Holography of novel QCD phases at high density and neutron stars

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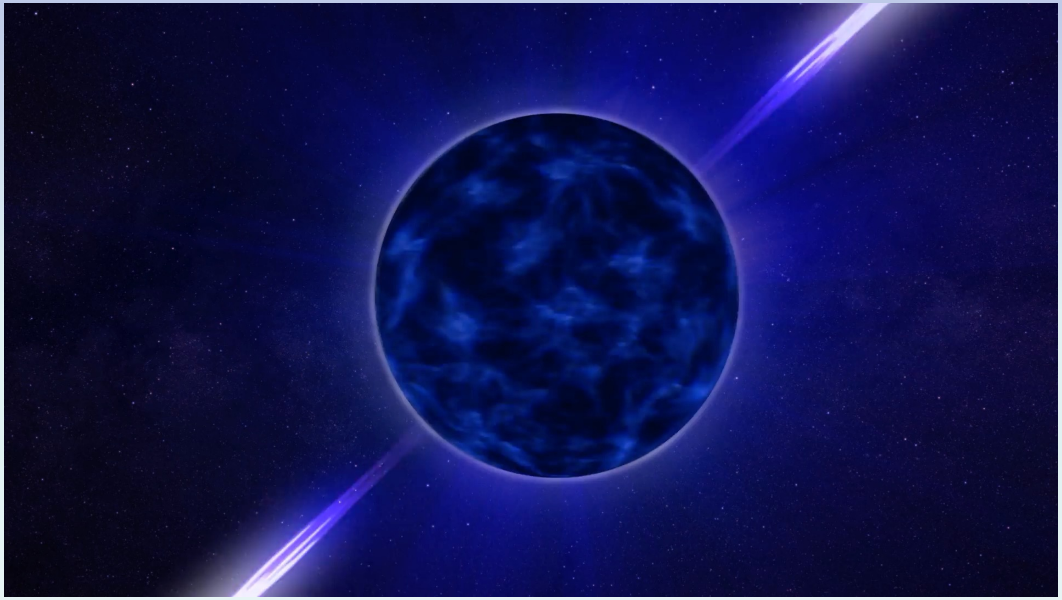


NASA's Goddard Space Flight Center Conceptual Image Lab

C. Hoyos, D. Rodríguez Fernández, N. Jokela and A. Vuorinen, Phys. Rev. Lett. **117**, no. 3, 032501 (2016) doi:10.1103/PhysRevLett.117.032501 [arXiv:1603.02943 [hep-ph]].

Say no quark matter in neutron stars

Can a running coupling or new phases change that from a D3/probe D7 perspective?

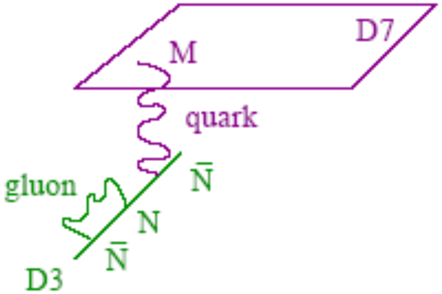
New AdS/QCD models for new descriptions.

Jesus Cruz-Rojas

Kazem Bitaghsir Fadafan

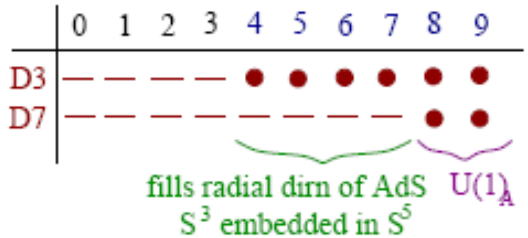
Jack Mitchell

Holography of Quark Matter - D3/probe D7



Quarks can be introduced via D7 branes in AdS

The brane set up is



Always in the probe limit – quenched.

Martín Kruczenski,[ab] David Mateos,[a] Robert C. Myers[ac] and David J. Winters[ac]

Fluctuations give meson spectrum. hep-th/0304032

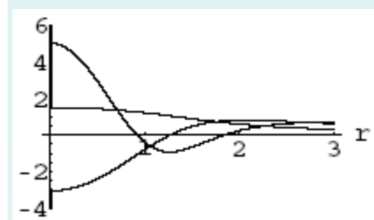
$$S_{D7} = -T \int d^4x d\rho \, \rho^3 e^{\phi} \sqrt{1 + (\partial_\rho L)^2}$$

$$\partial_\rho^2 \delta + \frac{3}{\rho} \partial_\rho \delta + \frac{M^2}{(\rho^2+1)^2} \delta = 0$$

$$\delta(\rho) e^{ik.x}$$

and the mass spectrum is

$$M = \frac{2d}{R^2} \sqrt{(n+1)(n+2)} \sim \frac{2m}{\sqrt{\lambda_{YM}}}$$

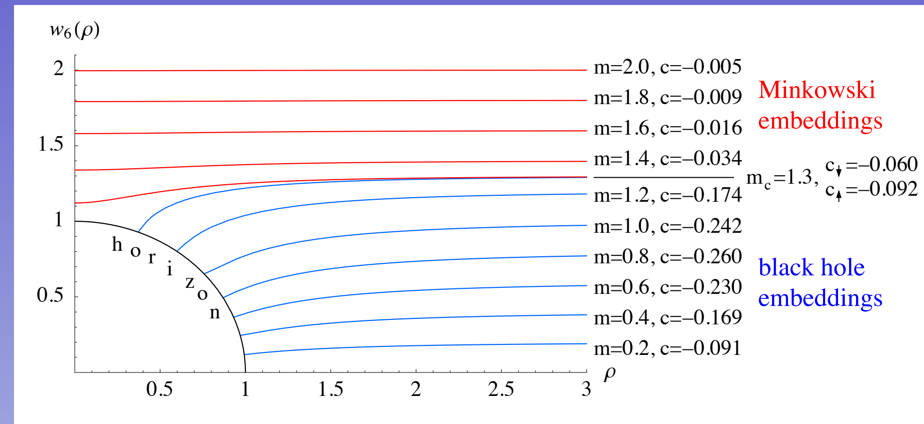


Can add

T - black hole

- instant deconfinement
- quasi-normal modes

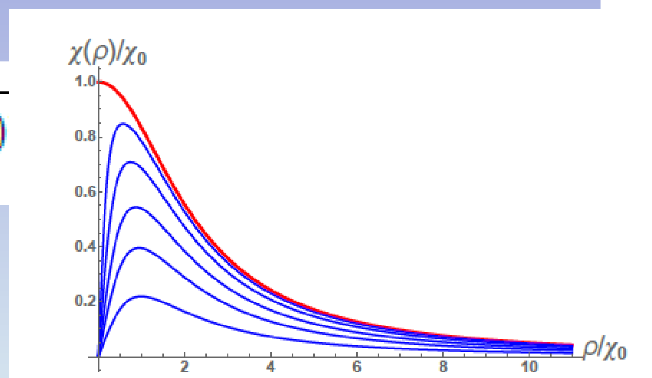
hep-th/0306018
hep-th/0605046
hep-th/0612169



$$ds^2 = \frac{K(r)}{R^2}d\tau^2 + R^2\frac{dr^2}{K(r)} + \frac{r^2}{R^2}d\vec{x}^2 + R^2 d\Omega_5^2\,,$$

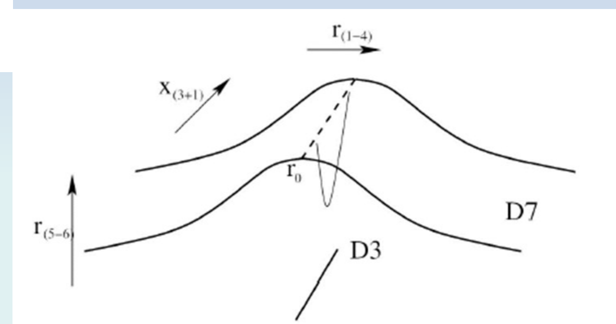
$$K(r) = r^2 - \frac{r_H^4}{r^2}\,.$$

$$\mathcal{L} = -\rho^3\sqrt{1+(\partial_\rho\chi)^2-(\partial_\rho A_t)}$$



μ – A_t

hep-th/0611099



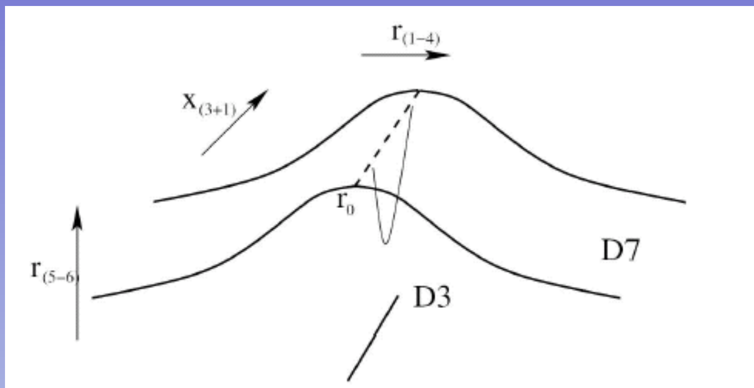
B – world volume F_{ab}

hep-th/0701001

DBI action translates background to quark physics so pheno descriptions in DBI…

γ=1 for Chiral Symmetry Breaking

1112.1261
1204.2474



λ

$$S_{D7} = -T \int d^4x d\rho \; \rho^3 e^{\phi} \sqrt{1 + (\partial_\rho L)^2}$$

$$S = \int d\rho \lambda(r) \rho^3 \sqrt{1 + L'^2}$$

We expand for small L

$$S = \int d\rho \left(\frac{1}{2} \lambda(r) \Big|_{L=0} \rho^3 L'^2 + \rho^3 \frac{d\lambda}{dL^2} \Big|_{L=0} L^2 \right)$$

we can now make a coordinate transformation

$$\lambda(\rho)\rho^3 \frac{d}{d\rho} = \tilde{\rho}^3 \frac{d}{d\tilde{\rho}}, \qquad \tilde{\rho} = \sqrt{\frac{1}{2} \frac{1}{\int_\rho^\infty \frac{d\rho}{\lambda \rho^3}}}$$

$$L = \tilde{\rho}\phi$$

$$S = \int d\tilde{\rho} \frac{1}{2} \left(\tilde{\rho}^5 \phi'^2 + 3\tilde{\rho}^3 \phi^2 \right) + \int d\tilde{\rho} \frac{1}{2} \lambda \frac{\rho^5}{\tilde{\rho}} \frac{d\lambda}{d\rho} \phi^2$$

$$m^2 = \Delta(\Delta - 4)$$

A scalar in AdS is stable until

$M^2 < -4$

ie $\Delta < 2$

The Standard Picture of Neutron Stars

K. Hebeler, J. M. Lattimer, C. J. Pethick and A. Schwenk, Astrophys. J. **773** (2013) 11 doi:10.1088/0004-637X/773/1/11 [arXiv:1303.4662 [astro-ph.SR]].

