Plasma-balls in large N confining gauge theories and black holes

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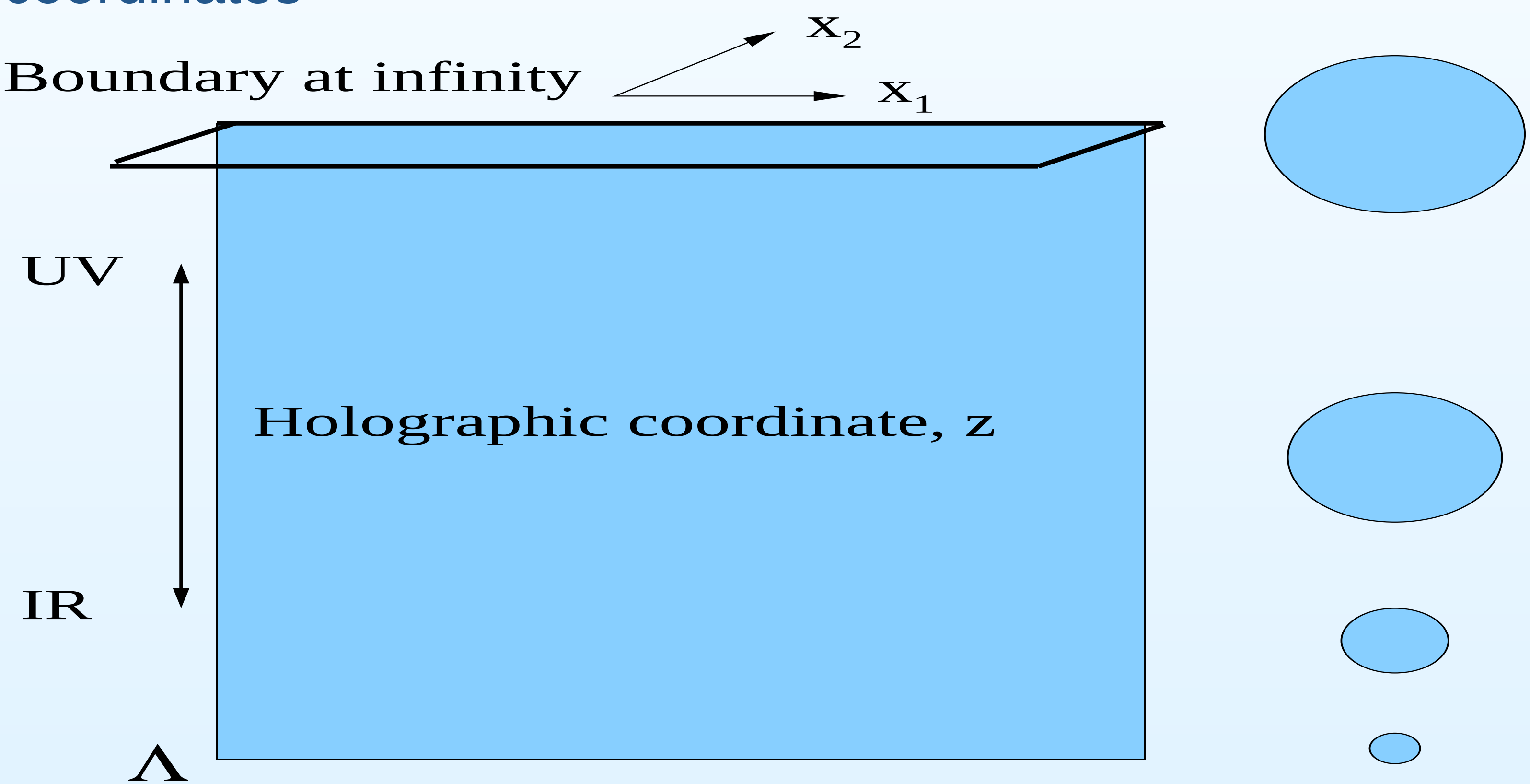
Introduction

- Aim to show new metastable objects (plasma-balls) exist for $E >> N^2\Lambda_{gap}$ in certain large N_c confining gauge theories.
- These are balls of hot deconfined phase sitting in the zero temperature confining vacuum.
- Where a gravity description exists at large t'Hooft coupling λ these are dual to novel black hole solutions.
- Plan

  Brief review of gravity duals to confining theories
  Large black holes in these gravity duals
  Some conjectures on general existance of plasma-balls
  Thermalization of plasma-balls
  Classical stability of plasma-balls
  Applicability to QCD and RHIC

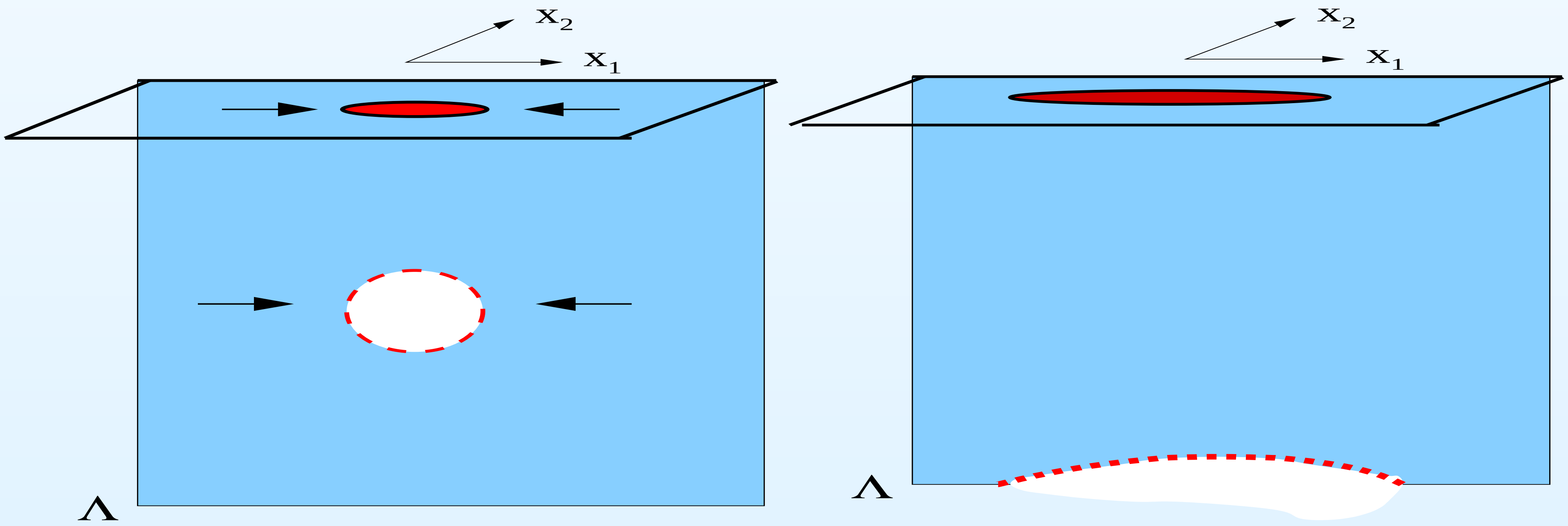
Gravity duals to confi ning theories

- There exist several duals to confining large N gauge theories. Here we study Witten's model.
- All have in common that holographic radial direction ends in IR, with a compact subspace vanishing - origin of polar coordinates



High energy scattering

- Giddings stressed how black holes dominate at very high energies, $E >> N^2\Lambda_{gap}$
  [See also Nastase]
- Black holes width $R \sim \log E$, saturate gauge theory unitarity bound
- What happens after collision? Plasma-balls!



Witten's model

- We take $AdS_5 - CFT_4$ on flat space
- Compactify one space direction with antiperiodic bc's for fermions; $R^{1,2} \times S^1$
- Light degrees of freedom are pure YM in 1+2 - fermions are massive due to boundary conditions, scalars massive due to radiative effects.
- Dual geometry takes form $ds^2_{(10)} = ds^2_{(5)} \times d(S^5)^2$
- Hence $ds^2_{(5)}$ is Einstein
- Vacuum is AdS-Soliton [Horowitz-Myers]
- All excitations about the vacuum are massive

Witten's model...

