ij} \to \tilde{f}^{n+1}_{ij} - \frac{\mathcal{R}_f|^n_{ij}}{\mathcal{J}_f|^n_{ij}} \qquad \left(\mathcal{R}_f|^n_{ij} = \mathcal{L}_{\tilde{f}}|^n_{ij} \text{ and } \mathcal{J}_f|^n_{ij} = \frac{\partial \mathcal{L}_f|^n_{ij}}{\partial f^{n+1}_{ij}}\right)$$

  (letting $\tilde{f}^{n+1}_{ij}$ be an approximate solution)
- iterate until $\mathcal{R}_f|^n_{ij}$ becomes sufficiently small

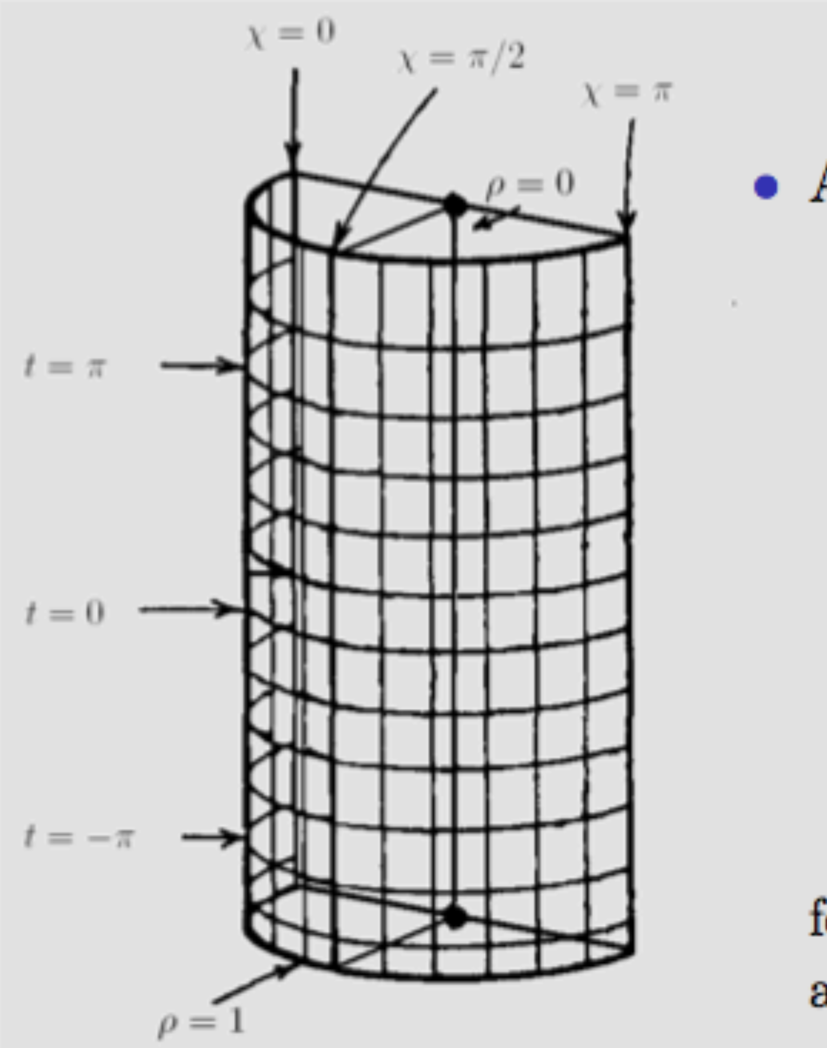
The anti-de Sitter Spacetime



- The AdS_5 spacetime
  - its boundary is causally connected to its interior
    - spacelike infinity $\cup$ null infinity
    - forms a timelike 4-surface
    - identified with $\mathbb{R} \times S^3$

FIGURE: Conformal sketch of the AdS_5 spacetime; there is an internal 2-sphere geometry at each point of this sketch.

Asymptotically anti-de Sitter Spacetimes



- An asymptotically AdS_5 spacetime
  - its boundary is causally connected to its interior
    - spacelike infinity $\cup$ null infinity
    - forms a timelike 4-surface
    - identified with $\mathbb{R} \times S^3$
  - metric in local coordinates:

$$\begin{cases} g_{mn} - g_{mn}^{AdS} \sim (1-\rho)^2 \\ g_{\rho\rho} - g_{\rho\rho}^{AdS} \sim (1-\rho)^2 \\ g_{\rho m} - g_{\rho m}^{AdS} \sim (1-\rho)^3 \end{cases} \quad \text{as } \rho \to 1$$

for $x^m = (t, \chi, \theta, \phi)$ boundary coordinates and ρ AdS radial coordinate

Figure: Conformal sketch of an asymptotically AdS_5 spacetime that preserves the SO(3) symmetry that rotates a 2-sphere at each point.

The anti-de Sitter Spacetime

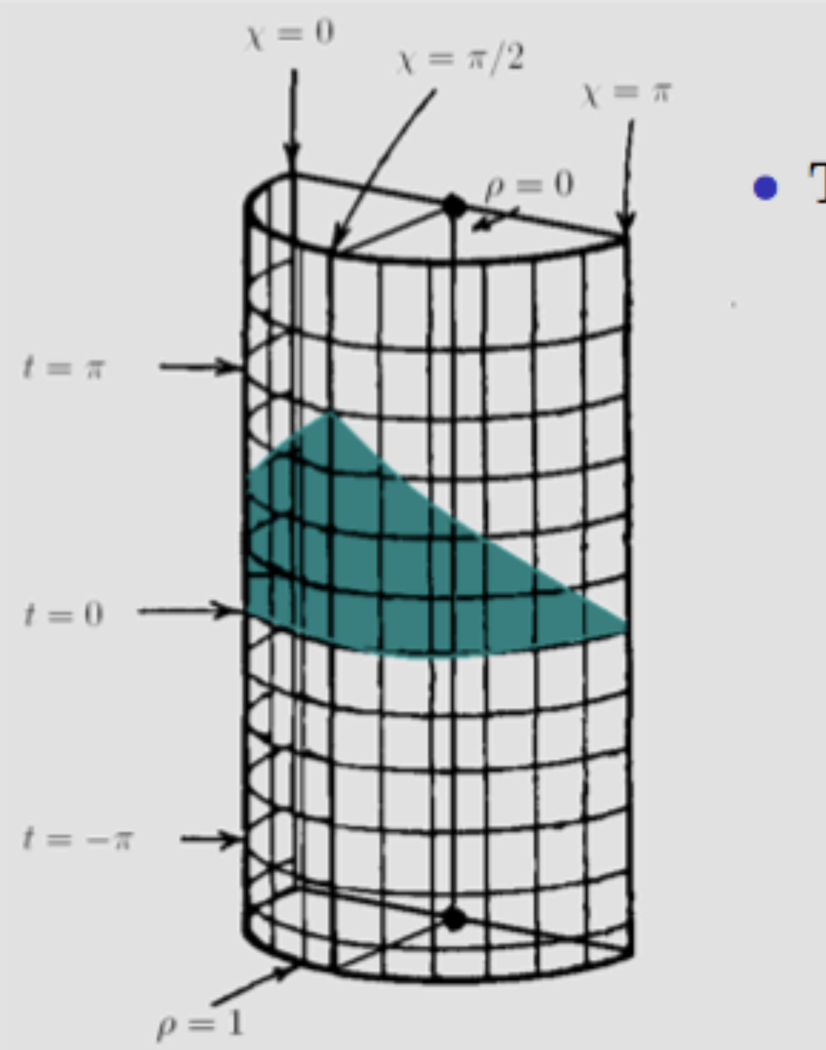


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FIGURE: Conformal sketch of the AdS_5 spacetime; there is an internal 2-sphere geometry at each point of this sketch.

