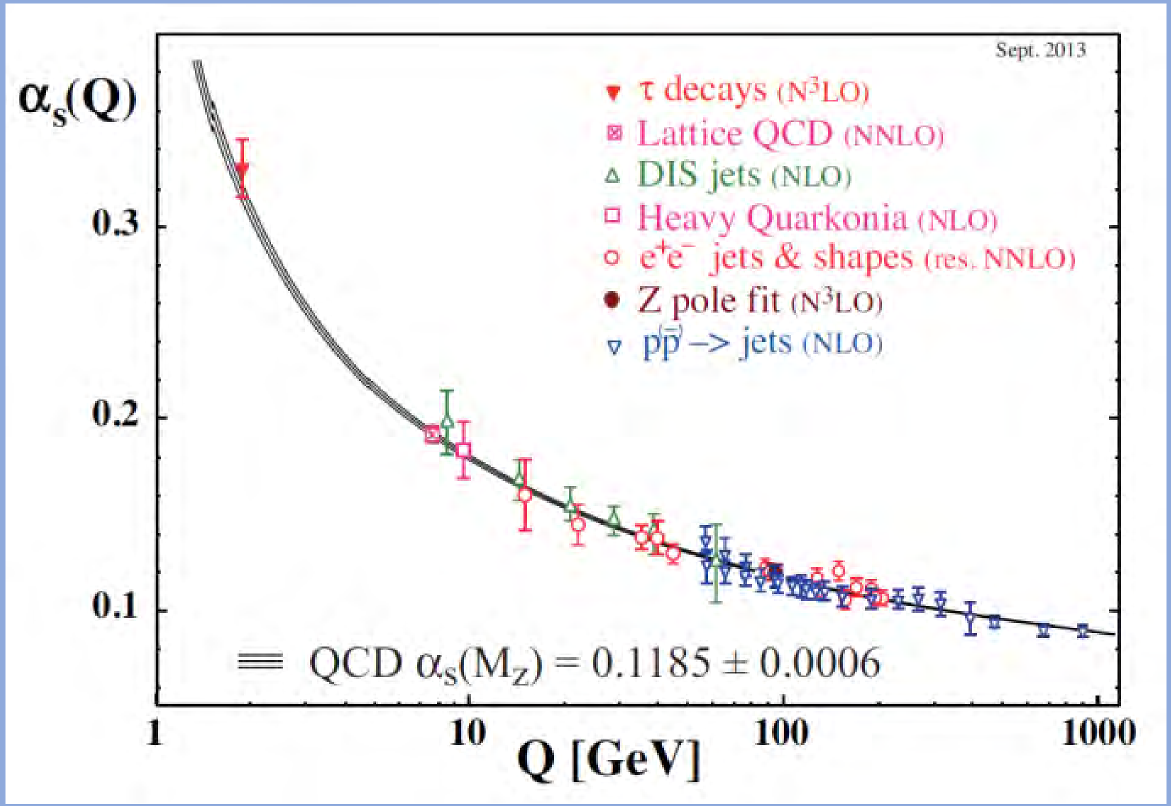
Chiral Symmetry Breaking & Confinement: Breaking the Link

Nick Evans University of Southampton

- Models with large separations
- Phase diagrams of theories with chiral symmetry but no confinement from AdS/CFT… & QCD
- Quark matter in neutron star cores

Asymptotic Freedom in QCD:



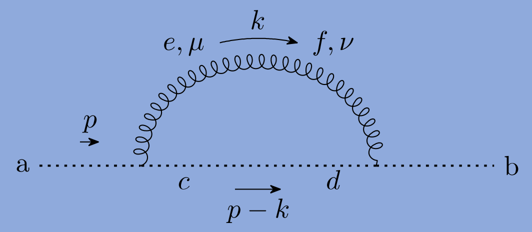
Quarks on top of each other are free…

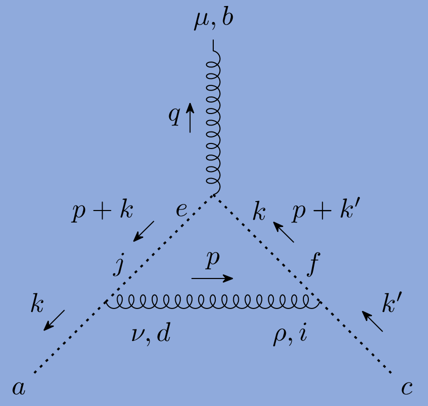
As they separate coupling strength grows

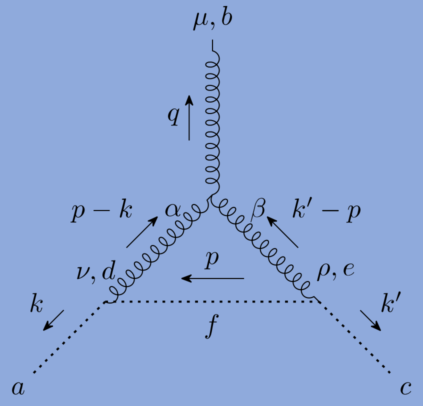
- Confinement
- Chiral symmetry breaking

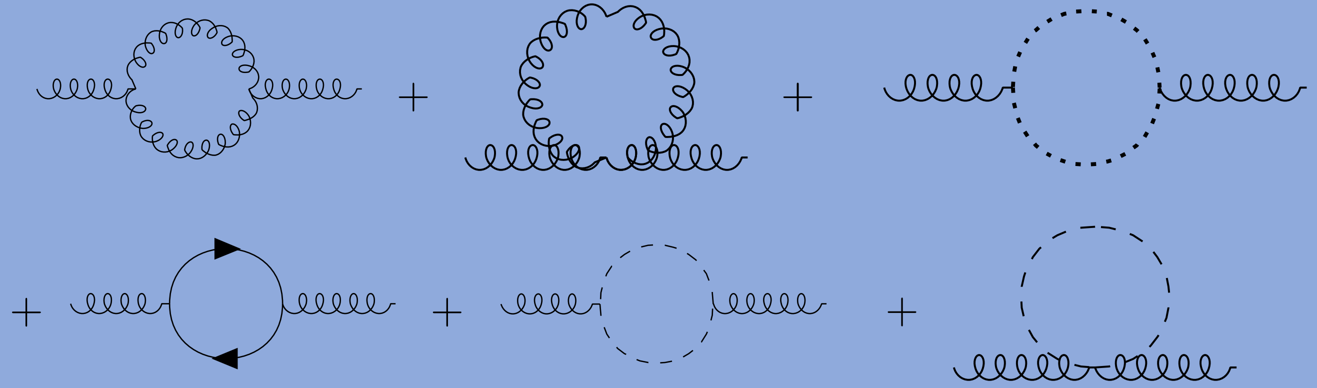
Quantum Field Theory III
Easter Problem
Non-Abelian Gauge and $N = 1, 2, 4$ SYM beta functions

Nakorn Thongyoi









$$\frac{\partial \alpha_R}{\partial \ln \mu^2} = -\frac{b\alpha_R^2}{4\pi}$$

$$\alpha_R = \frac{\alpha_0}{1 + \frac{b\alpha_0}{2\pi} \ln\left(\frac{\mu}{\mu_0}\right)}$$

$$b = \frac{11C_2(G)}{3} - \frac{4N_f C(r)}{3} - \frac{N_s C(r)}{3}$$

The Origin of QCD Mass

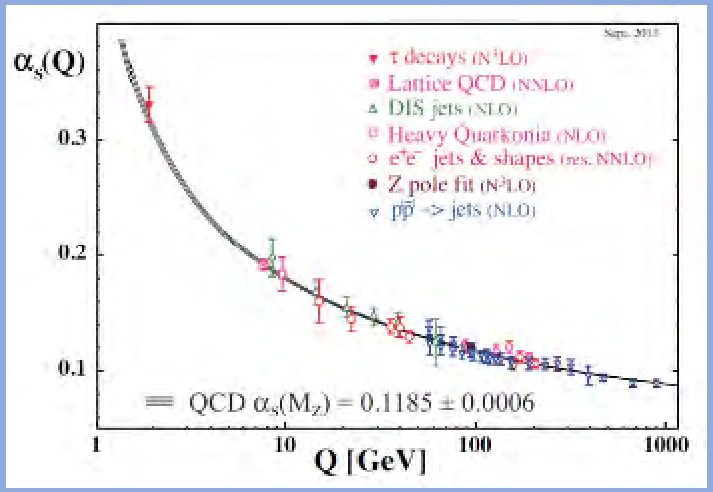
The Proton Mass – The QCD Vacuum

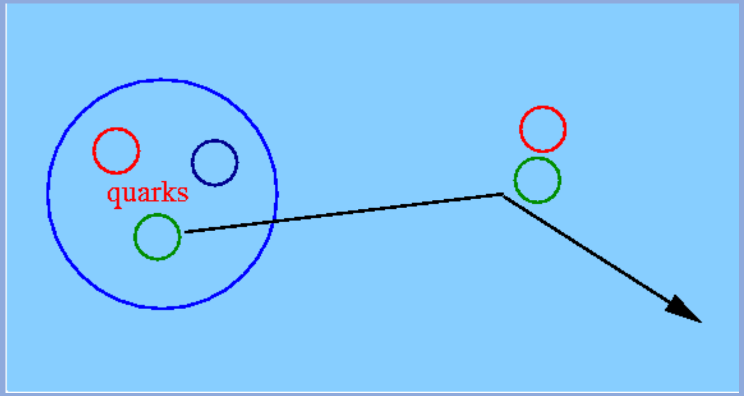
Every so often quantum effects create a quark anti-quark pair.

