Matching and synthesis at high T:
The QCD Equation of state from Black Hole and Hadronic Physics

Joaquín Grefa,
for the Holographic EoS module.

May 17th, 2024
2024 MUSES Meeting

Outline

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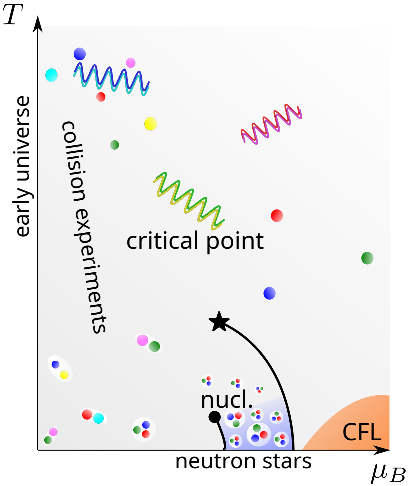
QCD Phase Diagram

We can explore the QCD phase diagram by changing $\sqrt{s}$ in relativistic heavy ion collisions

Many models predict a first order phase transition line with a critical point

Lattice QCD is the most reliable theoretical tool to study the QCD phase diagram.



QCD Phase Diagram

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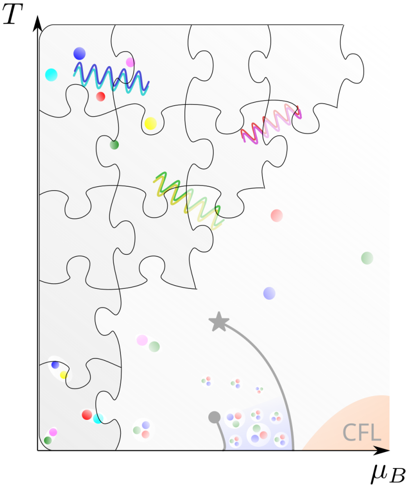
Sign problem:

Equation of state for low to moderate μ_B/T.

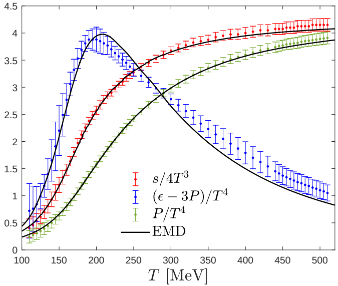
Borsányi, Fodor, Guenther et al., PRL **126** (2021)

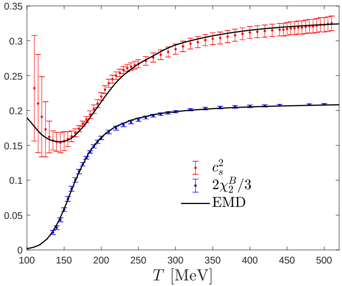


Gravitational Action

O DeWolfe et al. Phys.Rev.D 83, (2011). R Rougemont et al. JHEP(2016)102. R. Critelli et al., Phys.Rev.D96(2017).

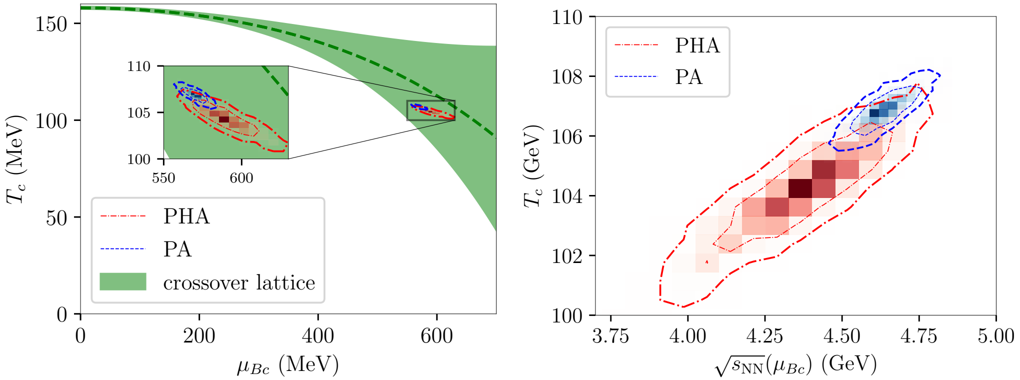
$$S = \frac{1}{2\kappa_5^2}\int_{M_5} d^5x\sqrt{-g}\left[R - \frac{(\partial_\mu\phi)^2}{2} - \underbrace{V(\phi)}_{\text{nonconformal}} - \underbrace{\frac{f(\phi)F_{\mu\nu}^2}{4}}_{\mu_B\neq 0}\right]$$





