Collisions, quasiparticles and collision dynamics: holographic lessons and puzzles

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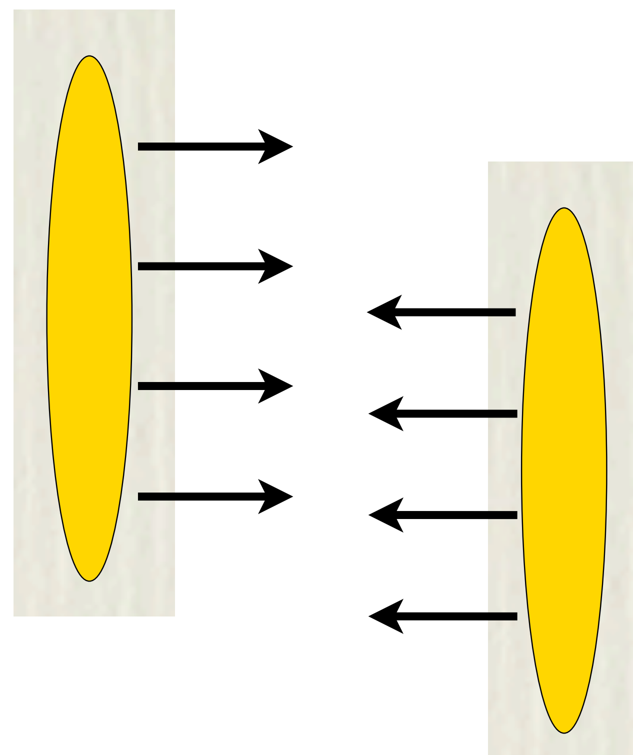
Outline

- holographic “heavy ion” collisions
- quasiparticles at strong coupling
- large N_c confinement dynamics