The attractive force is so strong that

binding energy >> mass energy

The vacuum has lower energy if it fills itself with quark anti-quark pairs!





Chiral Symmetry Breaking

The u and d quarks are basically massless

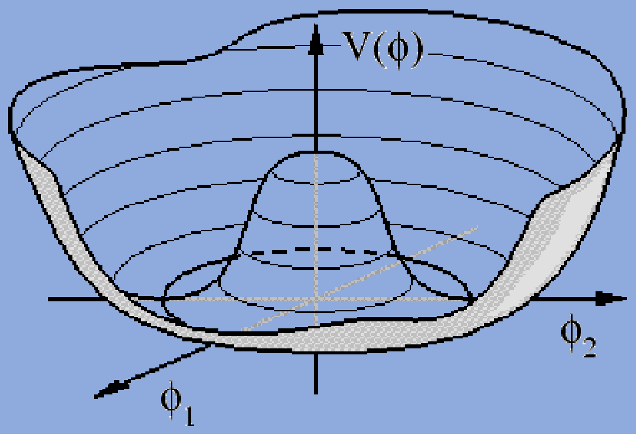
$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + h.c.)$$

$$\bar{u}\gamma^\mu u = \bar{u}_L\gamma^\mu u_L + \bar{u}_R\gamma^\mu u_R$$

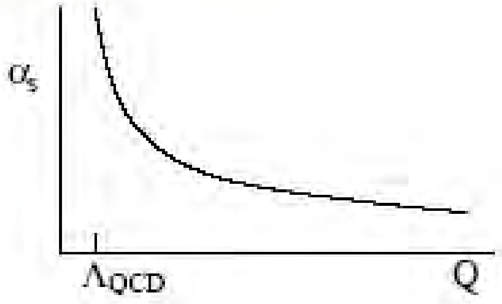
Evidence: lack of parity doubling, proton mass, Goldstone pions

$$\langle \bar{u}_L u_R + \bar{d}_L d_R + h.c.\rangle \neq 0$$



Confinement

The force is asymptotically free (Wilczek, Gross, Politzer)



Coulomb law vs linearity

Confinement:

Quarks can not be liberated from hadrons.

Localized, magnetically charged, scalar gauge configurations form and condense leading to a dual Meissner effect (?)….

‘tHooft speculation

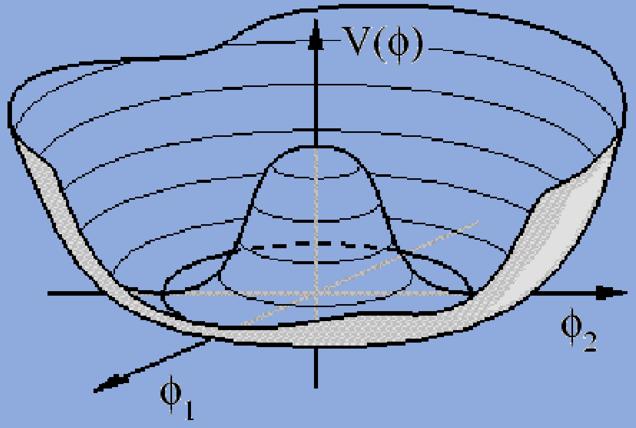
Seiberg Witten N=2 SYM realization

Meissner Effect

2 electrons bind to make an electrically charged scalar…

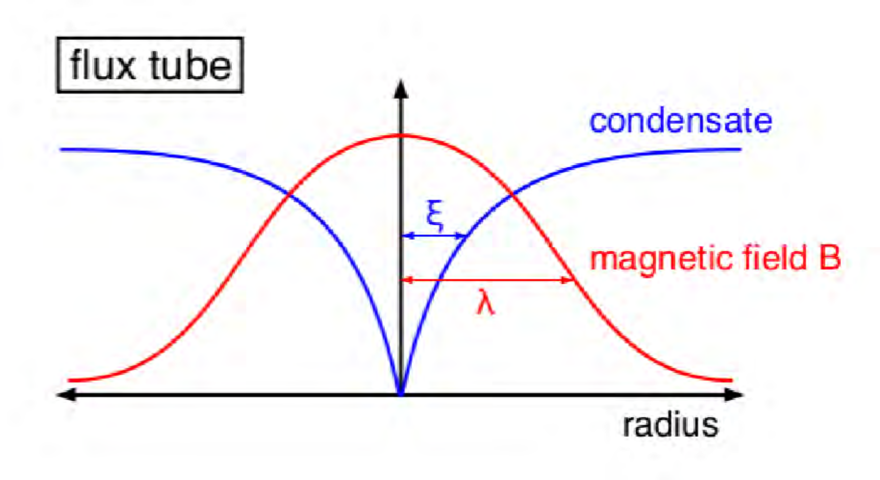
$$\mathcal{L}_i = \sum \left[D_\mu \varphi_i \left(D^\mu \varphi_i \right)^* - m_i^2 \left| \varphi_i \right|^2 - \lambda_i \left| \varphi_i \right|^4 \right]$$

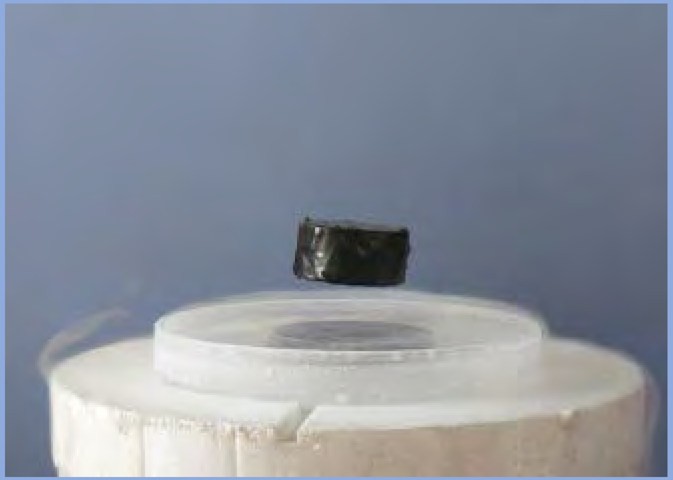
$$D_\mu \varphi_i = \left(\partial_\mu + i q_i A_\mu \right) \varphi_i$$



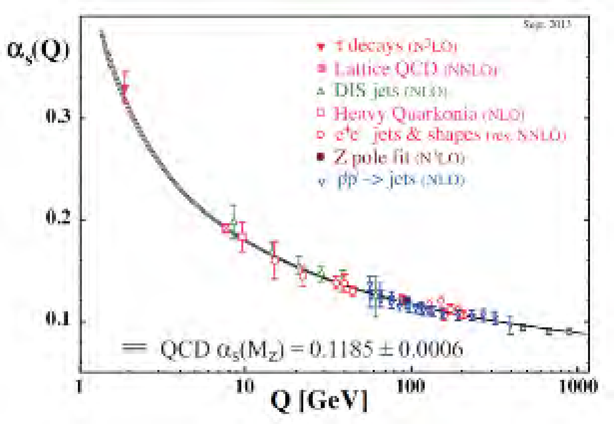
Which condenses giving a mass to the photon – electric fields are excluded from the material….

Flux tubes exist with the vev switching off in the middle allowing B – magnetic charges are confined…





Are chiral symmetry breaking and confinement part of the same dynamics in QCD or two separate dynamics that occur near the same strong coupling scale?



