Mapping the binary neutron star merger conditions to heavy-ion collisions with a single EoS

Dense Nuclear Matter Equation of State from Heavy-Ion Collisions

5-9 December 2022, INT WORKSHOP INT-22-84W

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What observables can we use to constrain the nuclear equation of state?

There are several observables that can be used to constrain the nuclear equation of state, including:

1. The maximum mass of a neutron star, which is determined by the stiffness of the EOS at high densities.
2. The maximum radius of a neutron star, which is determined by the pressure gradient of the EOS at low densities.
3. The symmetry energy, which is determined by the slope of the EOS at intermediate densities.
4. The tidal deformability of a neutron star, which is determined by the derivative of the EOS with respect to the baryon density.
5. The momentum dependence of the nuclear EOS, which can be probed by studying the transverse flow of particles in heavy-ion collisions.
6. The temperature dependence of the nuclear EOS, which can be probed by studying the expansion of the fireball in heavy-ion collisions.

These observables can be measured through a combination of astrophysical observations, nuclear experiments, and heavy-ion collision experiments.

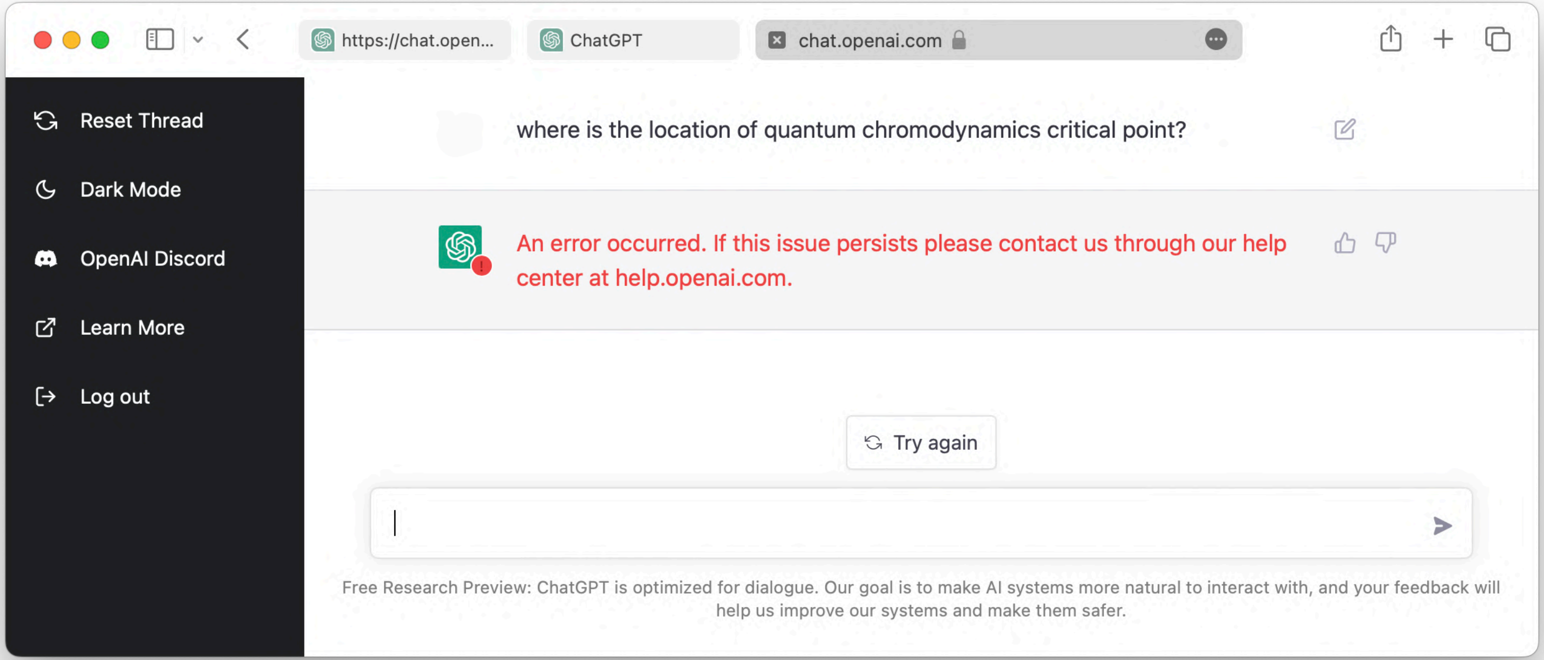
ChatGPT

From Wikipedia, the free encyclopedia

https://chat.opeai.com/