Hans Bantilan, CU Boulder, Oct 2014

Initial Data:

$$0 = \mathcal{L}_\zeta|_{ij} \qquad \text{(5 such equations, one for each } \mu\text{)}$$

Solve by a multigrid method:

1. Compute residual on fine grid
   $\mathcal{R}_{\zeta_h} = \mathcal{L}_{\tilde{\zeta}_h}$.
2. Inject fine grid residual $\mathcal{R}_{\zeta_h}$ and approx soln $\tilde{\zeta}_h$ onto coarse grid
   $\mathcal{R}_{\zeta_h} \to \mathcal{R}_{\zeta_{\rm inj}}$, $\tilde{\zeta}_h \to \tilde{\zeta}_{\rm inj}$.
3. Find approx soln $\tilde{\zeta}_{2h}$ on coarse grid by solving difference equation
   $\mathcal{L}_{\zeta_{2h}} = d_{2h}$ for $d_{2h} = \mathcal{L}_{\zeta_{\rm inj}} - \mathcal{R}_{\zeta_{\rm inj}}$.
4. Compute correction on coarse grid
   $\tilde{v}_{2h} = \tilde{\zeta}_{2h} - \tilde{\zeta}_{\rm inj}$.
5. Interpolate correction from coarse grid to fine grid
   $\tilde{v}_{2h} \to \tilde{v}_h$.
6. Generate next approx on fine grid using coarse-grid correction
   $\tilde{\zeta}_h^{\rm new} = \tilde{\zeta}_h + \tilde{v}_h$.

Numerical Relativity

Other ingredients:

- Kreiss-Oliger style numerical dissipation
- Apparent horizon finder and excision
- Lapse damping
- Coordinate choice near the AdS boundary

Coordinate Choice near the AdS Boundary

- Coordinate choice in asymptotically AdS spacetimes
  - not enough to simply demand b.c.s for $\bar{g}_{\mu\nu}$, $\bar{H}_\mu$, $\bar{\phi}$
    $g_{\mu\nu} = g^{AdS}_{\mu\nu} + (1-\rho)^{\#}\bar{g}_{\mu\nu}$
    $H_\mu = H^{AdS}_\mu + (1-\rho)^{\#}\bar{H}_\mu$
    $\varphi = (1-\rho)^{\#}\bar{\varphi}$
  - how to choose H_μ so that b.c.s are preserved by evolution?

- Example: tt component of field equations near $\rho = 1$

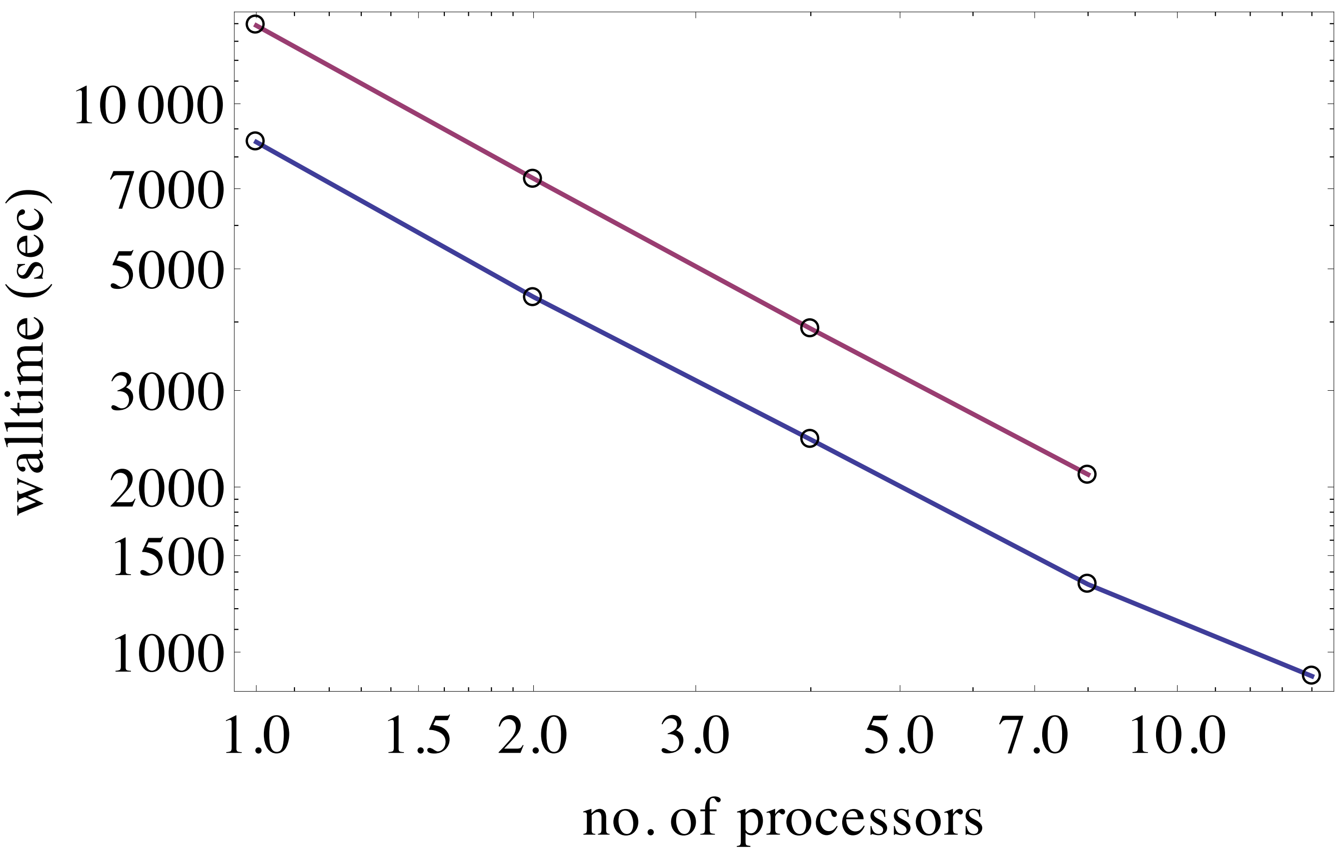
$$\tilde{\Box}\bar{g}_{(1)tt} = (-8\bar{g}_{(1)\rho\rho} + 4\bar{H}_{(1)\rho})(1-\rho)^{-2} + ...$$