Holographic Bayesian Analysis: posterior critical points

$(T_c, \mu_{Bc})_{PHA} = (104 \pm 3,\ 589^{+36}_{-26})$ MeV, $(T_c, \mu_{Bc})_{PA} = (107 \pm 1,\ 571 \pm 11)$ MeV.



- Both Ansätze overlap at $1\,\sigma$. **Robust results!**

M. Hippert, J.G., T.A. Manning. J. Noronha, J. Noronha-Hostler, I. Portillo, C. Ratti, R. Rougemont, M. Trujillo, arXiv:2309.00579.

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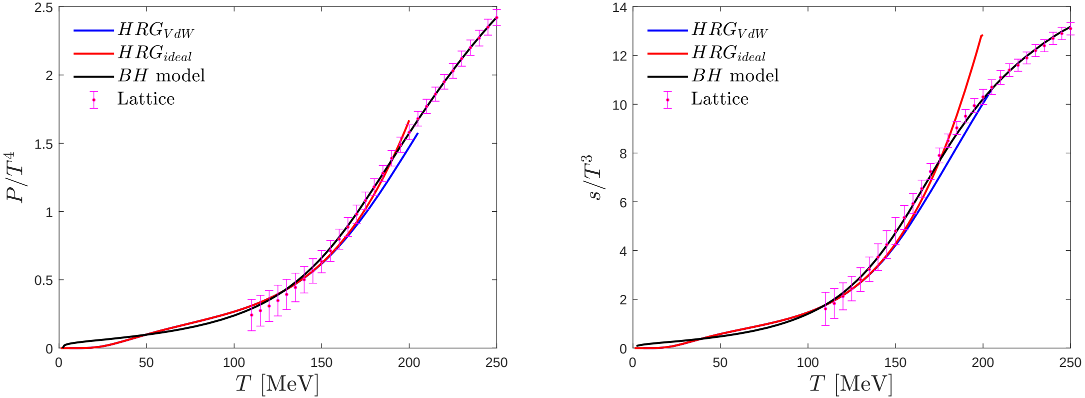
The low T problem



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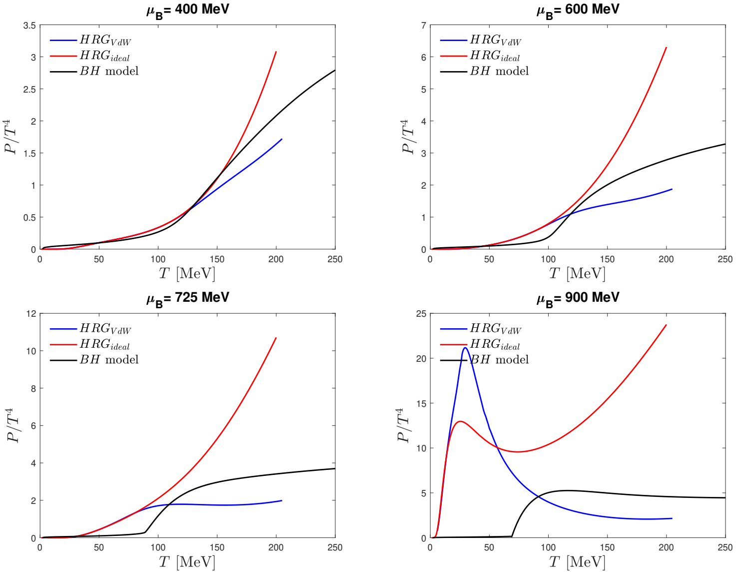