holographic “heavy ion” collisions



with Paul Chesler, arXiv:1501.04644

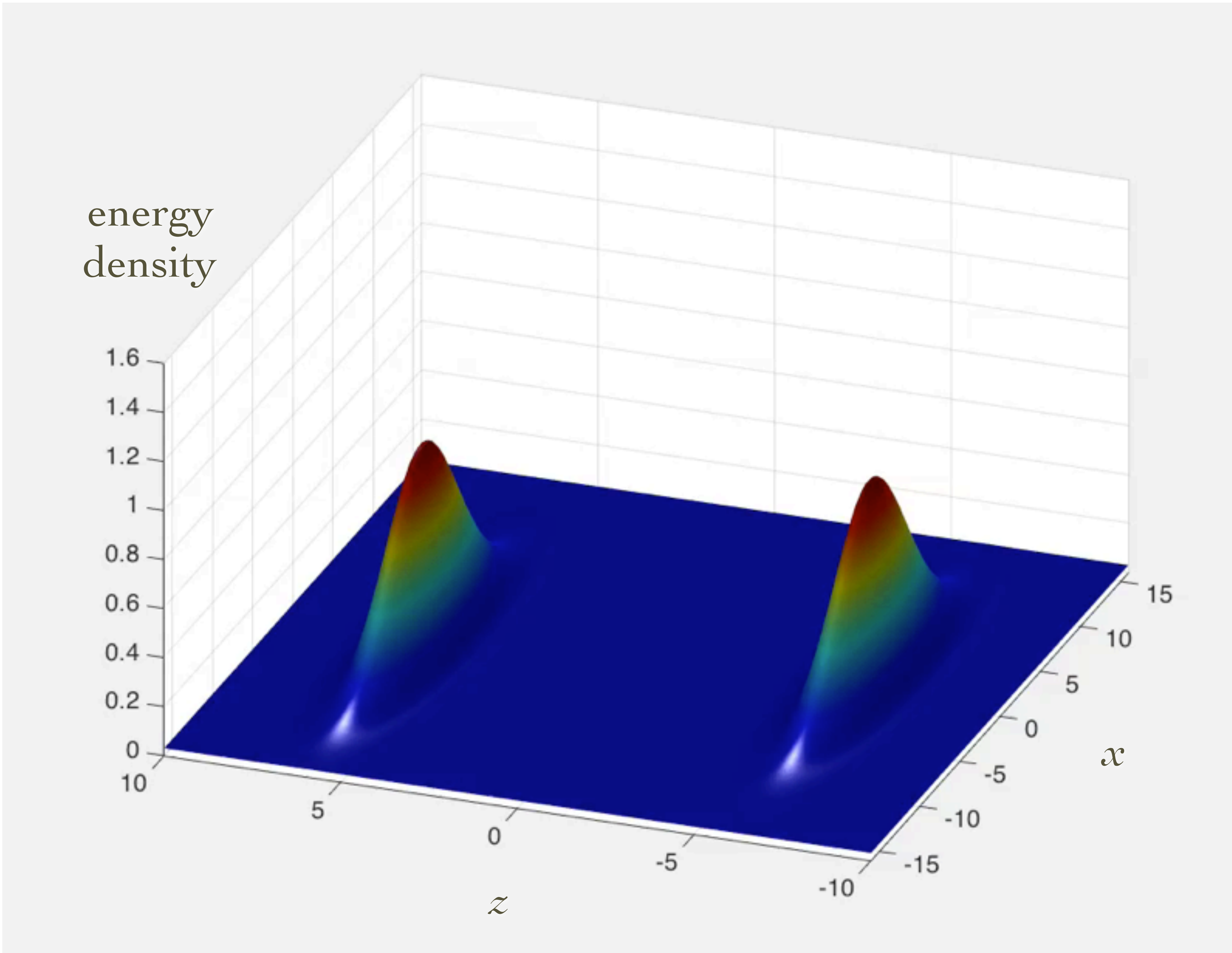
holographic collisions

Lesson 1: Feasibility

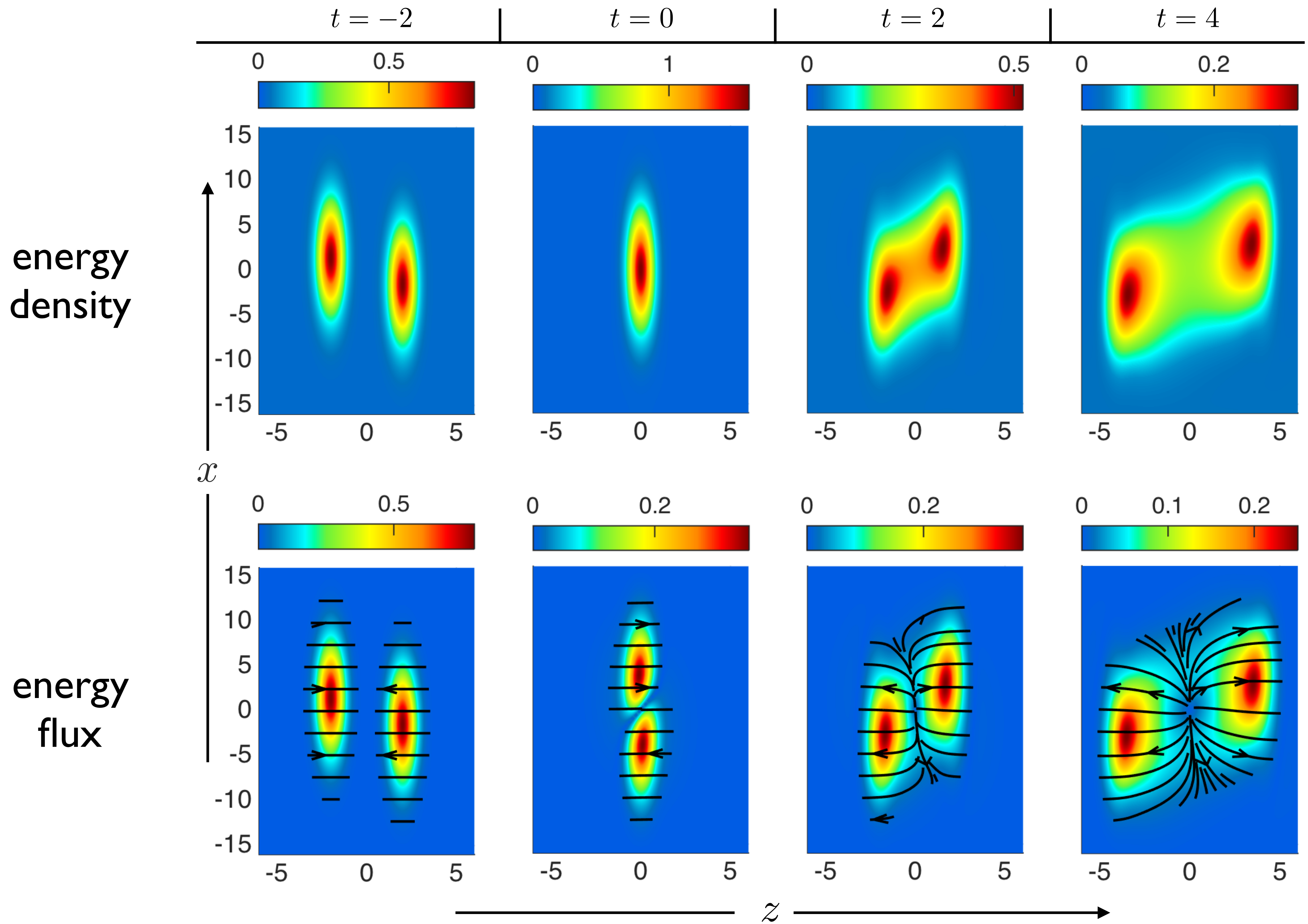
- Characteristic formulation of GR + spectral methods work very well for wide class of problems involving asymptotically AdS spacetime dynamics

- It is possible to study collisions of localized projectiles, off-center, with honest (longitudinal and transverse) dynamics, no dimensionality reducing symmetry assumptions, using only desktop computing resources