The usual argument to link the two is that a particle in a box has energy by the Uncertaintly Principle

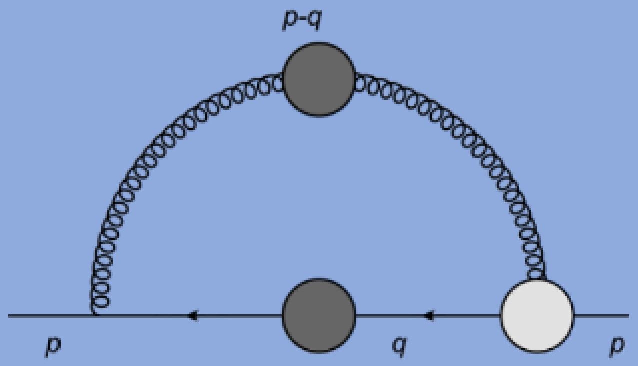
$\Delta\ p\ \ \Delta x\ \sim\ h/2\pi$

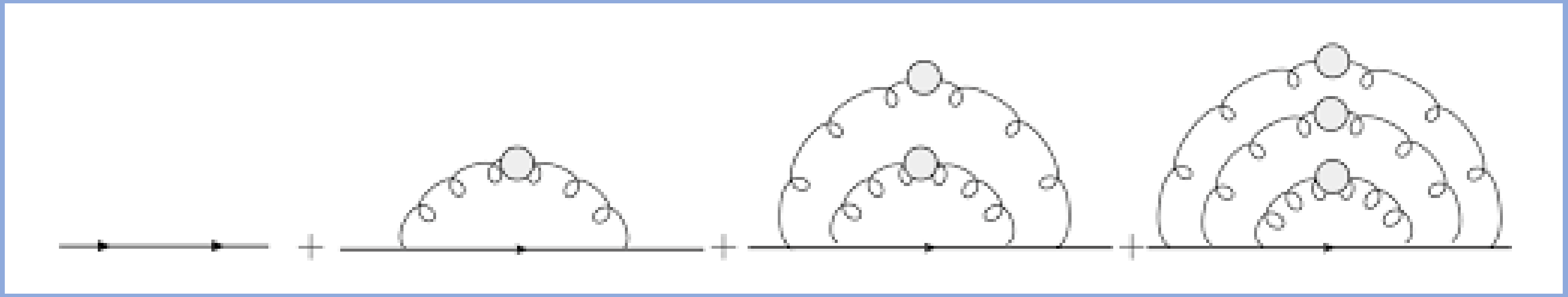
Yet this only implies confinement needs chiral symmetry breaking…

And quarks in pions are confined yet the pion is massless

1980s Gap Equations Ignored Confinement:

Cohen and Georgi, Nucl. Phys. B 314 (1989) 7





The computations showed a mass forms if γ (anomalous dimension of $\bar{q}\,q$) > 1.

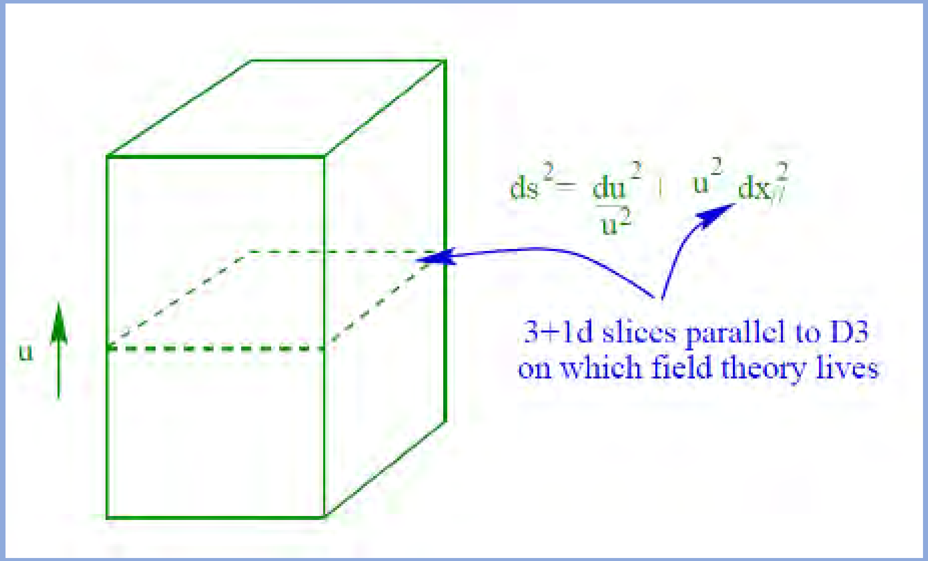
$$m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + h.c.)$$

At one loop: $\gamma = \dfrac{3\ C_2(R)}{2\pi}\ \alpha$

$C_2(R)$ is the quadratic Casimir of the representation.

Holography Supports This Criteria:

Matti Jarvinen, Elias Kiritsis. 1112.1261. Raul Alvares, Nick Evans, Keun-Young Kim 1204.2474



Dilatations in conformal $\mathcal{N} = 4$ SYM:

$$\int d^4x \; \partial^\mu \phi \partial_\mu \phi, \qquad x \to e^{-\alpha} x, \qquad \phi \to e^{\alpha} \phi$$

Become spacetime symmetry of AdS

$$u \to e^{\alpha} u$$

u is a continuous mass dimension

$\to$ RG Scale

A scalar in AdS represents the dimension 3 quark condensate…

If the dimension falls to 2 the BF bound is violated in AdS. ie $\gamma = 1$.

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

Eg B field induced chiral symmetry breaking:

Veselin G. Filev, Clifford V. Johnson, R.C. Rashkov, K.S. Viswanathan. hep-th/0701001

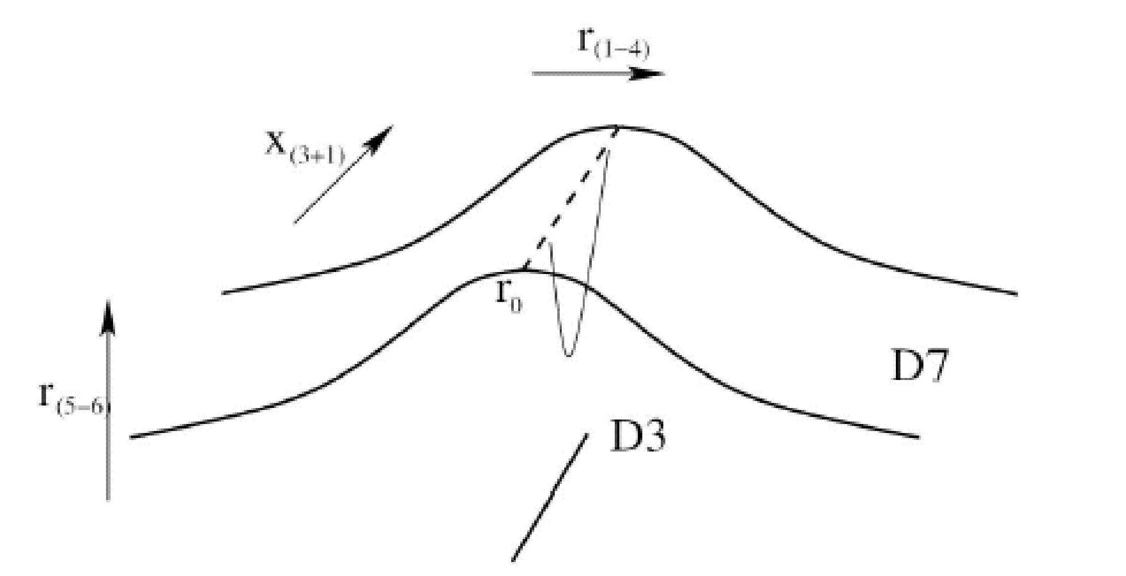
In a theory that is N=4 glue + N=2 quark multiplets + B field the chiral condensate is described by a field L

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

$$\beta = \sqrt{1 + \frac{B^2 R^4}{(\rho^2 + L^2)^2}}$$

Here ρ is r/u

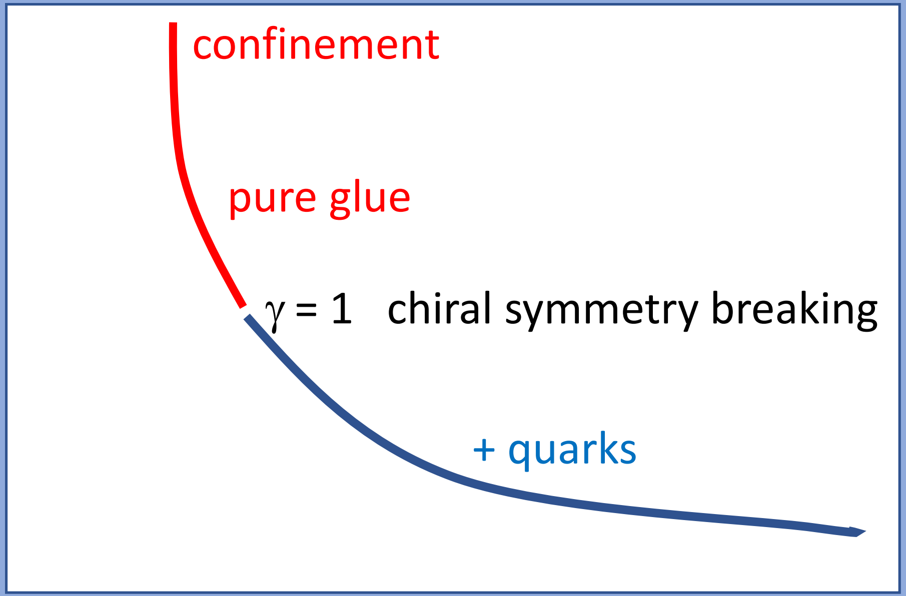
If you expand around L= 0 the L^2 term is rho dependent and violates the BF bound causing condensation.