Phase diagram validity for the Holographic Model

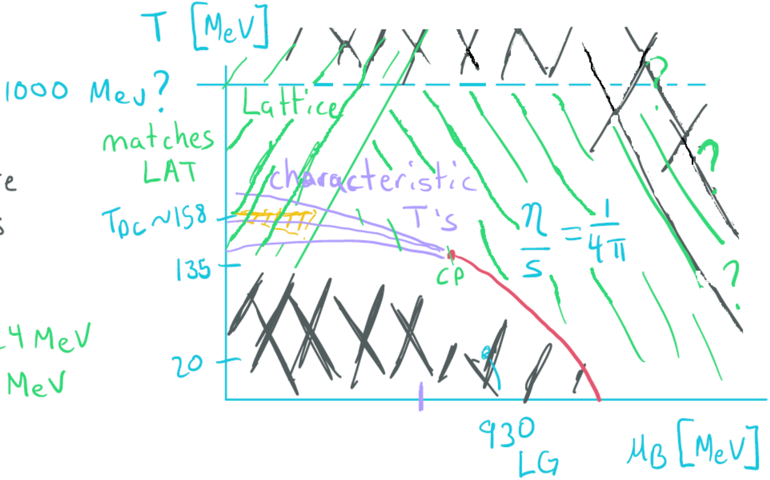
Holography

- Holography
- X areas where model fails

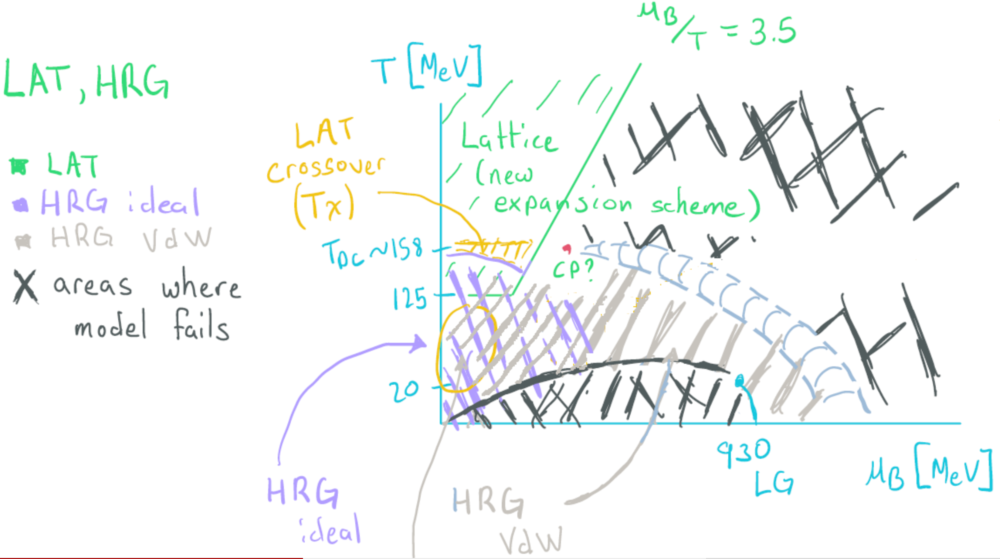
CP Prediction

$\mu_{BC} = 724$ MeV

$T_c = 90$ MeV



Phase diagram validity for lattice QCD and HRG



MERGING...?

SYNTHESIS...?