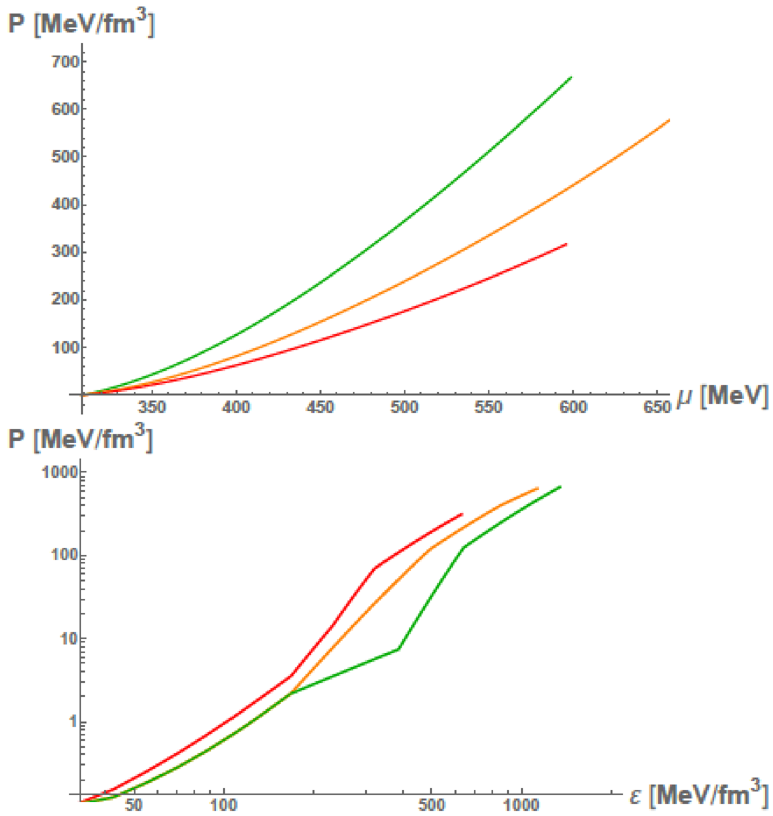
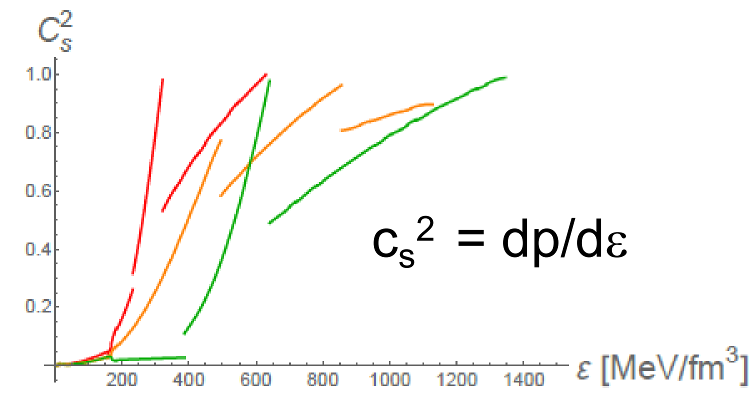
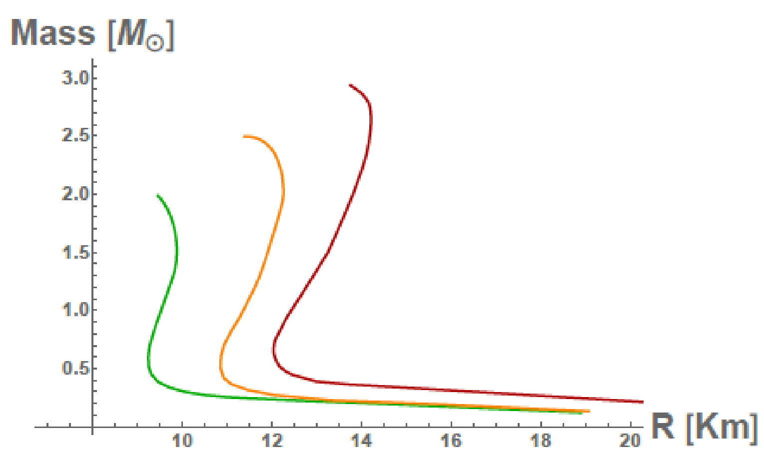


FIG. 2: *Data for the nuclear phase taken from [32]: we show both the pressure versus chemical potential and energy density. The Green line represents a soft EoS, the orange a medium EoS and the red line a stiff EoS.*





$$P = -\mathcal{F}, \qquad \mathcal{E} = \mu\frac{\partial P}{\partial \mu} - P.$$

TOV Equations

$$\frac{dP}{dr} = -G\left(\mathcal{E} + P\right)\frac{m + 4\pi r^3 P}{r(r-2Gm)},$$

$$\frac{dm}{dr} = 4\pi r^2 \mathcal{E}$$

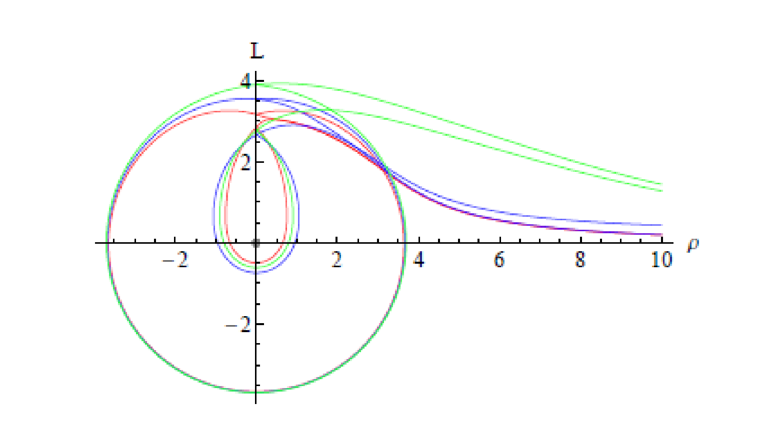
The Baryonic Phase From D3/D7

1204.5640 [hep-th]

Nick Evans,[a] Keun-Young Kim,[a,b] Maria Magou,[a] Yunseok Seo,[c] and Sang-Jin Sin[c]

Baryons in the AdS/CFT are D5 branes wrapped on S5

At finite density there can be configurations where the D3 and D7 touch (tied by strings/quarks)



$$\mathrm{d}w^2 + w^2\mathrm{d}\Omega_5^2 = \mathrm{d}\xi^2 + \xi^2\left(\mathrm{d}\theta^2 + \sin\theta^2\mathrm{d}\Omega_4^2\right) ,$$

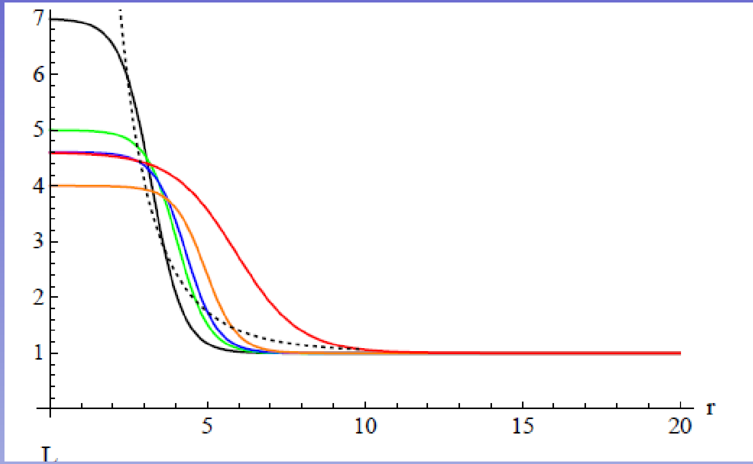
profile $\xi(\theta)$.

force balancing condition

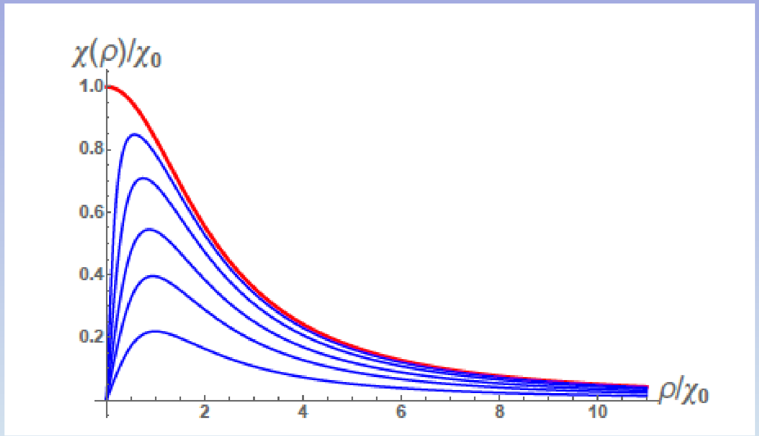
$$\begin{aligned}\delta\mathcal{F}_B \sim & \int_0^\infty \mathrm{d}\rho(\mathrm{EOM_L})\delta L + \frac{\partial\mathcal{L}_{D7}^{E,LT}}{\partial L'}\delta L\bigg|_0^\infty \\ & + \frac{2}{3\pi}\tilde{d}\int_0^\pi(\mathrm{EOM}_\xi)\delta\xi + \frac{2}{3\pi}\tilde{d}\frac{\partial\mathcal{L}_{D5}^E}{\partial\xi'}\delta\xi\bigg|_0^\pi \\ \sim & -\frac{\partial\mathcal{L}_{D7}^{E,LT}}{\partial L'}\delta L\bigg|_{\rho=0} + \frac{2}{3\pi}\tilde{d}\frac{\partial\mathcal{L}_{D5}^E}{\partial\xi'}\delta\xi\bigg|_{\theta=\pi} ,\end{aligned}$$

$$L'(0) = \frac{\xi'(\pi)}{\xi(\pi)}$$

We impose a dilaton form (representing the DBI in some unknown geometry we don't want to spend our life developing!)