holographic collisions



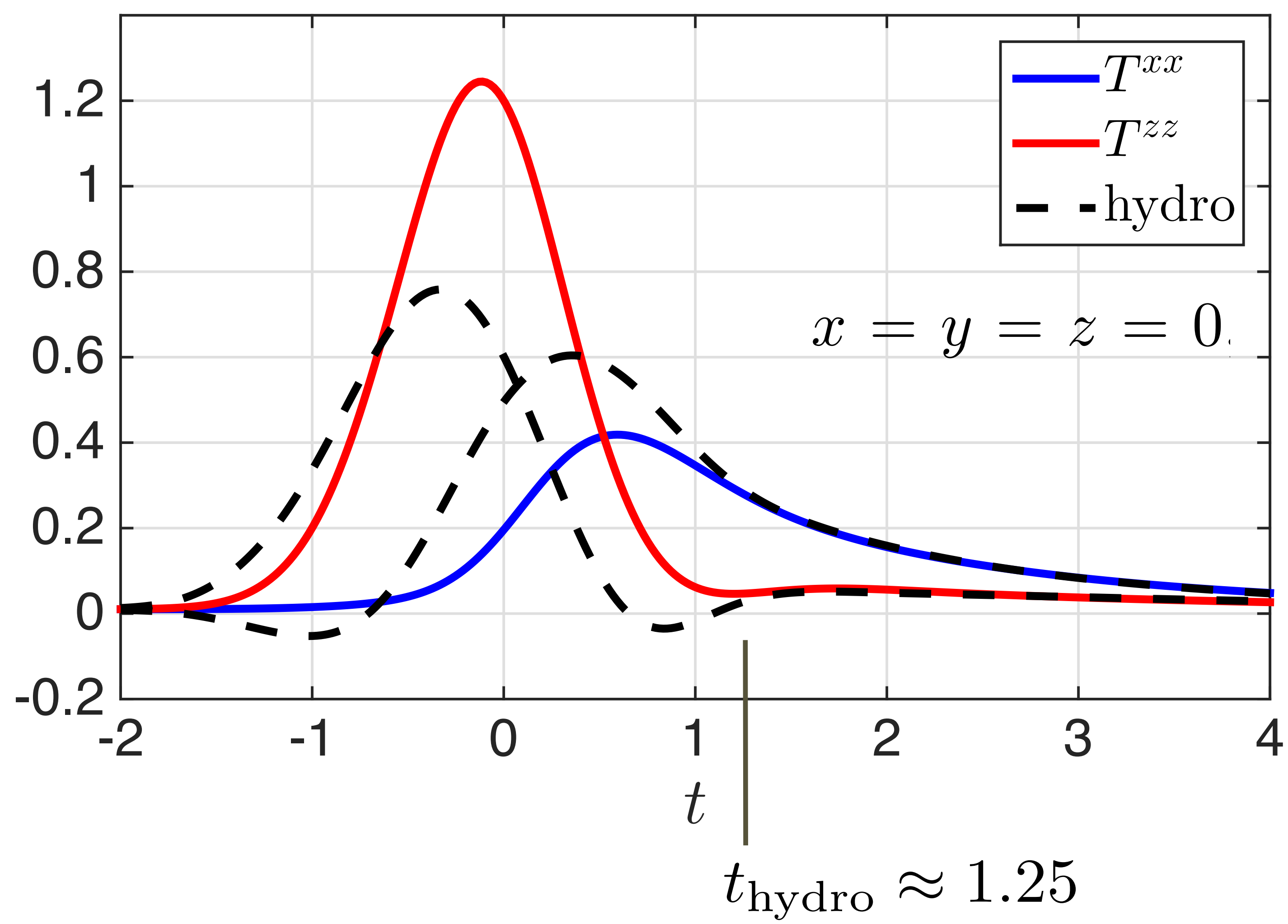
holographic collisions



holographic collisions

Lesson 2: hydro onset ≈ 30% faster than for planar shocks

transverse and longitudinal pressure

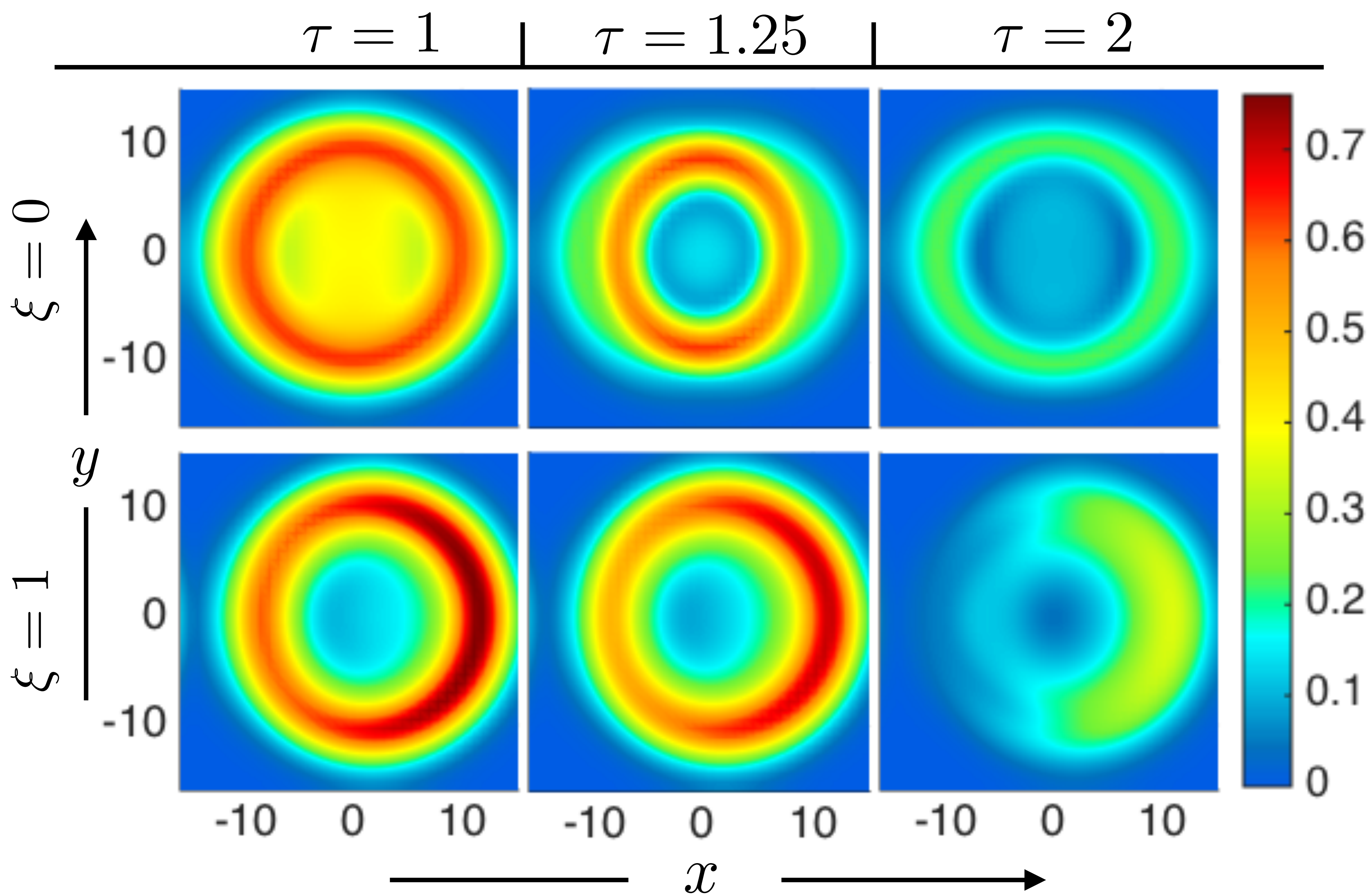


holographic collisions

hydrodynamic residual $\Delta \equiv (1/\bar{p})\sqrt{\Delta T_{\mu\nu}\Delta T^{\mu\nu}}$,