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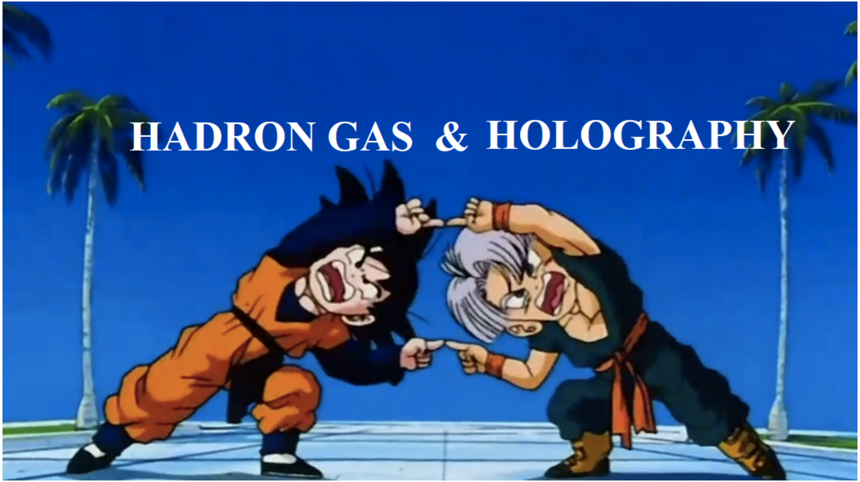
FUSION



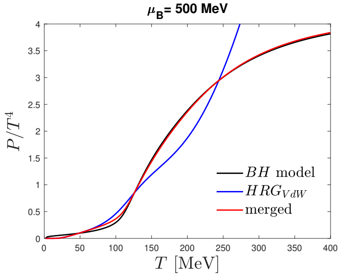
The merging algorithm (Following J. Kapusta et al. Phys. Rev. C, 2022)

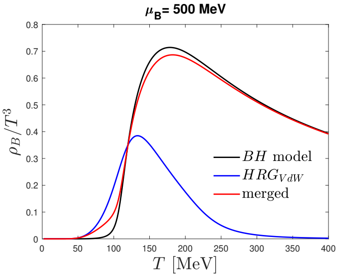
$$P_{BG} = S(T,\mu)P_{qg} + [1 - S(T,\mu)]P_h(T,\mu)$$

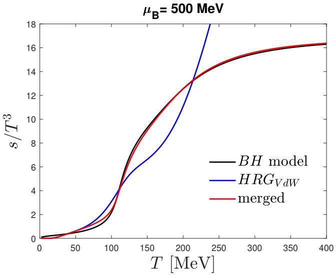
$$S(T,\mu) = \exp\left[-\left(T^2/T_s^2 + \mu^2/\mu_s^2\right)^{-2}\right]$$

with $T_s = 95$ MeV, $\mu_s = 1000$ MeV.

$$s = \partial P/\partial T|_{\mu_B} \qquad \rho_B = \partial P/\partial \mu_B|_T$$







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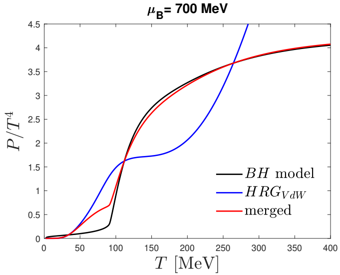