- Explicitly, the metric is;

$$ds^2_{(5)} = e^{2\rho}\left[-dt^2 + f_{2\pi}(\rho)d\theta^2 + d\vec{x}^2\right] + \frac{1}{f_{2\pi}(\rho)}d\rho^2$$

where $f_\beta(\rho) = 1 - \left(\frac{\beta}{\pi}e^\rho\right)^{-4}$

- The circle θ has coordinate period 2π
- The function f ensures the geometry closes smoothly in the IR at $\rho = \rho_0$ where;

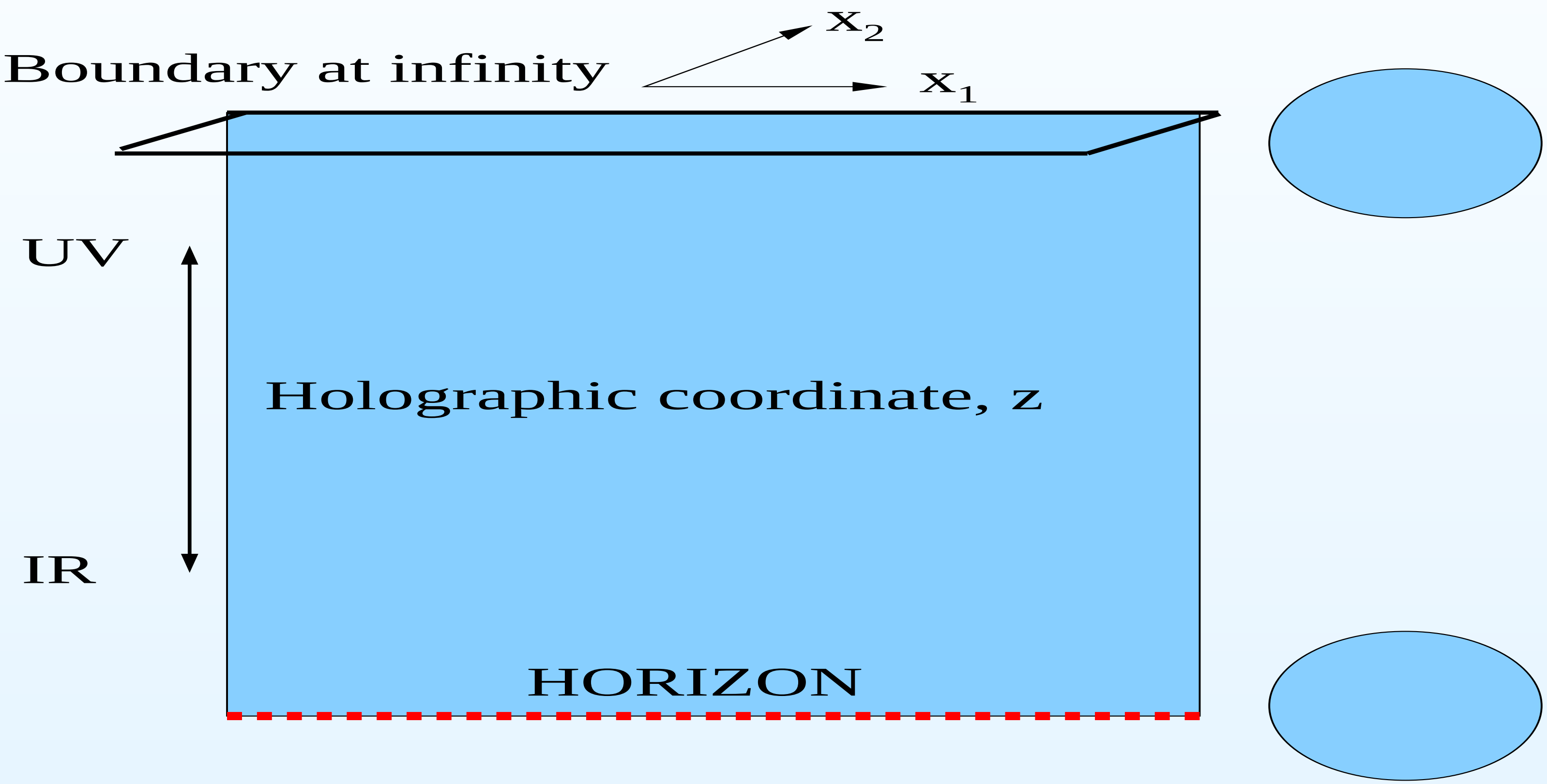
$$f_{2\pi}(\rho_0) = 0 \text{ and } f'_{2\pi}(\rho_0) = 1$$

Confinement/Deconfinement

- Working at finite temperature move to Euclidean signature, $0 \leq \tau \leq \beta$
- Find first order 'Hawking-Page' phase transition in bulk free energy as 2 saddle points;
- Confined $\beta > 2\pi$; AdS-Soliton
$$ds^2_{(5)} = e^{2\rho}\left[d\tau^2 + f_{2\pi}(\rho)d\theta^2 + d\vec{x}^2\right] + \frac{1}{f_{2\pi}(\rho)}d\rho^2$$
- Deconfined $\beta < 2\pi$; Homogenous black brane
$$ds^2_{(5)} = e^{2\rho}\left[f_\beta(\rho)d\tau^2 + d\theta^2 + d\vec{x}^2\right] + \frac{1}{f_\beta(\rho)}d\rho^2$$
- Clearly due to symmetry phase transition temperature is $\beta = 2\pi$
- For both have well defined boundary stress tensor

Confinement/Deconfinement

- Horizon ‘cuts off’ bulk ‘before’ the space circle shrinks.

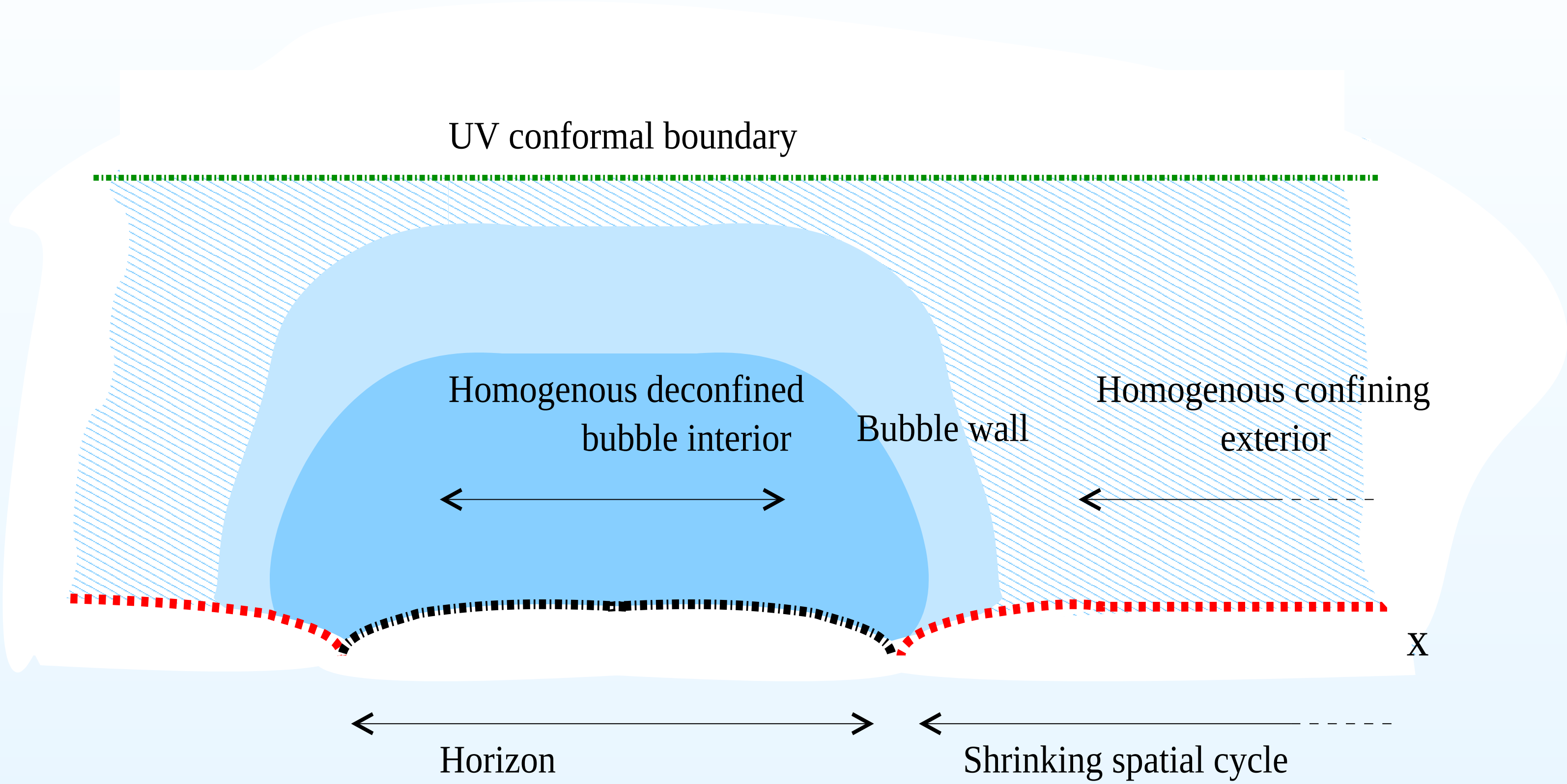


First order transition

- Note that the Euclidean topology of the manifold changes. Hence the gravity transition is first order.
- Recall for a first order transition, at transition temperature T_c have phase separation.
- At $T = T_c$ the pressures of the low and high temperature homogenous phases are equal.
- Here (defining stress tensor to vanish in confining vacuum) find this too, with pressure going as;