$\Delta T^{\mu\nu} \equiv T^{\mu\nu} - T^{\mu\nu}_{\text{hydro}}$

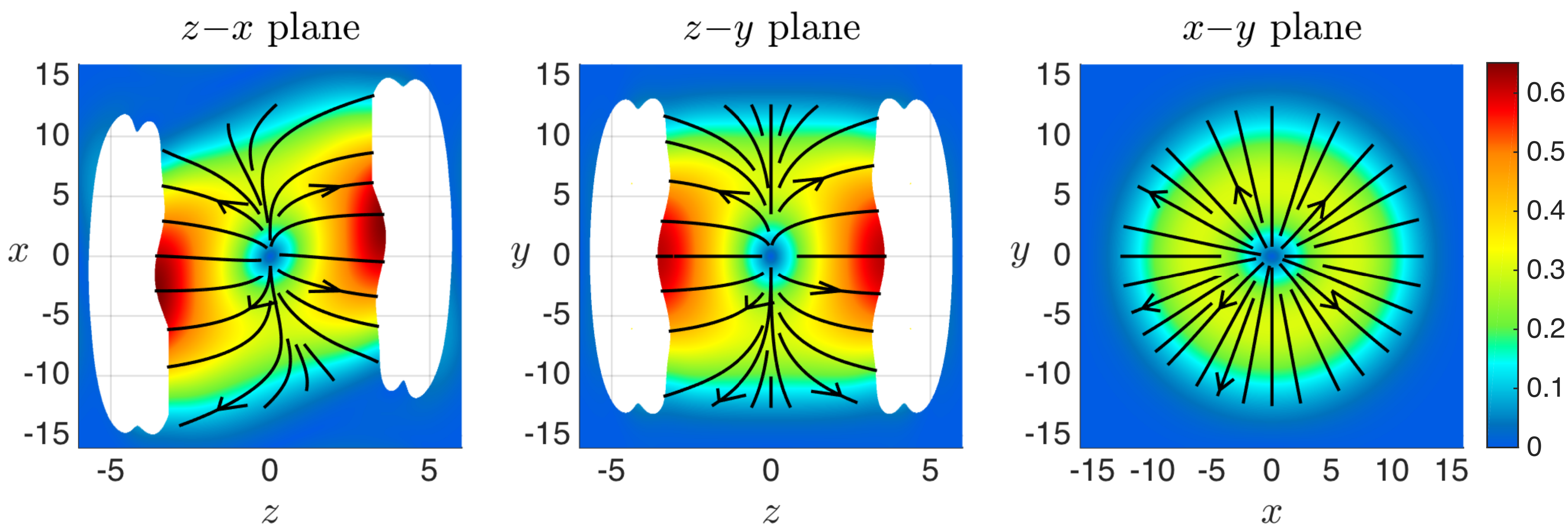
$\bar{p} \equiv \epsilon/3$



holographic collisions

Lesson 3: early development of substantial radial flow

$v_\perp(x_\perp = 5) \approx 0.3$ $v_\parallel^{\max} \approx 0.64$

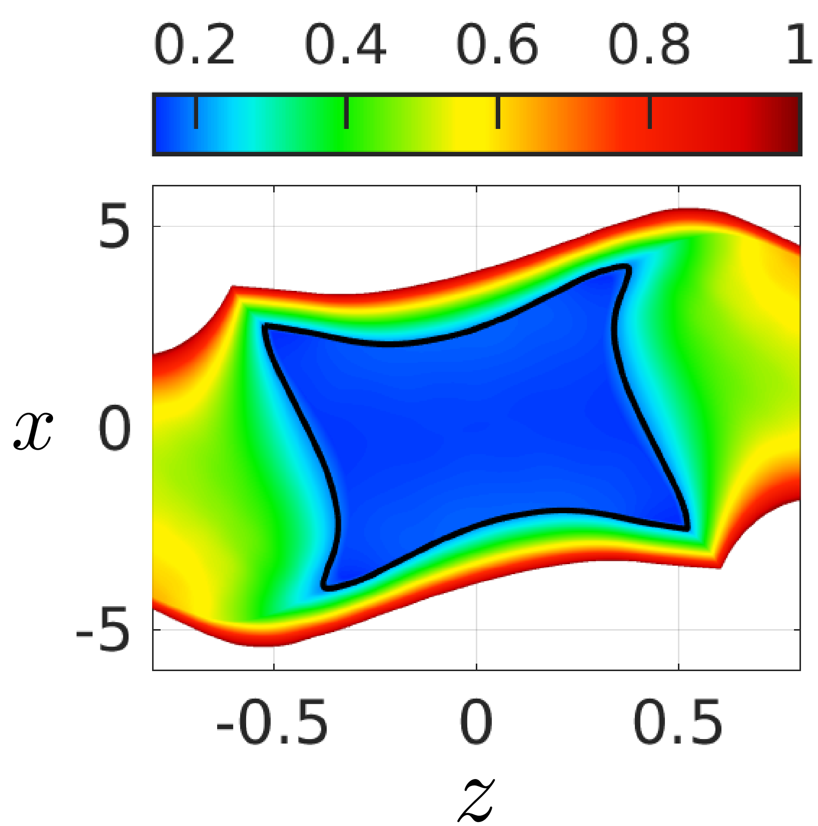


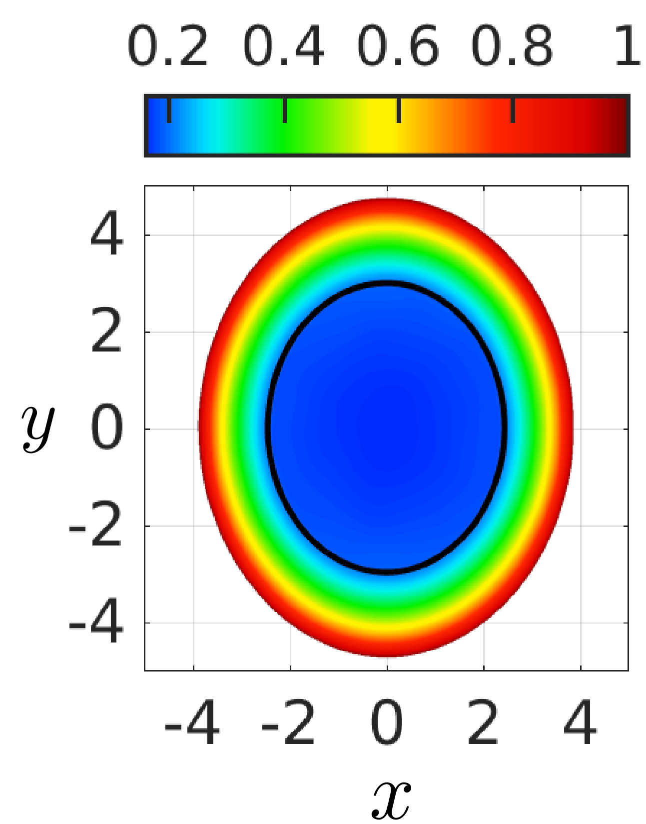
$t = 4$ non-hydro regions excised

holographic collisions

Lesson 4: hydrodynamics works unreasonably well. Onset of hydrodynamics when:

- viscous corrections ≈ 100% of pressure, not much smaller than pressure.
- minimal fluid droplet size: $RT_{\rm eff} \sim 0.5\text{-}1$, not $RT_{\rm eff} \gg 1$.
- decay of non-hydro d.o.f. (not gradients) controls hydro applicability.





P. Chesler, 1601.01583

quasiparticles at strong coupling?

with John Fuini and Christoph Uhlemann

quasiparticles at strong coupling

definition: quasiparticle

long-lived, weakly coupled excitation (narrow resonance)

lifetime ≫ 1/energy, mean free path ≫ de Broglie wavelength

definition: strongly correlated (or strongly coupled) system

ex: high T_c, strange metals, quark-gluon plasma, $\mathcal{N}$=4 SYM at $\lambda=\infty$

