# NEUTRON STARS IN HARD-WALL HQCD

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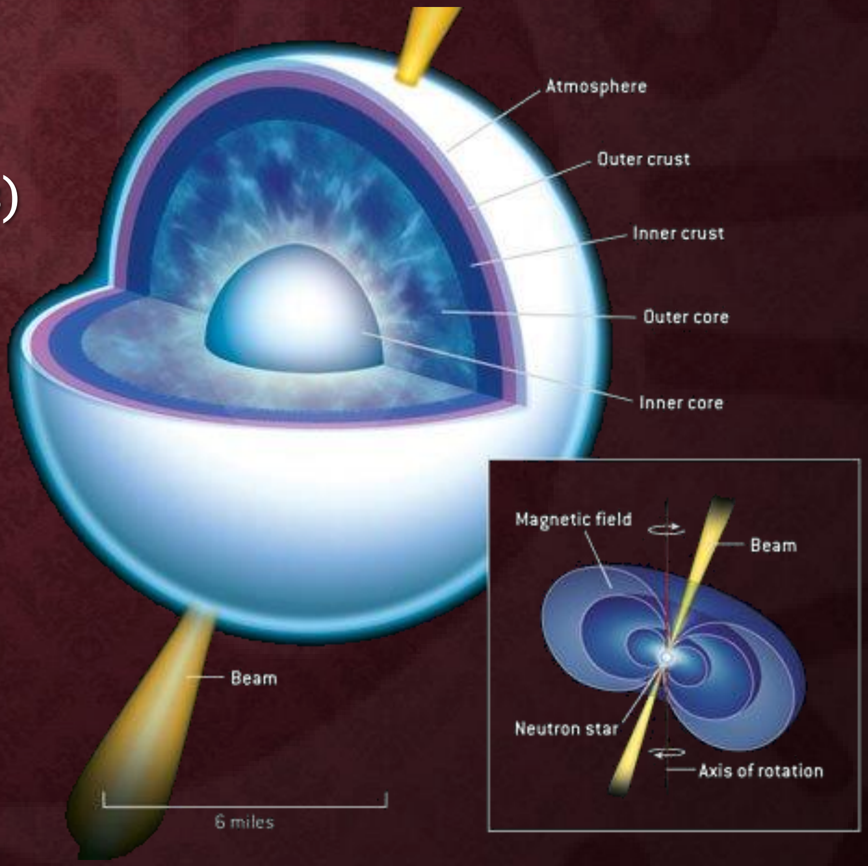
XVth Quark Confinement and the Hadron Spectrum Conference

University of Stavanger, August 1, 2022

# NEUTRON STARS

- Remnants of supernovae of supergiant stars.
- Most compact astrophysical objects (excluding BHs)
- Tolman-Oppenheimer-Volkov equations:

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




- PROBLEM: equation of state P(ε) for nuclear matter is not known at such densities.

# OBSERVATIONAL BOUNDS

- RADIUS:

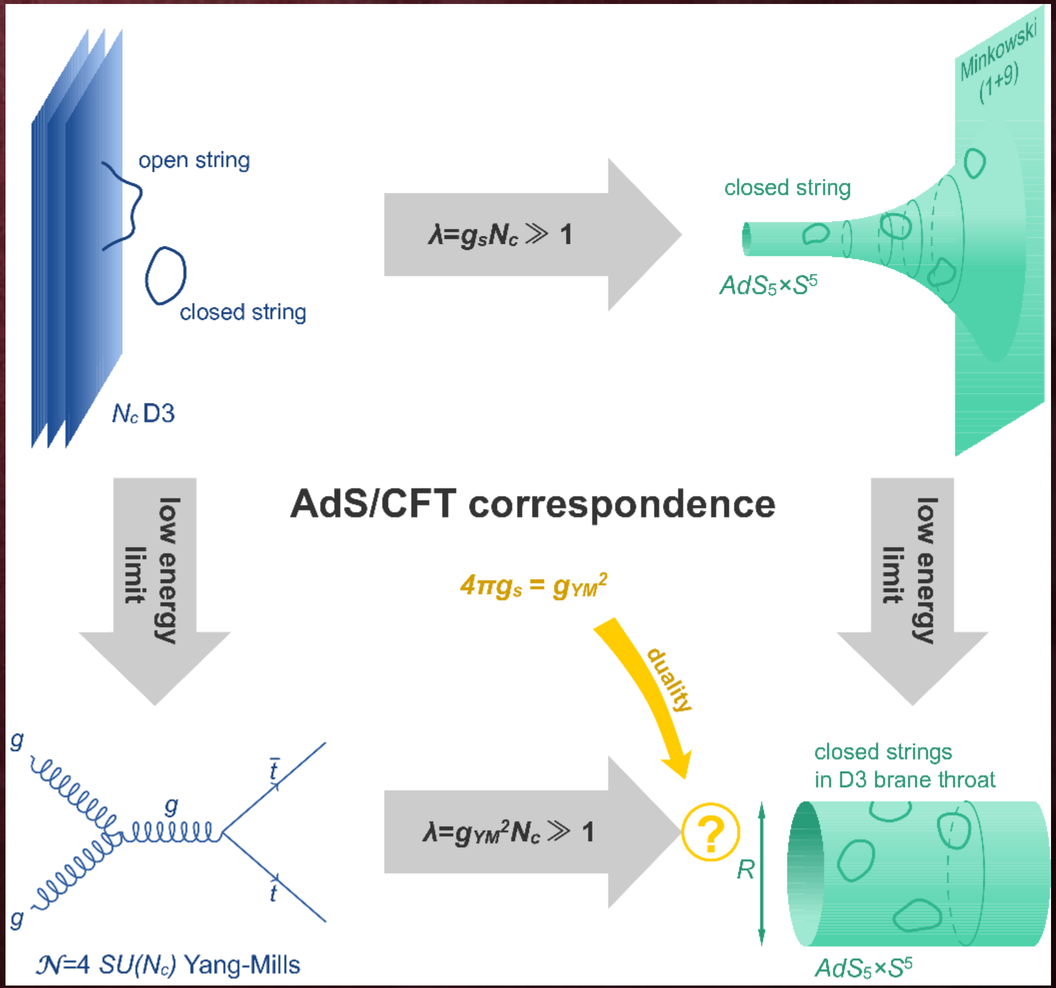
1. 11.4 to 13.7 km for stars of about 2.1 $M_\odot$ (PSR J0740+6620)
2. 12.2 to 16.3 km for stars of about 2.1 $M_\odot$ (PSR J0740+6620)
3. 11.5 to 13.9 km for stars of about 1.4 $M_\odot$ (J0030+0451)
4. 12.0 to 14.3 km for stars of about 1.4 $M_\odot$ (J0030+0451)

- MASS: maximum measured is $2.08 \pm 0.07\ M_\odot$ (PSR J0740+6620)

- TIDAL DEFORMABILITY: 70 to 620 for stars of about 1.4 $M_\odot$ (GW170817)

# HOLOGRAPHY IN ONE PAGE

- Duality between a QFT in flat spacetime and (Super-)gravity in higher dimension.
- Weak/Strong duality: can study strong interactions with weakly coupled gravity.
- Has natural field of application where LQCD and perturbative QCD fail to be precise: finite chemical potential, low energy.
- Top-down models: embedded into string theory.
- Bottom-up models: cook up a geometry and a handful of free parameters to fit data.



# SOME HOLOGRAPHIC RESULTS WITH NEUTRON STARS:

- D3-D7

1. [C. Hoyos, D. Rodríguez Fernández, N. Jokela, A. Vuorinen]
2. [K. B. Fadafan, J. C. Rojas, N. Evans]

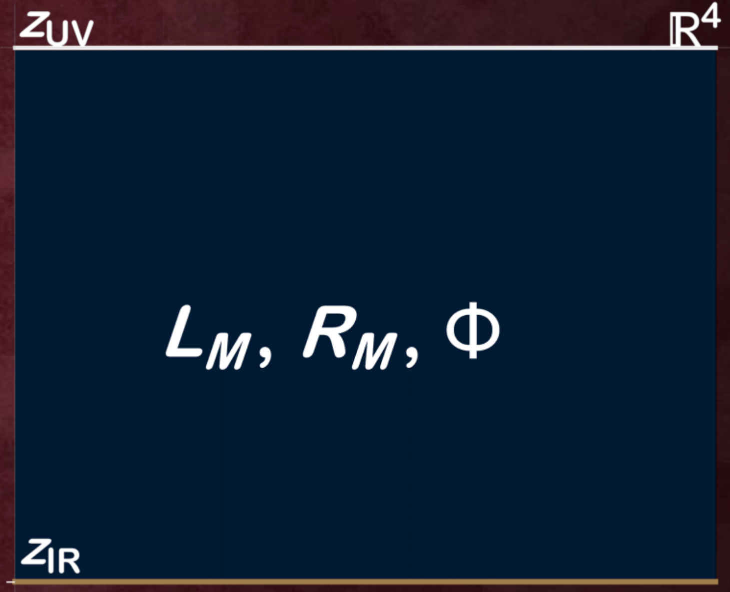
- D4-D8 [N. Kovensky, A. Poole, A. Schmitt]
- VQCD [N. Jokela, M. Järvinen, J. Remes]
- Hard-Wall [L.B., S. B. Gudnason, J. Leutgeb, A. Rebhan ]

MERGER EVENTS SIMULATIONS FROM HOLOGRAPHY:

THIS TALK

- VQCD [C. Ecker, M. Järvinen, G. Nijs, W. van der Schee]
- Hard-Wall [L.B., S. B. Gudnason, J. Leutgeb, A. Rebhan ]

# HARD-WALL MODEL (T=0)




- Metric from AdS$_5$ with artificial cut-off at $z = z_{IR}$:

$$ds^2 = \frac{L^2}{z^2}\left(dx_\mu dx^\mu - dz^2\right)$$

- YM+CS+Scalar action:

$$\begin{aligned}
S &= S_g + S_{CS} + S_\Phi, \\
S_g &= -\frac{M_5}{2}\int d^4x dz\, a(z)\left[\mathrm{Tr}\left(L_{MN}L^{MN}\right) + \frac{1}{2}\widehat{L}_{MN}\widehat{L}^{MN} + \{R \leftrightarrow L\}\right], \\
S_{CS} &= \frac{N_c}{16\pi^2}\int d^4x dz\, \frac{1}{4}\epsilon_{MNOPQ}\widehat{L}_M\left\{\mathrm{Tr}\left[L_{NO}L_{PQ}\right] + \frac{1}{6}\widehat{L}_{NO}\widehat{L}_{PQ} - \{R \leftrightarrow L\}\right\}, \\
S_\Phi &= M_5\int d^4x dz\, a^3(z)\left\{\mathrm{Tr}\left[\left(D_M\Phi\right)^\dagger D^M\Phi\right] - a^2(z)M_\Phi^2\,\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\right\},
\end{aligned}$$

# INFRARED POTENTIAL

- In hard-wall models the chiral condensate is encoded in the scalar:

$$\langle \Phi \rangle = M_q \frac{z}{z_{IR}} + (\xi - M_q) \left( \frac{z}{z_{IR}} \right)^3$$

- It is a free parameter of the theory: should originate from a boundary condition on the scalar.
- Infrared potential to stabilize its value:

$$\mathcal{S}_{IR} = \frac{m_b^2}{2} \xi^2 - \lambda \xi^4$$

- We are trading a free parameter for two, but we gain a dynamical ξ

# HOMOGENEOUS ANSATZ

- Assume homogeneity in $(x_1, x_2, x_3)$:

$$L_z = R_z = 0,$$

$$L_i = -R_i = -H(z)\frac{\tau^i}{2} \quad ; \quad \widehat{L}_0 = \widehat{R}_0 = \widehat{a}_0(z)$$

$$\Phi = \omega_0(z)\frac{\mathbb{1}}{2}.$$

- Good approximation for the core (high density)
- PDEs $\Longrightarrow$ ODEs
- Density encoded in IR boundary condition: $H(z_{IR} = 1) = \left(4\pi^2 d\right)^{\frac{1}{3}}$
- Chiral condensate encoded in IR boundary condition: $\omega_0(z_{IR} = 1) = \xi$
- Chemical potential encoded in UV boundary condition: $\widehat{a}_0(0) = \mu$

# FINITE TEMPERATURE

- Black-hole in AdS dual to thermal theory: $T = \frac{1}{\pi z_h}$

$$ds^2 = \frac{L^2}{z^2}\left(f(z)dt^2 - dx_i^2 - \frac{dz^2}{f(z)}\right), \qquad f(z) = 1 - \left(\frac{z}{z_h}\right)^4$$

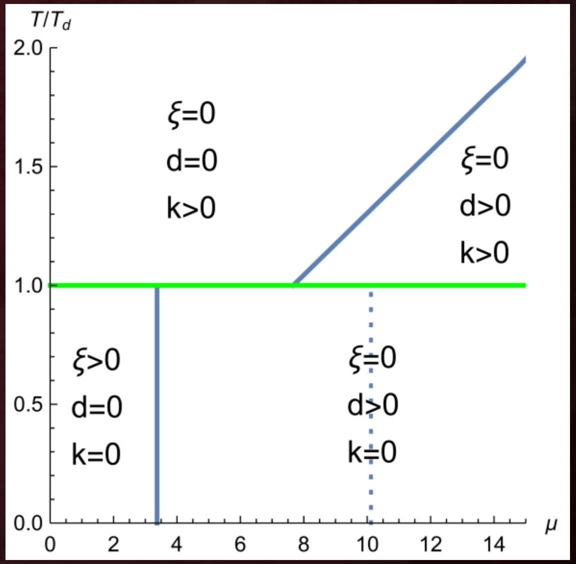
- When $z_h < z_{IR}$ :

1. Hard-wall disappears behind the horizon, deconfinement
2. Horizon sources a non-topological baryon density «k» $\Longrightarrow$ QGP

- Hawking-Page transition: happens at $T_d = \frac{2^{1/4}}{\pi z_0}$ :