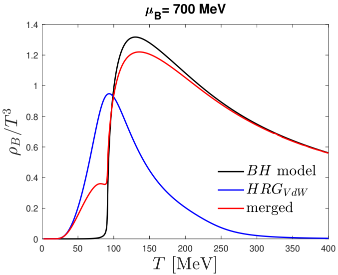

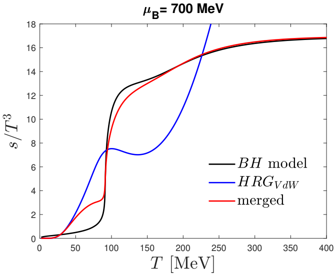

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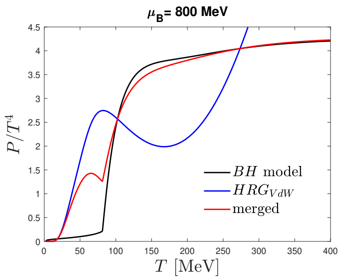
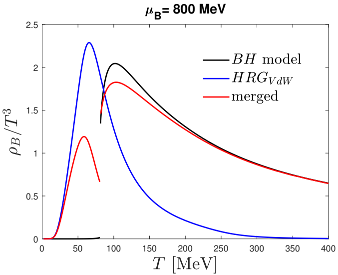
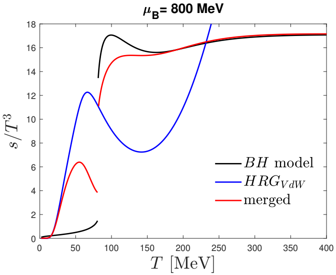
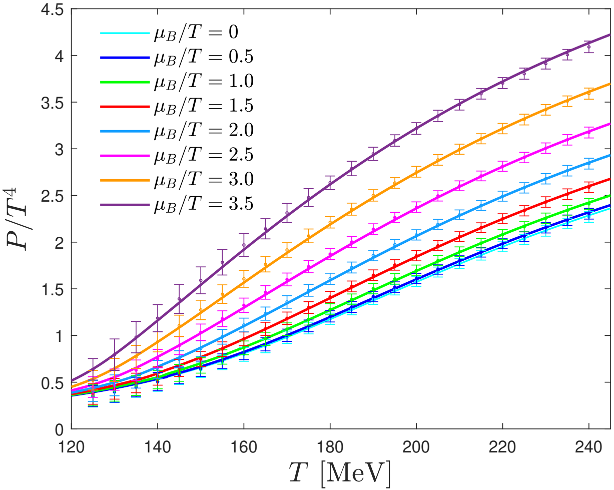






Comparison with the state-of-the-art lattice QCD thermodynamics



Lattice results: S. Borsanyi et al. 10.1103/PhysRevLett.126.232001

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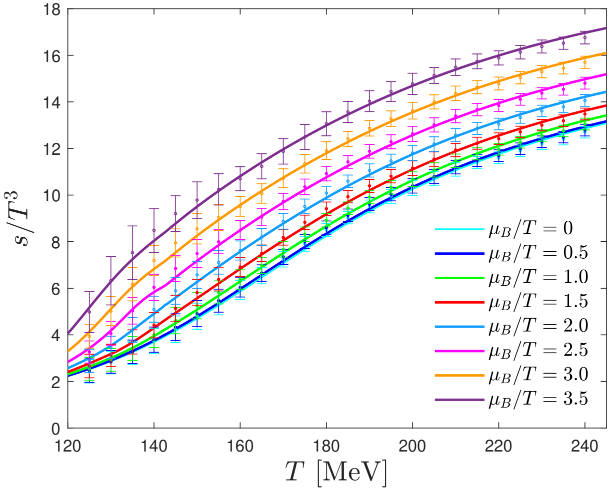

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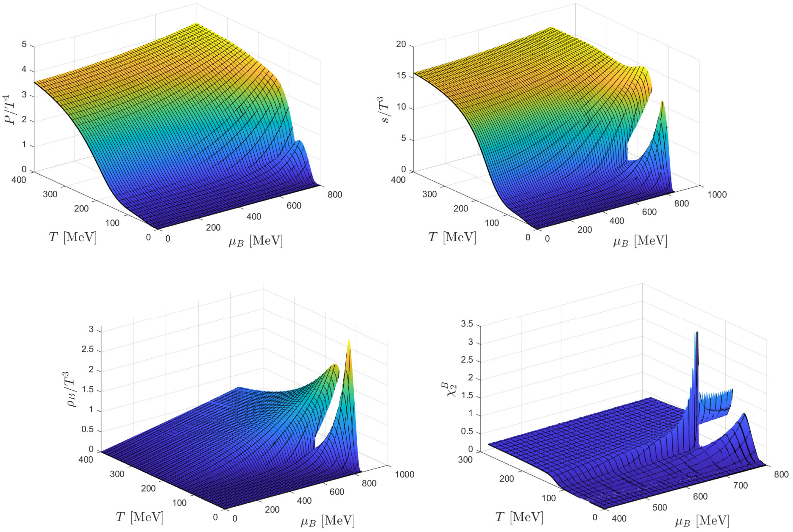
Equation of State



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Summary

1. The Holographic model offers a powerful description of the QGP, matching *finite-density* lattice results, but it does not describe hadronic matter.

