# From Holographic Baryons to Nuclear Matter and Neutron Stars

L. Bartolini
in collaboration with S. B. Gudnason, J. Mager, A. Rebhan

Institut für Theoretische Physik, TU Wien

21 August 2026

# Why holography for dense QCD?

- Neutron-star cores probe strongly coupled QCD at finite baryon chemical potential.
- Chiral EFT controls low density and perturbative QCD the asymptotic regime; cores of NS in the intermediate-density window.
- Lattice QCD is obstructed by the sign problem, while holography maps strong 4D dynamics to a classical 5D problem.
- A single model can connect mesons, baryons, interactions, dense matter and stellar observables.

**Appeal**

Few parameters, direct access to finite density.

mesons → solitonic baryons → dense matter → neutron-star observables

# WSS directly as a five-dimensional theory

The low-energy flavor sector is a curved 5D $U(2)$ gauge theory,

$$S = S_{\rm YM} + S_{\rm CS} + S_{\rm AK},$$

$$S_{\rm YM} = -\kappa M_{\rm KK} \int d^4x\, dz\, \mathrm{tr}\left[\frac{1}{2} h(z)\mathcal{F}_{\mu\nu}^2 + k(z)\mathcal{F}_{\mu z}^2\right],$$

$$S_{\rm CS} = \frac{N_c}{24\pi^2}\int \omega_5(\mathcal{A}),$$

$$S_{\rm AK} = c\int d^4x\, \mathrm{tr}\,\mathcal{P}\left[M\left(e^{-i\int dz\,\mathcal{A}_z} - \mathbb{1}\right) + \mathrm{h.c.}\right],$$

$$h(z) = (1 + M_{\rm KK}^2 z^2)^{-1/3}, \qquad k(z) = 1 + M_{\rm KK}^2 z^2,$$

$$\kappa = \frac{\lambda N_c}{216\pi^3}, \qquad c = \frac{\lambda^{3/2}}{3^{9/2}\pi^3}.$$

- $\lambda$ fixes the interaction strength; $M_{\rm KK}$ fixes the energy scale.
- $S_{\rm AK}$ introduces quark masses (we fix $m_\pi = 135\,\mathrm{MeV}$).

## Baryons are 5D solitons

$$N_B = \frac{1}{64\pi^2}\int d^3x\, dz\, \epsilon^{MNPQ} F_{MN}^a F_{PQ}^a.$$

- Instanton core: $\rho \sim \lambda^{-1/2}$, localized near $z = 0$.
- Chern–Simons term sources EM potential $\widehat{A}_0$.
- Linearized tails are an infinite tower of vector/axial mesons plus the pion.

## Dense nuclear matter

Many-soliton problem in curved space

# Homogeneous ansatz: successes

## Ansatz structure

$$\mathcal{A}_i = -\frac{H(z)}{2}\sigma_i, \qquad \mathcal{A}_0 = \frac{\widehat{a}_0(z)}{2}\mathbf{1}.$$

Spatial smearing removes the $\vec{x}$-dependence: the gauge fields depend only on $z$.

## Advantages

- 13 coupled nonlinear PDEs $\longrightarrow$ 2 coupled ODEs.
- Dense matter and beta equilibrium become numerically tractable.
- Enables phase diagrams, symmetry energy and neutron-star predictions.

## WSS

- Li–Schmitt–Wang (2015): onset; symmetric EOS.
- Kovensky–Schmitt (2021): isospin; symmetry energy.
- Kovensky–Poole–Schmitt (2022a,b): composition/crust, NS observables.
- LB–Gudnason (2023): beta EOS, $c_s^2$, realistic composition, NS observables.
- Ecker–Kovensky–Papadopoulos–Schmitt (2026): multijump HA; incompressibility.

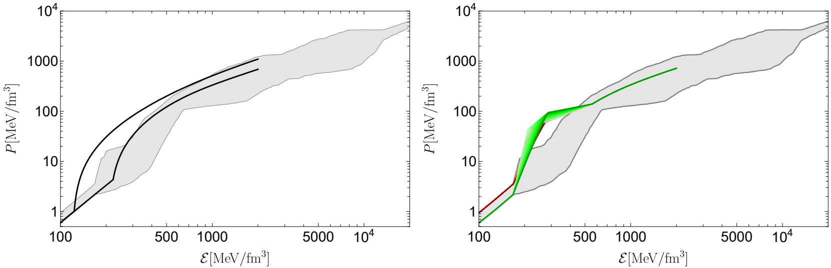
## Hard-wall

- LB–Gudnason–Leutgeb–Rebhan (2022): onset, phase diagram, core EOS, NS observables.
- LB–Gudnason (2024): symmetry energy.
- Wang–Yang–Liu–Ma (2025): hybrid EOS; NS observables.
- Fujii–Hosaka–Iwanaka–Sakai–Tachibana (2026): EOS; NS observables.