$$P \propto (1 - \left(\frac{\beta}{2\pi}\right)^4)$$

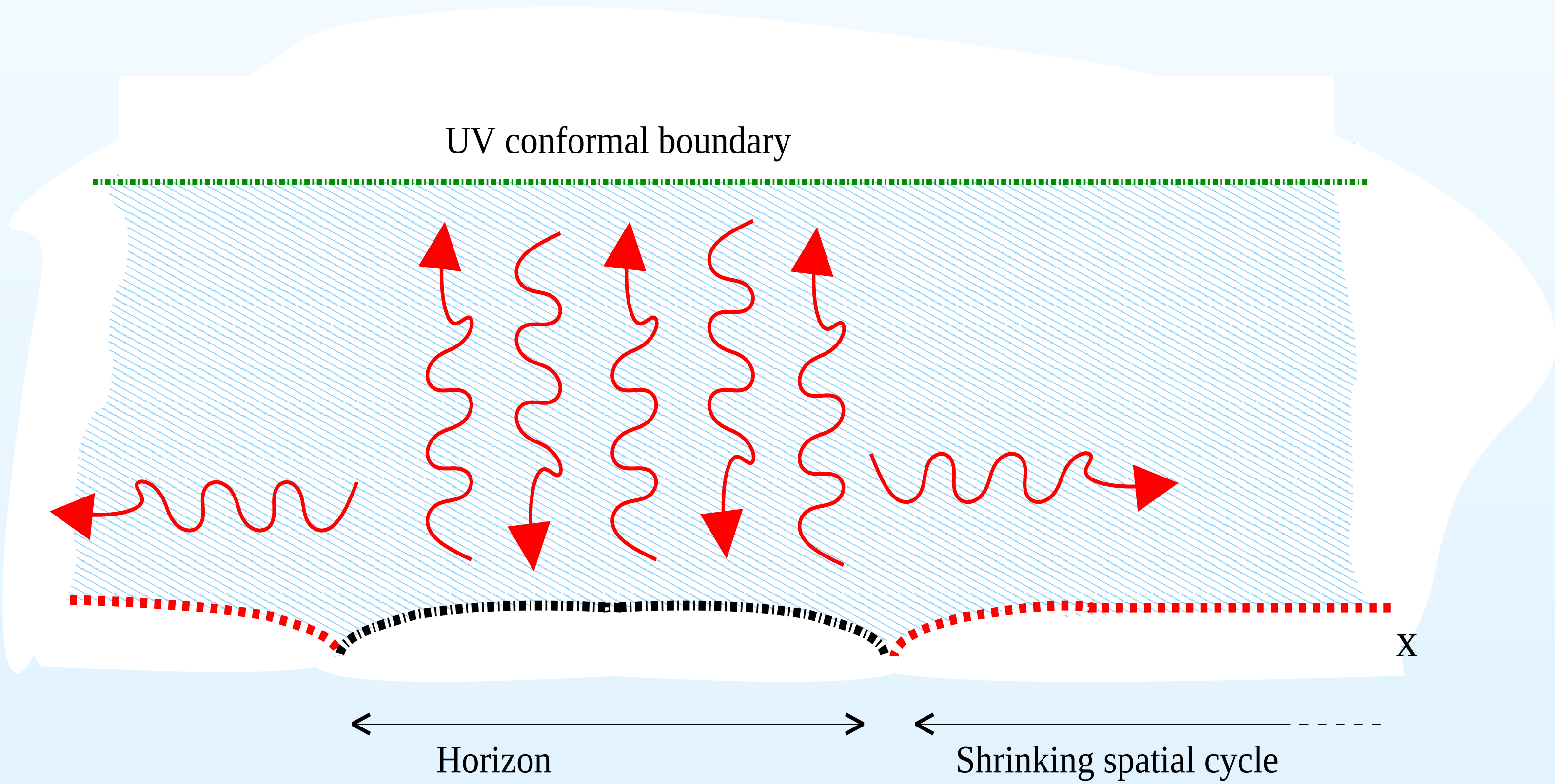
Localized black holes and plasma-balls



- For large radius ($R >> \Lambda_{gap}^{-1}$) these are homogenous and represent a bubble of deconfined phase in the confining phase - a plasma-ball

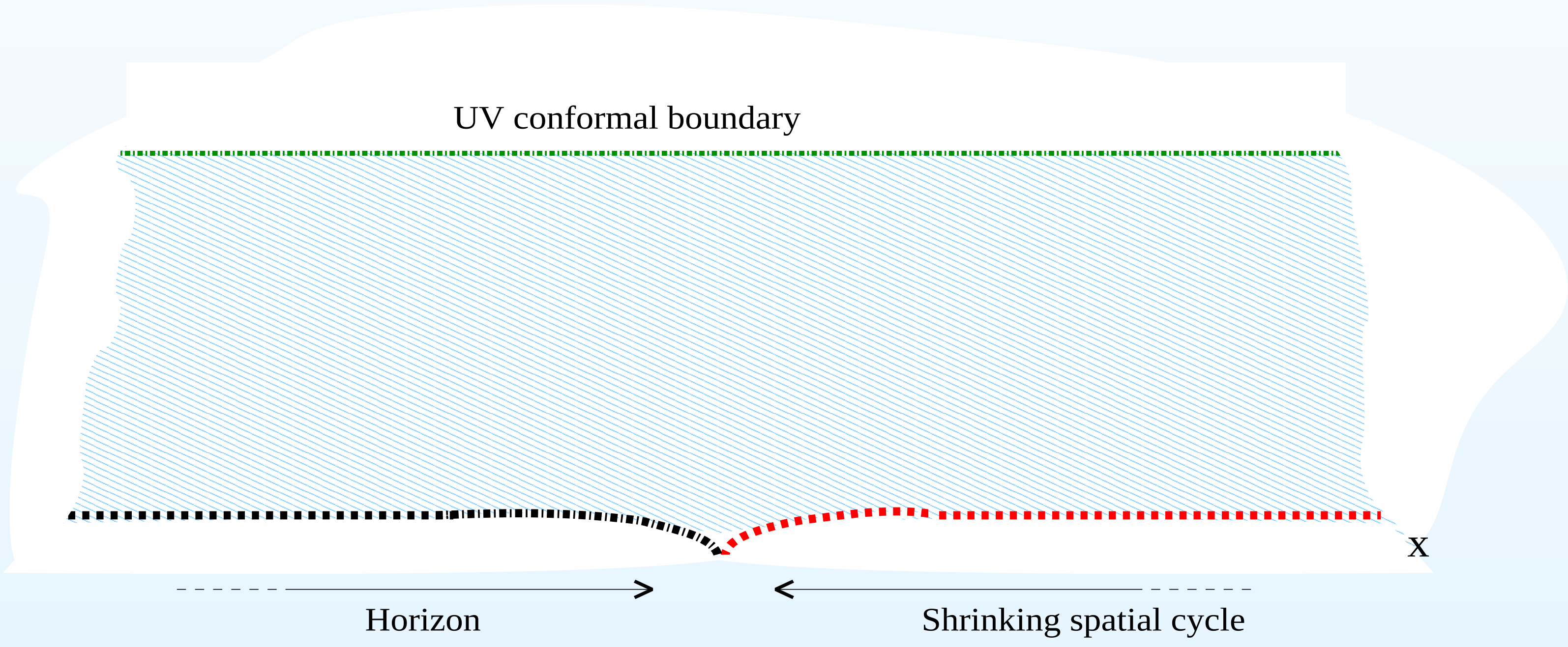
Localized black holes and plasma-balls...