  - regularity requires a delicate cancellation between terms in the near-boundary limit
  - smart coordinate choice: $\bar{H}_{(1)\rho} = 2\bar{g}_{(1)\rho\rho}$

Infiniband connections essential

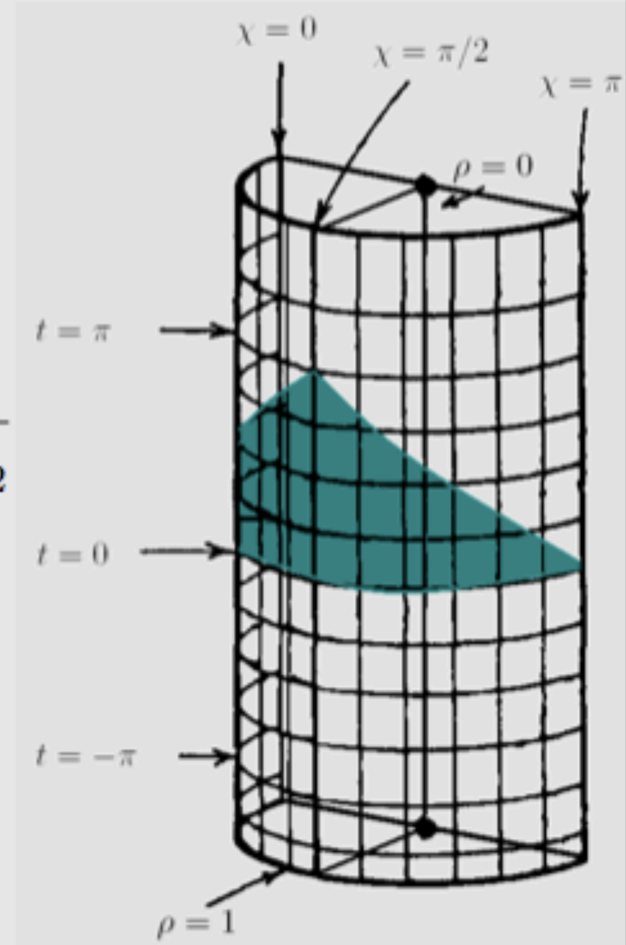
Lnxfarm: single node, multiple cores used

Eridanus: single core on <u>different</u> nodes used



From Bulk to Boundary

$$
\begin{aligned}
t' &= W \sin t \\
x_1 &= W \sin\chi \sin\theta \cos\phi \\
x_2 &= W \sin\chi \sin\theta \sin\phi \\
x_3 &= W \cos\chi \\
W &\equiv 1/(\cos t + \sin\chi\cos\theta) \\
&= \sqrt{(t')^2 + \frac{1}{4}(1 + x_1^2 + x_2^2 + x_3^2 - (t')^2)^2} \\
g^{ab}_{\mathbb{R}^{3,1}} &= W^{-2} \frac{\partial x^a}{\partial x^\mu} \frac{\partial x^b}{\partial x^\nu} g^{\mu\nu}_{\mathbb{R}\times S^3} \\
\epsilon_{\mathbb{R}^{3,1}} &= W^{-4} \epsilon_{\mathbb{R}\times S^3} \\
u^a_{\mathbb{R}^{3,1}} &= W^{-1} \frac{\partial x^a}{\partial x^\mu} u^\mu_{\mathbb{R}\times S^3} \\
T^{ab}_{\mathbb{R}^{3,1}} &= W^{(-d-2)} \frac{\partial x^a}{\partial x^\mu} \frac{\partial x^b}{\partial x^\nu} T^{\mu\nu}_{\mathbb{R}\times S^3}
\end{aligned}
$$



Hans Bantilan, CU Boulder, Oct 2014

Conformal Field Theory Dual

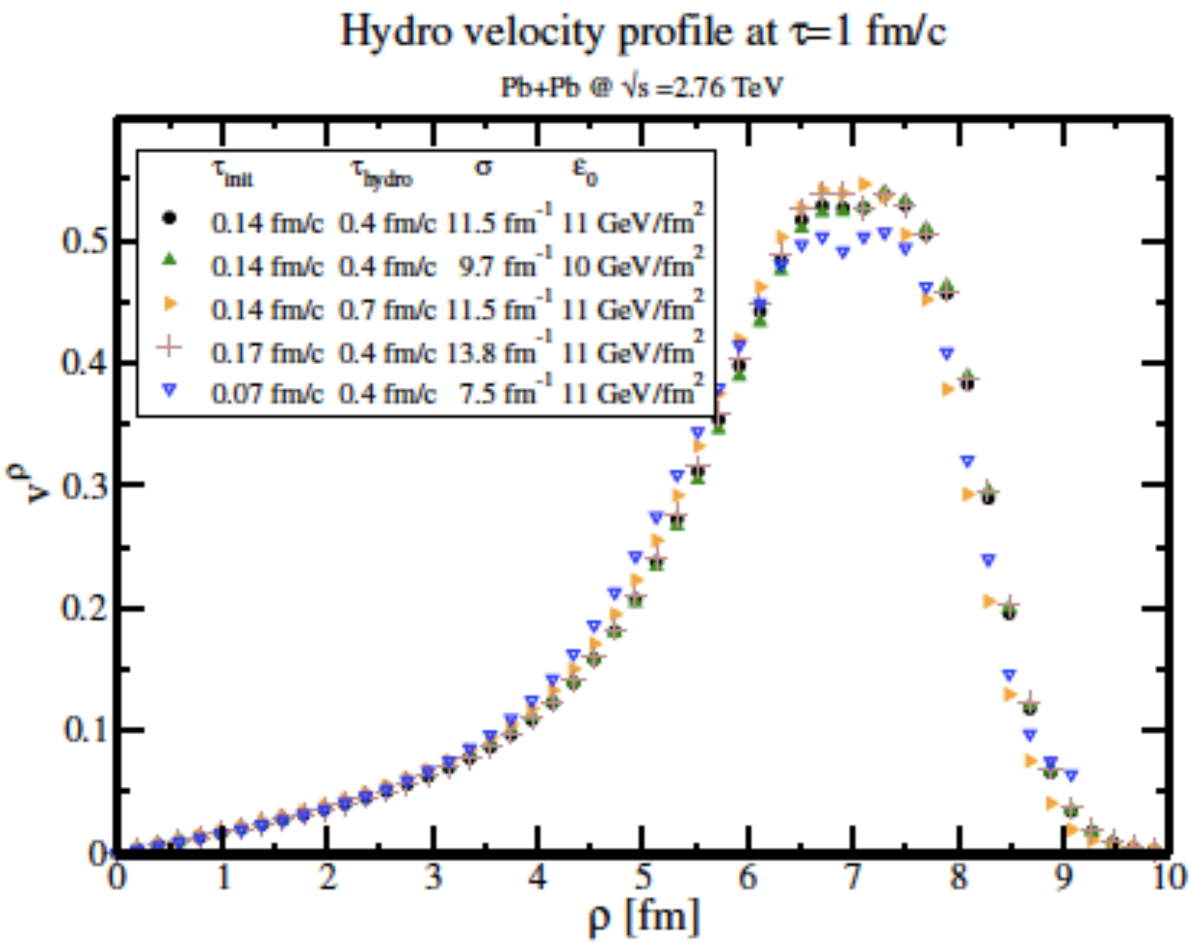
- Bulk field / CFT operator
  - e.g. metric dynamics / CFT stress tensor one-point function
    $\bar{g}_{\mu\nu}(x^m, \rho)$ $\qquad$ $\langle T_{\mu\nu}(x^m)\rangle_{\mathrm{CFT}}$