## V-QCD

- Jokela–Järvinen–Nijs–Remes (2021): hybrid EOS; NS observables.
- Järvinen (2022): review of phase diagram, EOS and NS.
- LB–Gudnason–Järvinen (2025): symmetry energy, composition, NS observables.
- Ecker–Jokela–Järvinen (2026): finite-$T$ phase diagram; QCD critical point.

# Homogeneous ansatz: shortcomings



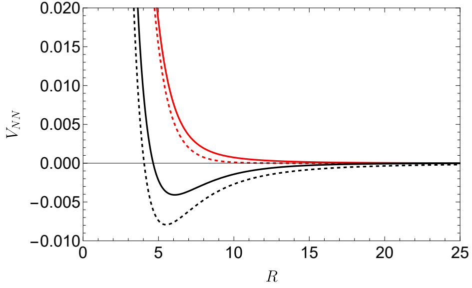

## Shortcomings

- Baryon number is represented by a discontinuity. Introduces IR boundary terms, require ad-hoc counterterms.
- With tyical fits: saturation density is much too large in WSS and hard-wall models, much too small in V-QCD; the symmetry energy is typically too large.
- Recalibrating with $(\lambda, M_{\mathrm{KK}})$: pressure, energy density, chemical potential and incompressibility cannot all be matched continuously to low-density physics.
- Using WSS only at high density and bridgeing with polytropes: extremely stiff EOS, also kills the purpose.
- Multijump HA in WSS: better but still $K(n_{\mathrm{S}})$ an order of magnitude too large.

# Holographic two-baryon potential

For two separated solitons with orientations $B, C \in SU(2)$, $E = 2M_B + V(r, B^\dagger C)$.

$$V(r,B,C) = \frac{27\pi^2 N_c}{2\lambda}\left[\sum_{n=1}^{\infty}\frac{1}{c_{2n-1}}\frac{e^{-k_{2n-1}r}}{r} + \sum_{n=1}^{\infty}\frac{\zeta}{b_n}M_{ij}(B^\dagger C)P_{ij}(\vec{r},k_n)\frac{e^{-k_n r}}{r^3} - \frac{\zeta}{\pi}M_{ij}(B^\dagger C)P^{\pi}_{ij}(\vec{r},k_0)\frac{e^{-k_0 r}}{r^3}\right].$$




Black: "combed skyrmions".
Red: "defensive skyrmions".
Solid: physical pion mass; dashed: chiral limit.

## Orientation and tensor structure

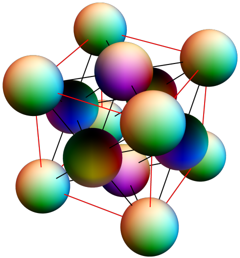
$$M_{ij}(G) = \frac{1}{2}\operatorname{tr}(\sigma_i G \sigma_j G^\dagger),$$

$$P^{\pi}_{ij}(\vec{r},k) = \delta_{ij}(rk+1) - \frac{r_i r_j}{r^2}\left[(rk)^2 + 3rk + 3\right],$$

$$P_{ij}(\vec{r},k) = \delta_{ij}(rk)^2 + P^{\pi}_{ij}(\vec{r},k), \qquad \zeta = \frac{\lambda^2\rho^4}{3^6\pi^2}.$$

- The $\omega$ tower gives universal monopole repulsion.
- Vector/axial towers and the pion generate the orientation-dependent force and long-distance attraction.

# From the two-body force to an FCC crystal



- FCC cell: $B = 4$, $V_{\text{cell}} = 2\sqrt{2}R^3$.
- Twelve nearest neighbors: $\vec{r} = \frac{R}{\sqrt{2}}(\pm 1, \pm 1, 0)$, and permutations.
- Relative orientations select the maximally attractive channel.
- Lattice shells are retained through $n = 30$.