no useful quasiparticle description of excitations

typical

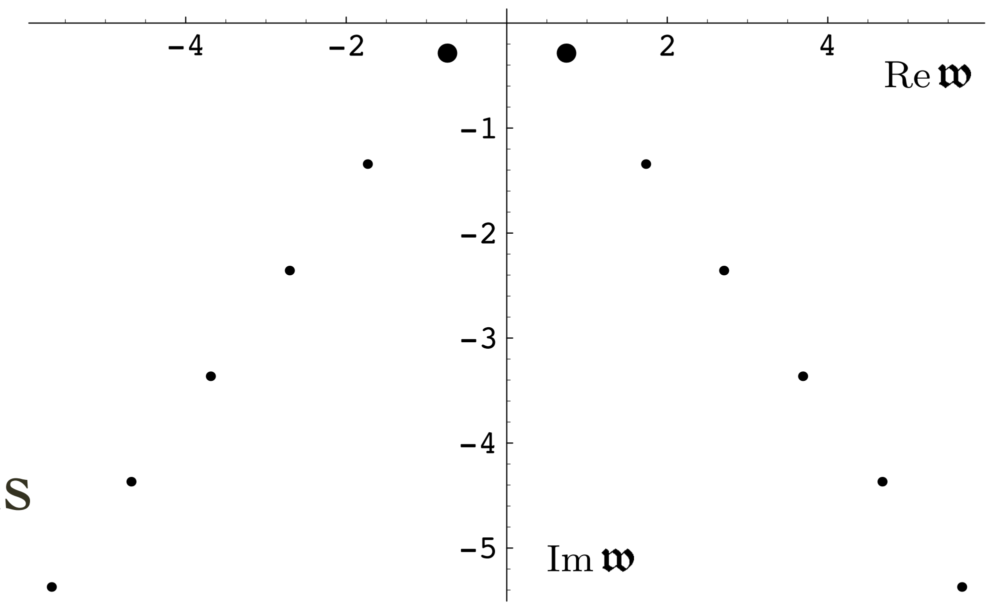
what about rare, atypical excitations?

quasiparticles at strong coupling

thermal $\mathcal{N}$=4 SYM:

temperature T = characteristic scale

quasinormal mode (QNM) frequencies $\{\omega_n(k)\}$ characterize spectrum of excitations



Kovtun & Starinets

provided $k \lesssim O(T)$:

- Im $\omega_n(k) \gtrsim$ Re $\omega_n(k)$ (except for $k \to 0$ sound mode)
- non-hydrodynamic relaxation times = $O(1/\pi T)$
- ∴ no good quasiparticles

what about $k \gg T$?

quasiparticles at strong coupling

QNM asymptotics:

- high level, $n \gg 1$:

Kovtun & Starinets

$$\omega_n(k) \sim 2\pi T\, n\, (\pm 1 - i)$$

- large wavenumber, $k \gg T$:

Fuini, Uhlemann, LY

$$\omega_n(k) = k \left[\pm 1 - i s_n\, e^{\pm i\pi/6} (\pi T/k)^{-4/3} + O(T^2/k^2)\right]$$

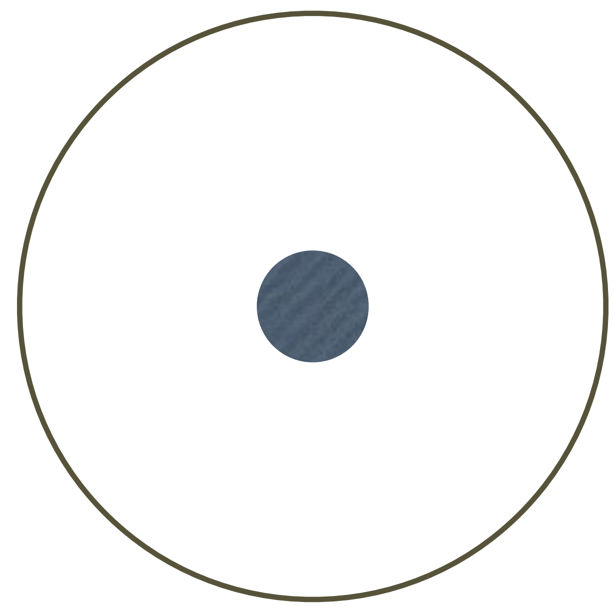
n	$s_n^{\ell=0}$	$s_n^{\ell=1}$	$s_n^{\ell=2}$
1	1.178	2.7009	4.46404
2	4.774	6.9101	9.15514
3	9.387	11.890	14.4814
4	14.69	17.468	20.3279

large k excitations = good quasiparticles, nearly lightlike ($\omega^2 \approx k^2$), weakly damped ($\mathrm{Im}\,\omega \ll \mathrm{Re}\,\omega$)

quasiparticles at strong coupling

- top-down (strong coupling) vs. bottom-up (weak coupling) thermalization?
  - fast relaxation of high level QNMs ≈ fast dephasing of highly virtual fluctuations
  - hard, on-shell modes slowest to thermalize at *both* weak and strong coupling
- narrow planar shocks on thermal background = superposition of high k QNMs
  - analogous to signal propagation in dispersive media
  - $dv_g/dk = d^2\omega/dk^2 > 0$ ➡ fine structure outlives coarse

large N_c confinement dynamics



with Alex Buchel and Paul Chesler

large N_c confinement dynamics

SU(N_c) $\mathcal{N}$=4 SYM on $S^3 \times R$:

- thermodynamic limit = $N_c \to \infty$ limit
- $T < T_c$: confined phase, O(N_c^0) free energy

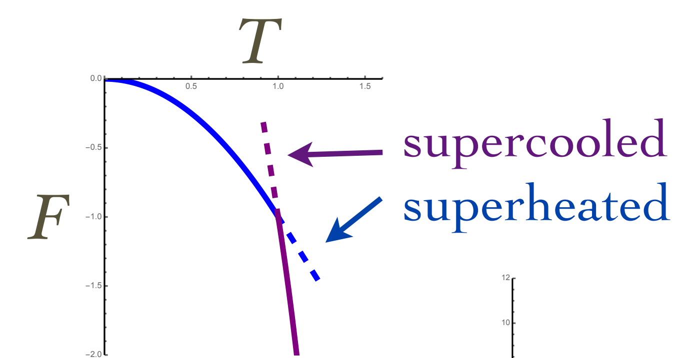
  dual description = "thermal" AdS
- $T > T_c$: deconfined phase, O(N_c^2) free energy