ChatGPT is a prototype artificial intelligence chatbot developed by OpenAI that focuses on usability and dialogue. The chatbot uses a large language model trained with reinforcement learning and is based on the GPT-3.5 architecture.

ChatGPT was launched in November 2022 and has garnered attention for its detailed responses and historical knowledge, although its accuracy has been criticized.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where is the location of quantum chromodynamics critical point?
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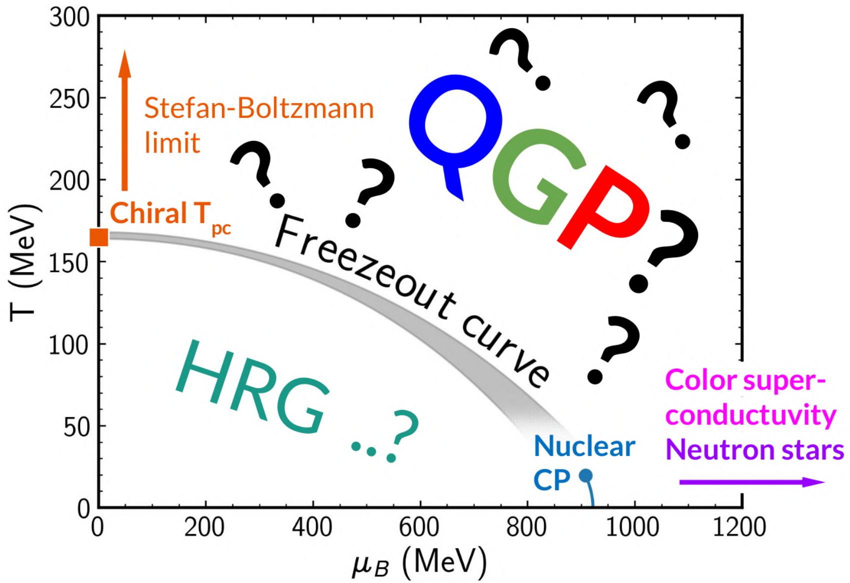
Free Research Preview: ChatGPT is optimized for dialogue. Our goal is to make AI systems more natural to interact with, and your feedback will help us improve our systems and make them safer.

QCD phase diagram

$$\mathcal{L}_{\mathrm{QCD}} = \sum_{\mathrm{i,j}} \bar{\psi}_{\mathrm{i}} \left(\mathrm{i}\gamma^{\mu} \left(\partial_{\mu}\delta_{\mathrm{ij}} - \tfrac{\mathrm{i}}{\mathrm{s}}\mathrm{g}\mathcal{A}^{\mathrm{a}}_{\mu}\lambda_{\mathrm{a,ij}}\right) - \mathrm{m}_{\mathrm{i}}\delta_{\mathrm{ij}}\right) \psi_{\mathrm{j}} - \tfrac{1}{4}\mathrm{G}^{\mathrm{a}}_{\mu\nu}\mathrm{G}^{\mu\nu}_{\mathrm{a}}$$

$$\mathrm{G}^{\mathrm{a}}_{\mu\nu} = \partial_{\mu}\mathcal{A}^{\mathrm{a}}_{\nu} - \partial_{\nu}\mathcal{A}^{\mathrm{a}}_{\mu} + \mathrm{g}\mathrm{f}^{\mathrm{abc}}\mathcal{A}^{\mathrm{b}}_{\mu}\mathcal{A}^{\mathrm{c}}_{\nu}$$

How to map the well established QCD theory to its phase diagram?