There's no confinement in this model (for infinitessimal+ T).

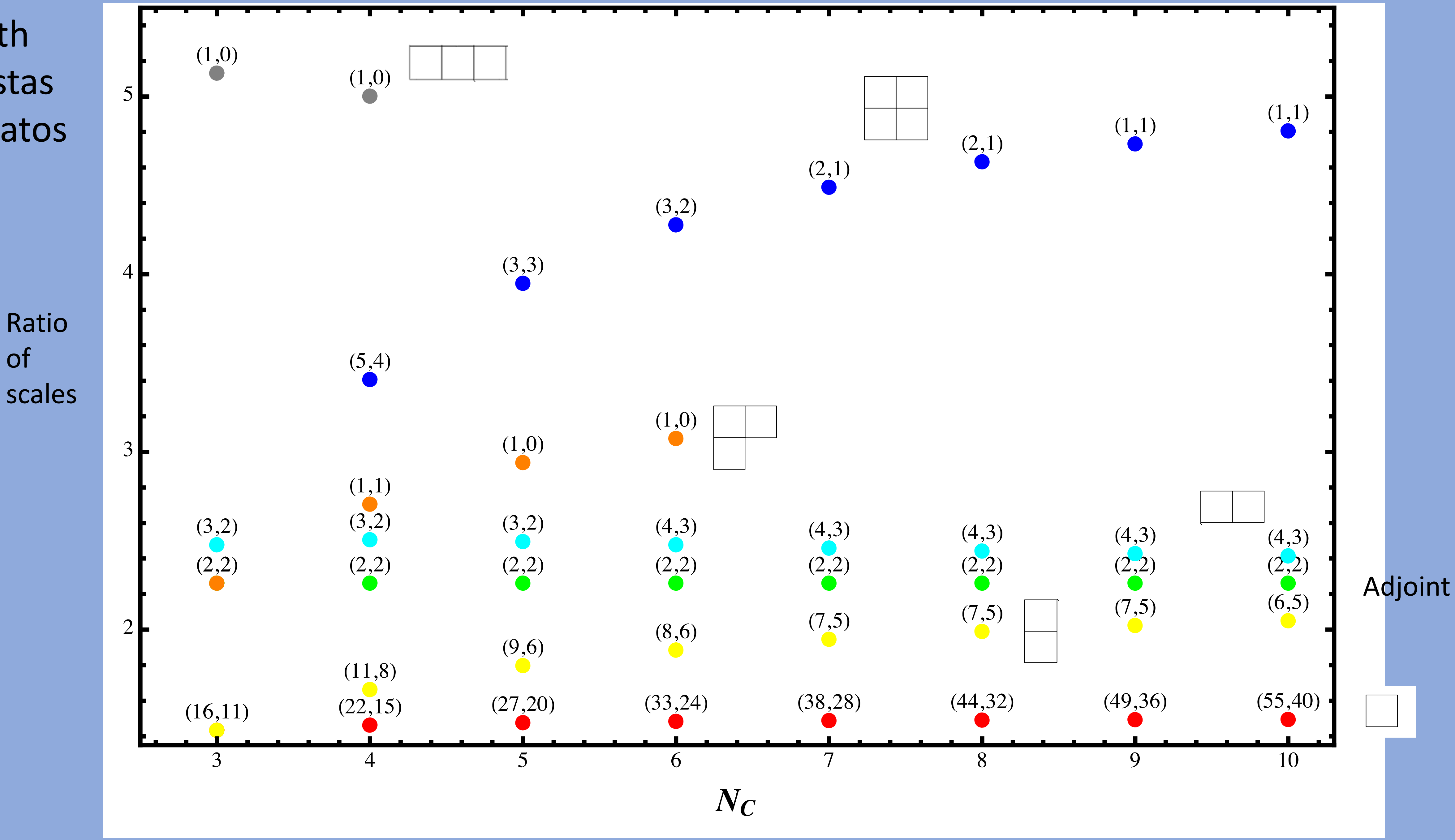
Splitting the scales:

We run the coupling with glue + quarks until $\gamma = 1$ .. then just run with quarks to the Landau pole…



In QCD these scales are very close – but can we separate them with different choices of quark representation?

With Kostas Rigatos



A Challenge to the Lattice:

EG SU(5) with 2 staggered quarks in the 50 rep could be simulated on the lattice and should have a factor of 4 between the scales….

Introduce finite T and there should be a deconfined massive quark phase…

χSBing scale

Temperature scale

confinement scale

It's possible that all these theories have such a phase at just the right the right T, mu…

Phase Diagram For Theories with only χSBing:

N=4 glue + N=2 quark multiplets + B field. (no susy, no conformality)

In the gravity dual. T -> blackhole in centre of geometry

μ -> extra AdS field At

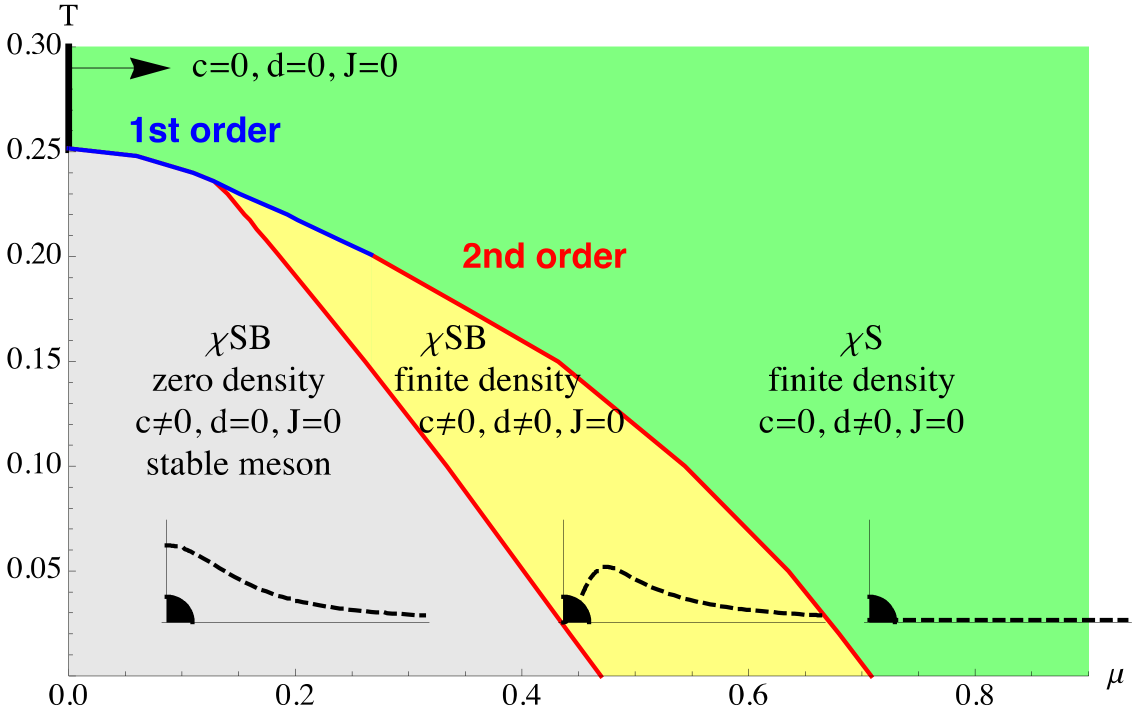
$$\mathcal{L} = -T_7 \rho^3 \left(1 - \frac{w_H^4}{w^4}\right) \sqrt{\left(1 + \frac{w_H^4}{w^4}\right)^2 + \frac{R^4 B^2}{w^4}}$$

$$w = \sqrt{\rho^2 + L^2}$$

$$\sqrt{1 + (\partial_\rho L)^2) - \frac{w^4(w^4 + w_H^4)}{(w^4 - w_H^4)^2}(2\pi\alpha' A_t)^2}$$

Holographic Description of the Phase Diagram of a Chiral Symmetry Breaking Gauge Theory

Nick Evans, Astrid Gebauer, Keun-Young Kim, Maria Magou. e-Print: 1002.1885 [hep-th]