$$e^{\phi} = A + 1 - A \tanh(r - \lambda)\,,$$

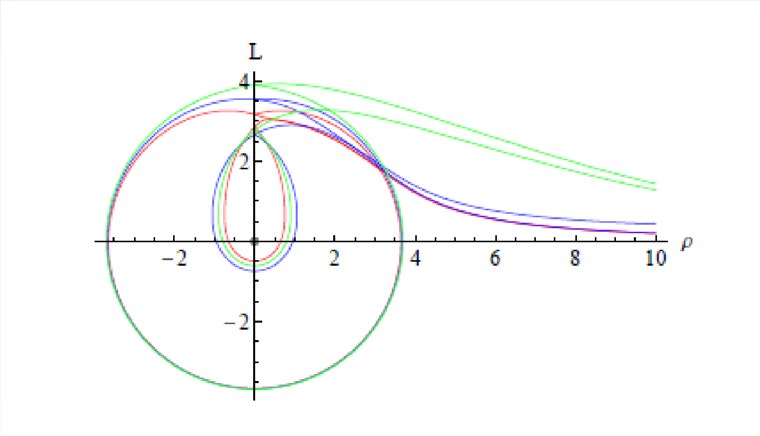


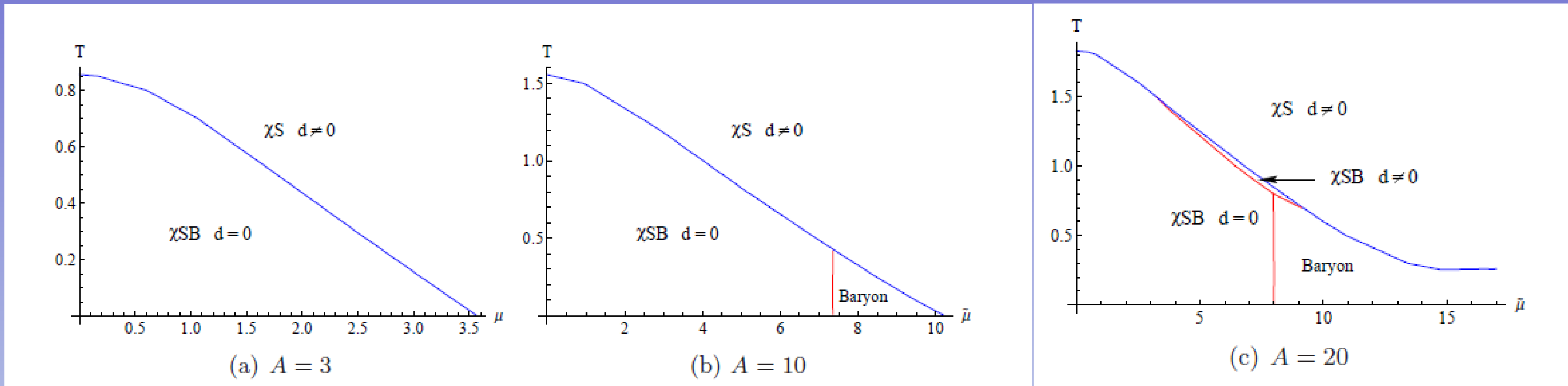
This represents the rough form of the QCD running

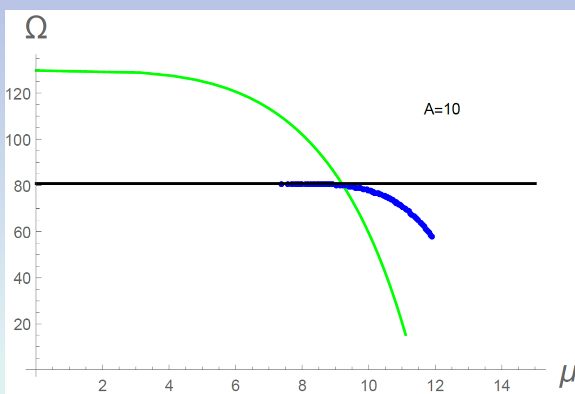
Large IR value discourages spike dense D7 embeddings

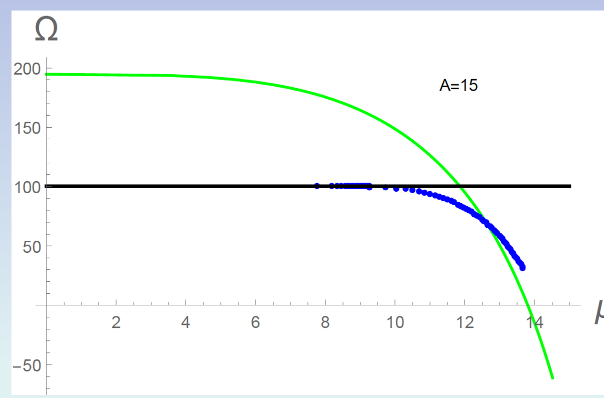
Large derivative causes chiral symmetry breaking BF bound violation

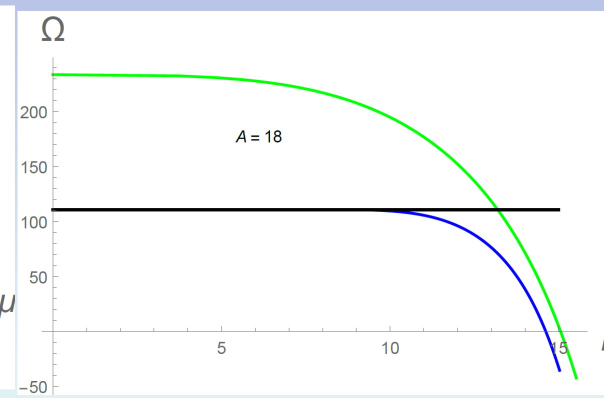
Large IR value stops D5 shrinking to point











We're currently seeking dilaton profiles that give perfect QCD phenomenology… but plausible that neutrons are the full answer…

Quark Cores

The Basic D3/D7 Model

C. Hoyos, D. Rodríguez Fernández, N. Jokela and A. Vuorinen, Phys. Rev. Lett. **117**, no. 3, 032501 (2016) doi:10.1103/PhysRevLett.117.032501 [arXiv:1603.02943 [hep-ph]].

$$S = -\frac{N_f N_c}{\lambda} T_{D7} V_3 \int d\rho \rho^3 \sqrt{1 + (\partial_\rho \chi)^2 - 2\pi\alpha' (\partial_\rho A_t)^2}$$

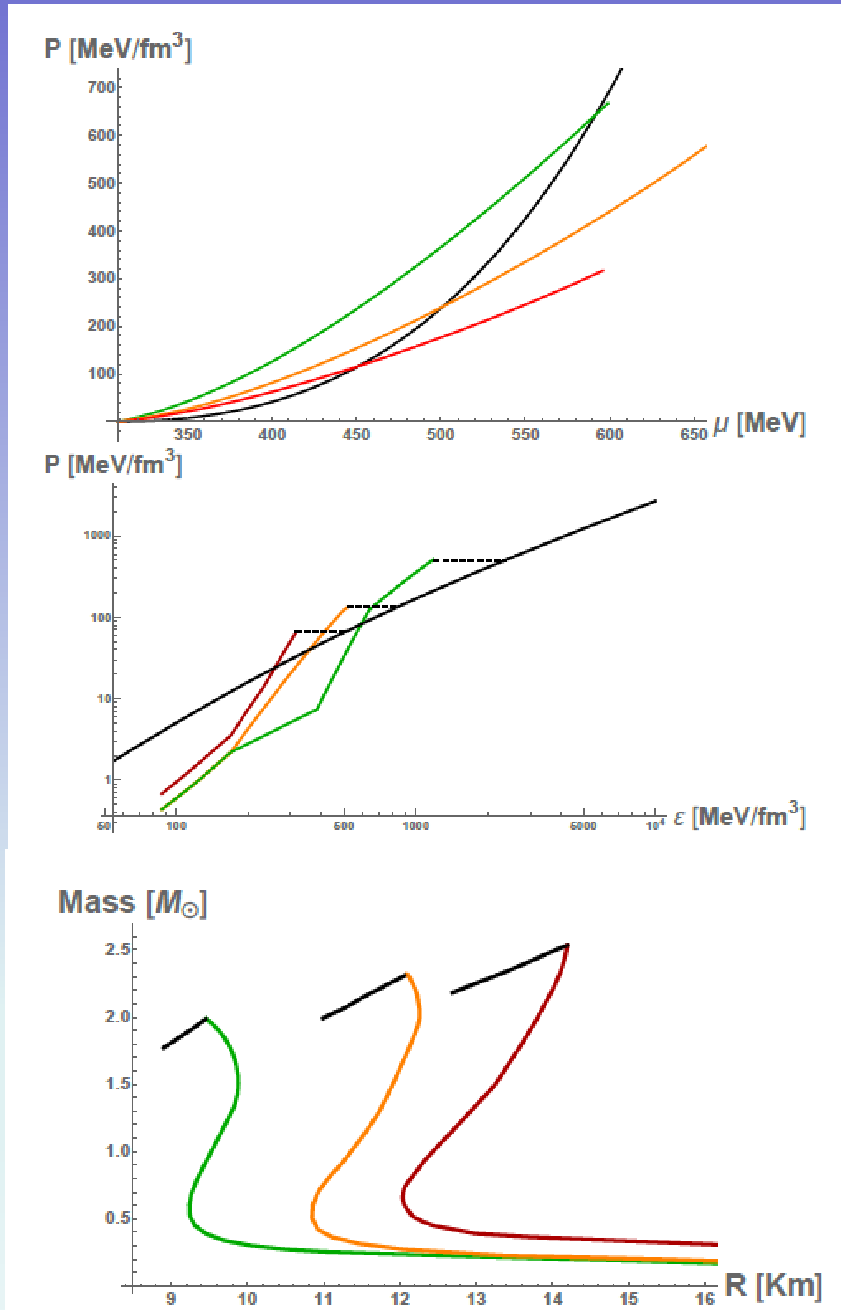
$$\mathcal{F} = \frac{1}{\eta^3}(\mu^2 - m^2)^2 + \mathcal{O}(\mu^3 T, T^4) \qquad \eta = \frac{\Gamma(7/6)\Gamma(1/3)}{\sqrt{\pi}}$$

$$\lambda = 3\pi/\eta^3$$

$$P = -\mathcal{F}, \qquad \mathcal{E} = \mu \frac{\partial P}{\partial \mu} - P.$$