Lattice QCD inspired qualitative phase diagram

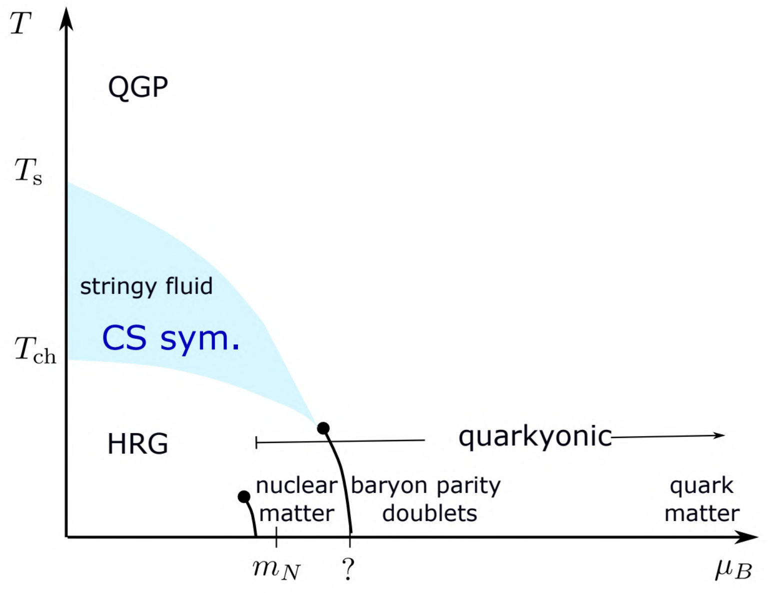
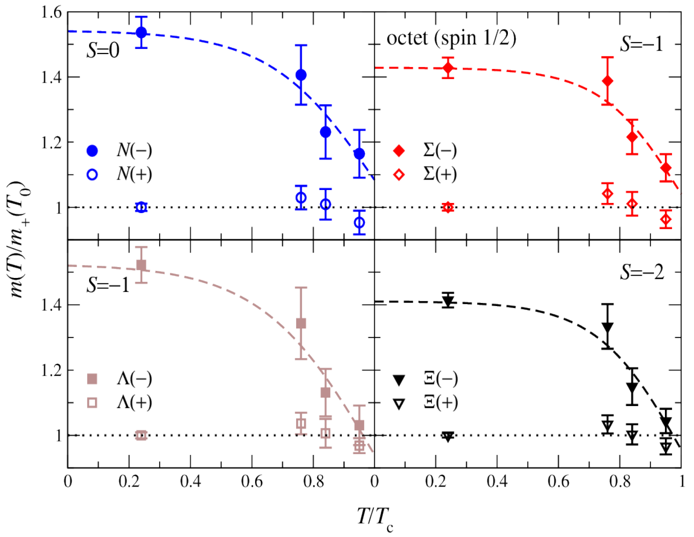


Figure 4. Qualitative sketch of a possible QCD phase diagram with a band of approximate chiral spin symmetry terminating at the critical end point of a non-analytic chiral phase transition.

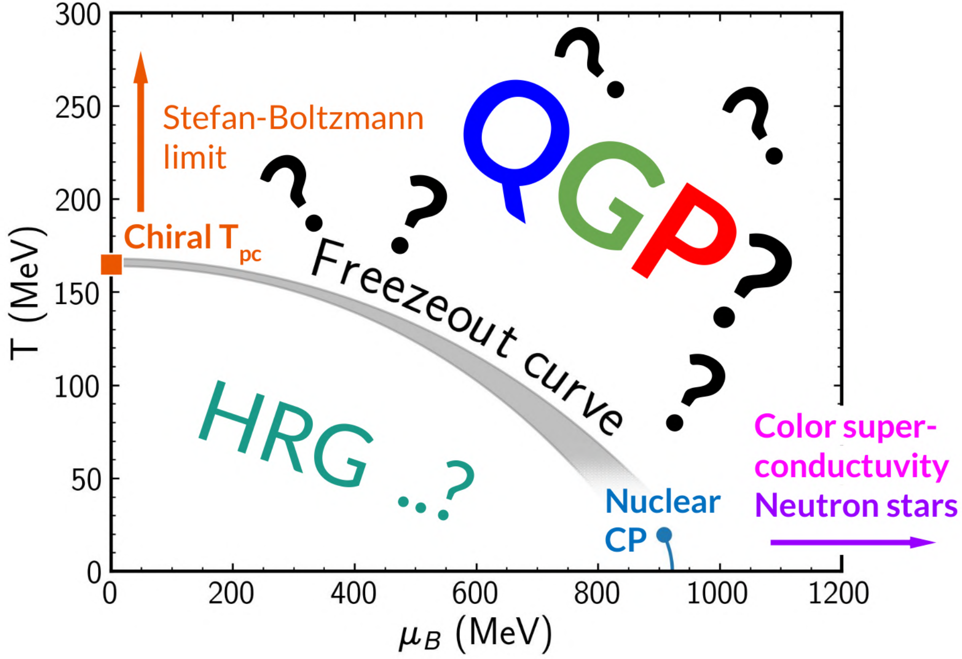
Glozman, Philipsen, Pisarski, e-Print: 2204.05083 [hep-ph]