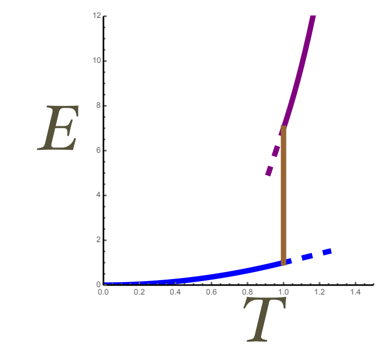
  dual description = global AdS black hole
- $T = T_c$: first order phase transition (at $N_c = \infty$)

large N_c confinement dynamics

typical first order transition:

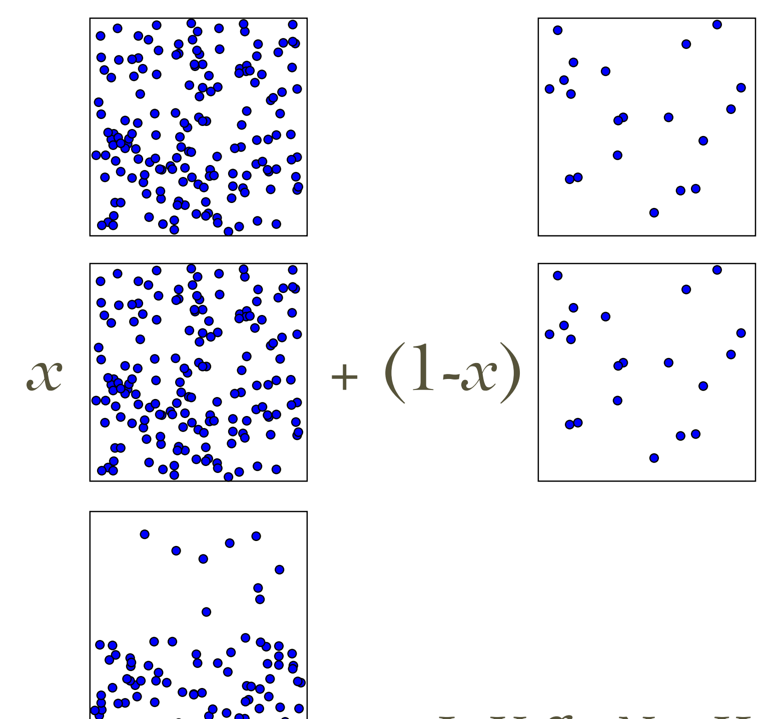
- thermodynamic limit = volume $V \to \infty$
- kink in free energy
- jump in internal energy $E = \dfrac{\partial(\beta F)}{\partial \beta}$
- latent heat L = jump in internal energy
- coexisting equilibrium states at T=T_c:





physically realizable, satisfies cluster decomp.

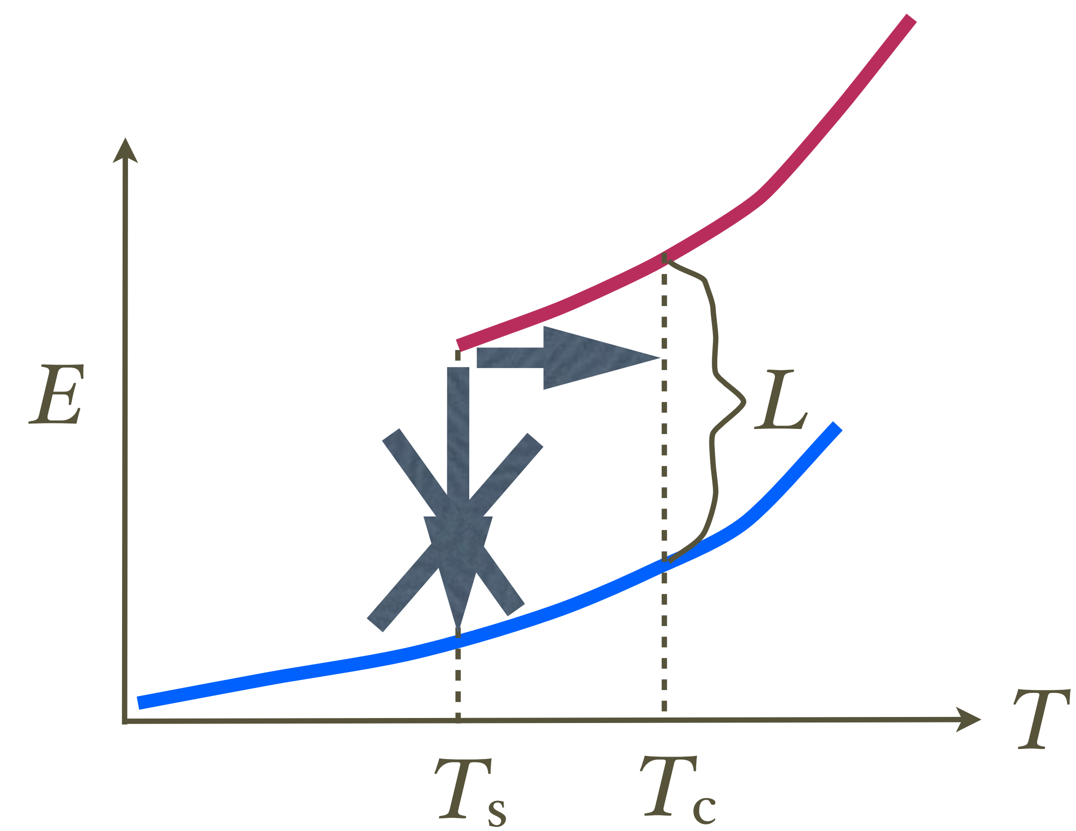
- extremal, homogeneous
- non-extremal, mixed
- extremal, phase separated