## Crystal EOS

$$E_p(R) = M_B + \frac{1}{2}\sum_{q\neq p} V_{pq}(R),$$

$$n_B = \frac{4}{2\sqrt{2}R^3} = \frac{\sqrt{2}}{R^3}, \qquad \mathcal{E}(n_B) = n_B E_p(R(n_B)),$$

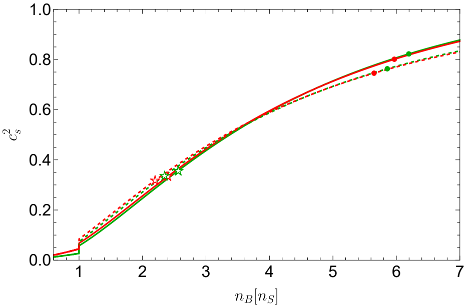
$$\mu_B = \frac{\partial \mathcal{E}}{\partial n_B}, \qquad P = \mu_B n_B - \mathcal{E},$$

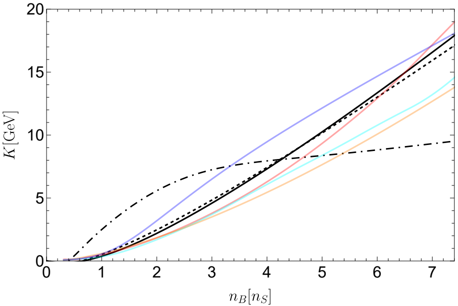
$$K = 9 n_B \frac{\partial \mu_B}{\partial n_B}.$$

## Conceptual payoff

The EOS follows directly from localized baryons and their holographic interaction: binding and saturation are now well-defined.

# Holographic symmetric nuclear matter

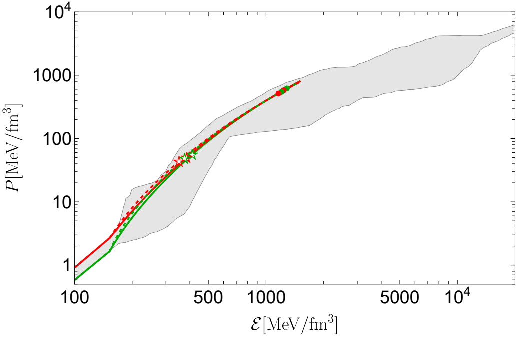


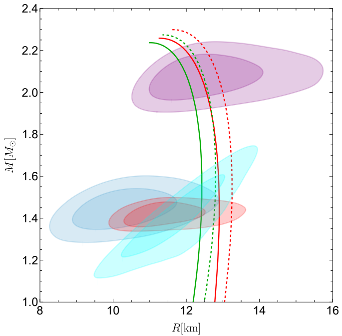




Non-HQCD incompressibility curves: A. Perego, D. Logoteta, D. Radice, S. Bernuzzi, R. Kashyap, A. Das, S. Padamata, A. Prakash, PRL 129, 032701.

| quantity | FCC–BPST | FCC–non-BPST | reference scale |
|---|---|---|---|
| $\lambda$ | 18.26 | 45.54 | mesons: 16.63 |
| $M_{\mathrm{KK}}$ | 661.5 MeV | 457.2 MeV | mesons: 949 GeV |
| $M_B$ | 942.0 MeV | 958.5 MeV | 939 MeV |
| $E/A - M_B$ | −19.3 MeV | −35.8 MeV | $\sim -16$ MeV |
| $K(n_{\mathrm{S}})$ | 374.9 MeV | 517.6 MeV | 200–300 MeV |

- BPST is closest to the empirical mass, binding and mesonic $\lambda$.
- Non-BPST is more strongly bound and gives larger $K(n_{\mathrm{S}})$ and $\lambda$.
- Both improvements at saturation over HA.




## Hybrid EOS construction

$$E(n_B,\delta) = E_S(n_B) + S(n_B)\delta^2,$$

$$\mu_n - \mu_p = 4S(n_B)\delta = \mu_e = \mu_\mu.$$

$E_S$ from FCC; a phenomenological $S(n_B)$ and leptons impose beta equilibrium and charge neutrality.

- Use the low-density EFT EOS below $n_{\mathrm{S}}$ and the beta-equilibrated FCC EOS above it.
- Mass–radius curves and tidal deformabilities are viable for the softer constructions.
- A $1.4M_\odot$ star reaches only 2.2–2.6 $n_{\mathrm{S}}$, where the soliton cores are still separated.

# Future directions and take-home message

## Main message

Holographic QCD could describe nuclear matter at saturation,
but not via homogeneous approximations.

## What this establishes

- Localized WSS baryons reproduce the relevant nuclear scales.
- The hybrid EOS can connect continuously to the low-density EFT regime.
- The same construction gives viable neutron-star observables.

## What comes next

- Derive symmetry energy directly from WSS.
- Include finite-core effects.
- 3-body forces?
- Holographic crust?

# Thank you

## Thank you for your attention!

Questions?