$c_s^2 = dp/d\varepsilon = 1/3$

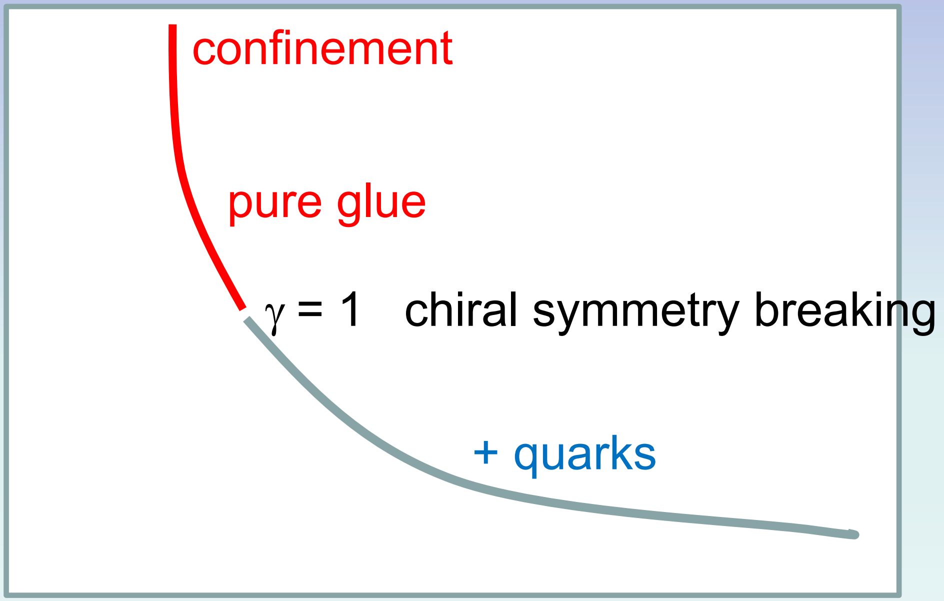
The core is too fluffy and stars with quark cores are unstable.



How can QCD be different?

Running coupling
New phases – chiral symmetry breaking but no confinement
- confinement but no chiral symmetry breaking

A Massive Deconfined Phase

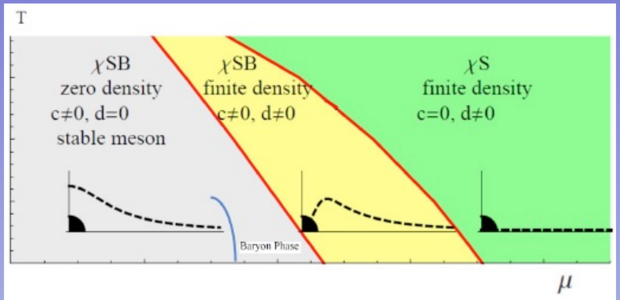


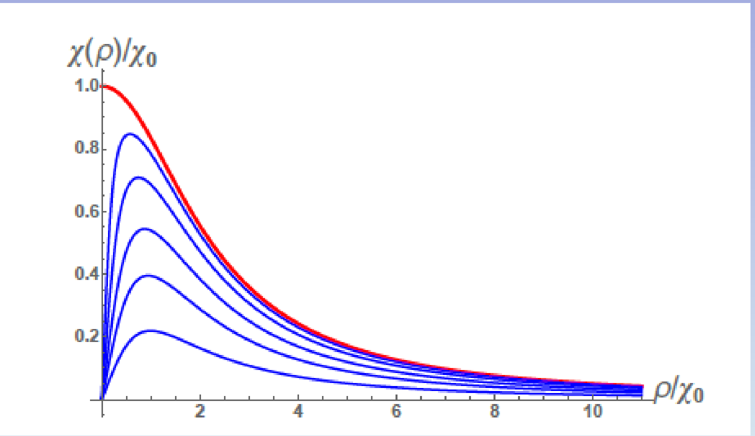
One can imagine μ inserting itself to switch off confinement but chiral symmetry breaking persisting… maybe…

D3/probe D7 has such phases…

A Massive Deconfined Phase D3/probe D7 1911.12705

$$\mathcal{L} = -\int d\rho \; h[\rho^2+\chi^2] \; \rho^3 \sqrt{1+(\partial_\rho \chi)^2 - (\partial_\rho A_t)^2}$$





$$h = 1 + \frac{1}{(\rho^2+\chi^2)^{\frac{q}{2}}}$$

$$m^2 = -3 + h\frac{\rho^5}{\tilde{\rho}^4}\frac{dh}{d\rho}$$

$$m^2 = -3 - \delta m^2, \; \delta m^2 = \frac{4q}{(2-q)^2}$$

$$q = 0.536$$

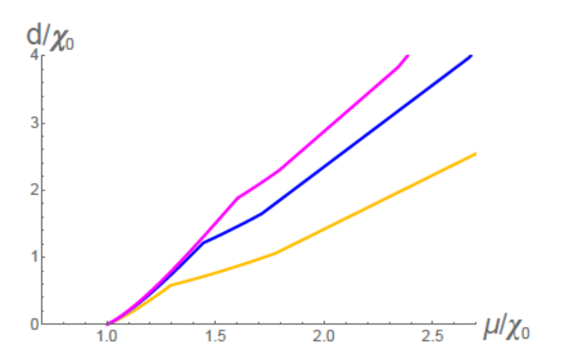
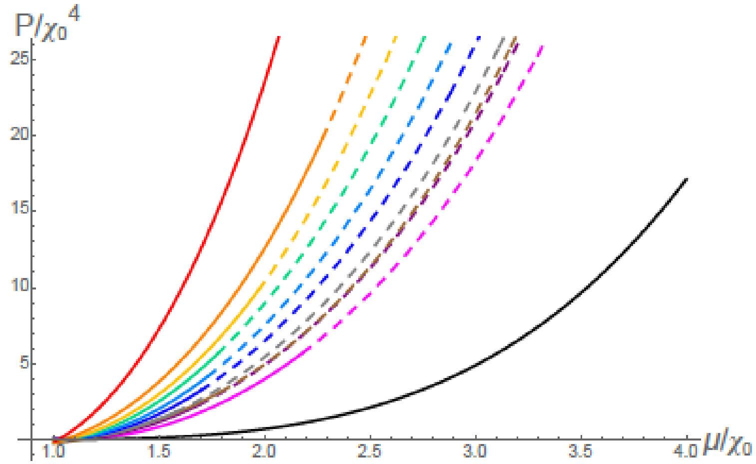
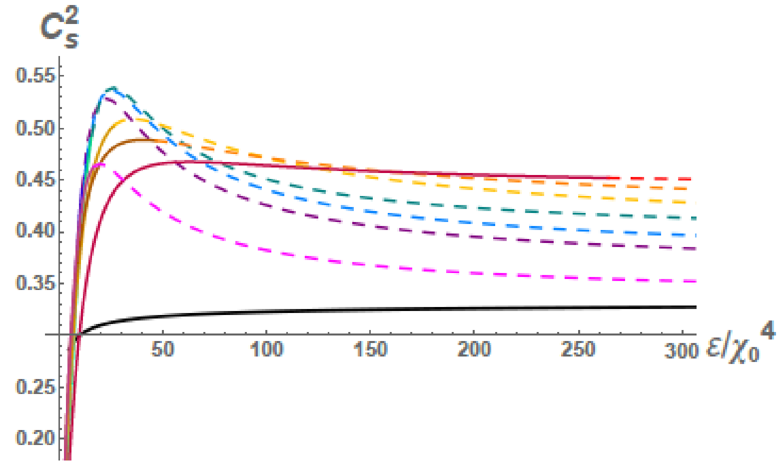


FIG. 6: *d vs μ for different values of q. The different coloured lines represent different values of q; (yellow) q=1.6, (dark blue) q=1.99, (magenta) q=2.3*





different values of q; (Red) q=1, (orange) q=1.3, (yellow) q=1.45, (green) q=1.6, (blue) q=1.8, (purple) q=1.99, (magenta) q=2.8. Solid lines are the massive quark phase, dotted lines the chirally symmetric phase. The black line is the case of a constant dilaton.

All theories asymptote to the standard D3/probe D7 quark plasma at large μ but show larger c_s^2 and pressure at lower densities…

Fit χ_0 to 300-440 MeV

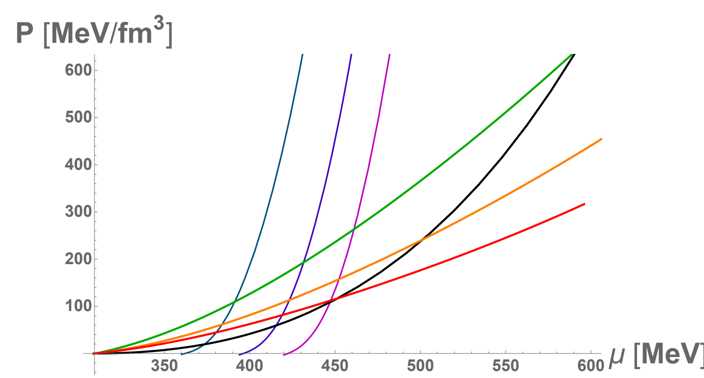


FIG. 12: *Transition from nuclear to quark matter for the case of q=1.8. The Black line correspond to the case of a constant dilaton and the green, orange and red curves represent nuclear matter as in Fig 4. The dark teal curve corresponds to $\chi_0 = 360$ MeV, the purple curve corresponds to $\chi_0 = 395$ and the magenta curve corresponds to $\chi_0 = 420$.*