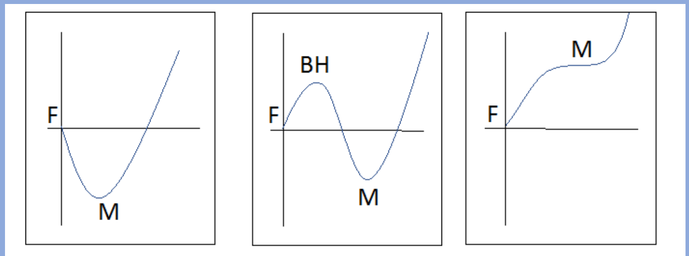


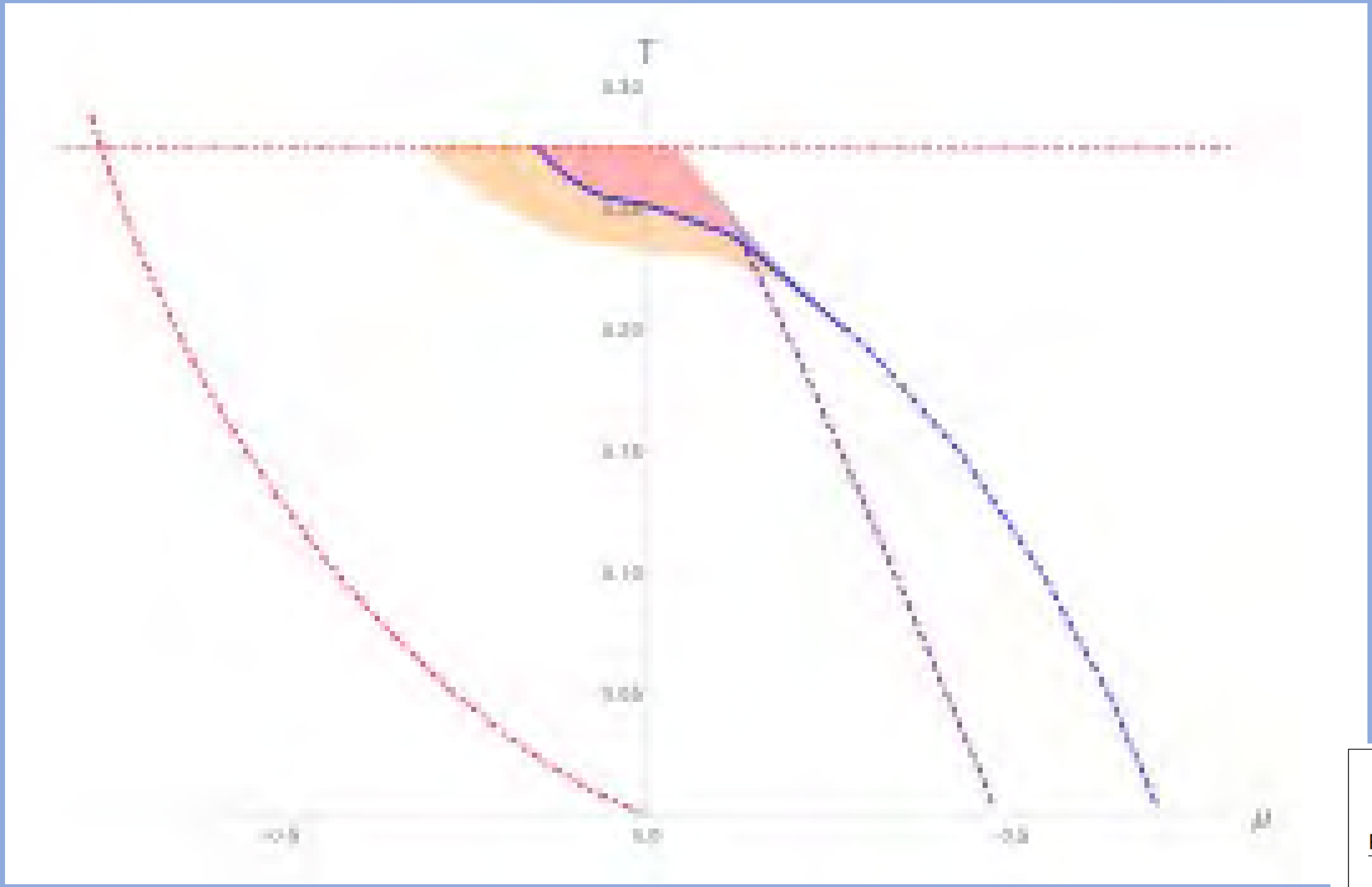
(a) T-μ phase diagram. The inset diagrams are representative probe brane embeddings (dotted lines), where a black disk represents a black hole.

- Low energy d=0, χSBing phase
- High energy dense quark phase
- Intermediate dense, massive quark phase
- First and second order transitions
- Critical point

The dense massive quark phase has to exist if the transitions are second order

2020 NE & Mathew Russell



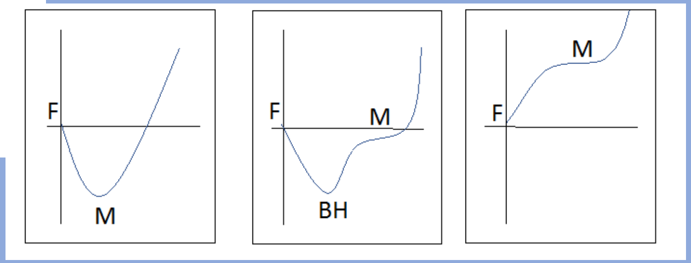


We’ve extended to imaginary chemical potential…

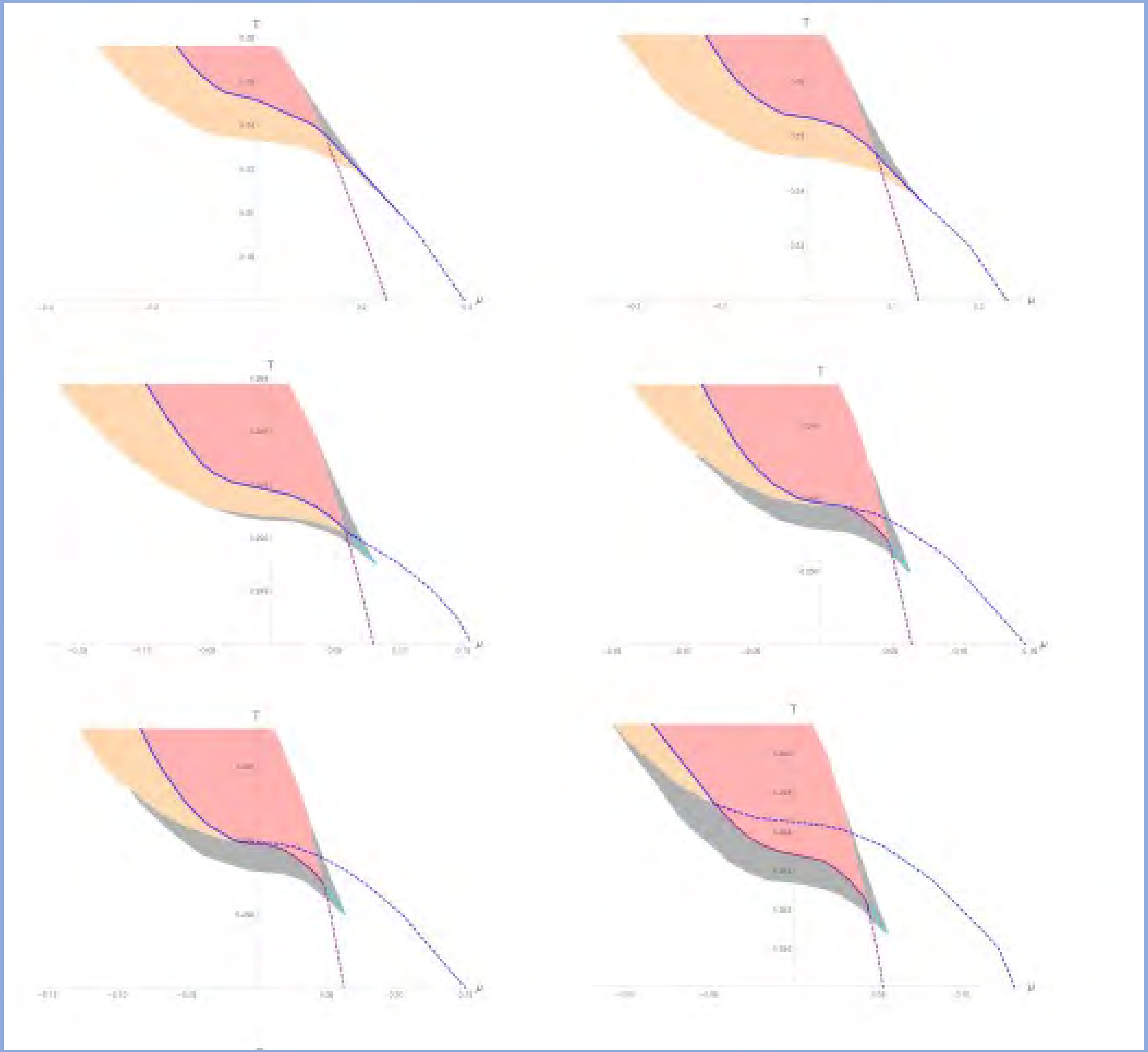
We’ve added “spinodal” regions with metastable vacua…

The second order lines are natural continuations of the boundaries of the spinodal regions

Note the arrows pointing to the critical points!