- In the Lorentzian theory these continue to a static black hole in vacuum dual to a static metastable plasma-ball in vacuum
- Quantum instability through Hawking radiation
  Radiation escapes only from surface of plasma-ball



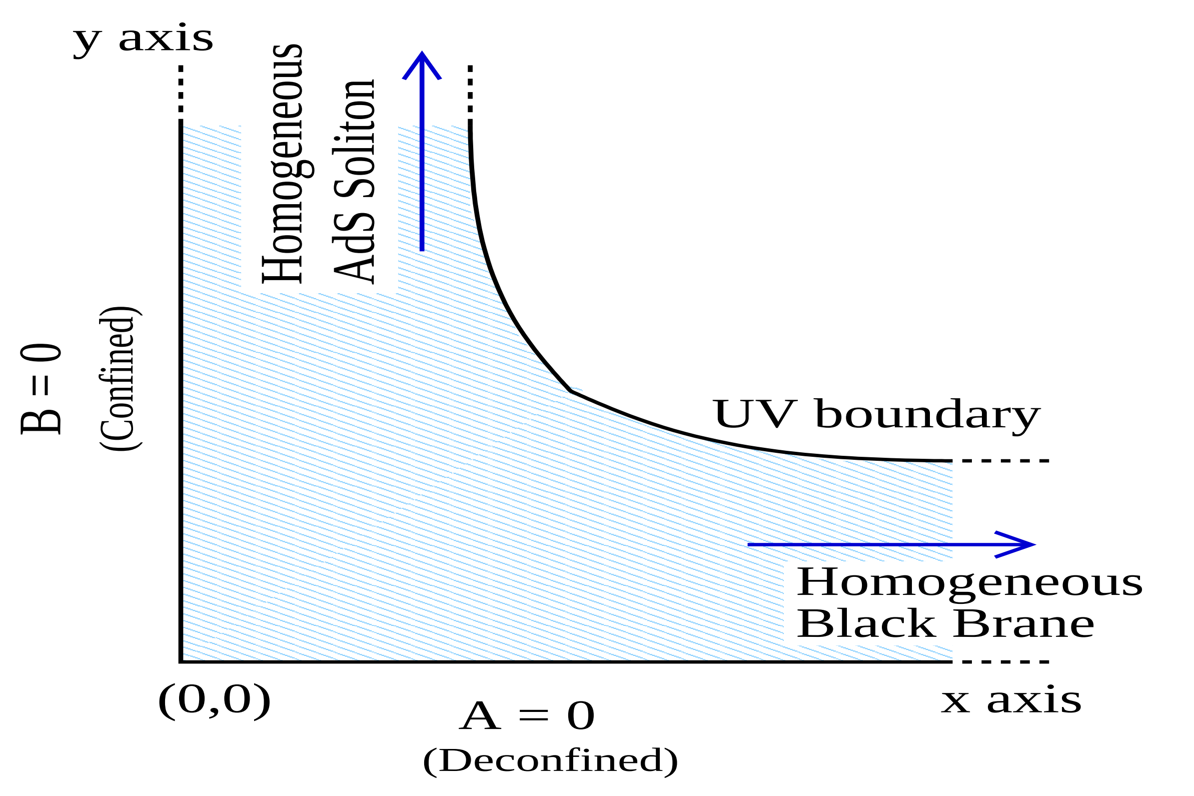
Localized black holes and plasma-balls...

- Since the spectrum is gapped, for large radii the black hole tends to domain wall separating the confined and deconfined phases.



Geometric construction of domain wall

- Metric depends on 2 coordinates; (x,y)
  combination of radial and normal to wall
  $$ds^2 = A^2 d\tau^2 + B^2 d\theta^2 + e^{2C} d\vec{r}^2 + e^{2D}(dx^2 + dy^2)$$
- Residual conformal invariance fixed by boundaries



Geometric construction of domain wall...

- At origin of (x,y) 2 circles shrink simultaneously
- The geometry is smooth if;

$$e^{2D}\left[\left(dx^2 + e^{2(A-D)}d\tau^2\right) + \left(dy^2 + e^{2(B-D)}d\theta^2\right)\right] + e^{2C}d\vec{r}^2$$

$$\simeq$$

$$\text{cnst}\left[\left(dx^2 + (\tfrac{2\pi}{\beta})^2 x^2 d\tau^2\right) + \left(dy^2 + y^2 d\theta^2\right)\right] + \text{cnst}\ d\vec{r}^2$$

so locally just $R^5 = R^2 \times R^2 \times R$

- So (x,y)=(0,0) is simply origin for double polar coordinates
- Metric functions are finite provided right angle boundary

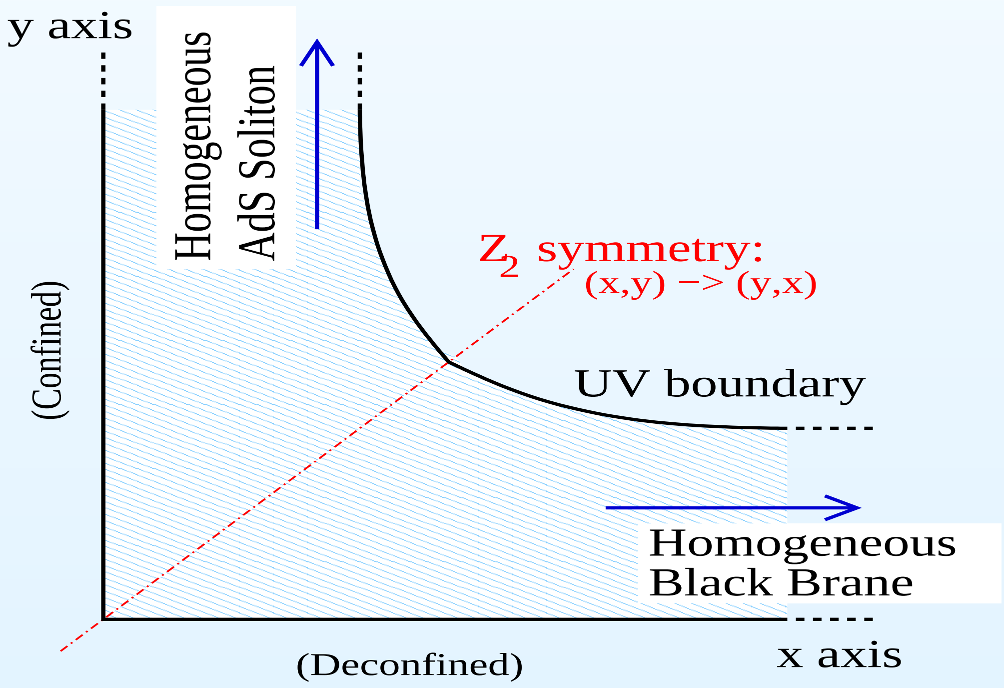
Equations

- Use 'elliptic' equations for A, B, C, D
  $$\nabla^2 A = src_A(A, B, C, D), \text{ with } \nabla^2 = \partial_x^2 + \partial_y^2$$
- Remaining 2 equations arise from gauge fixing - 'constraints'
  $$\alpha = \sqrt{g} G^x{}_y, \; \beta = \frac{1}{2}\sqrt{g}\left(G^x{}_x - G^y{}_y\right)$$
- Bianchi identity implies Cauchy-Reimann relations; $\partial_x \alpha = \partial_y \beta$ and $\partial_y \alpha = -\partial_x \beta$
- Solve elliptic equations subject to boundary conditions that ensure C-R relations are satisfied

Symmetry

- The equations and boundary conditions are then symmetric under Z_2;

$$A(x,y) = B(y,x)$$
$$C(x,y) = C(y,x)$$
$$D(x,y) = D(y,x)$$



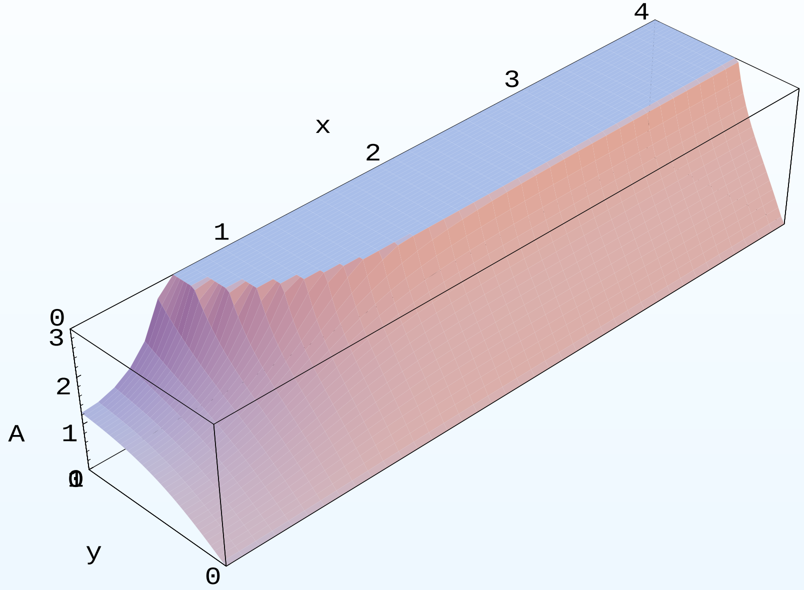
Domain wall black hole/plasmaball temperature