- How do bulk fields encode boundary CFT operators?

$$\langle T_{\mu\nu}\rangle_{\mathrm{CFT}} = \lim_{\rho\to 1}\left[\frac{1}{8\pi}\left({}^{(\rho)}\Theta_{\mu\nu} - {}^{(\rho)}\Theta\Sigma_{\mu\nu} - \frac{3}{L}\Sigma_{\mu\nu} + {}^{(\rho)}G_{\mu\nu}\frac{L}{2}\right) - t_{\mu\nu}\right]$$

Given a $\rho =$ const. time-like hypersurface ∂M_ρ, ${}^{(\rho)}\Theta_{\mu\nu} = -\Sigma^\alpha{}_\mu \Sigma^\beta{}_\nu \nabla_{(\alpha}S_{\beta)}$ is the extrinsic curvature of ∂M_ρ, S^μ is a space-like, outward pointing unit vector normal to the surface ∂M_ρ, $\Sigma_{\mu\nu} \equiv g_{\mu\nu} - S_\mu S_\nu$ is the induced 4-metric on ∂M_ρ, ∇_α is the covariant derivative operator, and ${}^{(\rho)}G_{\mu\nu}$ is the Einstein tensor associated with $\Sigma_{\mu\nu}$. Setting $L=1$, the non-zero components of the (non-dynamical) Casimir contribution $t_{\mu\nu}$ that we have explicitly subtracted above are $t_{tt} = 3(1-\rho)^2/(64\pi)$, $t_{\chi\chi} = (1-\rho)^2/(64\pi)$, $t_{\theta\theta} = (1-\rho)^2\sin^2\chi/(64\pi)$, and $t_{\phi\phi} = t_{\theta\theta}\sin^2\theta$.

Shocks with Transverse Profiles



[van der Schee, PR & Pratt, 2013]

Use AdS/CFT initial conditions and compare to data

- Idea: pre-equilibrium flow for smooth, central collisions is simple
- Parametrize as

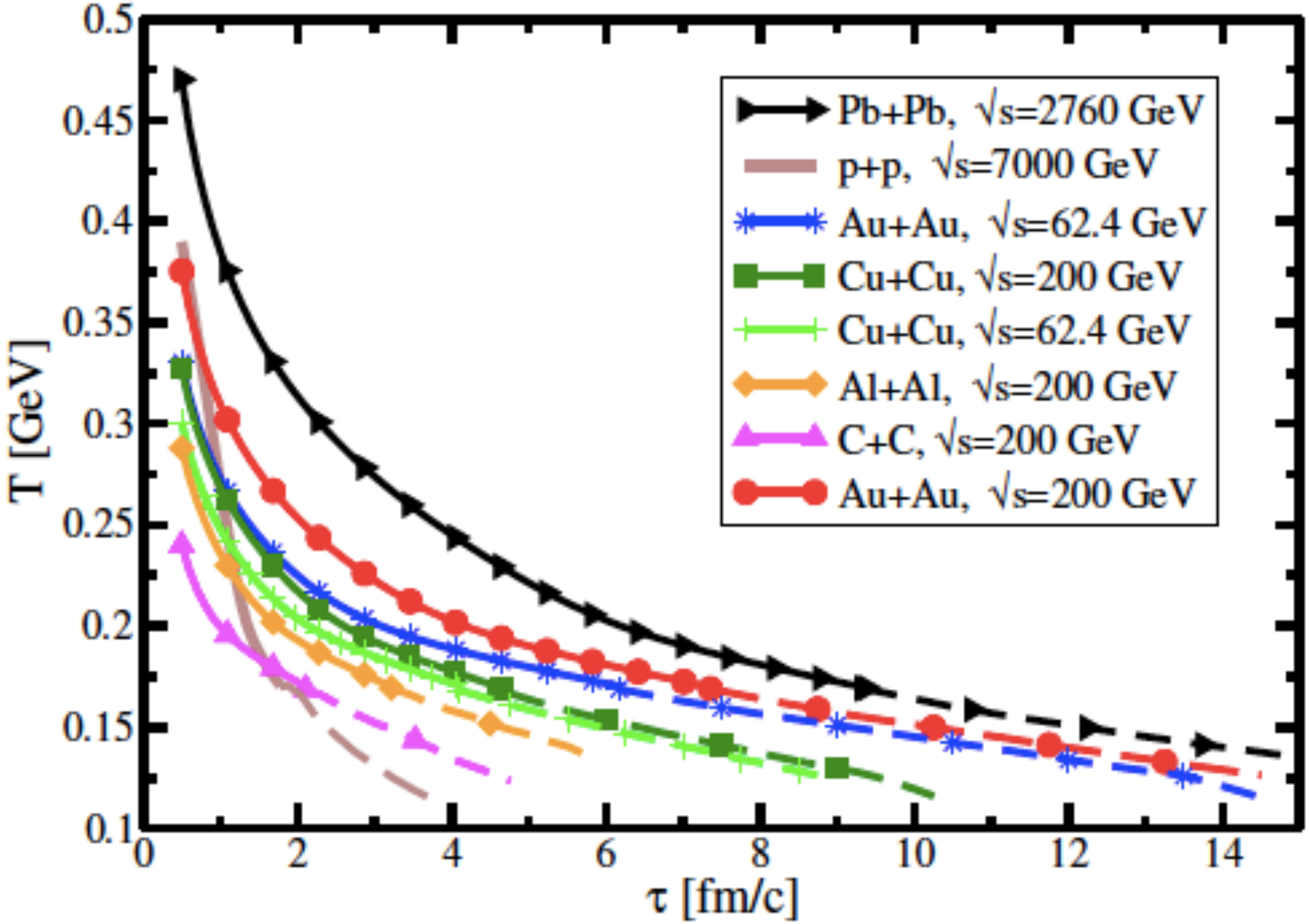
$$v^r(\tau, r) = -\frac{\tau}{3}\partial_r \ln T_A^2(r)$$