We can distort the black hole horizon – not really kosher – and move the critical point into the imaginary mu plane!

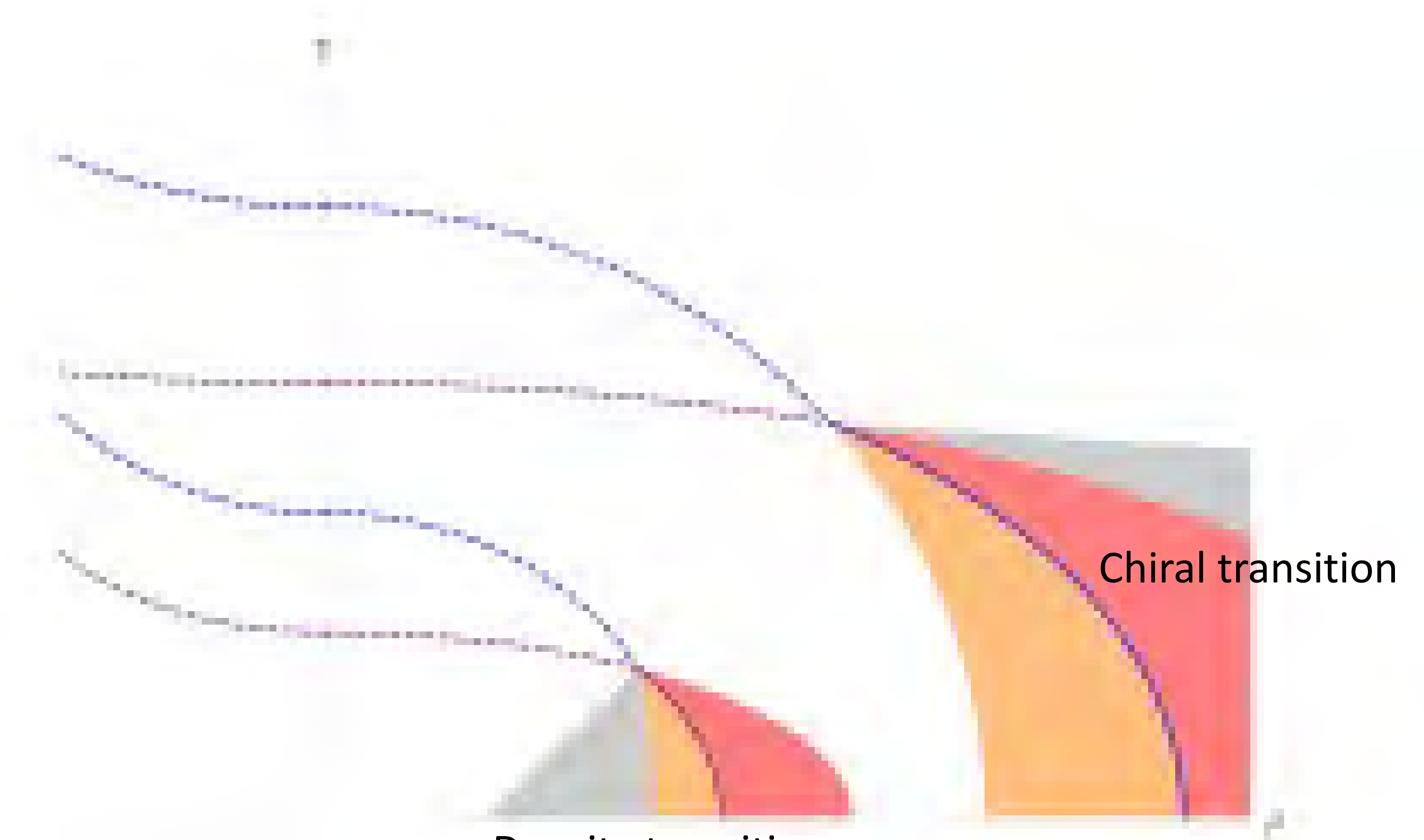


Lessons for QCD(?):

Cross over region with deconfined massive quarks – or are they confined?

Are there sub-transitions within crossover?

Could metastable region spill over to low mu?

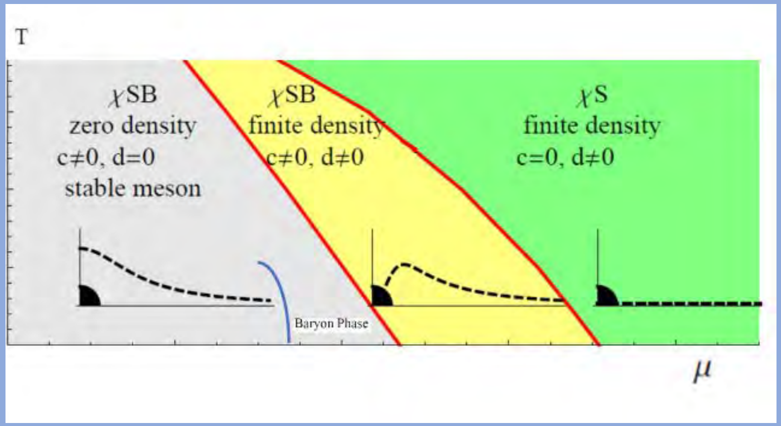


Density transition
-> liquid- gas nuclear transition?

Neutron Star Physics:

Carlos Hoyos, David Rodríguez Fernández, Niko Jokela, Aleksi Vuorinen 1603.02943

Kazem Bitaghsir Fadafan,Jesus Cruz Rojas, Nick Evans 1911.12705 [hep-ph]



Here I'm going to treat the deconfined massive phase as a real thing… and use holography to describe the transition to that….

So steal the nuclear liquid-gas transition from the literature.

