Neutron stars and speed limits in AdS/CFT

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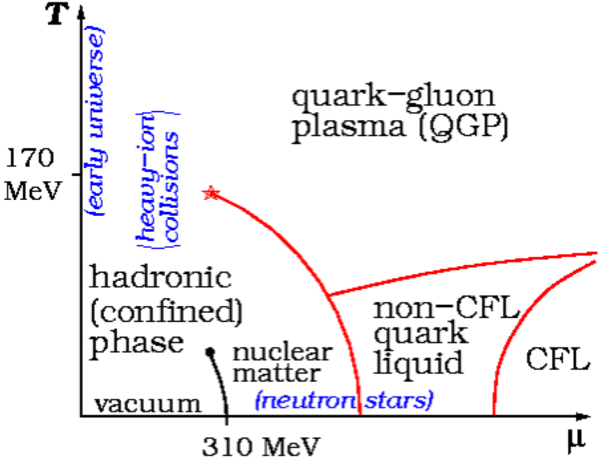
Motivation

QCD phase diagram

Finite density region mostly outside present first principle methods



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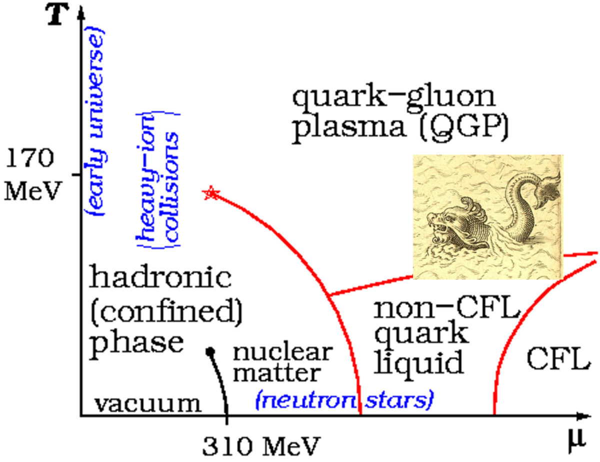
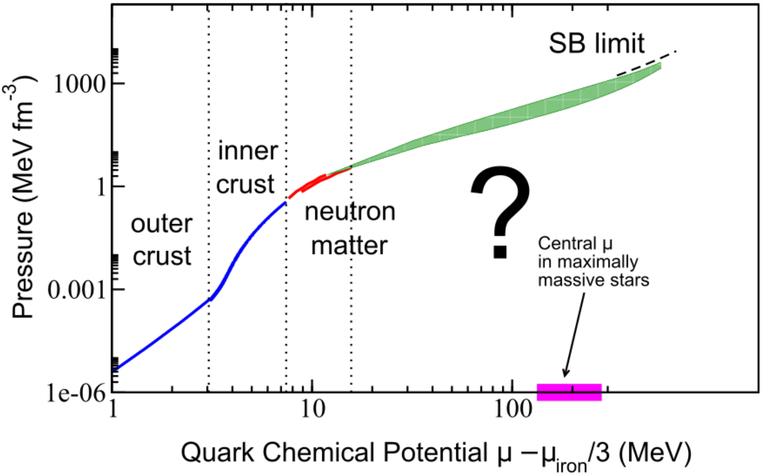


Uncertainty in EoS



(From [Kurkela, Fraga, Schaffner-Bielich, Vuorinen 1402.6618])

What can we say about strongly coupled gauge theories at finite density?
(Like QCD inside neutron stars)

Two possibilities:

- Confined phase: nuclear matter (tough because of large N_c)
  Solitons in Sakai-Sugimoto [Kim, Sin, Zahed '06; Bergman, Lifschytz, Lippert '07; Rozali, Shieh, Van Raamsdonk, Wu '07; Kim, Sin, Zahed '07 Kaplunovsky, Melnikov, Sonnenschein '12; Li, Schmitt, Wang '15; Rho, Sin, Zahed '09] and D3/D7 [Ammon, Jensen, Kim, Laia, O'Bannon '12]
- Deconfined matter: well studied (for instance D3/D7 [Kobayashi, Mateos, Matsuura, Myers and Thomson '06])

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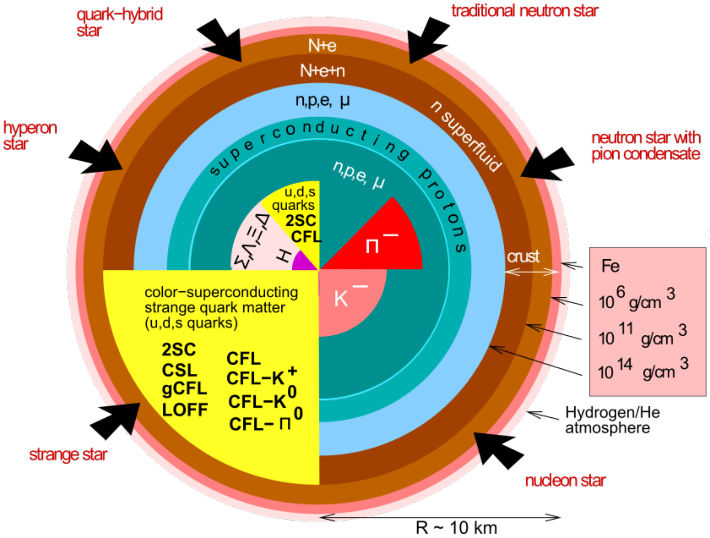
Two more concrete questions:

- Is there deconfined matter inside neutron stars?
- If we use AdS/CFT to describe it do we get sensible results?

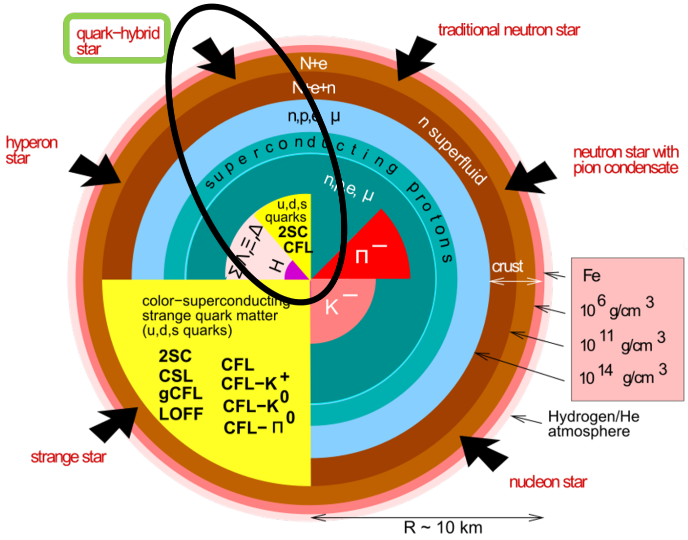
Quark matter in neutron stars

Possible neutron star structures



(From [Weber astro-ph/0407155])

Possible neutron star structures



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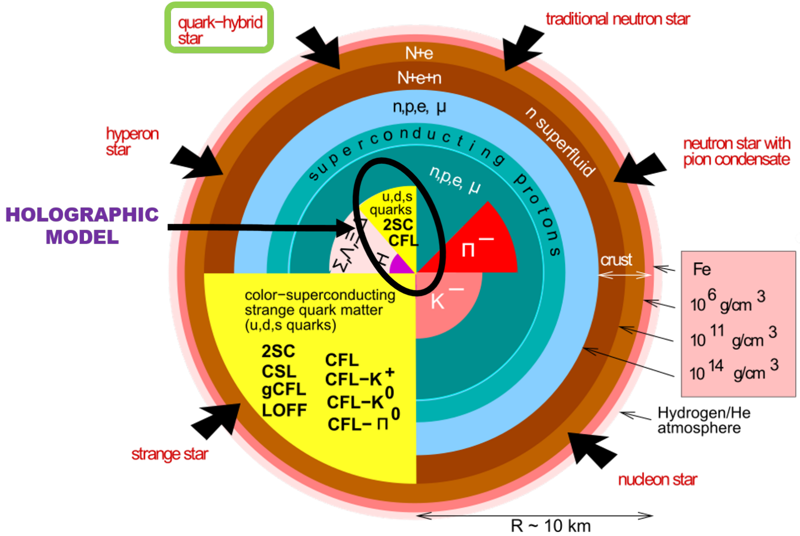

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TOV equation

- Self-gravitating spherically symmetric object in hydrostatic equilibrium
- Metric

$$ds^2 = -e^{\nu(r)}dt^2 + \frac{dr^2}{1 - \frac{2M(r)}{r}} + r^2 d\Omega_2^2$$

- Structure determined by Tolman-Oppenheimer-Volkoff equation

$$P'(r) = -\frac{1}{r^2}\frac{\varepsilon(r) + P(r)}{1 - \frac{2M(r)}{r}}\left(M(r) + 4\pi r^3 P(r)\right)$$

and

$$\nu'(r) = -\frac{2P'(r)}{\varepsilon(r) + P(r)}, \quad M'(r) = 4\pi r^2 \varepsilon(r)$$

- Boundary condition on the surface $P(r = R) = 0$
- Equation of State $P(\varepsilon)$

Holographic model

- $\mathcal{N} = 4$ $SU(N_c)$ SYM plus $N_f \ll N_c$ fundamental hypers
- Dual: $AdS_5 \times S^5$ with N_f probe D7 branes
- Pressure ($\gamma \simeq 1.4$):

$$P = \frac{N_c N_f}{4\gamma^3 \lambda_{YM}} (\mu_q - m)^4 + O(\mu_q^3 T, T^4).$$