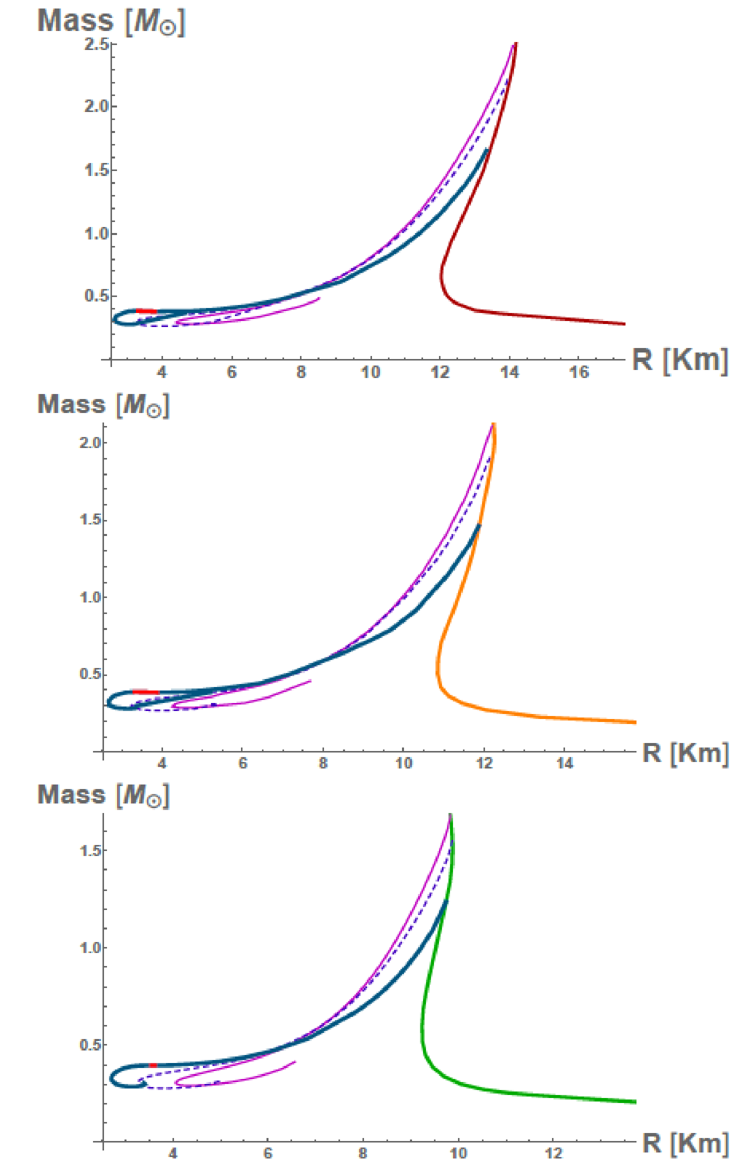
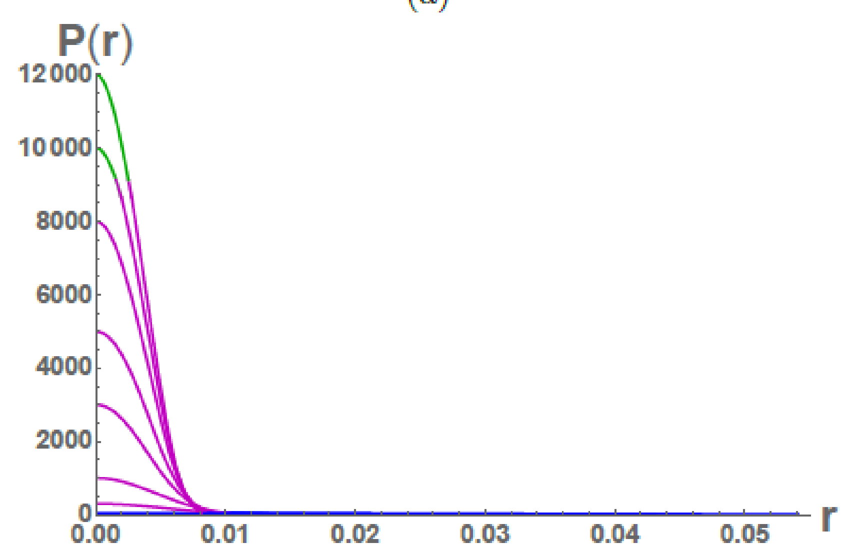


FIG. 14: *Mass vs radius curves for the case of q=1.8. The three curves leaving the green/red/orange nuclear EoS prediction are the three transitions to a quark phase from Figure 13. The small stable branch is indicated in red.*

The material is still not stiff enough though to support neutron stars…

Accepting some weird guys you probably can't make astrophysically…



(b)

pink line corresponds to the massive chirally broken phase and the green line corresponds to the massless chirally symmetric phase)

Getting Stuck into a First Order Transition 2009.14079

A continuous transition to the standard quark plasma didn't help…

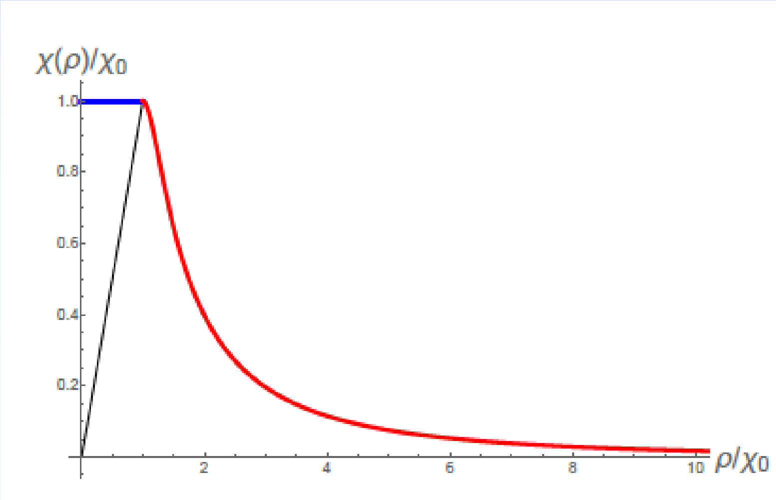
$$\mathcal{L} = -\rho^3\sqrt{1 + (\partial_\rho \chi)^2 - (\partial_\rho A_t)^2} - \rho \Delta m^2 \, \chi^2$$

$$m^2 = \Delta(\Delta - 4)$$

$$\Delta m^2 = -2\gamma_1 = -\frac{3\,(N_c^2 - 1)}{2N_c\pi}\alpha$$

$$\gamma_1 = \frac{3C_2}{2\pi}\alpha, \quad C_2 = \frac{(N_c^2 - 1)}{2N_c}$$

$$Q\frac{d\alpha}{dQ} = -b_0\alpha^2, \qquad b_0 = \frac{1}{6\pi}(11N_c - 2N_f)$$



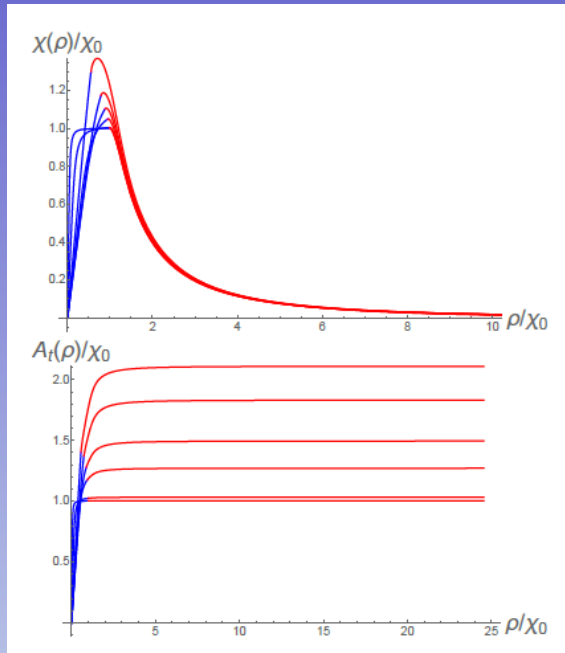
How cope with quark decoupling below it's dynamical mass scale?

Setting $\Delta m^2 = 0$ – return to N=2 – gives sensible embedding… (?)

Extending the prescription to finite μ gives a first order transition…

There is a free parameter for how you weight the UV and IR parts of the action

k_{IR}



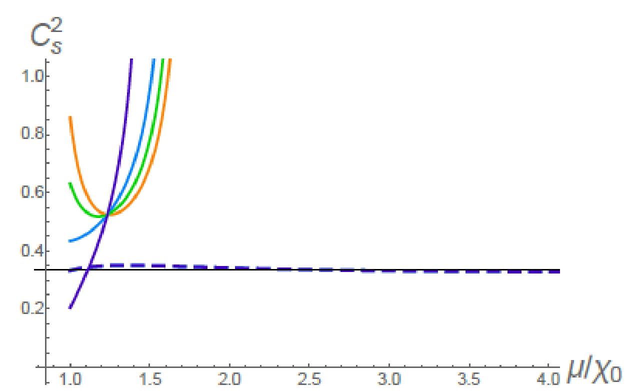


Figure 5: The speed of sound squared as a function of μ for the Figure 4 solutions. The top lines represent the chirally broken phase with different values of k_{IR}; $k_{IR} = 0.1$ (purple), $k_{IR} = 0.575$ (blue), $k_{IR} = 1$ (green) and $k_{IR} = 2$ (orange). The lower dark blue line corresponds to the chirally restored phase ($L = 0$ phase) which asymptotes to $1/3$.