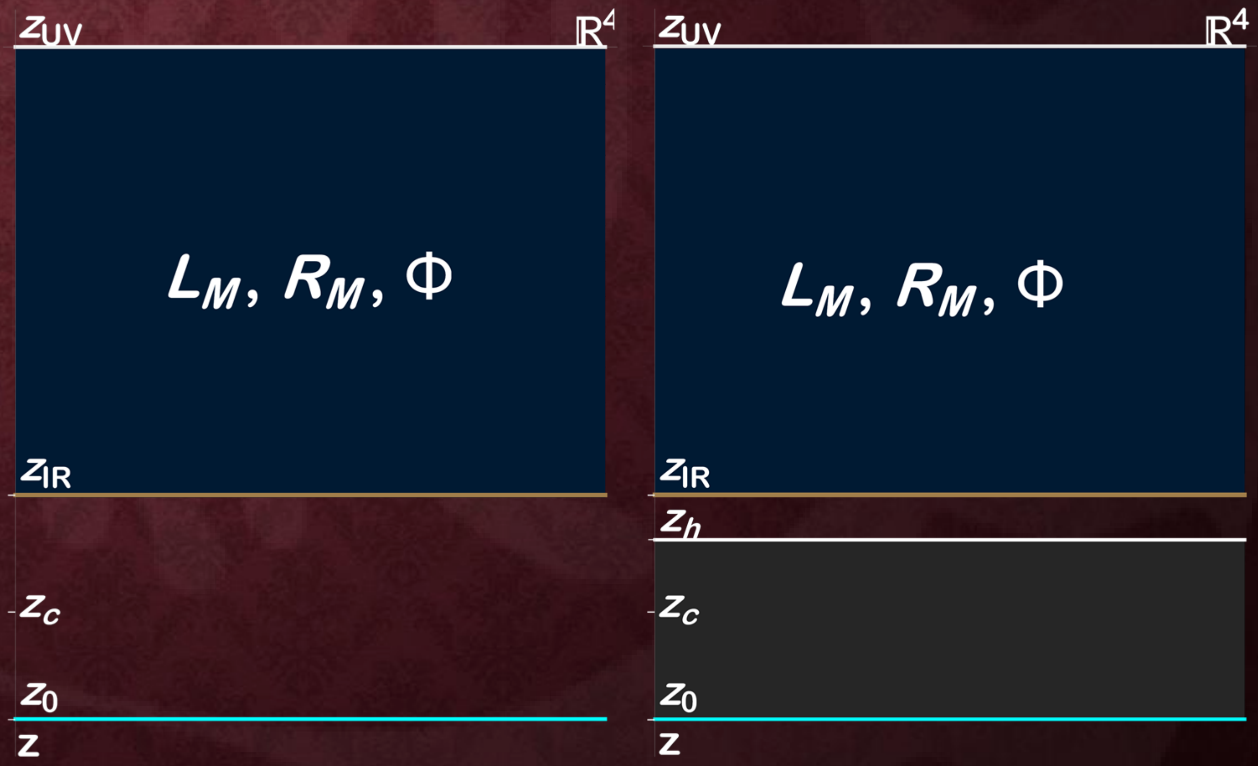
1. Temperature dependence only for deconfined phase
2. Deconfinement and chiral symmetry restoration coincide

TRIVIAL PHASE DIAGRAM



# DOUBLE HARD-WALL

- We introduce a second cut-off $z_0$ :
- If $z_0 > 2^{1/4} z_{IR}$ , HP transition can happen for $T_d < T_c$
- Lowers $T_d$: effectively it is the same as treating $T_d$ as a free parameter
- Artificial construction? Present in top-down models (D4-D8)
- No effects on neutron stars (T=0)
- Richer phase diagram