   J. G, J. Noronha, J. Noronha-Hostler, I. Portillo, C. Ratti, R. Rougemont, PRD **104** (2021)
   J. G, M. Hippert, J. Noronha, J. Noronha-Hostler, I. Portillo, C. Ratti and R. Rougemont, PRD **106** (2022)

   M. Hippert, J.G., T.A. Manning. J. Noronha, J. Noronha-Hostler, I. Portillo, C. Ratti, R. Rougemont, M. Trujillo, arXiv:2309.00579.

2. HRG model describes hadronic matter, and VdW interactions can be added for a more realistic EoS, but it does not exhibit deconfinement.

3. A smooth switching function $S(T, \mu_B)$ can be used to merge the Holographic and HRG_{VdW} EoS', and thermodynamics can be obtained as derivatives of the resulting pressure.

4. The resulting EoS exhibits a critical point and transition line inherited from the holographic EoS and preserves the agreement with lattice QCD.

Challenges:

- Derivatives/integrals are computed numerically. Thus, the resulting EoS inherits the noise from the parent EoS'. Parent EoS' must be smooth
- Systematic implementation of filters/interpolation for higher order derivatives might be needed. c_s^2, C_ρ, χ_4^B, etc.

Outlook:

- Holographic EoS that includes more than one conserved charge at the same time.
- Implement the merging with other hadronic EoS. Example: extension of hadronic EoS from UTK, χEFT and CMF synthesis at finite T.
- Employ the merged EoS as an input for hydro simulations.

Appendix

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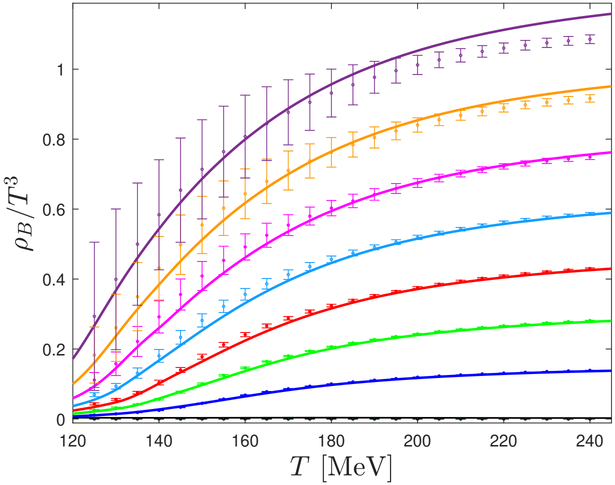

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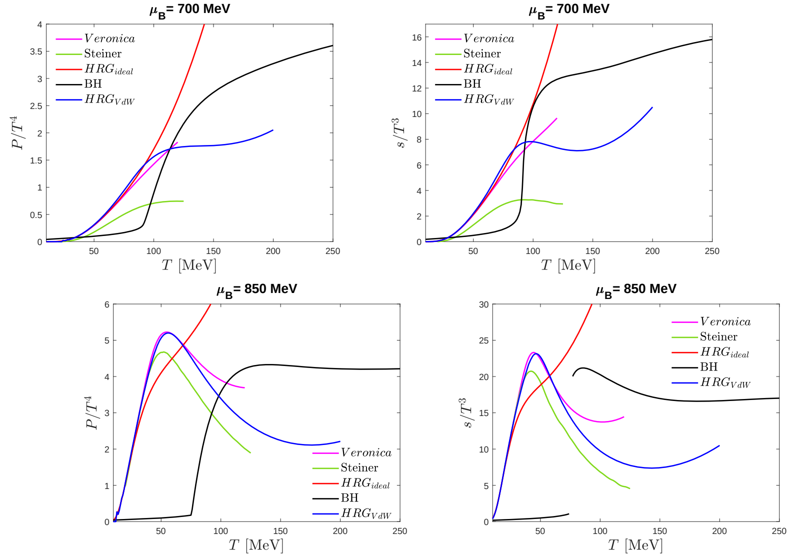
EoS comparison



Holographic Equation of State