- Parity doubling is confirmed on lattice
- Leaves a possibility for a phase transition at high density and lower temperatures.
- Is not a transition to QGP



Aarts et al., e-Print: 1710.08294 [hep-lat]

An approach for QCD EOS: CMF model

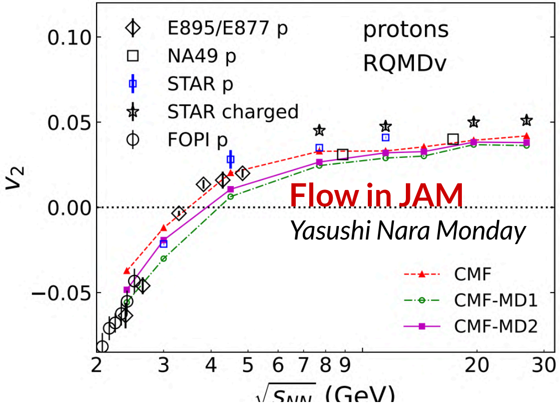


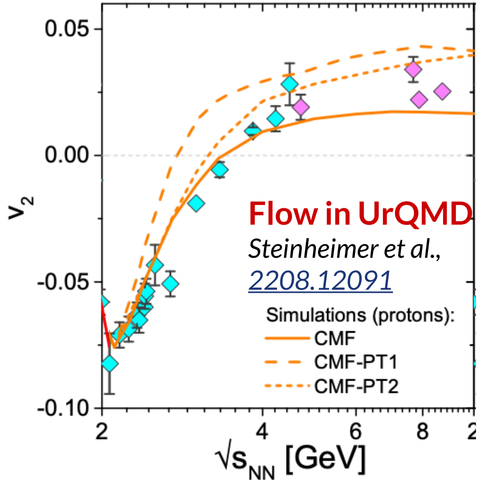
Chiral Mean Field model is a **single framework** for QCD thermodynamics, can be used for

- **analysis of lattice QCD** data
- description of **nuclear matter**
- modeling of heavy ion collisions
- as well as **neutron star** description

Papazoglou, Schramm, Schaffner-Bielich, Stoecker, Greiner, nucl-th/9706024
Papazoglou, Zschiesche, Schramm, Schaffner-Bielich, Stoecker, Greiner, nucl-th/9806087
Dexheimer, Schramm, 0901.1748
Steinheimer, Schramm, Stoecker 1009.5239
AM, Steinheimer, Vovchenko, Schramm, Stoecker, 1905.00866