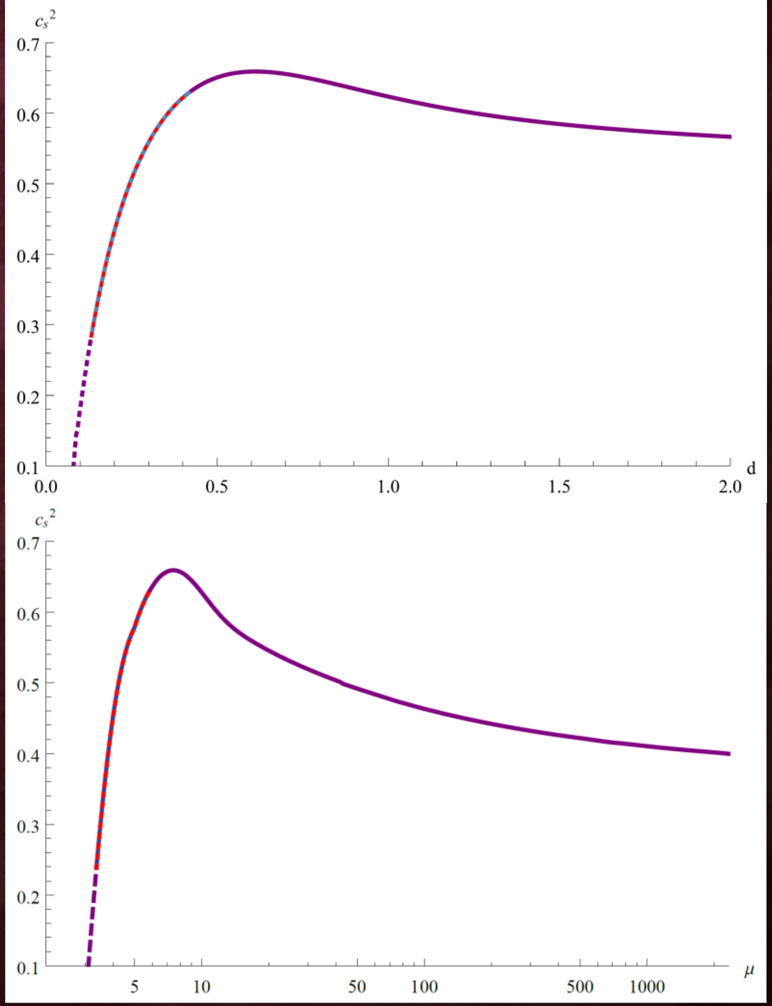
# SPEED OF SOUND

- Depends only on M5, NOT on other free parameters.
- Not monotonic, has a peak above the sound barrier.
- Reaches $c^2=0.659$ $\Longrightarrow$ The highest we encountered among holographic models.
- Asymptotically falls down to the conformal value:

$$c_s^2 = 1/3$$

$$\Downarrow$$

BUT perturbative QCD should take over and eventually the curve should approach 1/3 from below.



# FIT CHOICES

WE EMPLOYED TWO DIFFERENT SETS OF PARAMETERS:

- FIT A: $L^{-1} = 186\mathrm{MeV} \quad ; \quad \lambda = 2 \times 10^{-3} \quad ; \quad \xi_0 = 1.05,$
- FIT B: $L^{-1} = 150\mathrm{MeV} \quad ; \quad \lambda \xi_0^4 = 1.024,$

- «FIT A» fits the baryonic onset and the baryon mass (computed with the $AdS_5$ soliton), leaving freedom to choose the best equation of state among the allowed ones.

  $\Rightarrow$ IMPOSSIBLE to find satisfying EoS.

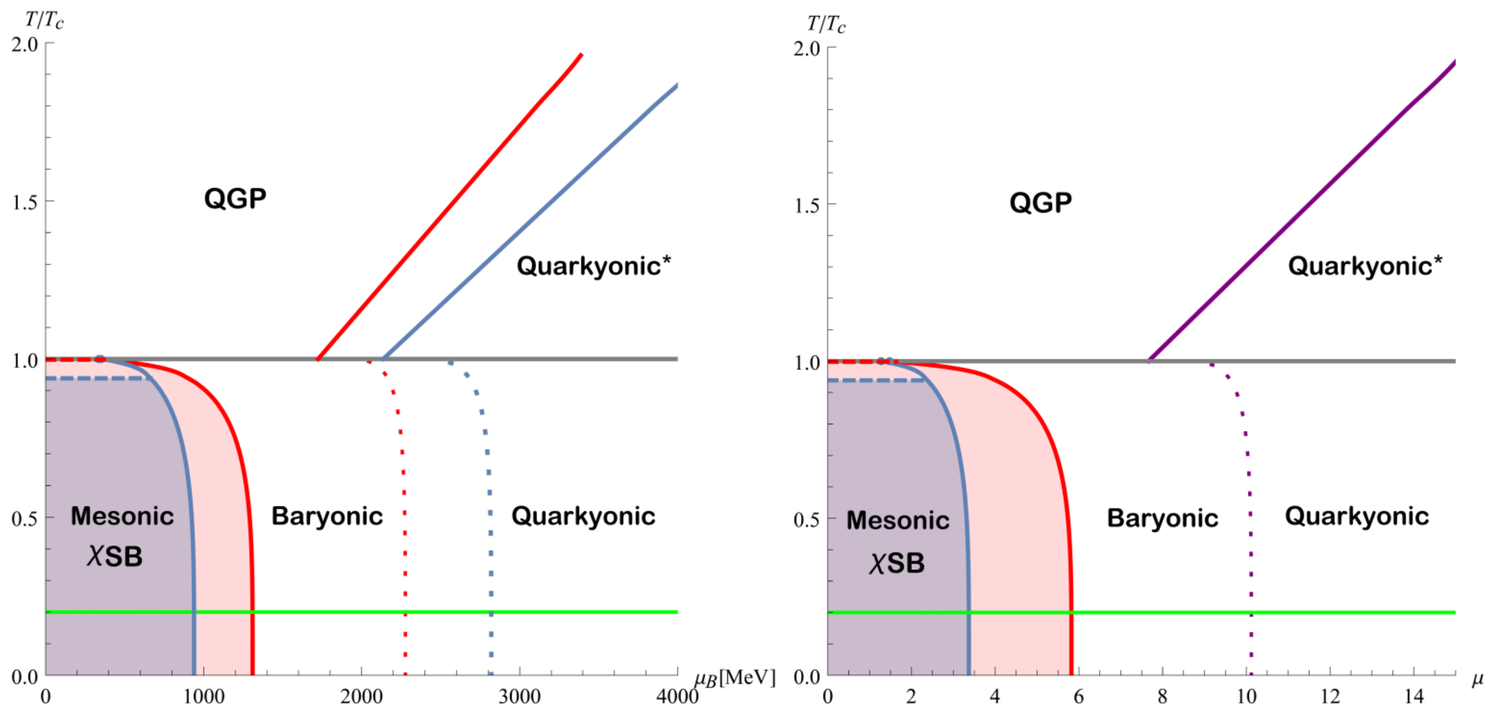
- «FIT B» is purely chosen to reproduce the best compromise between the measured properties of neutron stars.