[Habich, Nagle and PR, 1409.0040]

and use for different collision systems (Pb+Pb, Au+Au, Cu+Cu, Al+Al, C+C, p+p)

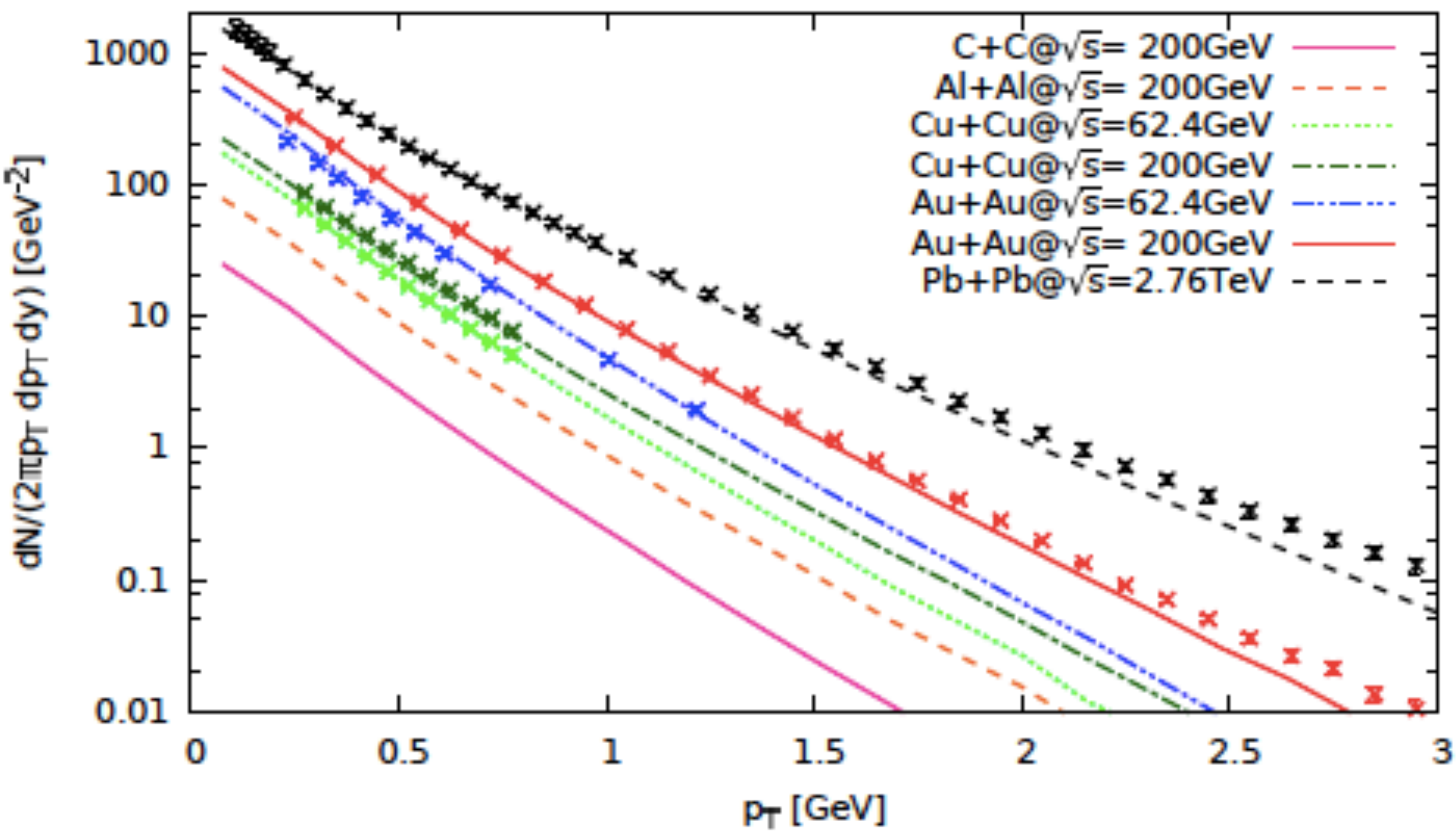
Compare: $\frac{T_{0x}}{T_{00}} \approx -\frac{\partial_x T_{00}}{2T_{00}} t,$ [Scott & Vredevoogd, PRC79 2009]

Central Temperature Evolution



[Habich, Nagle and PR, 1409.0040]

SONIC: AdS+Hydro (eta/s=0.08)+Hadron Cascade



[Habich, Nagle and PR, 1409.0040]

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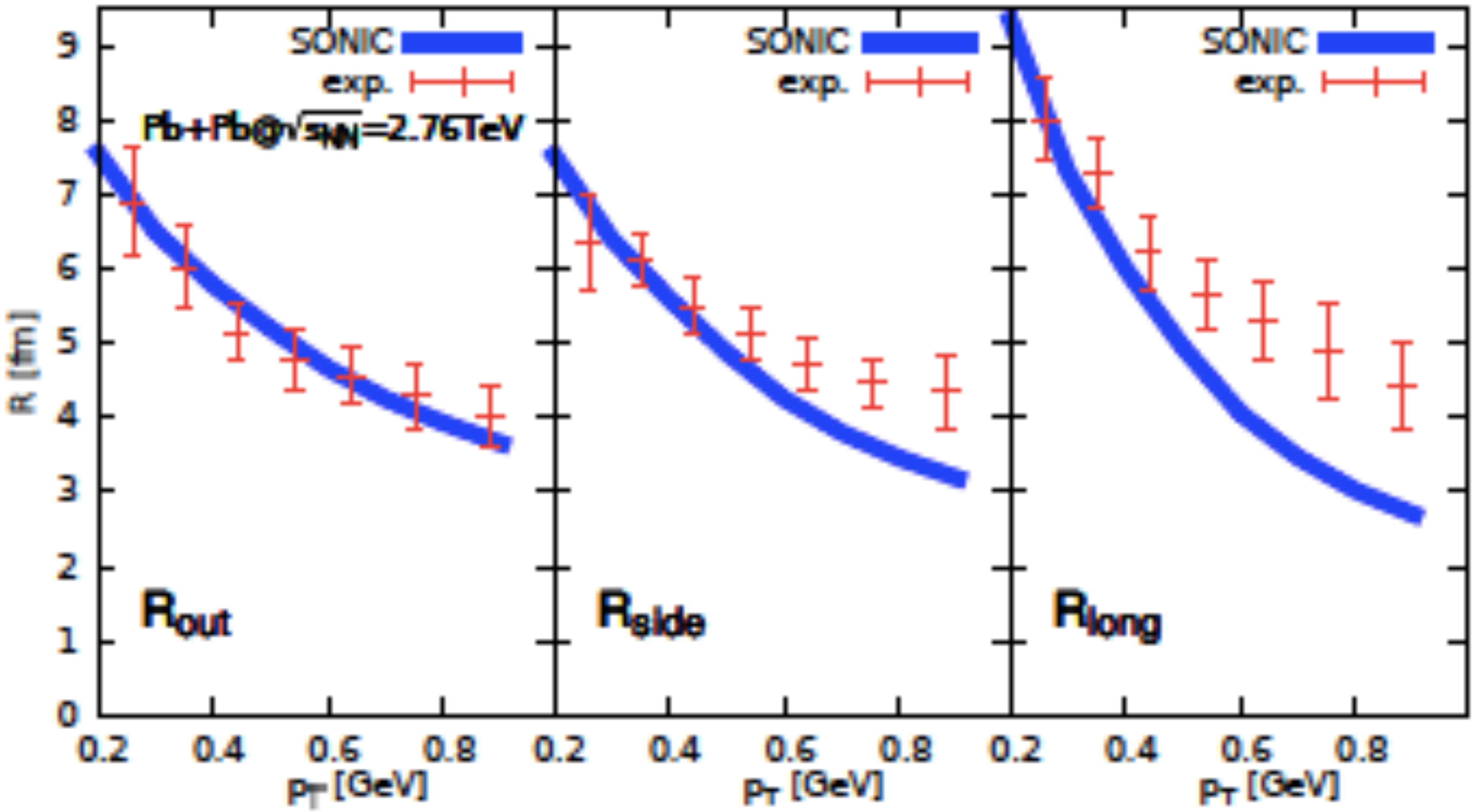