K. Hebeler, J. M. Lattimer, C. J. Pethick and A. Schwenk, 1303.4662

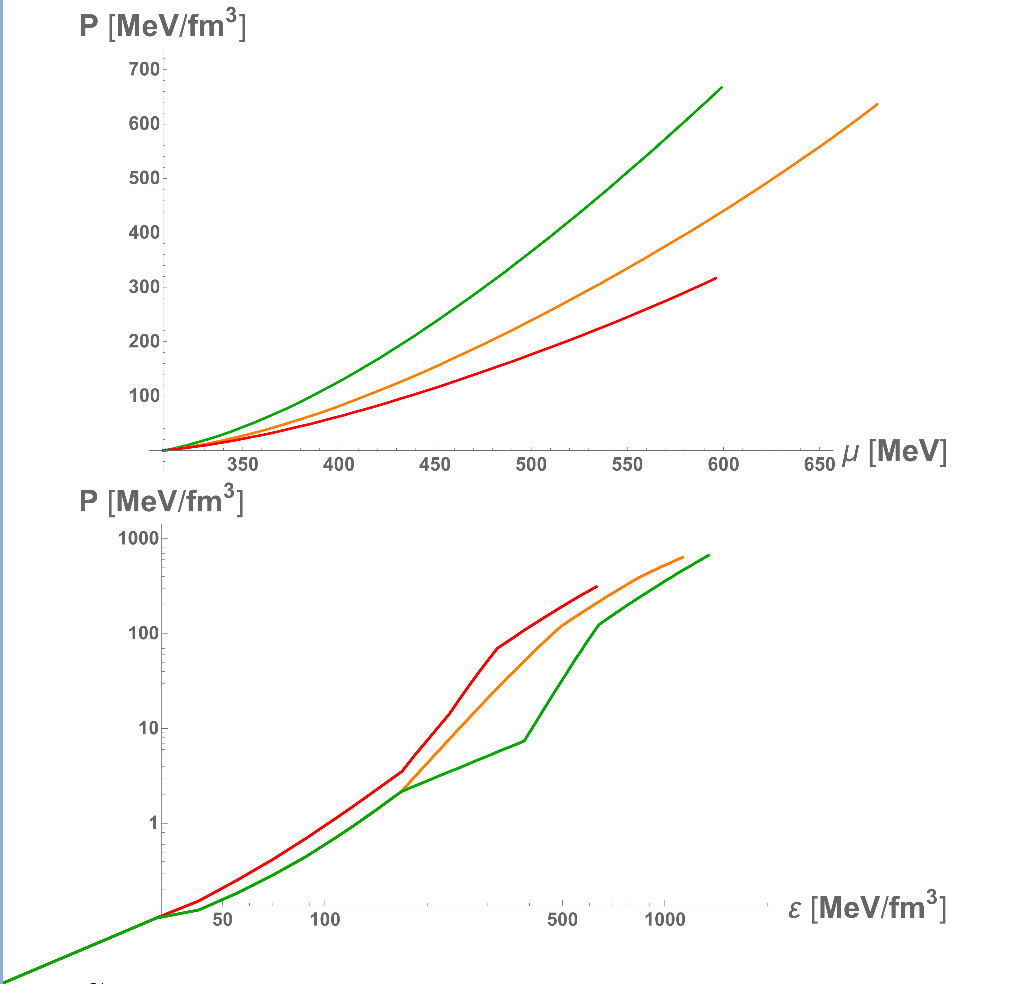


FIG. 2: *Data for the nuclear phase taken from [32]: we show both the pressure versus chemical potential and energy density. The Green line represents a soft EoS, the orange a medium EoS and the red line a stiff EoS.*

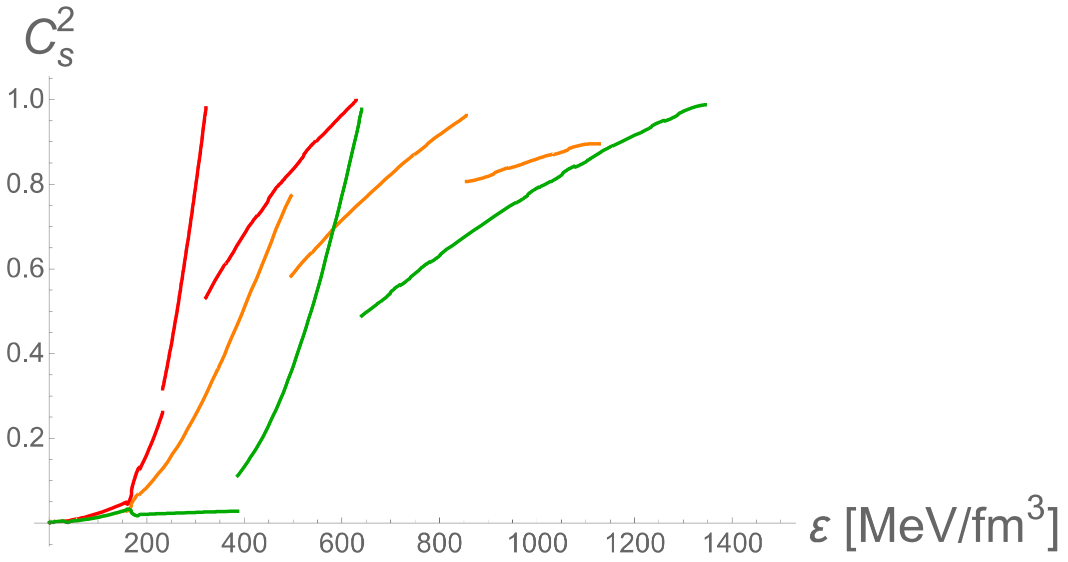


FIG. 3: *Speed of Sound squared as a function of the energy density for nuclear matter [32]. The different coloured lines represent nuclear matter from EFT EoS; (Green) soft EoS, (orange) medium EoS and (red) stiff EoS.*

TOV

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

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

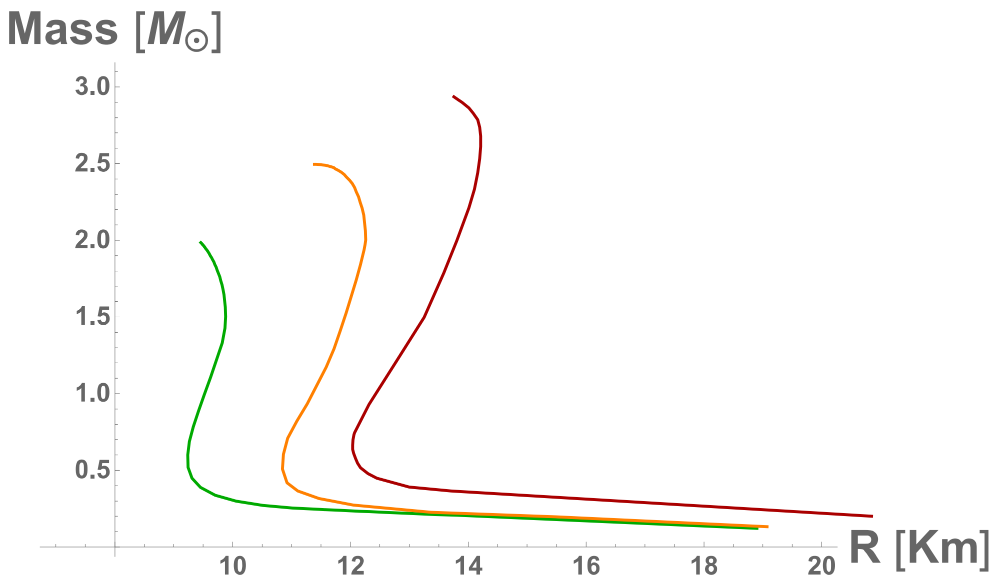


FIG. 10: *Mass of the Neutron Star (in units of solar mass $M_\odot$) as a function of its radius (in kilometres) for nuclear matter from EFT EoS. The Green line represents a soft EoS, the orange a medium EoS and the red line a stiff EoS.*

The Holographic Model

UV $\gamma = 0$

IR

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

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

$$\gamma = 1 - \sqrt{1 - \frac{4q}{(2-q)^2}}.$$

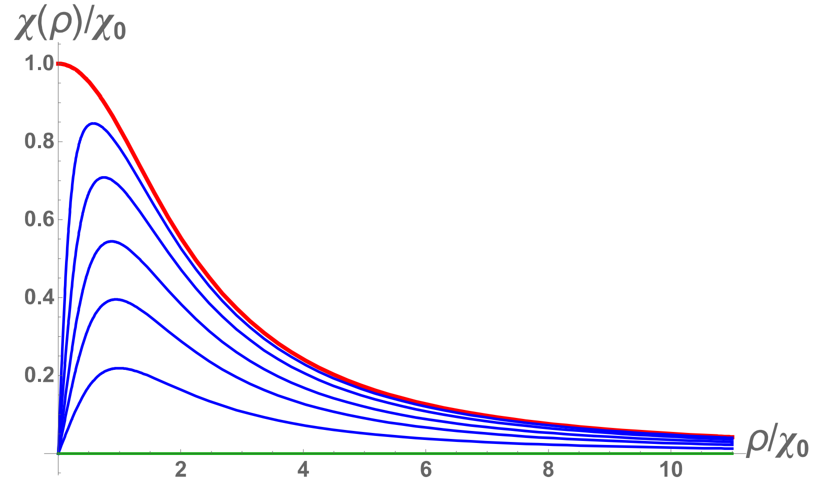
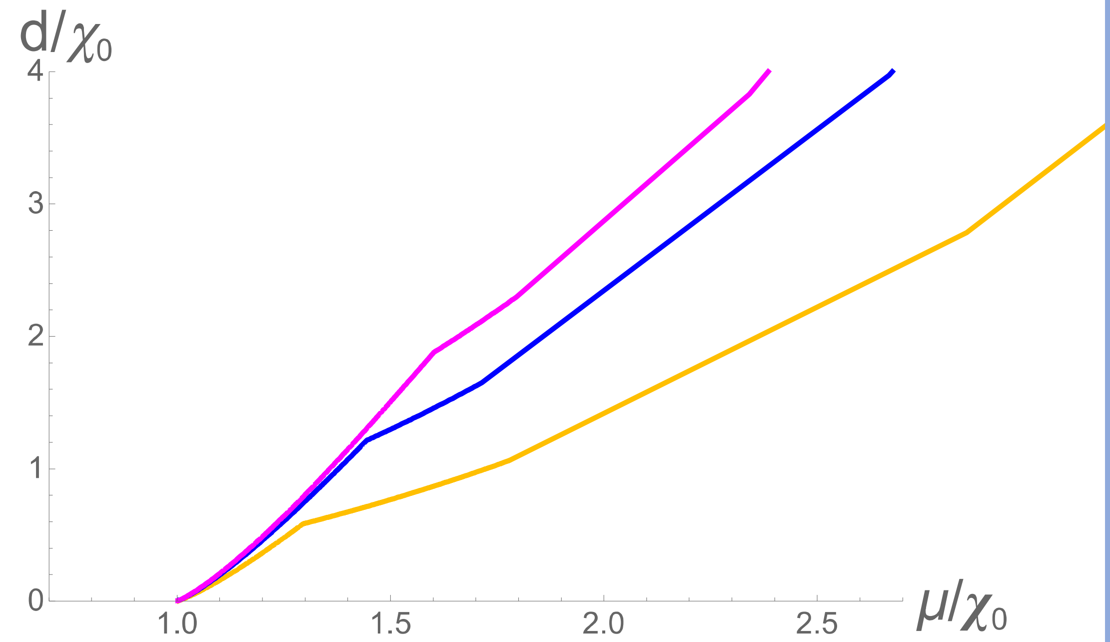