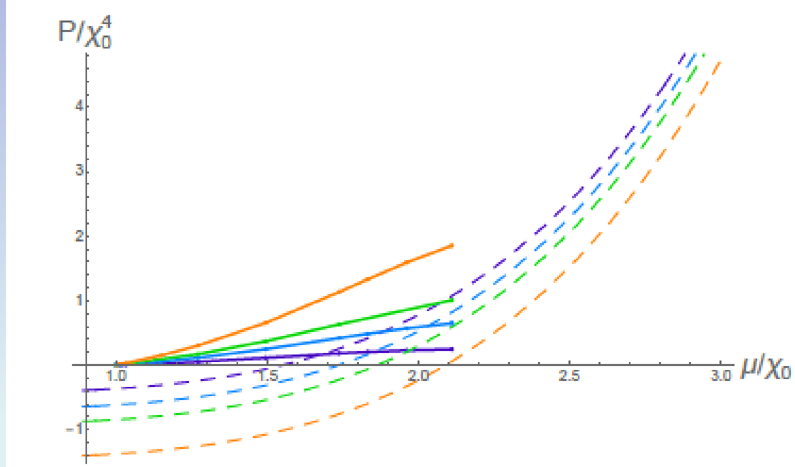
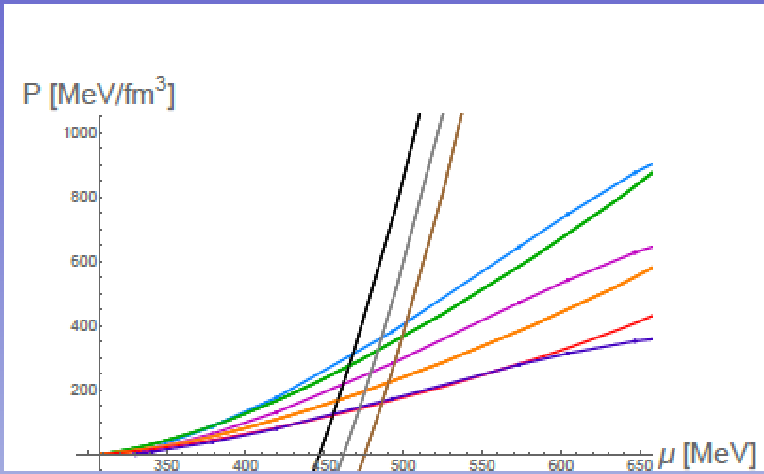
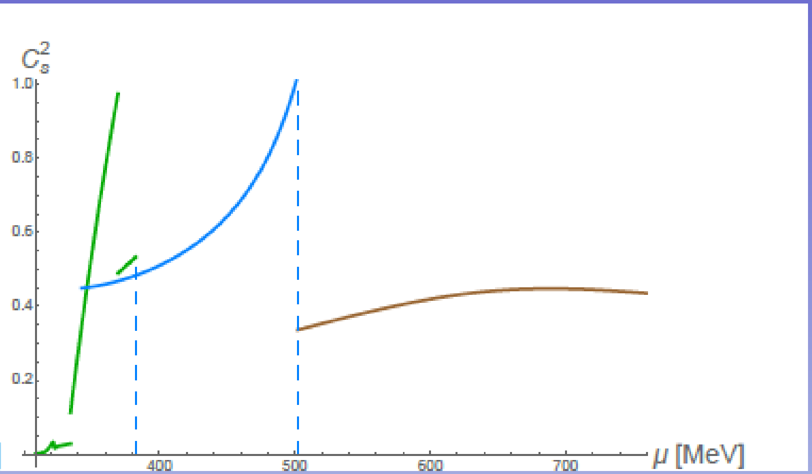
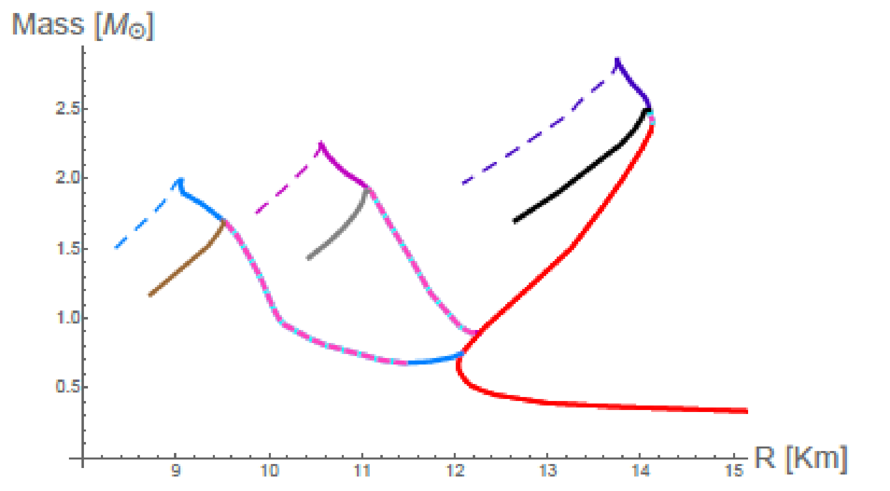
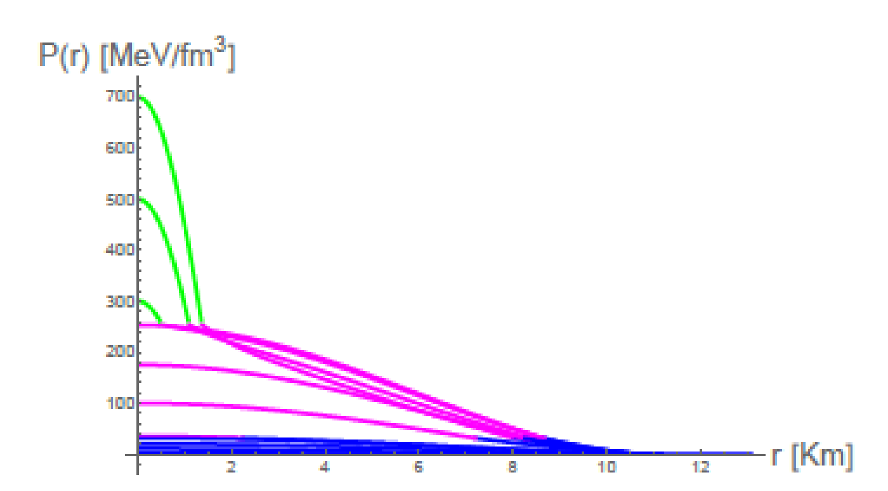


Figure 4: Pressure versus chemical potential. The solid line corresponds to the deconfined massive phase, and the dashed line represents the chirally restored phase ($\chi = 0$ phase). The different colors represent different values of k_{IR}; $k_{IR} = 0.1$ (purple), $k_{IR} = 0.575$ (blue), $k_{IR} = 1$ (green) and $k_{IR} = 2$ (orange).









Realizes quark core paradigm…

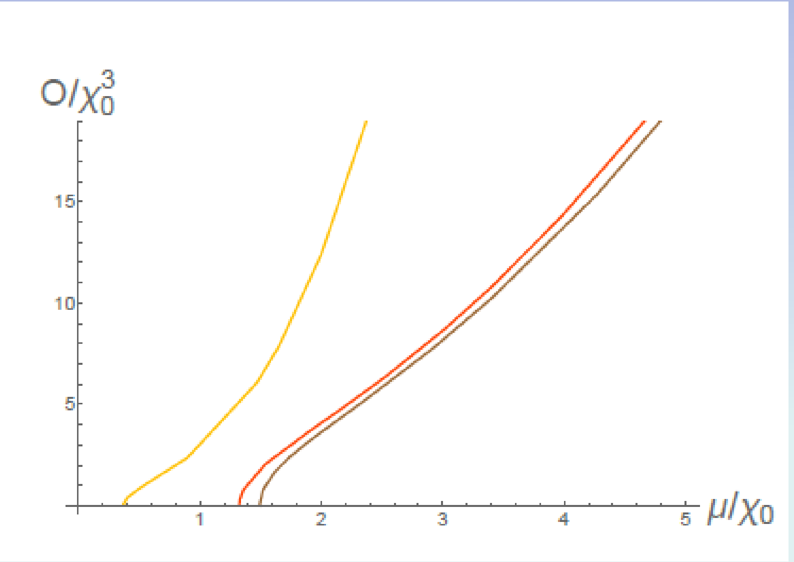
Colour superconducting phases

1803.03107 [hep-ph]

Here we don't worry about colour breaking – quark and magnetic monopole soup screen gluons anyway… just add fields to describe the qq operators of interest (3 for CFL).

$$\mathcal{L} = -\rho^3\sqrt{1+(\partial_\rho\chi)^2-(\partial_\rho A_t)^2} - \rho^3 g_{\rho\rho}\sum_i (D\psi_i)^2 - \rho\Delta m^2\chi^2, \qquad D_\mu = \partial_\mu - iG[\rho]QA_\mu$$

$$G[\rho]^2 = \kappa\,\alpha(\rho)$$

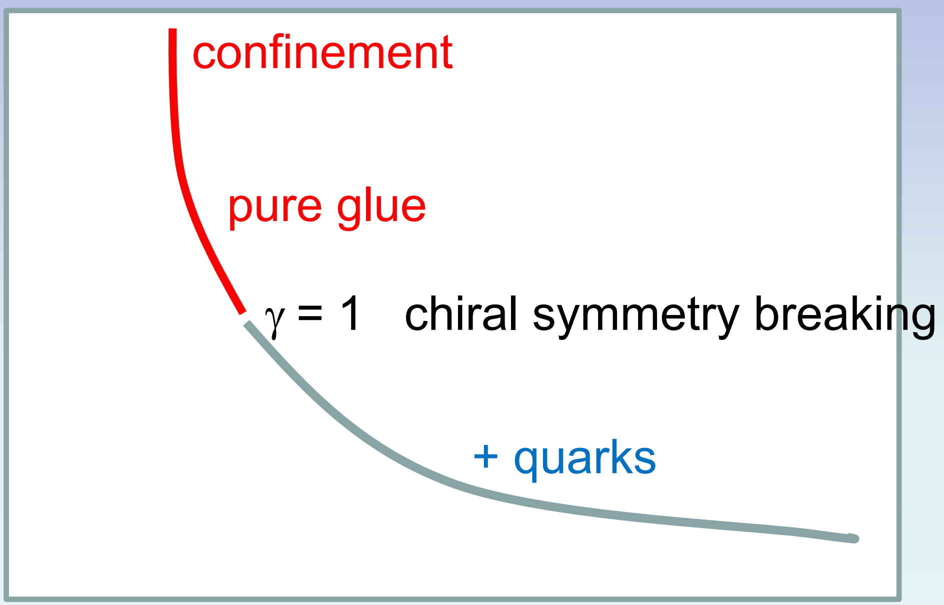


This isn't a big change to the high m quark phase action/P but allowed us to control the first order transition whilst $c_s^2 < 1$

How can QCD be different?

Running coupling
New phases – chiral symmetry breaking but no confinement
- confinement but no chiral symmetry breaking

Quarkyonic confined phase

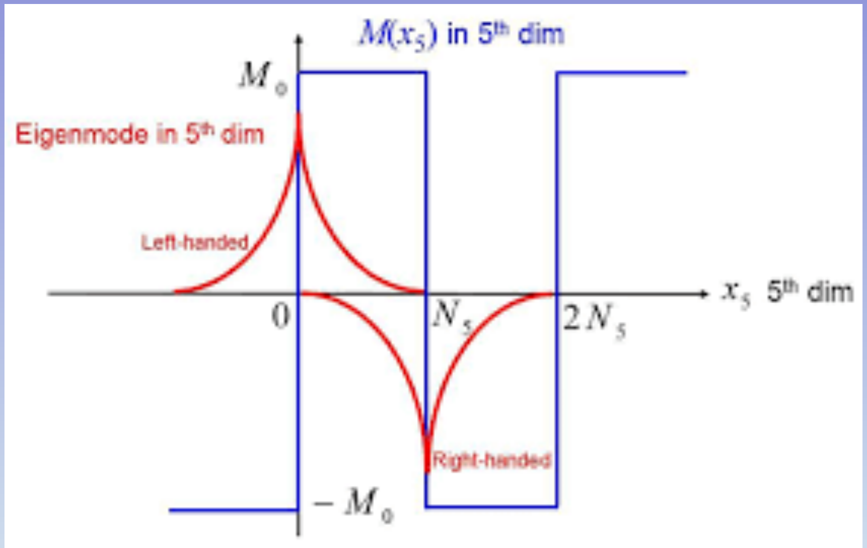


This picture maybe stupidly naïve…

To include confinement we need to go beyond the D3/probe D7 systems…

Sakai-Sugimoto might be sensible.. But hard to identify the quark mass and condensate…