[Karch, O'Bannon '07]

- EoS:

$$\varepsilon = \mu_q \frac{\partial P}{\partial \mu_q} - P = 3P + \frac{\sqrt{2} m^2}{2\pi} \sqrt{P} \qquad v_s^2 = \frac{\partial P}{\partial \varepsilon} < \frac{1}{3}$$

Extrapolation to QCD

- $N_c = N_f = 3$
- Stefan-Boltzman value as $\mu_q \to \infty$

$$P \sim \frac{N_c N_f}{12\pi^2}\mu_q^4$$

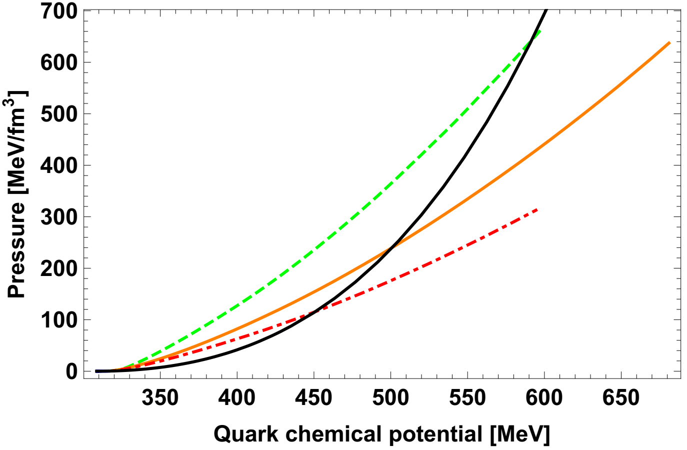
This fixes

$$\lambda_{YM} = \frac{3\pi^2}{\gamma^3} \simeq 10.74$$

- $P(\mu_q = m) = 0 \Rightarrow m \sim m_p/3$

$$m \simeq 308.55 \text{ MeV}$$

Comparison to nuclear matter models



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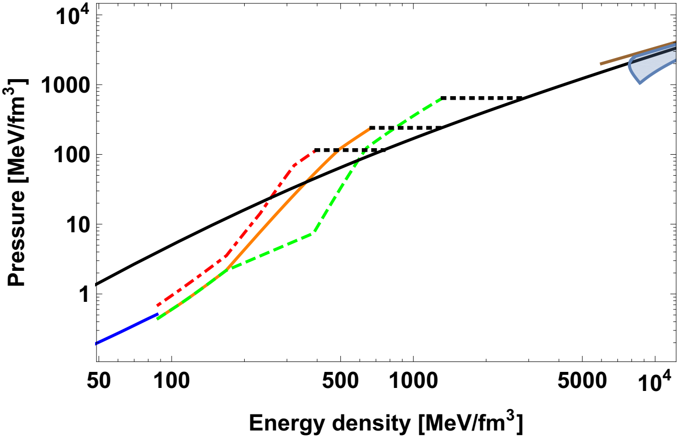
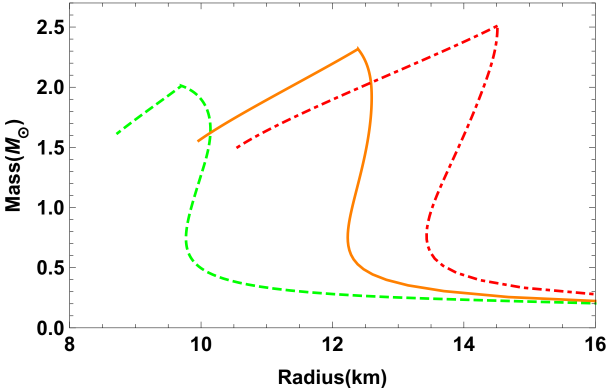


Mass versus Radius



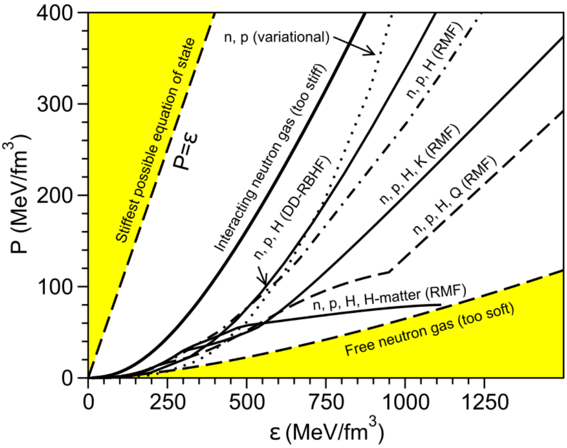
No stable star with pure quark matter at the core