  $\Rightarrow$ «Good» neutron stars can be found.

# PHASE DIAGRAM(S)

- FIT A
- FIT B

- Free quarks when $z_h < z_{IR}$
- Quarkyonic* is a phase with both baryons AND free quarks.
- Quarkyonic has NO free quarks (baryon popcorn).

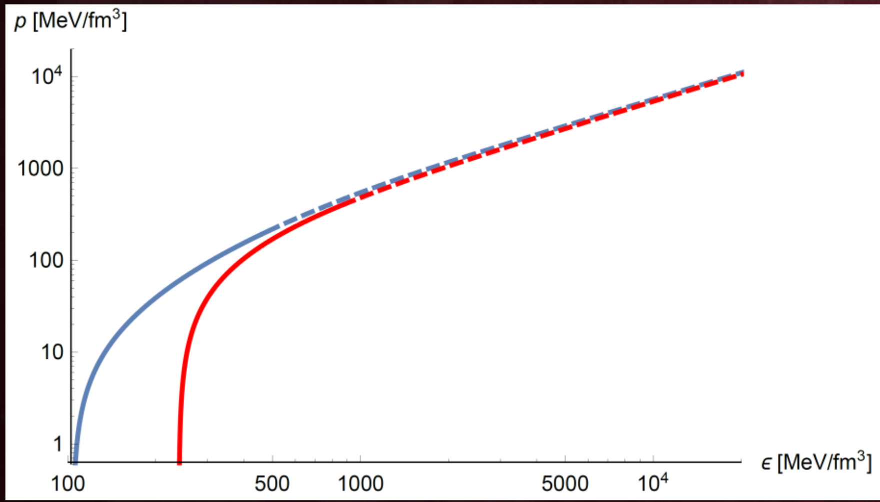



PHYSICAL

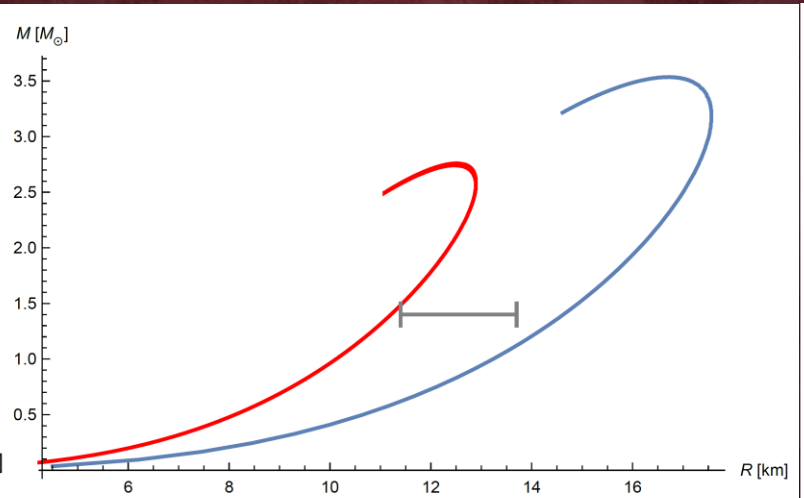
ADIMENSIONAL

# RESULTS FOR NEUTRON STARS

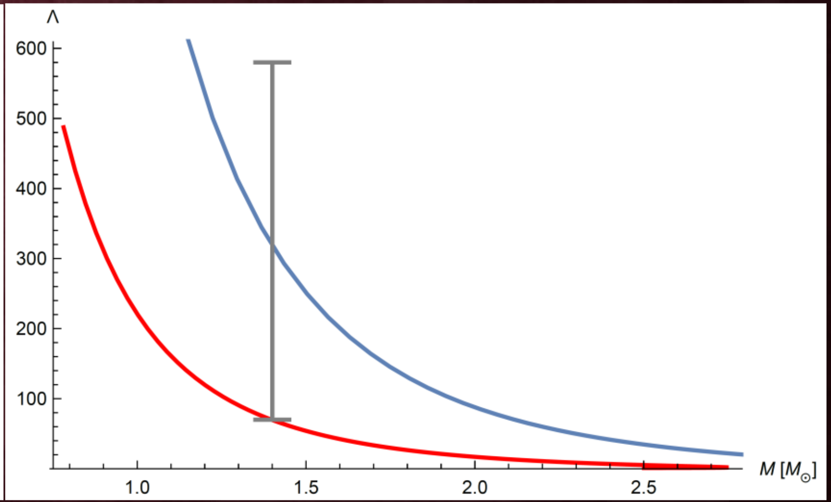
- Equation of state




- Mass-Radius curve

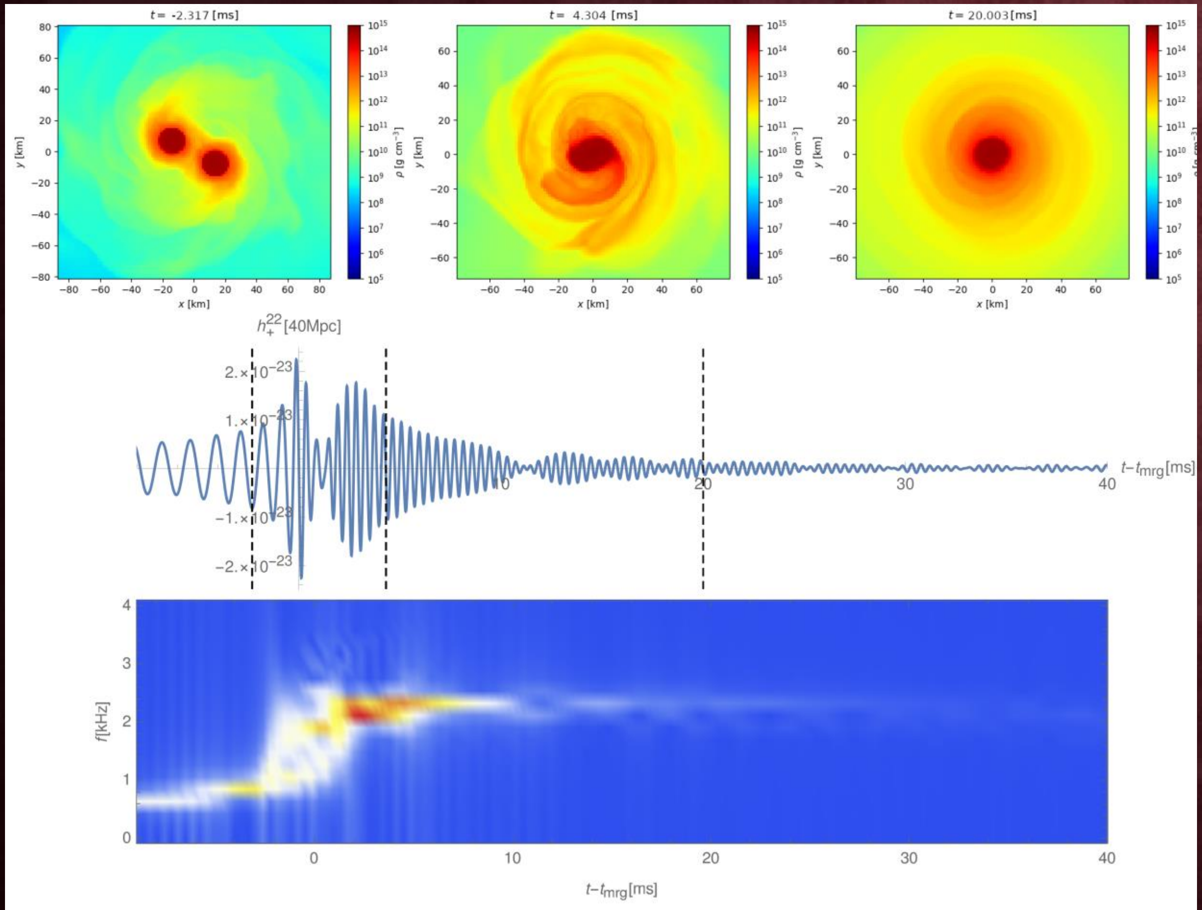


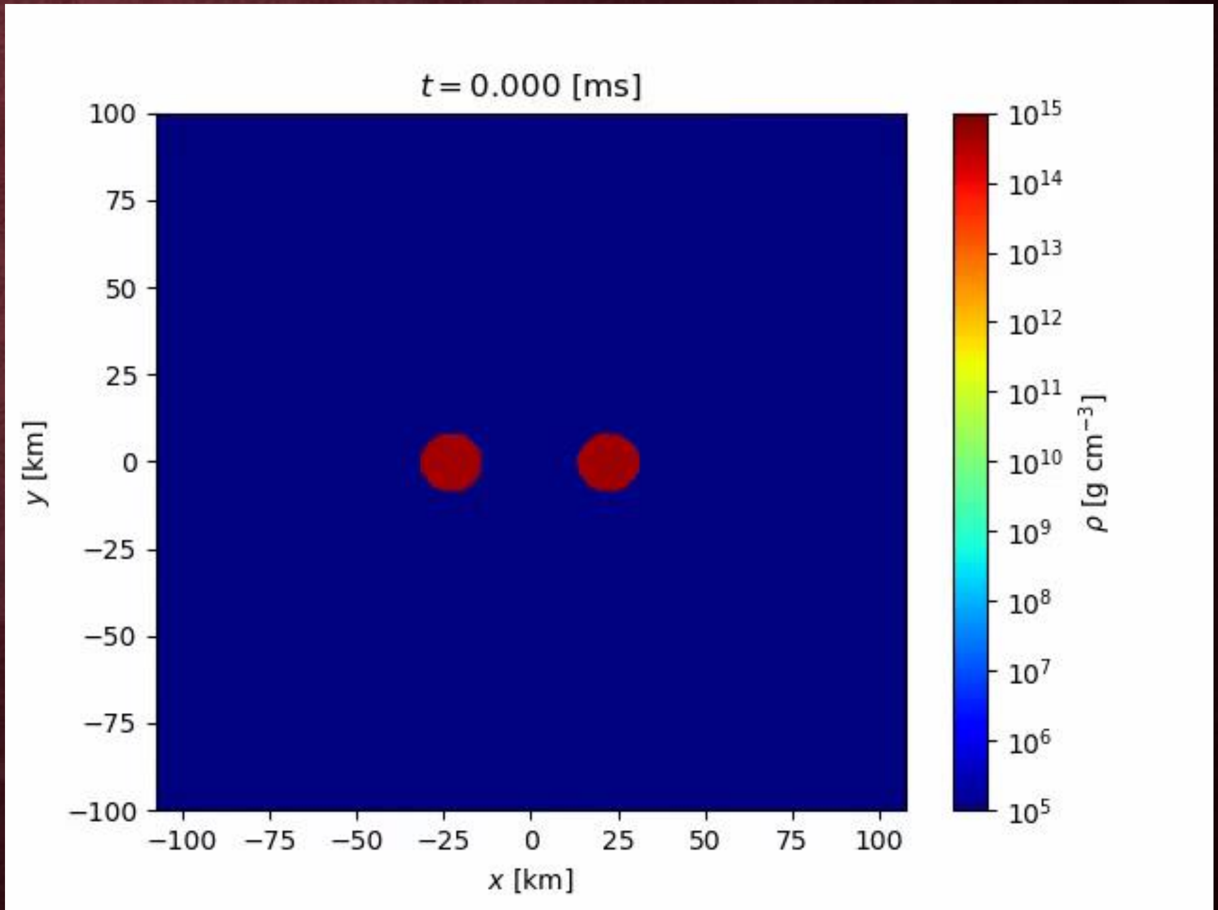

- Tidal deformability




- «FIT A» well outside radius measurements, within $\Lambda$, unrealistically massive stars.
- «FIT B» just slightly small radius and $\Lambda$ compared to measurements, lower masses but still very heavy.
- We expect (supported by educated guesses) that refinement in the assumptions will move every curve into the experimentally admitted regions, and lower the highest mass for a stable star.

# NEUTRON STARS MERGER SIMULATION (1.4 SOLAR MASSES, FIT B)



# FUTURE DIRECTIONS

- Priority for the future of our model: refine the assumptions on the structure of neutron stars

  $\Rightarrow$ Step one is to give the stars a suitable crust.

- The crust has low density and it is very unlikely to change the highest masses in the MR curves, BUT it:

1. Sensibly increases the radii
2. Qualitatively change the low mass behaviour of the MR curve

These two effects can be combined with the freedom to choose a fit for the free paramenters: larger radii would allow for lower masses just by changing calibration of the model.

# WHAT WE EXPECT

Small improvement in EoS (crust)

⇩

- Find at least one set of parameters that satisfies every observational bound.
- Perform simulations of neutron stars mergers with realistic masses that result in the formation of a black hole.
- Inspect the differences in MR curves and gravitational wave signals, between fully holographic EoS, and hybrid ones.
- … (we are open to suggestions)

# THANK YOU FOR YOUR ATTENTION!