Domain Wall Chiral Quarks



Kaplan
92

5d -> 4d generates chirl fermions on the domain walls

4d -> 3d splits the 4 component fermioninto two 2 component fermions – not chiral

Domain Wall Chiral Quarks

2106.08753 with Jack Mitchell, Jesus Cruz-Rojas

THE D3/PROBE-D7 SYSTEM & DOMAIN WALLS

	0	1	2	3	4	5	6	7	8	9
D3	-	-	-	-	•	•	•	•	•	•
D7	-	-	-	-	-	-	-	-	•	•

We include a hard wall at r=1 so IR is imperfect…

$$S_{D7} \approx \int d^4x \; d\rho \; \rho^3 \sqrt{1 + (\partial_\rho u_i)^2 + \frac{R^4}{(\rho^2 + u_i^2)^2}(\partial_x u_i)^2}$$

$$\partial_\rho \left(\rho^3 \partial_\rho u_1\right) + \frac{1}{\rho}(\partial_z^2 u_1) = 0$$

$$u_1 = f_k(\rho) \cos kz$$

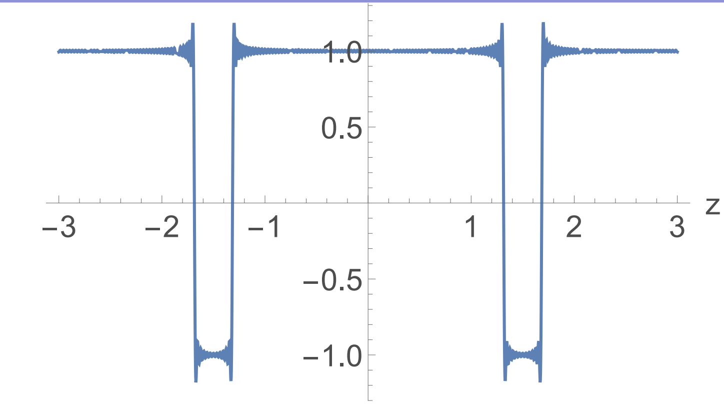
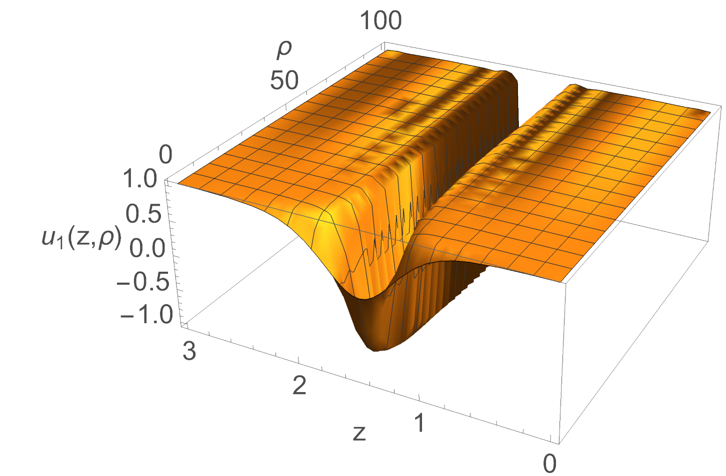


Figure 2: The Fourier representation of the even periodic mass function we use (100 Fourier terms are used) - in each period it has two domain walls separated by a width w.



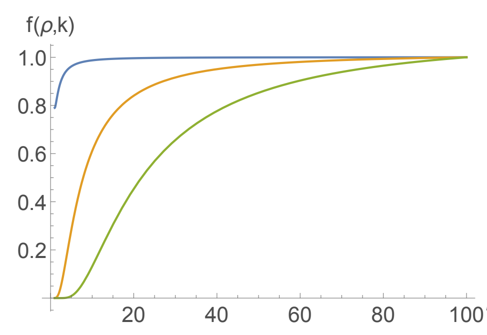
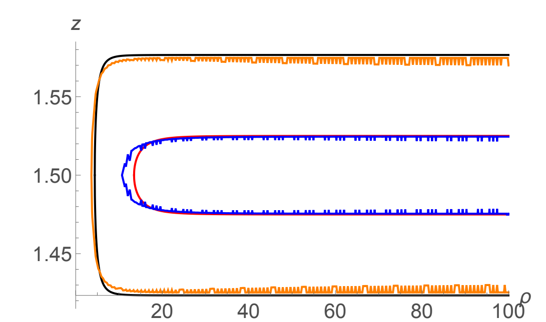


Figure 1: The solutions for $f_k(\rho)$ in pure AdS with a hardwall at $\rho = 1$ for $k = 1$(blue), 10(orange), 30(green).



Sakai-Sugimoto-esque Us for chiral symmetry breaking…

The Large Mass Limit

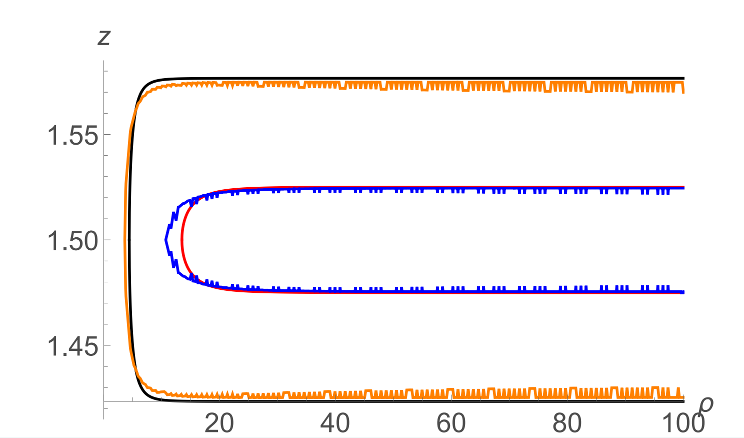
$$S_{D7} \approx \int d^4x \, d\rho \, \rho^3 \sqrt{1 + (\partial_\rho u_i)^2 + \frac{R^4}{(\rho^2 + u_i^2)^2} (\partial_x u_i)^2}$$

u is constant except on some z(ρ) where δ_ρ u diverges

$$\partial_\rho u_i = \frac{1}{\sqrt{g_{\rho\rho}(\partial_z \rho)^2}} \delta(z - z_0) \Big|_{\text{locus}}$$

$$S = \int d^3x \, d\rho \, \rho^2 \sqrt{1 + \rho^4 (\partial_\rho z)^2}$$

The action is precisely that of the D3 /probe D5 anti-D5 system and the Us the same…

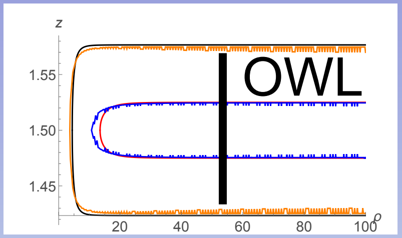


The Large Mass Limit

$$\partial_\rho u_i = \frac{1}{\sqrt{g_{\rho\rho}(\partial_z \rho)^2}}\delta(z - z_0)\Big|_{\text{locus}}$$

There remain fluctuations on the domain wall

hep-th/
0803.3547



Non-local q_L q_R operators at the IR tip become local and mix with the 4d local qq operator – source each other?

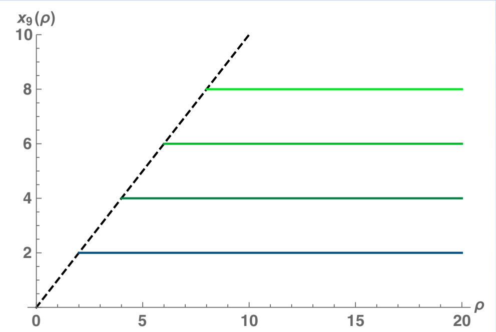
$$\mathcal{L} \approx \rho^4(\partial_\rho z)\sqrt{1 + \mathcal{A}(\partial_\rho u_i)^2 + \frac{(\partial_{x_{2+1}} u_i)^2}{(\rho^2 + u_i^2)^2}}$$

with

$$\mathcal{A} = 1 + \frac{1}{(\partial_\rho z)^2(\rho^2 + u_i^2)^2}$$

where from (5) we know

$$\partial_\rho z = \frac{\rho^4_{\text{min}}}{\sqrt{\rho^{12} - \rho^8_{\text{min}}\rho^4}}$$



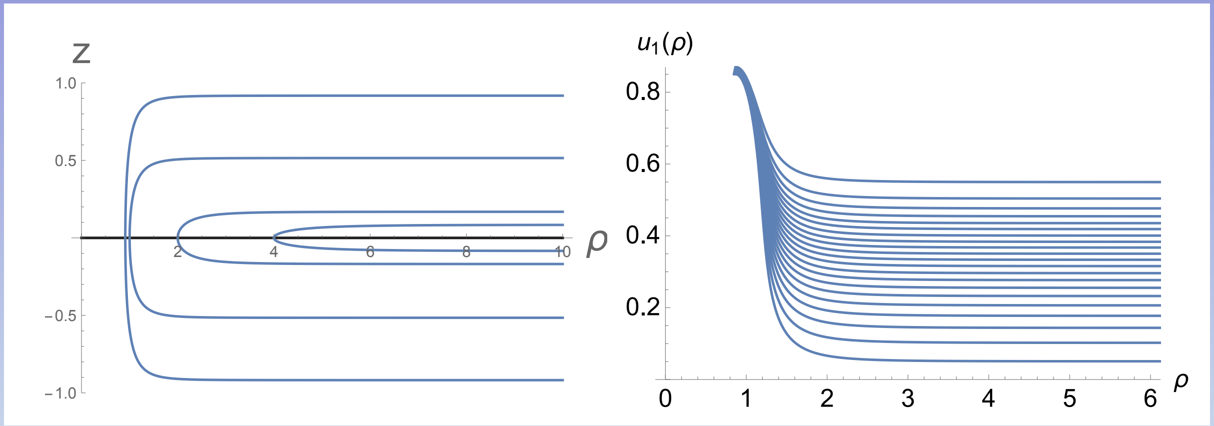
u_i = constant mass =
IR gap

Suggests these theories'
chiral symmetry breaking is purely a
hard mass. (m_{IR} proportional 1/width)