CMF + transport

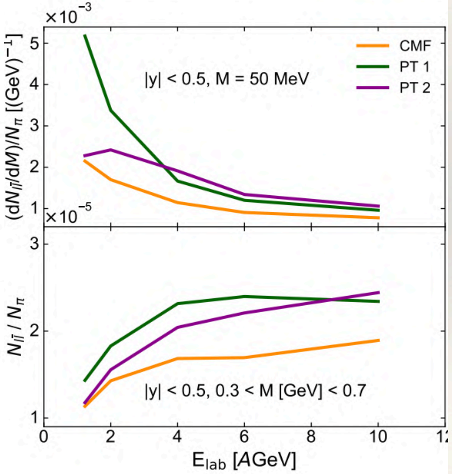




Dileptons in UrQMD

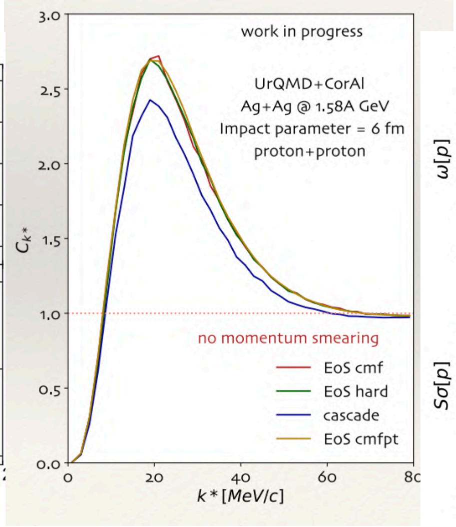
Oleh Savchuk Monday

2209.05267



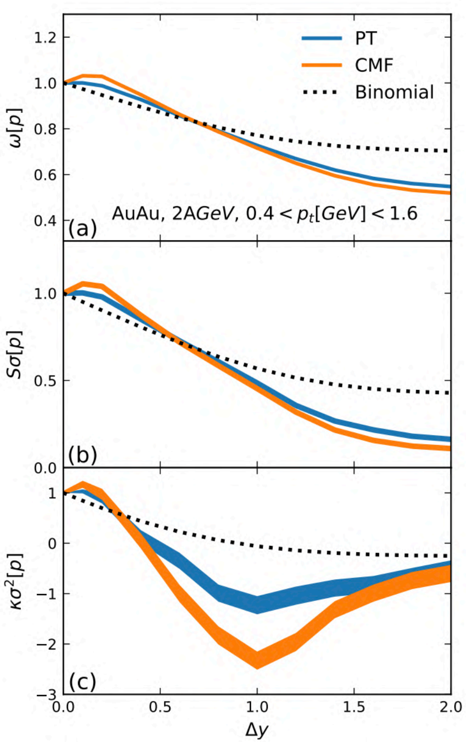
Correlations in UrQMD

Maria Stefaniak Tuesday



Fluctuations in UrQMD

Oleh Savchuk



Implementation here:

A Chiral Mean-Field Equation-of-State in UrQMD: Effects on the Heavy Ion Compression Stage

Manjunath Omana Kuttan[1,2,3], Anton Motornenko[1], Jan Steinheimer[1], Horst Stoecker[1,2,4], Yasushi Nara[5], and Marcus Bleicher[2,4,6]

- e-Print: 2201.01622 [nucl-th]

The CMF model

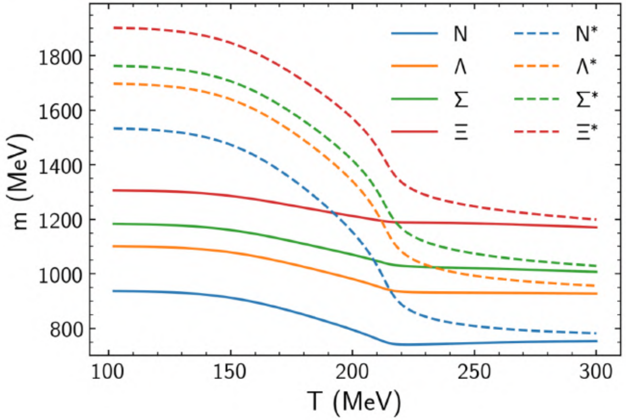
$$\Omega = \Omega_{\mathrm{q}} + \Omega_{\bar{\mathrm{q}}} + \Omega_{\mathrm{h}} + \Omega_{\bar{\mathrm{h}}} - (U_{\mathrm{sc}} + U_{\mathrm{vec}} + U_{\mathrm{Pol}})$$