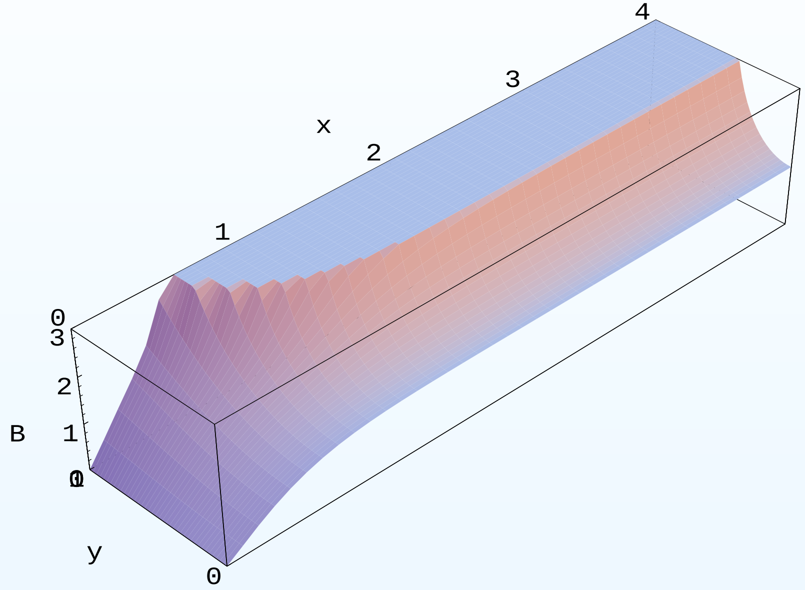
- Find unique symmetric solution so $\beta = 2\pi$, and horizon temperature is determined.
- Note it is exactly at the phase transition temperature,
- We can understand this independently of the symmetry.
- The Bianchi identities ensure the boundary stress tensor is conserved.
- Let σ be the field theory coordinate normal to the wall
- Since the boundary metric is flat, conservation implies $\partial_\sigma T_{\sigma\sigma} = 0$
- Thus the normal pressures ($T_{\sigma\sigma}$) are equal on the two sides of the wall.
- Since transition is first order, this exactly implies $T = T_c$.

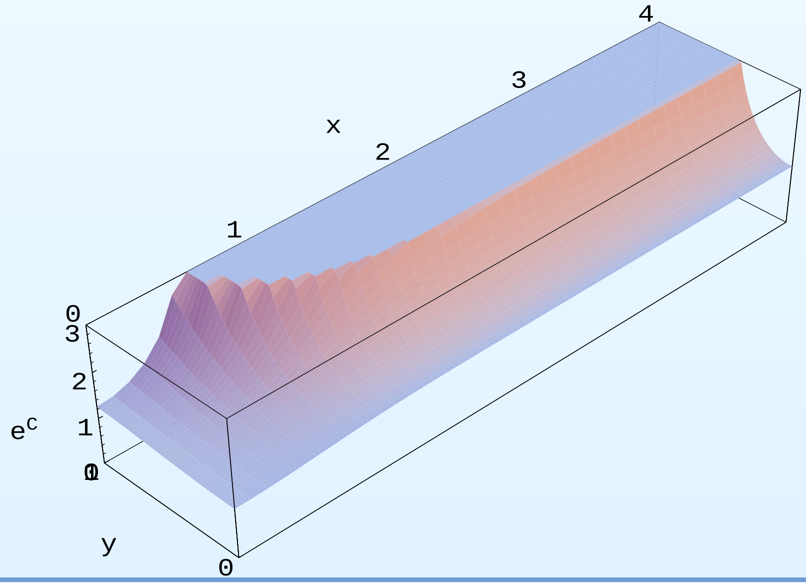
General backgrounds and finite radius

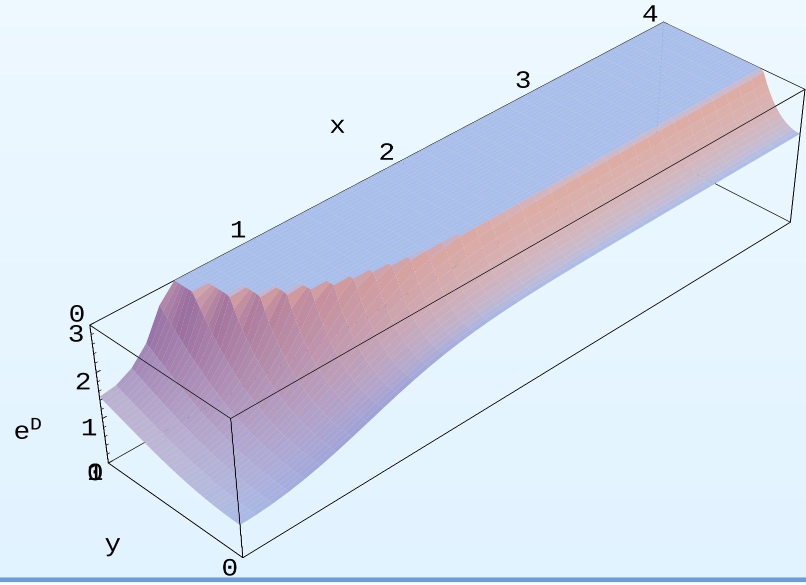
- Expect the same domain walls for any confining gravity background, with a well defined boundary stress tensor, and smooth geometry for both confined and deconfined phases.
- Domain wall horizon at deconfinement temperature T_c.
- For finite radius R expect solutions too.
- Again temperature will be fixed analagously from stress energy conservation. Expect $T = T(R)$, with higher temperature at finite radius, decreasing to T_c as increase R.
- Important point is we may continue these solutions to Lorentzian space; No boundary conditions depended on signature; Hence these black holes exist metastably in vacuum.