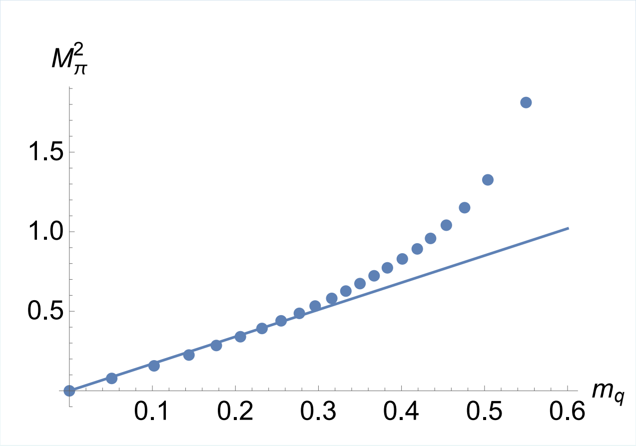
Applied Magnetic Field/Dilaton Profile

$$h^2 = 1 + \frac{1}{\rho^q}$$

Violate the BF bound by hand in the interior of the space via a dilaton profile



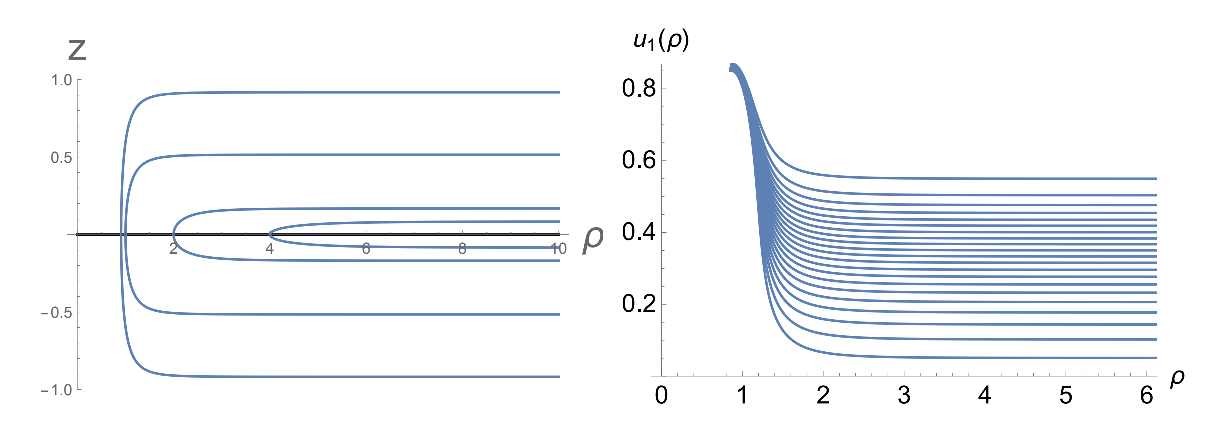
Us pile up at IR point… surface u_i show chiral symmetry breaking and…



Goldstones show a Gell-Mann-Oakes Renner relation….

The interpretation of the set up is self consistent and the first U system we know with an explicit measure of mass and the condensate

Hard Mass vs NJL



Witten's "double trace" prescription:

$$L = m + \frac{c}{\rho^2}$$

$$\frac{g^2}{\Lambda_{UV}^2}\left(\langle \bar{q}_L q_R \rangle\right)^2$$

$$m = \frac{g^2}{\Lambda_{UV}^2}\langle \bar{q}_L q_R \rangle$$

In the NJL interpretation must change boundary conditions on the fluctuations (m can now vary) and a Goldstone results.

You can also introduce other double trace terms in the fluctuation spectrum using the same prescription…

Domain Wall AdS/QCD

2108.12152

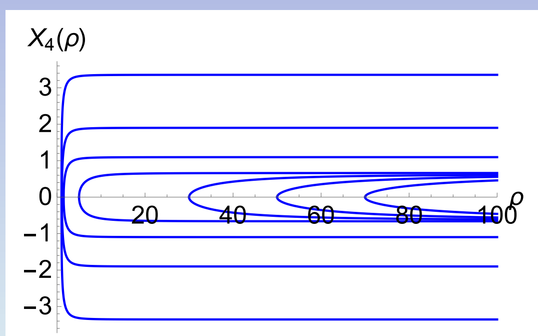
	0	1	2	3	4	5	6	7	8	9
D5	-	-	-	-	-	(-)	•	•	•	•
D7	-	-	-	-	-	•	-	-	-	•

The UV is rather odd – the fluctuations aren't normalizable… all Us asymptote to the same width irrespective of the mass gap… but IR seems OK…

hep-th/0605017

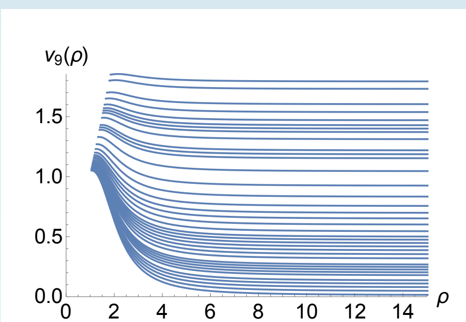
Compactifying in x_5 ➡ confinement

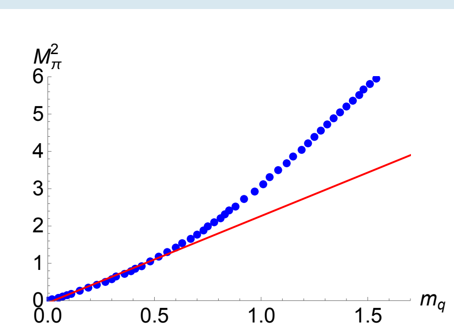
Domain wall $m(x_4)$ ➡ 3+1d chiral quarks



Us pile up… surface field shows χSBing… GMOR relation…

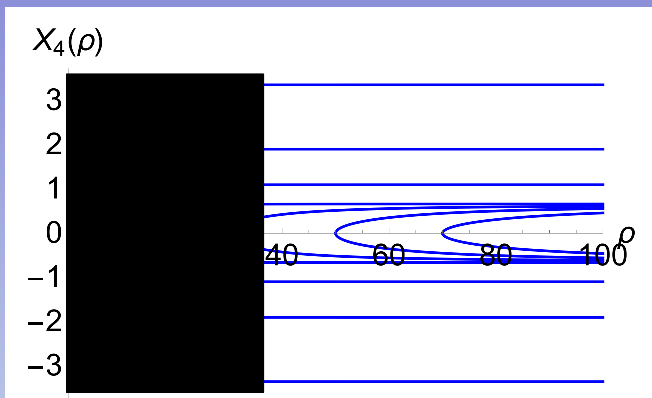
	QCD	DW AdS/QCD	Improved DW AdS/QCD
m_ρ	775 MeV	775*	$g_q = 0.247$
m_π	139 MeV	139*	$g_v = 0.656$
m_a	1230 MeV	1,955	$g_A = 1.287$
F_V	345 MeV	345*	
F_A	433 MeV	726.7	
f_π	93 MeV	135.3	128.8
$M_{v,n=1}$	1465 MeV	3284	1881.8
$M_{A,n=1}$	1655 MeV	5043	2752.5

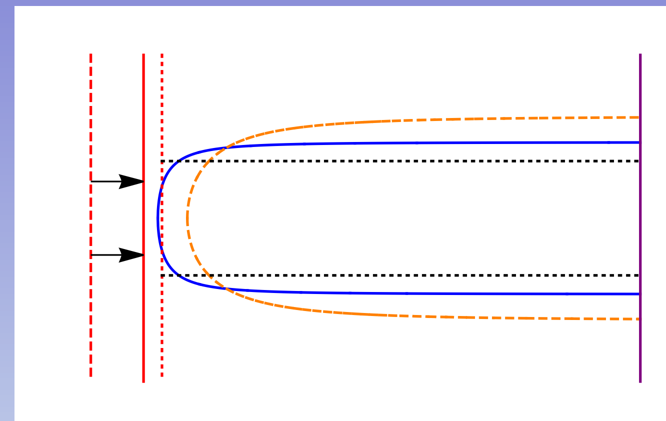




Thermal Transitions
2207.10374 [hep-th]

Naively the black hole horizon eats sequential Us and there’s a first order meson melting transition…. In the far UV all Us share the same width…





Here with Λ_{UV} and T, you must be careful not to make a one to one identification between width and UV mass… the surface fluctuation lets you precisely ID the mass…

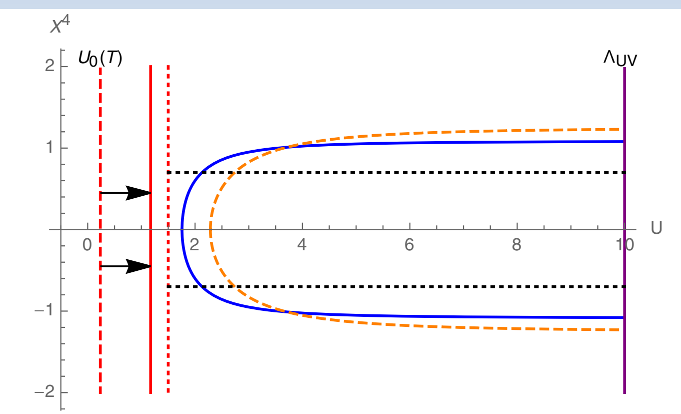
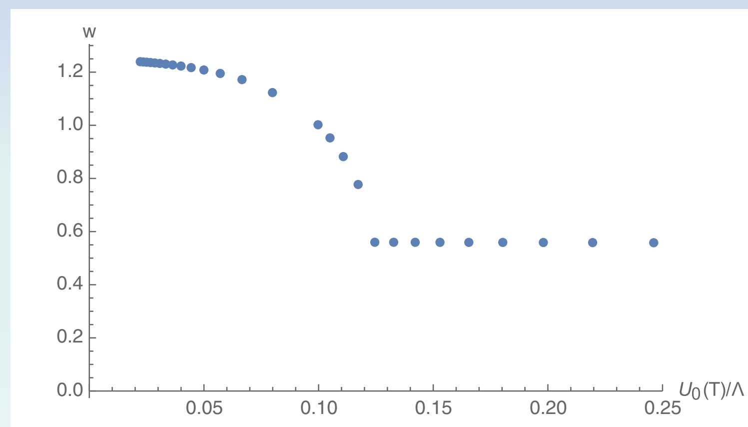


FIG. 4. A cartoon showing the evolution of a domain wall system with constant m/Λ under an increase of temperature T



The transition is second order

Onwards

We now plan to include density, baryons and work towards neutron star equations of state… quarkyonic modes etc…

Summary

Deconfined massive phases might be possible as quark cores of neutron stars…

Domain wall fermions are a promising new holographic approached to AdS/QCD…