FIG. 5: *Solutions for $\chi(\rho)$ for the case $q = 1.8$ in equation (14) for $d = 0$ (Red), $d = 0.005, 0.015, 0.075, 0.15, 0.29$ (from top to bottom in Blue) and $d = 0.501$ (Green).*



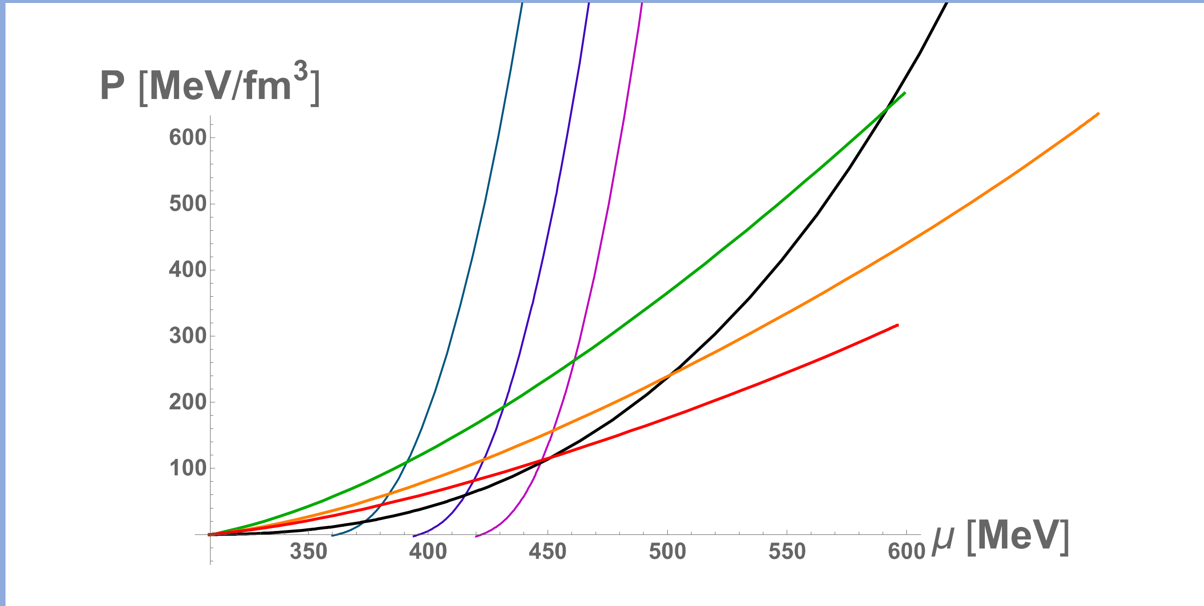
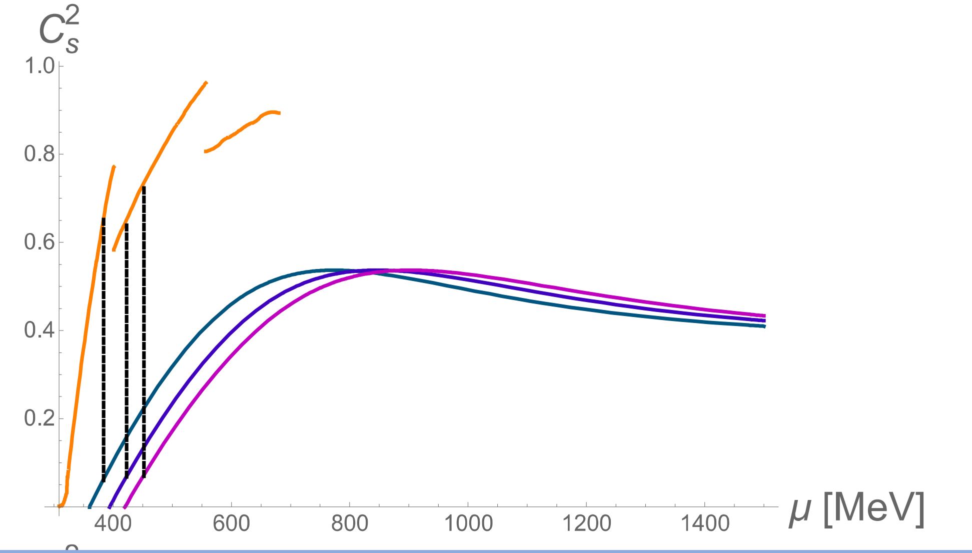
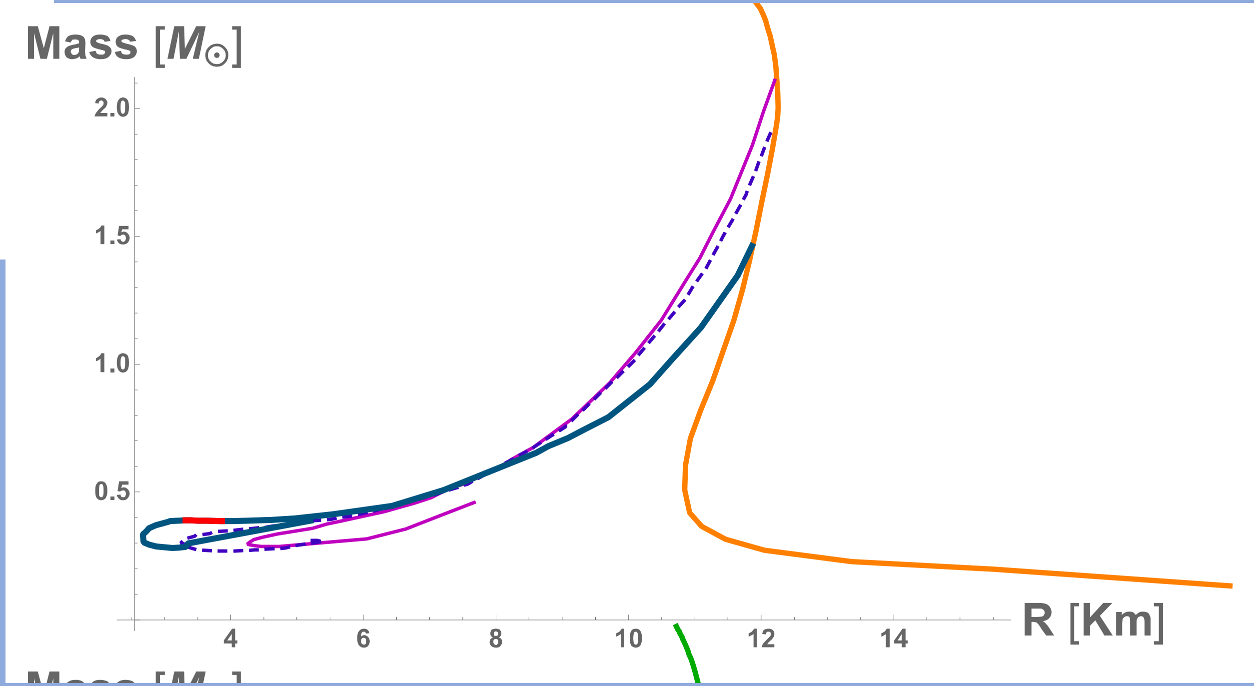


FIG. 12: *Transition from nuclear to quark matter for the case of q=1.8. The Black line correspond to the case of a constant dilaton and the green, orange and red curves represent nuclear matter as in Fig 4. The dark teal curve corresponds to* $\chi_0 = 360$ *MeV, the purple curve corresponds to* $\chi_0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





So can get some exotic small stars but not at the same time as 2 solar mass neutron stars… need something to strengthen the quark phase even more eg confinement or CSC?

Future

Encourage our lattice colleagues to investigate

SO(N) and Sp(N) gauge theories? Use the conformal window?

Adding confinement to our chiral symmetry breaking holographic dual (eg by adding compact spatial directions) – does confinement enhance chiral symmetry breaking?

Can we add confinement/color superconductivity and further harden neutron star cores?

How does B field effect the separation?