Results

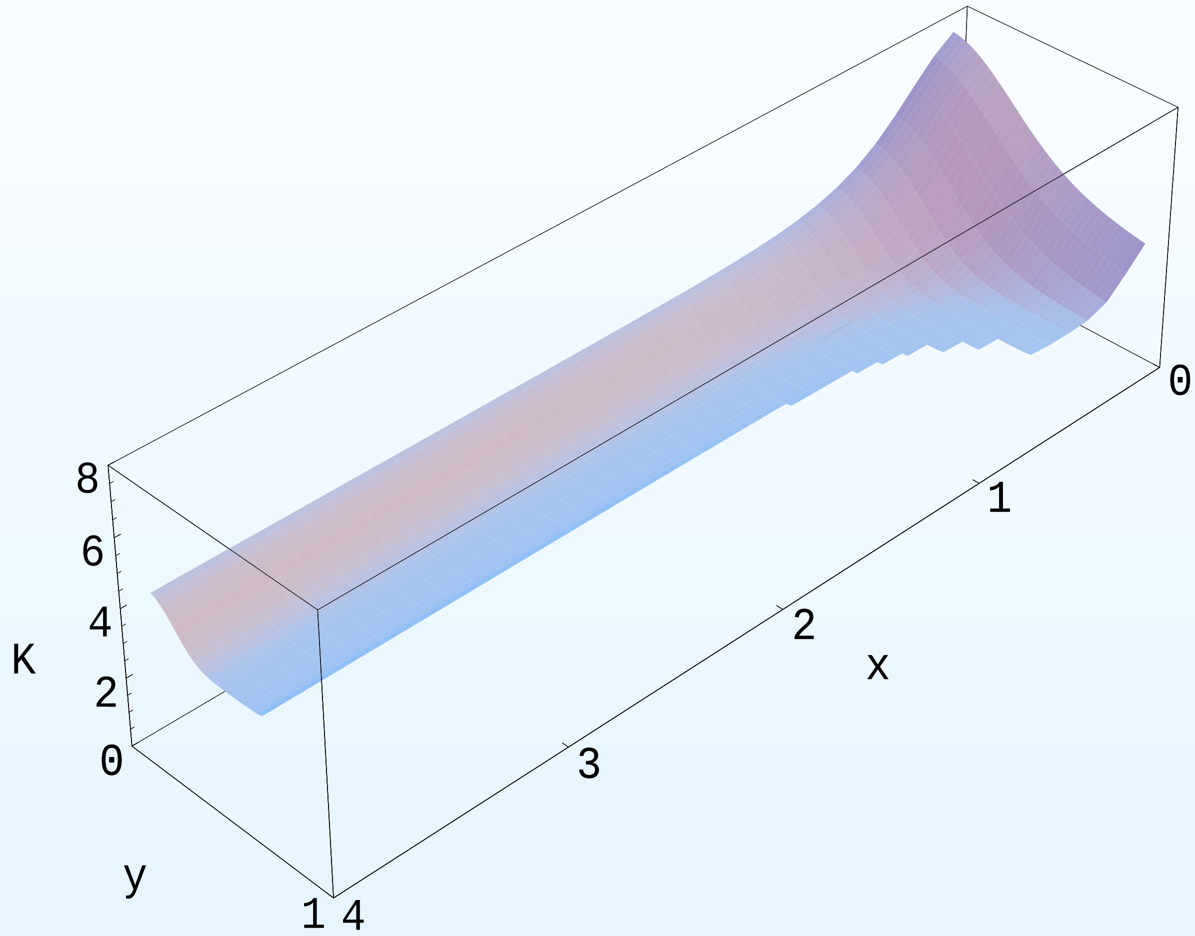








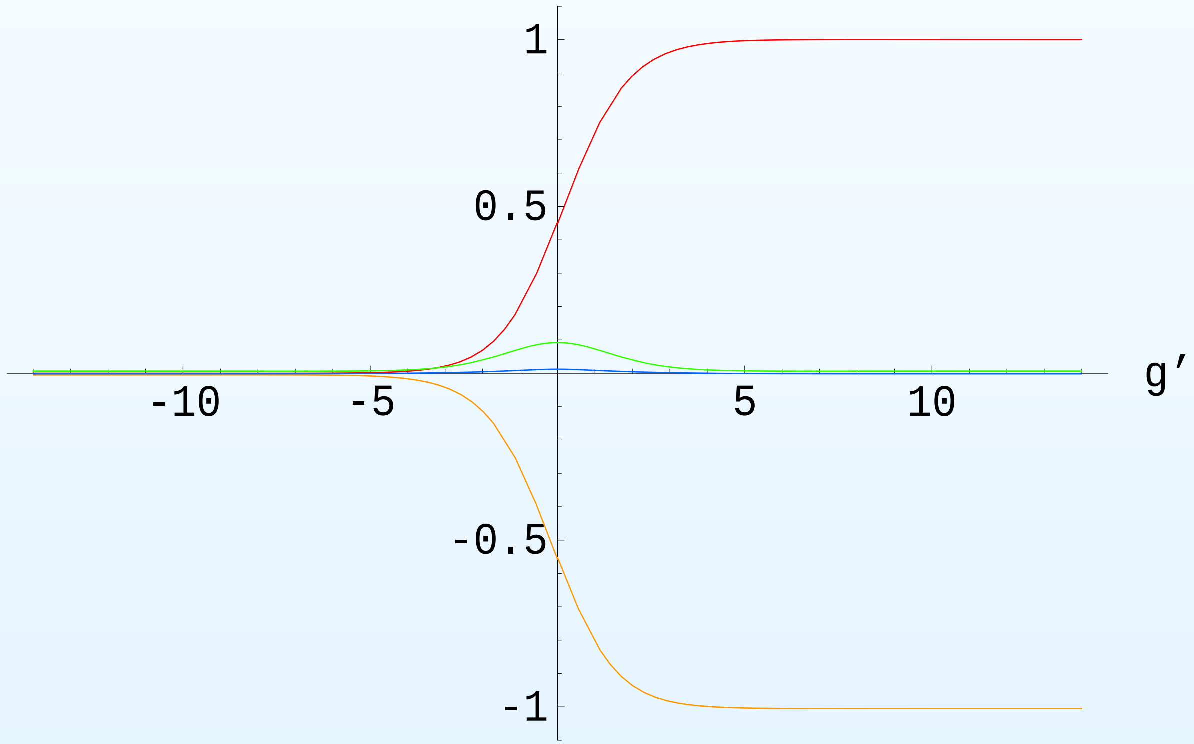
Results



Tension

- Domain wall tension is determined from integrating the boundary stress tensor;

$$T = \int d\sigma T_{rr}$$

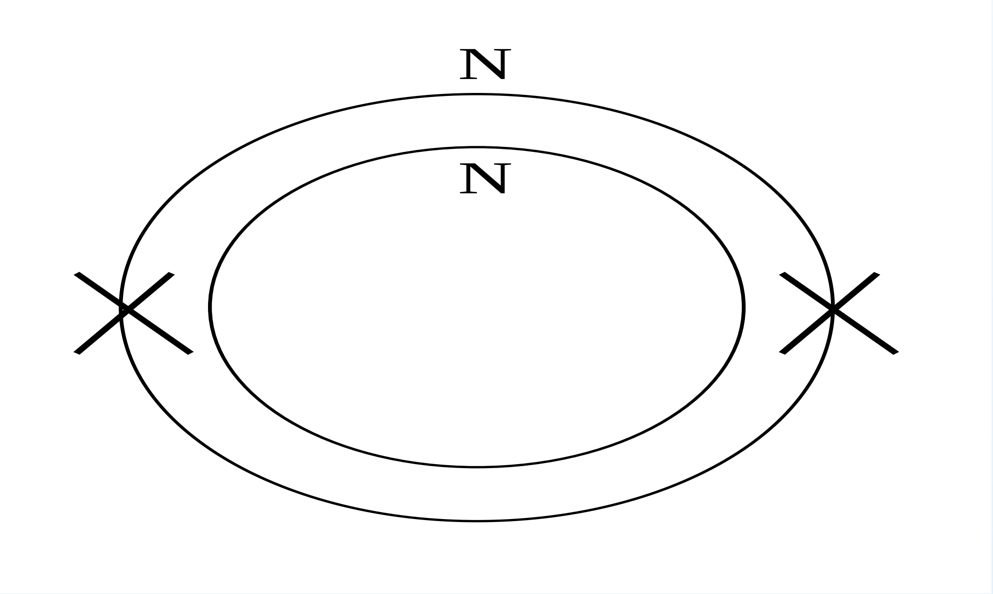


Various conjectures...

- **Conjecture I:** these black holes occur at large λ in theories with gravity dual that is smooth for both phases
- These are bizarre black holes; At large radii they become domain walls with non-zero temperature.
- Correspond to metastable plasma-balls of hot deconfined glue in vacuum
- **Conjecture II:** at any t'Hooft coupling in a large N theory such plasma-balls exist provided it is;
  1) a confining theory
  2) the confinement/deconfinement transition is 1st order
  3) the plasma-balls have positive surface tension
     eg. large N QCD