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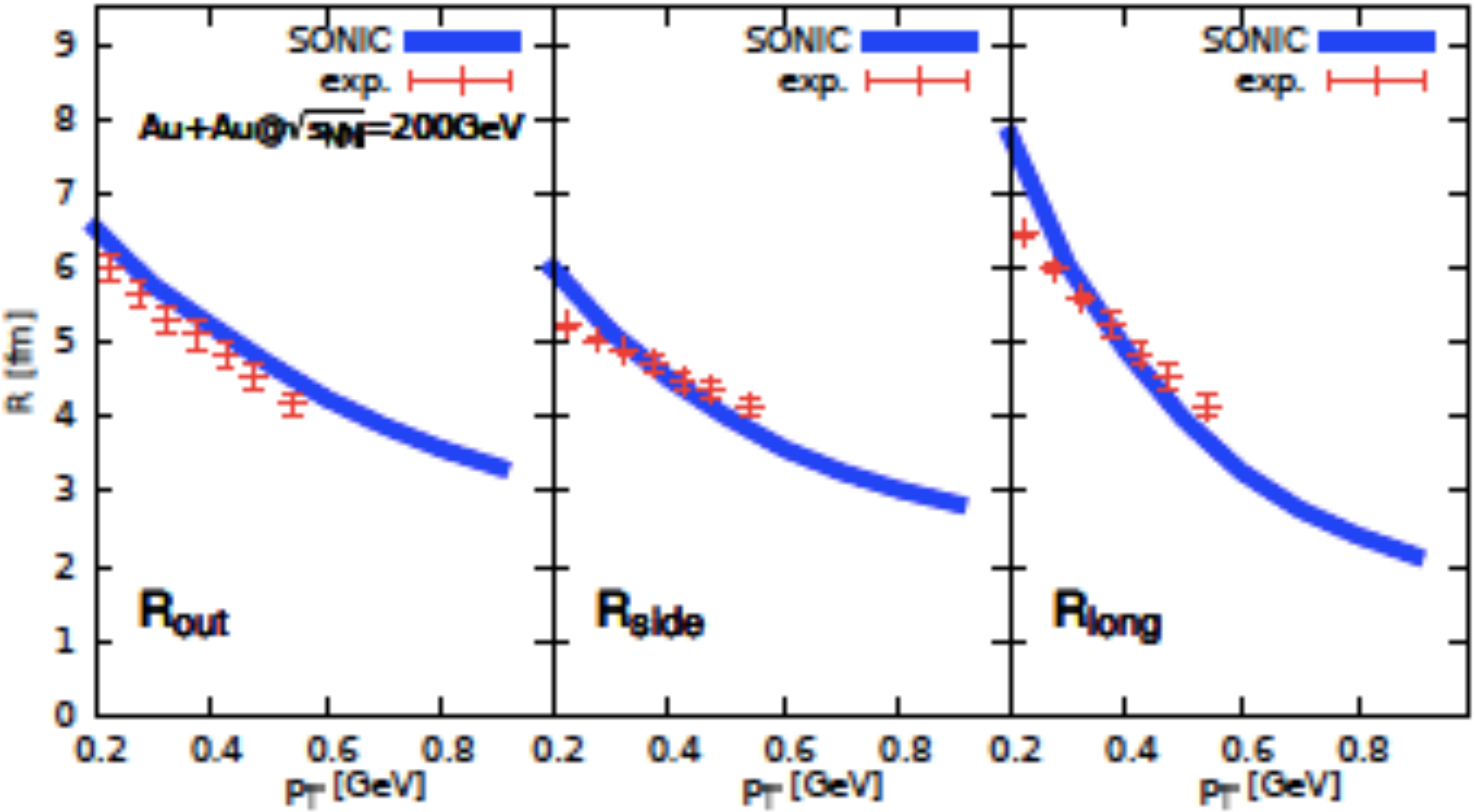