Baryon octet:

$$\mathcal{L}_B = \sum_b (\bar{B}_b i\partial\!\!\!/ B_b) + \sum_b (\bar{B}_b m_b^* B_b)$$
$$+ \sum_b [\bar{B}_b \gamma_\mu (g_{\omega b}\omega^\mu + g_{\rho b}\rho^\mu + g_{\phi b}\phi^\mu) B_b]$$
$$\mu_b^* = \mu_b - g_{\omega b}\omega - g_{\phi b}\phi - g_{\rho b}\rho$$

Baryon parity doubling:

$$m_{b\pm}^* = \sqrt{\left[\left(g_{\sigma b}^{(1)}\sigma + g_{\zeta b}^{(1)}\zeta\right)^2 + (m_0 + n_s m_s)^2\right]} \pm g_{\sigma b}^{(2)}\sigma$$



Attractive scalar fields:

$$U_{\mathrm{sc}} = V_0 - \frac{1}{2}k_0 I_2 + k_1 I_2^2 - k_2 I_4 + k_6 I_6 + k_4 \ln\frac{\sigma^2\zeta}{\sigma_0^2\zeta_0} - U_{\mathrm{sb}}$$
$$I_2 = (\sigma^2 + \zeta^2), \quad I_4 = -(\sigma^4/2 + \zeta^4), \quad I_6 = (\sigma^6 + 4\zeta^6)$$
$$U_{\mathrm{sb}} = m_\pi^2 f_\pi \sigma + \left(\sqrt{2} m_K^2 f_K - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi\right)\zeta$$

Repulsive vector mean fields for the octet:

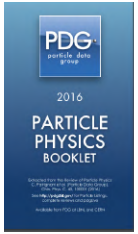
$$U_{\mathrm{vec}} = -\frac{1}{2}(m_\omega^2\omega^2 + m_\rho^2\rho^2 + m_\phi^2\phi^2)$$
$$-g_4\left[\omega^4 + 6\beta_2\omega^2\rho^2 + \rho^4 + \frac{1}{2}\phi^4\left(\frac{Z_\phi}{Z_\omega}\right)^2 + 3(\rho^2+\omega^2)\left(\frac{Z_\phi}{Z_\omega}\right)\phi^2\right].$$

u,d,s quark d. of f.:

$$\Omega_{\mathrm{q}} = -VT\sum_{q_i\in Q}\frac{d_{q_i}}{(2\pi)^3}\int d^3k \frac{1}{N_c}\ln\left[1 + 3\Phi e^{-(E_{q_i}^* - \mu_{q_i}^*)/T} + 3\bar{\Phi} e^{-2(E_{q_i}^* - \mu_{q_i}^*)/T} + e^{-3(E_{q_i}^* - \mu_{q_i}^*)/T}\right],$$
$$m_{u,d}^* = -g_{u,d\sigma}\sigma + \delta m_{u,d} + m_{0u,d}$$
$$m_s^* = -g_{s\zeta}\zeta + \delta m_s + m_{0q}.$$

Polyakov loop:

$$U_{\mathrm{Pol}}(\Phi, \overline{\Phi}, T) = -\tfrac{1}{2}a(T)\Phi\overline{\Phi} + b(T)\ln[1 - 6\Phi\overline{\Phi} + 4(\Phi^3 + \overline{\Phi}^3) - 3(\Phi\overline{\Phi})^2],$$
$$a(T) = a_0 T^4 + a_1 T_0 T^3 + a_2 T_0^2 T^2,$$
$$b(T) = b_3 T_0^4.$$