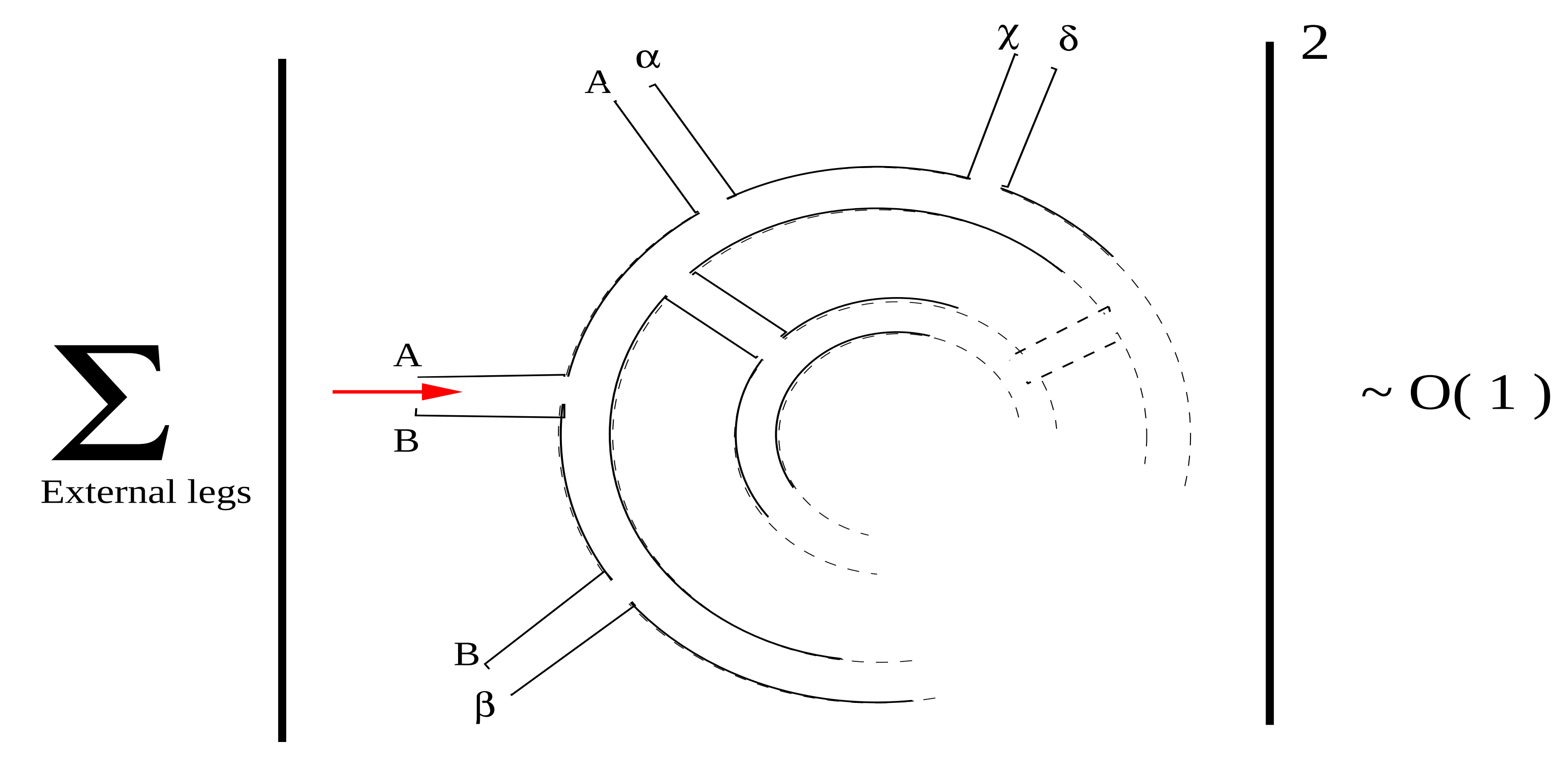
Metastable plasma-balls at all λ

- Thermalisation (via glueball production) will be subleading at large N compared to dynamical timescales.
- Intuitive reason; large number of fields N^2 per volume in deconfined phase BUT must interact to form a color singlet glueball, with chance $1/N^2$
- Approximate glueball operator $\frac{1}{N}\mathrm{Tr}F^2$ so $|g> \simeq \frac{1}{N}\mathrm{Tr}F^2|0>$
  Note $1/N$ normalization so $< g|g >= 1$ from graph



Dynamical time-scale

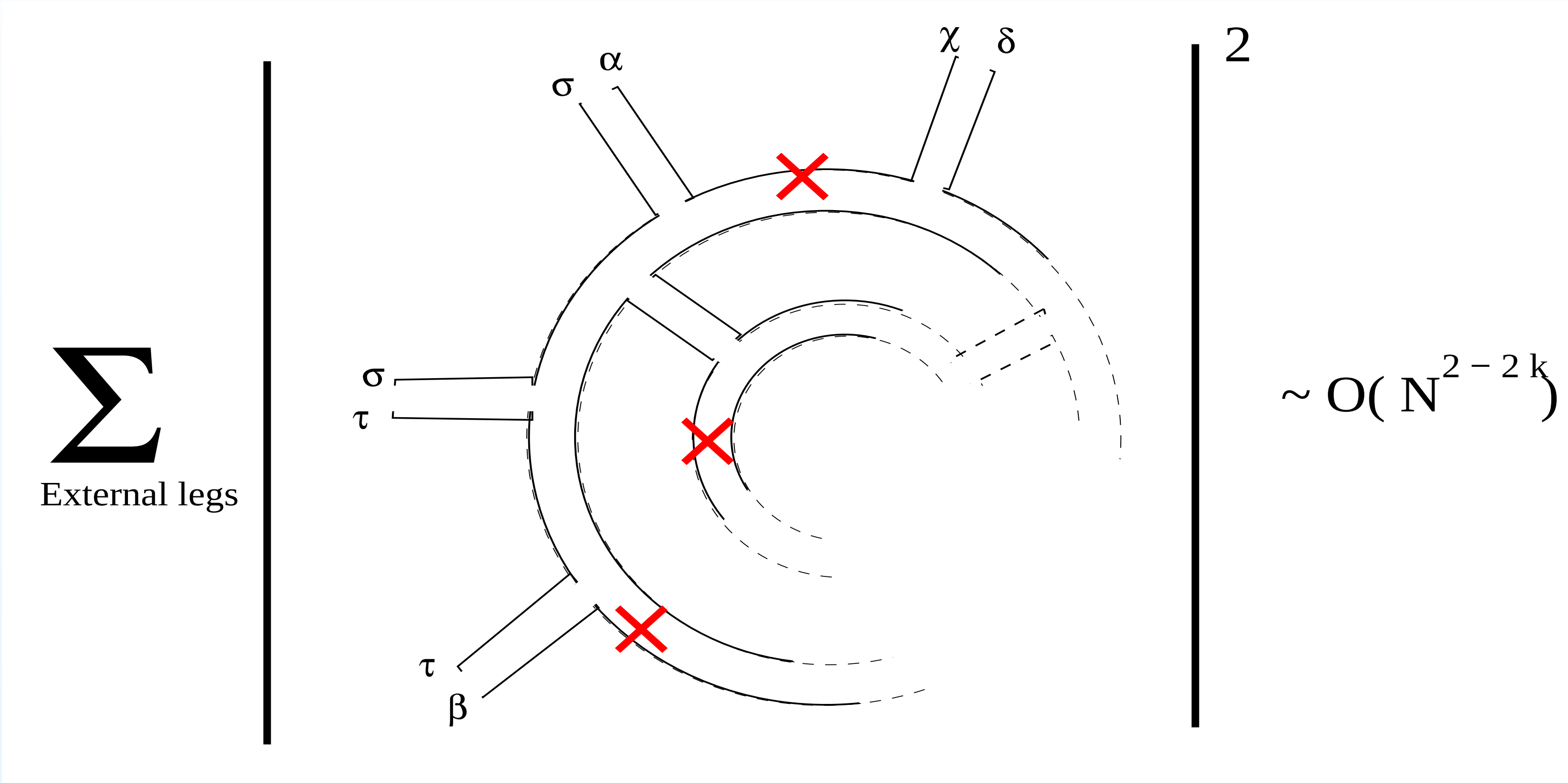
- Dynamical timescale for plasma-ball from graphs for inclusive scattering cross section



- Relaxation time order $O(1)$

Thermalisation time-scale

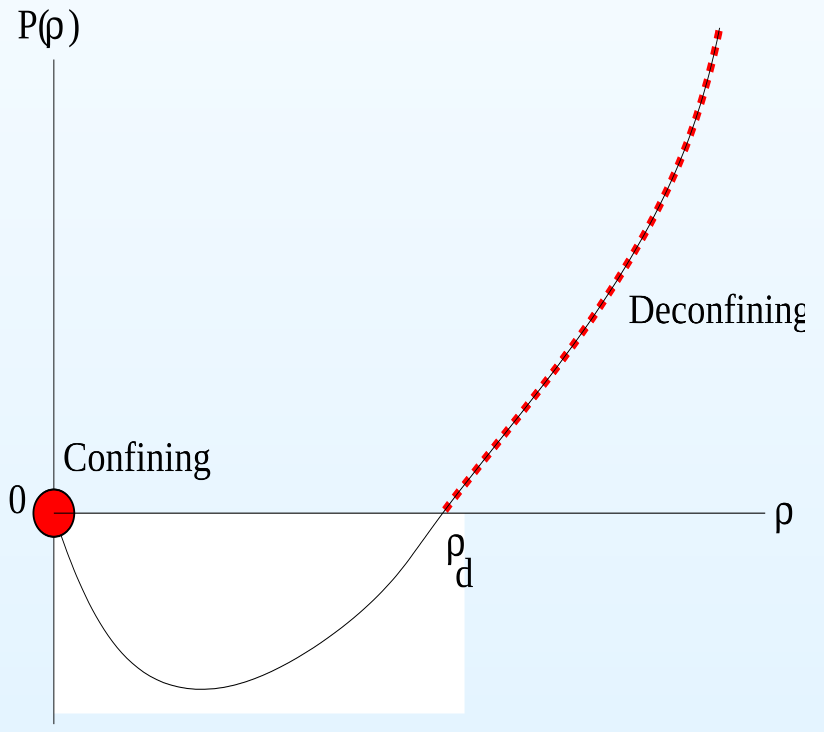
- Consider k-glueball production per volume



- Evaporation time $O(N^2)$
- Glueballs can only escape from volume near the edge, or else simply reabsorbed

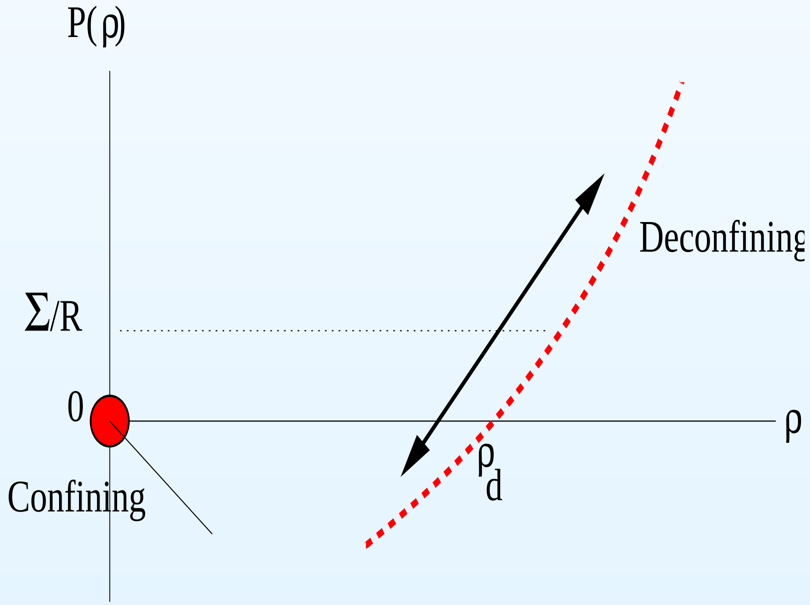
Large N Confinement/Deconfinement

- In confined phase, potentials scale independent of N
- In deconfined phase, potentials scale as N^2, ie. $O(N^2)$.
- Divide potentials by N^2 to get finite quantities,