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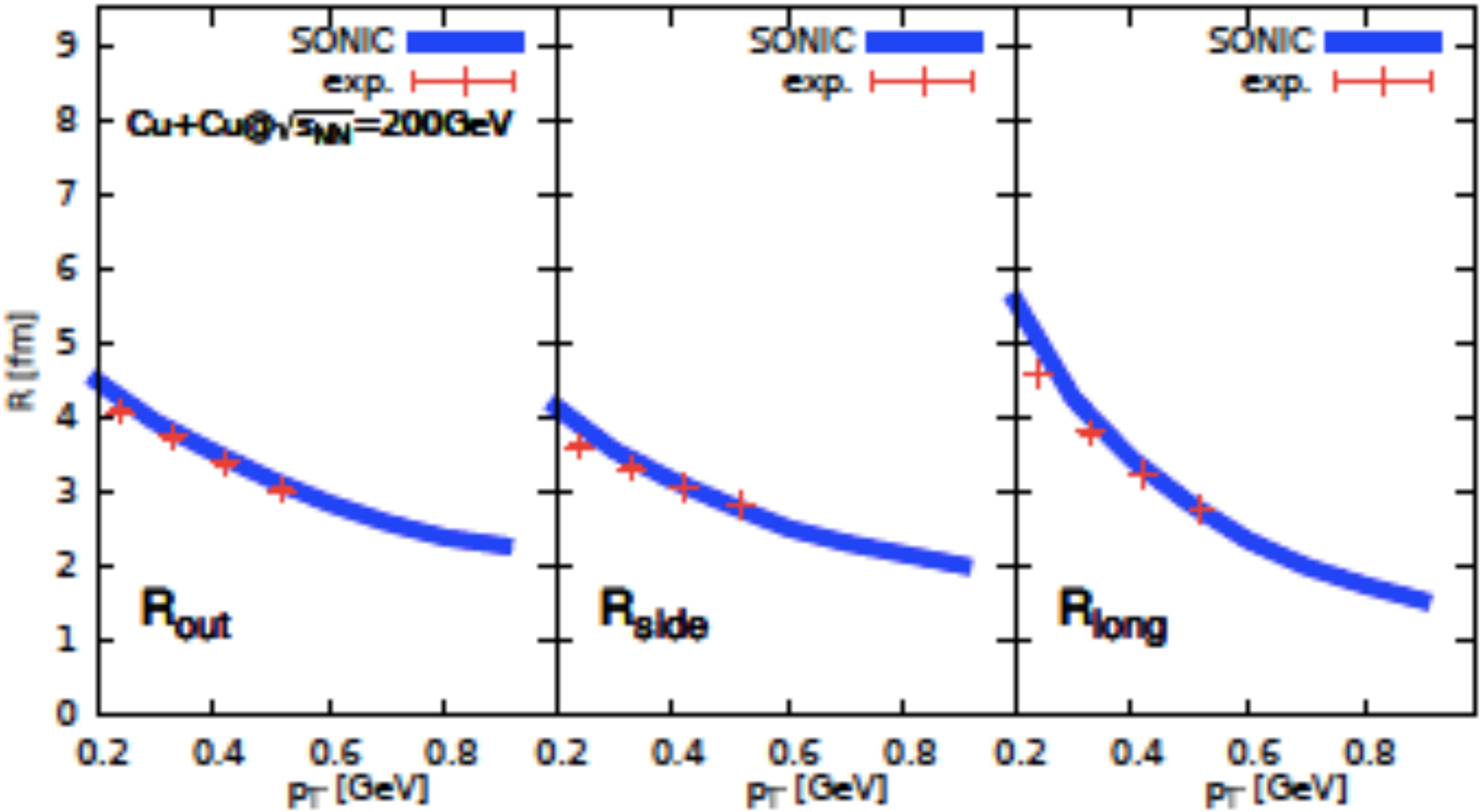

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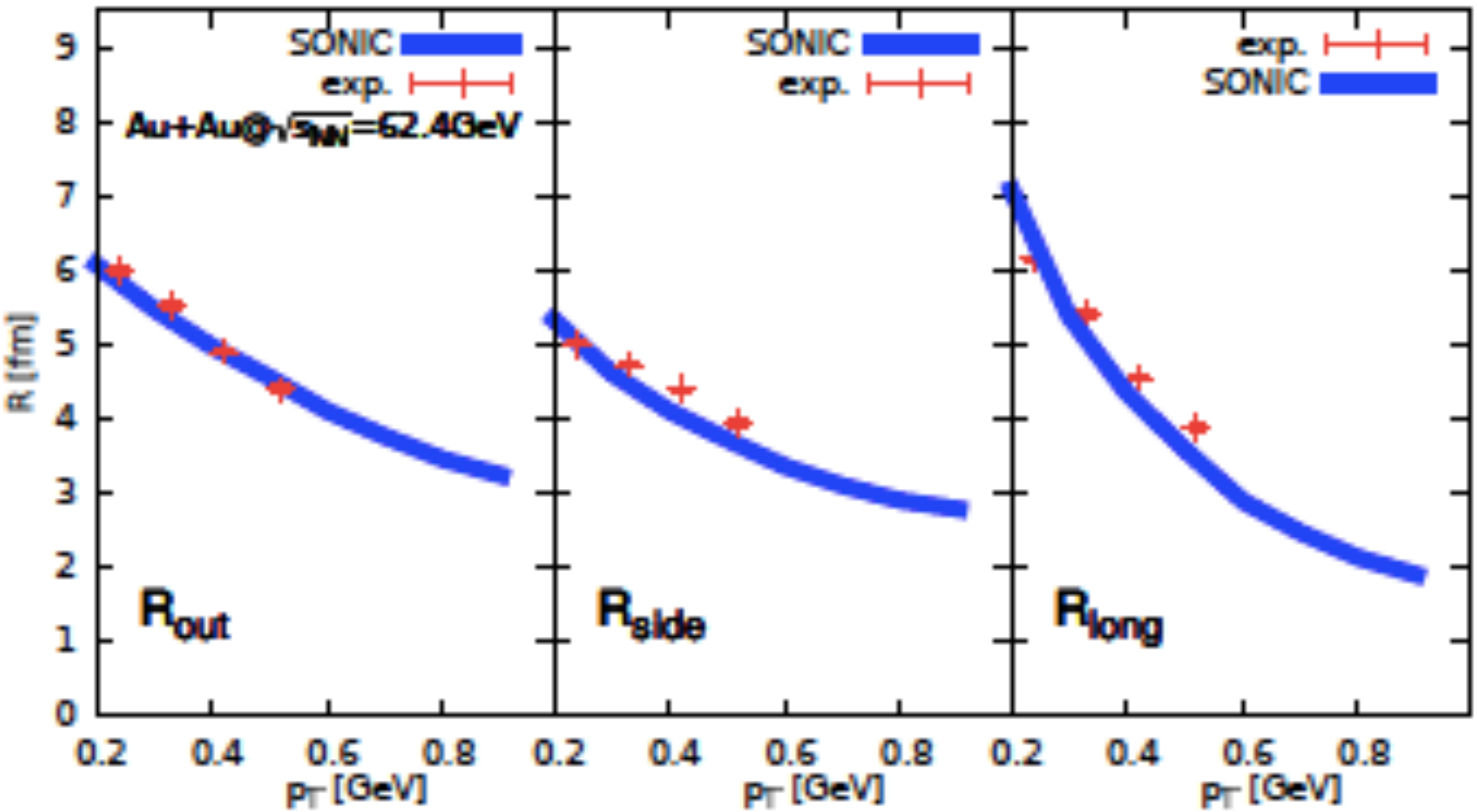