Stiffness

- Compress the fluid $\Rightarrow$ increase energy density
- Pressure also increases $\Rightarrow$ opposes compression
- The larger $\frac{\partial p}{\partial \varepsilon}$ is, the less compressible is the fluid
- The EoS is 'stiffer' or 'softer' for larger or smaller speed of sound

$$v_s^2 = \frac{\partial p}{\partial \varepsilon}$$

Neutron stars EoS



(From [Weber astro-ph/0612054])

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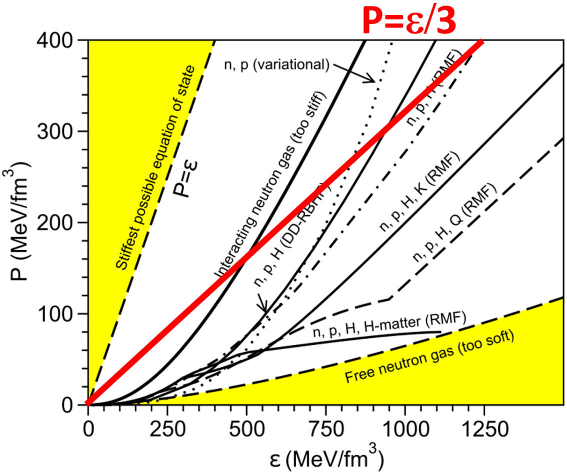

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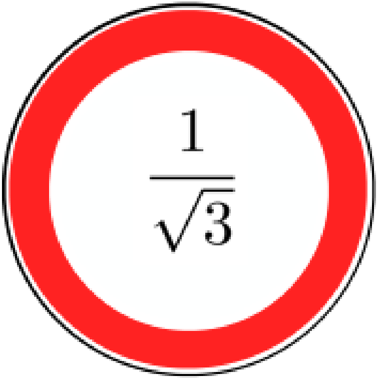
Speed limits in holographic models



Holographic models ($RG flows$)

- First computed in $\mathcal{N} = 4$ SYM [Policastro, Son, Starinets '02]

$$v_s = \frac{1}{\sqrt{3}}$$

- Masses for fermions (m_f) and scalars (m_b) ($\mathcal{N} = 2^*$)
  [Benincasa, Buchel, Starinets '05]

$$v_s = \frac{1}{\sqrt{3}}\left(1 - \frac{\left[\Gamma\left(\frac{3}{4}\right)\right]^4}{3\pi^4}\left(\frac{m_f}{T}\right)^2 - \frac{1}{18\pi^4}\left(\frac{m_b}{T}\right)^4 + \cdots\right)$$

- Klebanov-Strassler ($\mathcal{N} = 1$): logarithmic running with scale Λ
  [Aharony, Buchel, Yarom '05]

$$v_s^2 = \frac{1}{3} - \frac{2}{9}\frac{1}{\log\frac{T}{\Lambda}} + \cdots$$

Holographic models ($RG flows$)

For a class of models:
relevant deformation ($\Delta < 4$) of a CFT$_4$ $=$ minimally coupled scalar field

$$S = \frac{1}{2\kappa^2}\int d^5x\left(R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right)$$

At high temperatures the speed of sound is below the conformal value [Cherman, Cohen, Nellore '09; Hohler, Stephanov '09]

$$v_s^2 = \frac{1}{3} - C(\Delta)(LT)^{\Delta-4} + \cdots$$

Holds for several scalars [Cherman, Nellore '09]

Conjecture: universal bound

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Further evidence: D-brane intersections

D-brane intersections

- $D3/D7$: flavor mass m, condensate c [Mateos, Myers, Thomson '07]

$$v_s^2 - \frac{1}{3} \simeq \frac{\lambda_{YM}}{24\pi^2}\frac{N_f}{N_c}\left(mc + \frac{1}{3}mT\frac{\partial c}{\partial T}\right) < 0.$$

- $D3/D7$ (flavors) at $T = 0$, $\mu \neq 0$
  Massless [Karch, Son, Starinets '08] and massive [Kulaxizi, Parnachev '08]

$$v_s^2 = \frac{\mu^2 - m^2}{3\mu^2 - m^2} \leq \frac{1}{3} \quad (v_s^2 < 1)$$

The bound in neutron stars

- Neutron stars: largest mass depends on equation of state
- Observations find up to $\sim 2M_\odot$ [Demorest, Pennucci, Ransom, Roberts, Hessels '10]
- Needs stiff equation of state
- Bound on the speed of sound strongly disfavored [Bedaque, Steiner '14]

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Can the bound be violated in holographic models?

- Yes, for non-relativistic models or not having a UV fixed point
- Large densities?
- Holographic nuclear matter?

Outlook

Quark matter at the core?

- Mixed phases
- Are there holographic models with stiffer EoS?

Nuclear matter

- Large-N_c makes baryonic matter difficult to study
- New approach needed?

Thank you!