large N_c confinement dynamics

typical first order transition:
cooling dynamics

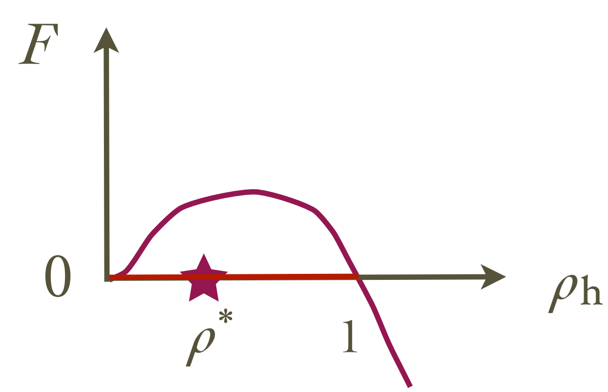
- E, T, S all ↘
- T=T_c: enter metastable supercooled phase
- T=T_s: spinodal decomposition = limit of metastability
- re-equilibrates to *phase separated* state at T=T_c if $E^+(T_s) > E^-(T_c)$

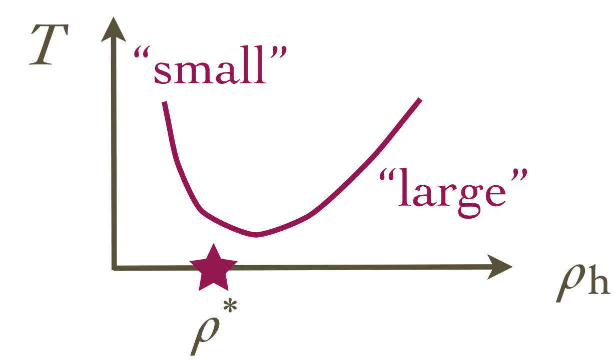


large N_c confinement dynamics

SU(N_c) $\mathcal{N}$=4 SYM on $S^3 \times R$:

- deconfined plasma ➡ dual geometry = AdS_5 x S^5 black hole
- metric: $$ds^2 = -g(\rho)\,dt^2 + \frac{d\rho^2}{g(\rho)} + \rho^2\,d\Omega_3^2 + d\Omega_5^2\,, \qquad g(\rho) \equiv \rho^2 + 1 - (1+\rho_h^2)\,\frac{\rho_h^2}{\rho^2}$$
- free energy $$F = C\,(1-\rho_h^2)\,\rho_h^2 + (\text{Casimir})$$
- temperature $$T = \frac{2\rho_h^2+1}{2\pi\rho_h}$$





- "large" BH branch ($\rho_h > 1$): deconfined equilibrium states
- "small" BH branch ($\rho_h < 1$): thermodynamically unstable
  - $\rho_h < \rho^* = 0.44$: dynamically unstable wrt. deformation of S^5

large N_c confinement dynamics

- $\rho^* < \rho_h < 1$: supercooled plasma, stable at $N_c = \infty$
- $\rho_h = \rho^*$: spinodal decomposition threshold
- $\rho_h < \rho^*$: dynamical instability leads to ???

does system re-equilibrate to new stationary solution with broken $SO(6)_R$ symmetry?

  - known "lumpy" $S^3 \times S^5$ horizon topology BH solutions have lower entropy
  - recent S^8 horizon topology BH solutions, localized on S^5, have higher entropy but $T > T_c$ O. Diaz, J. Santos, B. Way

common expectation: BH should undergo Gregory-Laflamme-like instability, develop thin "necks" which break at string scale, settle down to localized S^8 BH

large N_c confinement dynamics

But: microcanonical description should be consistent with canonical description in thermodynamic ($N_c \to \infty$) limit

- what is complete manifold of coexisting equilibrium states at T_c?
  - do extremal phase separated states exist? no sign, no evidence
- is $T > T_c$ understanding wrong?
  - does broken R-symmetry phase exist? no sign, no evidence
- do dynamically unstable supercooled states fail to re-equilibrate (on $O(N_c^0)$ time-scale)? Occam's razor preferred scenario
  - consistent with basic large N_c lore and existence of islands of stability in perturbations of global AdS spacetime

large N_c confinement dynamics

in progress: study time dependent solutions numerically

- 10D GR + self dual 5-form, SO(4) × SO(5) invariant

  10D GR → 3D PDEs

- multiple towers of scalar condensates

  complex boundary asymptotics, initial value constraints

  more challenging than expected/hoped

- stay tuned...

conclusions

- numerical holography allows exploration of interesting far-from-equilibrium dynamics.

  numerics "easier" than might have been expected

  AdS asymptotics & dissipative dynamics helps

- phenomenologically relevant insight for heavy ion collisions can be (and has been) obtained.

- many open questions, even on basic thermodynamics!