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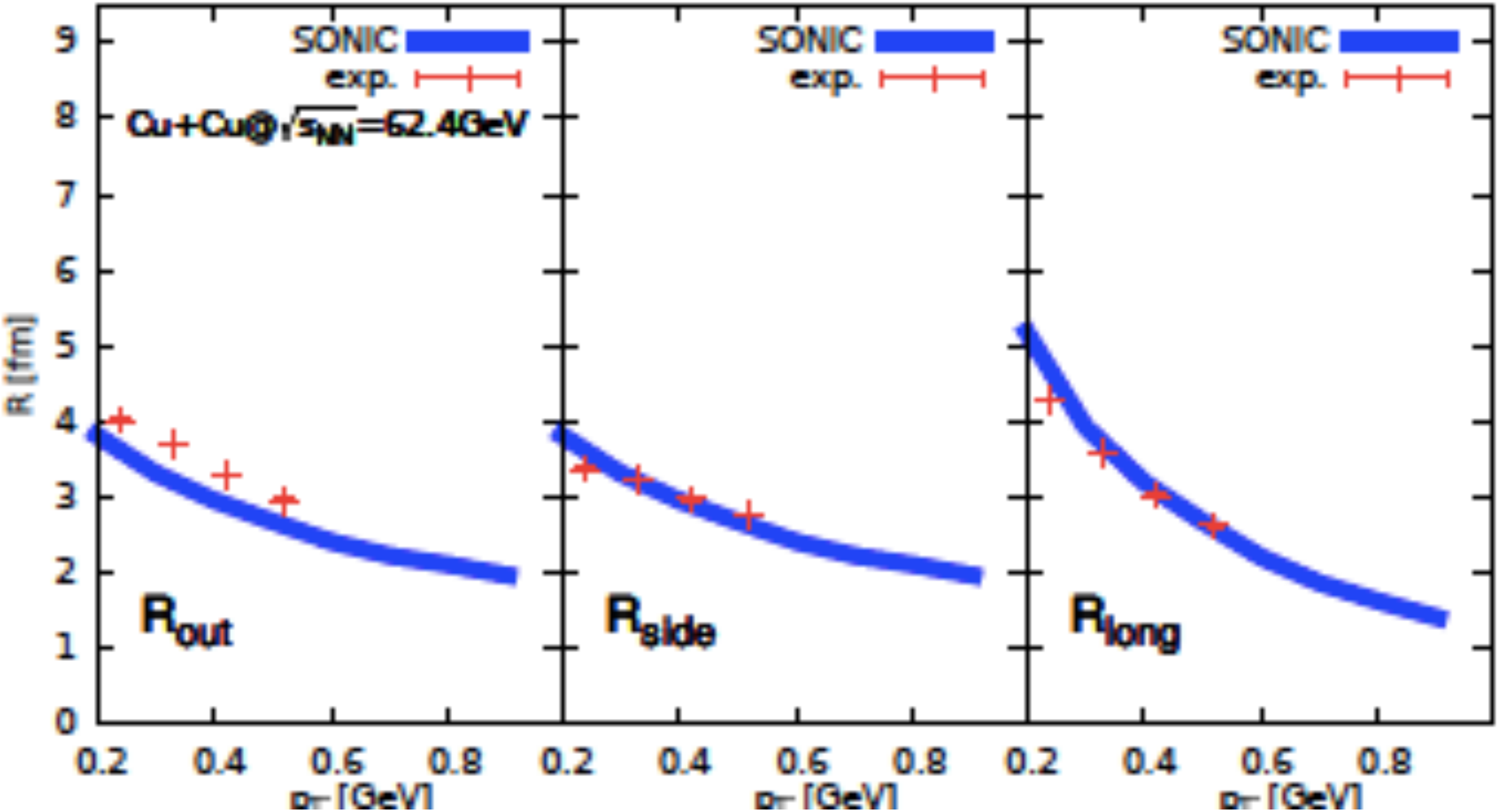

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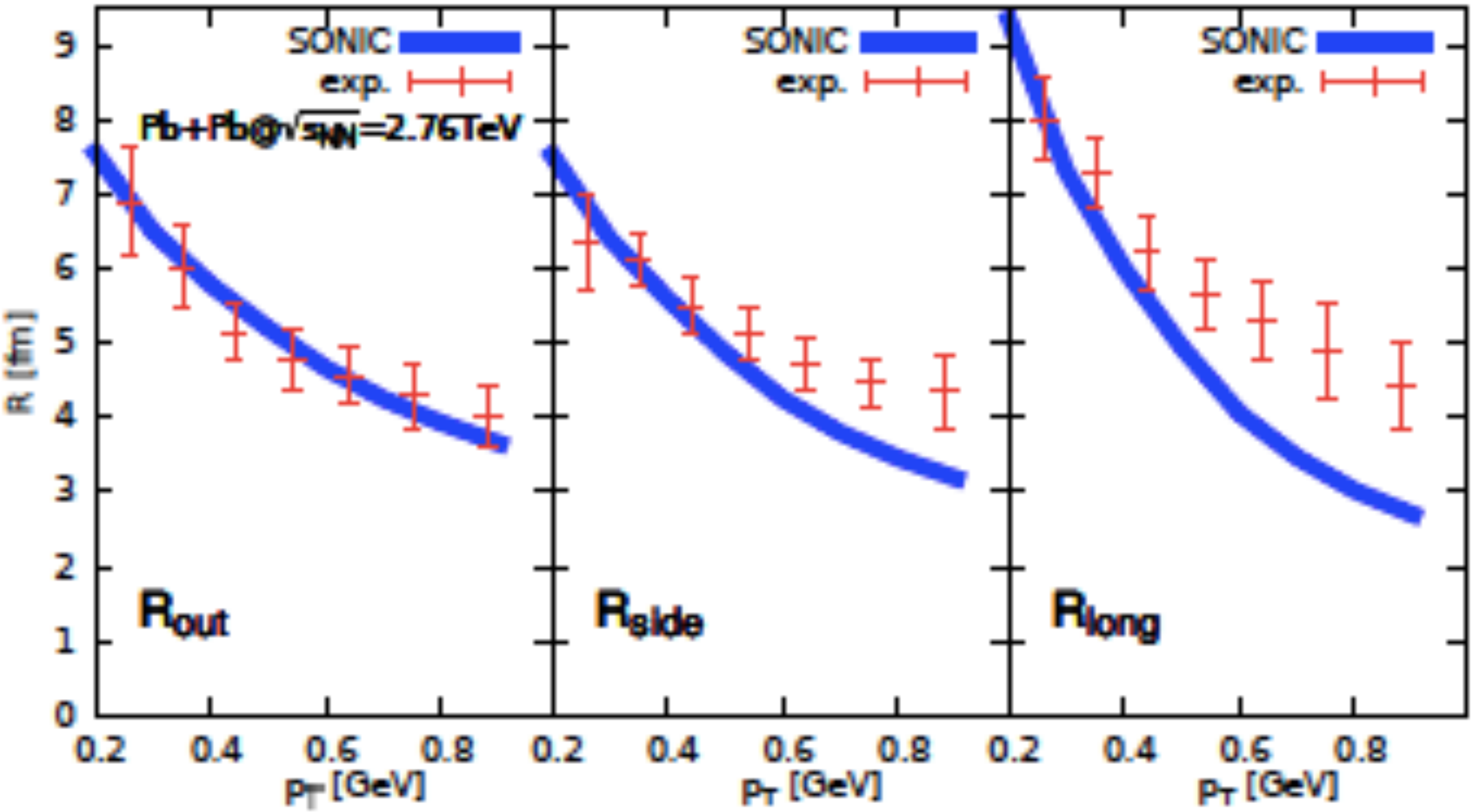

[Habich, Nagle and PR, 1409.0040]