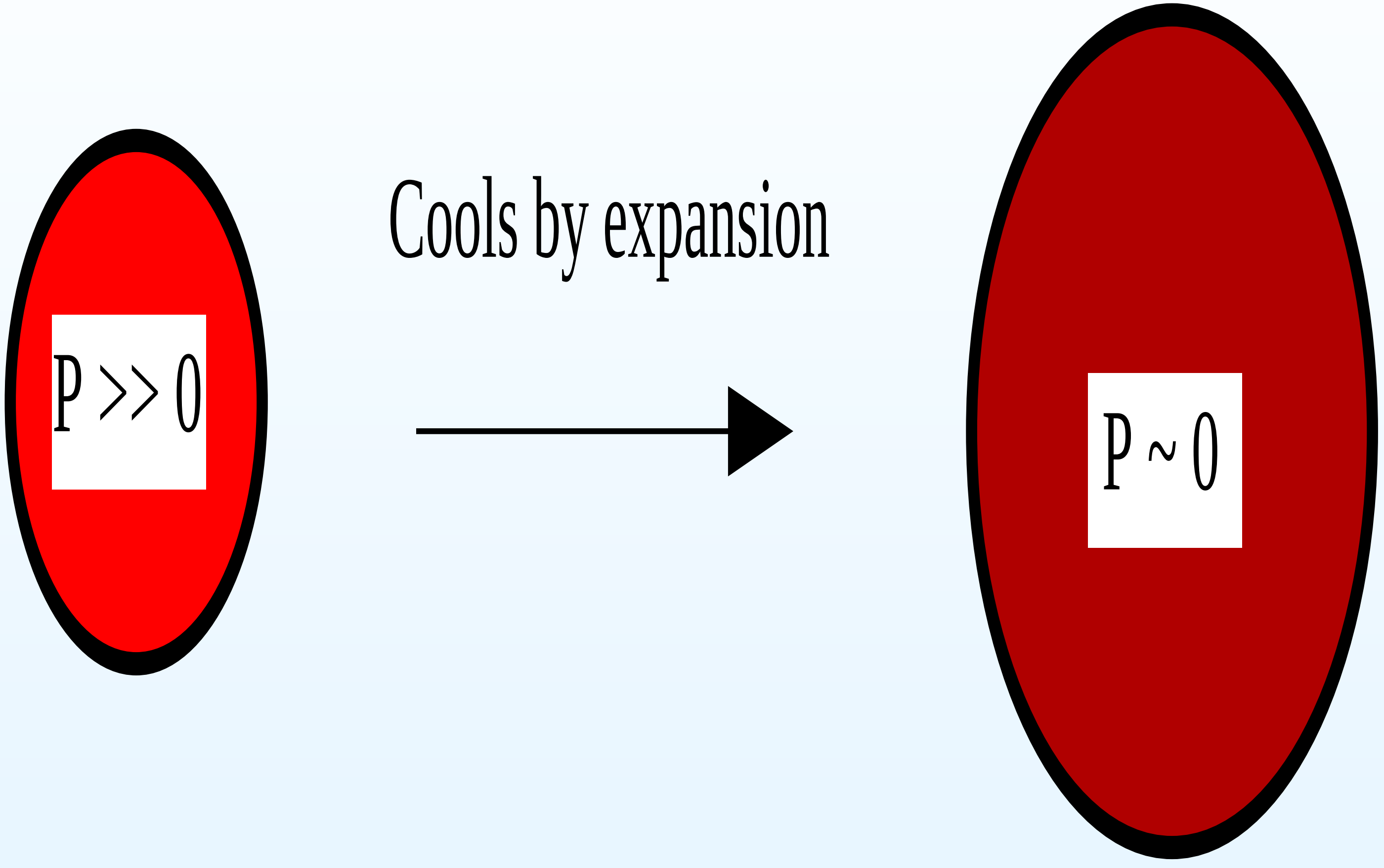


Static plasma-balls at all λ

- So first order transition: $P(\rho_d) \sim 0$
- For ball radius R, with surface tension Σ, force balance requires $P(\rho) \simeq \Sigma/R$
- Plasma-ball in vacuum expands (or contracts) to equilibrium size with $\rho > \rho_d$. As $R \to \infty$, $\rho \to \rho_d$

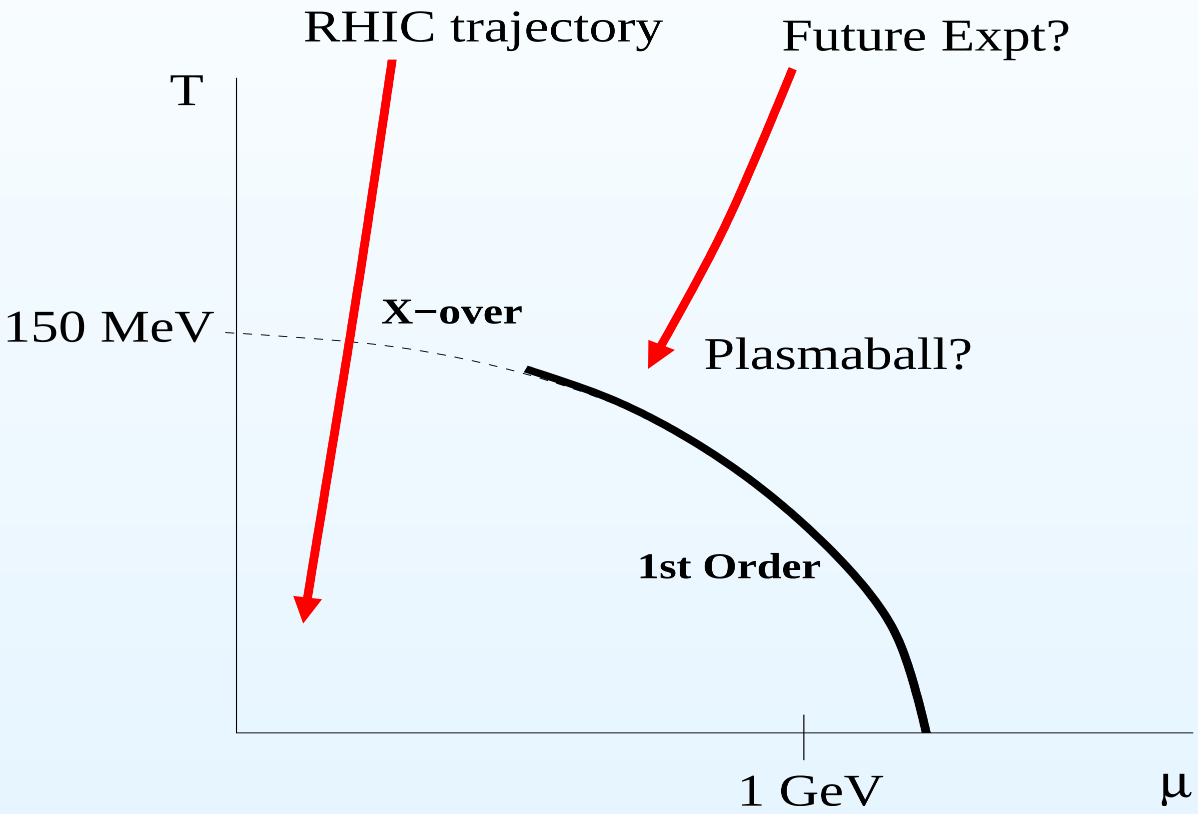


Dynamics



QCD and RHIC

- At low baryon density QCD is though to have a cross-over confinement/deconfinement transition



- For QCD $N^2 = 9$; but recall also $N_f = 3$...

Conclusion

- New black hole solutions exist in Witten's confining backgrounds dual to plasma-balls in the confining large N gauge theory
- We conjecture these black holes exist in any confining dual gravity background
- We conjecture that metastable plasma-balls exist more generally at large N provided the confinement/deconfinement transition is first order

- Is there any hope of seeing plasma-balls experimentally?
- Can we study dynamics?