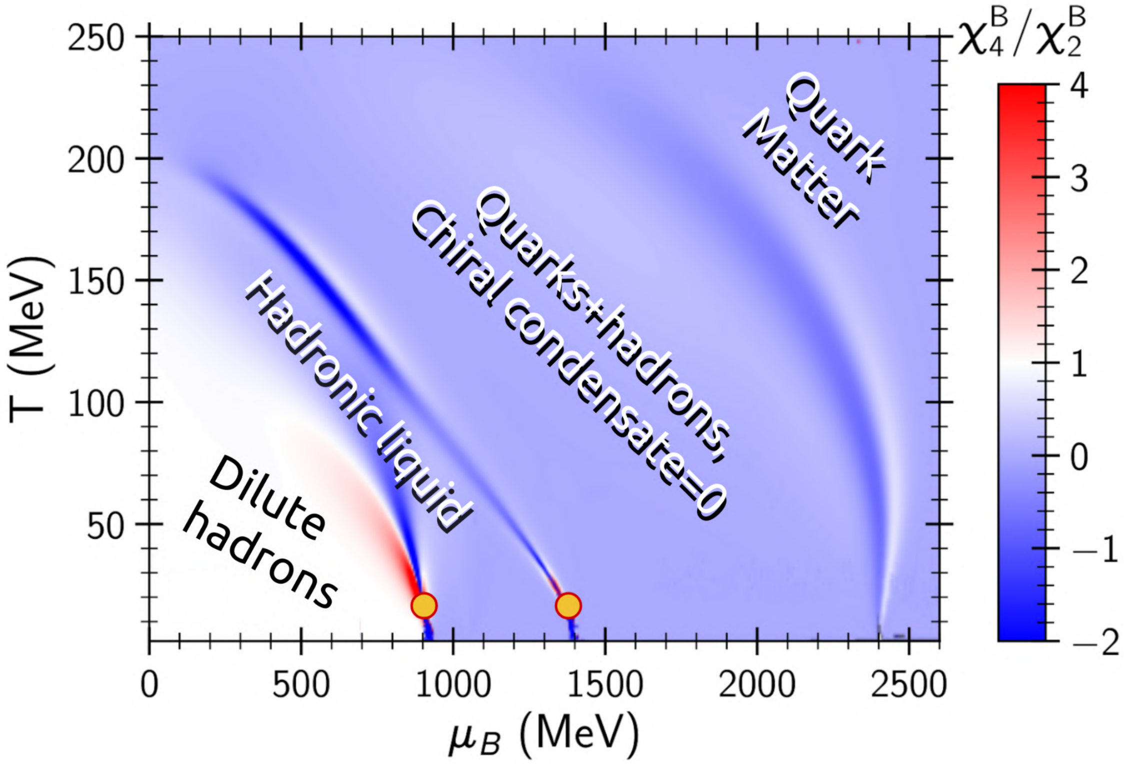


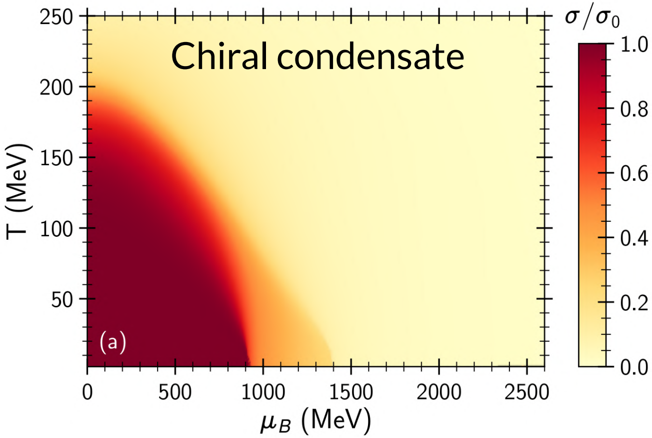
Hadronic d.of.f + excluded volume (Full PDG hadronic list):

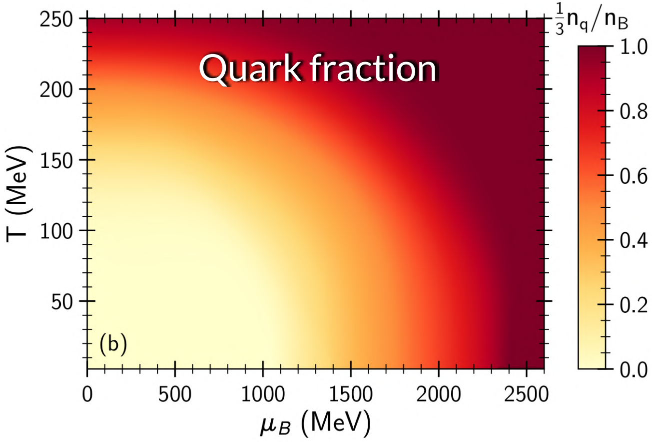
$$\rho_i = \frac{\rho_i^{\mathrm{id}}(T, \mu_i^* - v_i P)}{1 + \sum_{j\in\mathrm{HRG}} v_j \rho_j^{\mathrm{id}}(T, \mu_j^* - v_j P)}$$
$$\mu_j^{\mathrm{eff}} = \mu_j^* - v_j P,$$

The CMF phase diagram

AM, Steinheimer, Vovchenko, Schramm, Stoecker, *Phys. Rev.* C 101, no.3, 034904 (2020)







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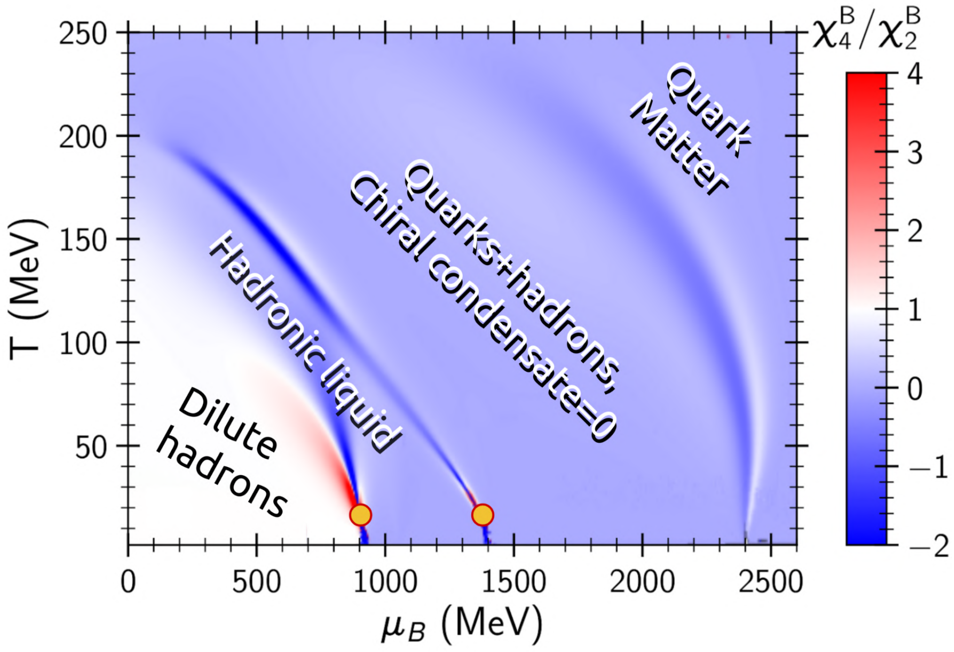
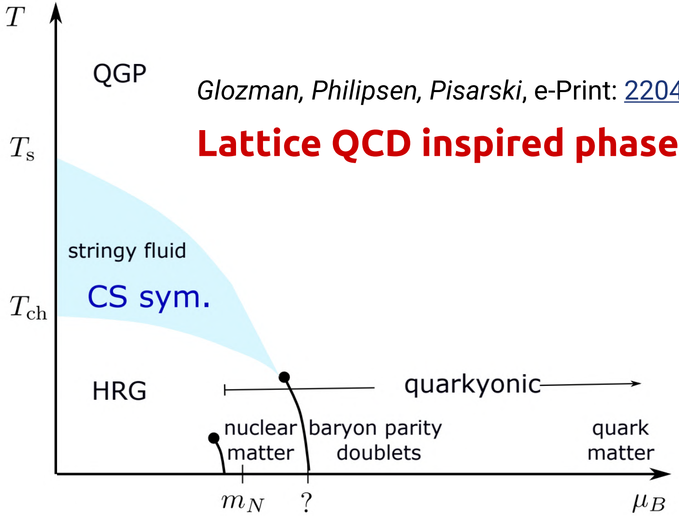


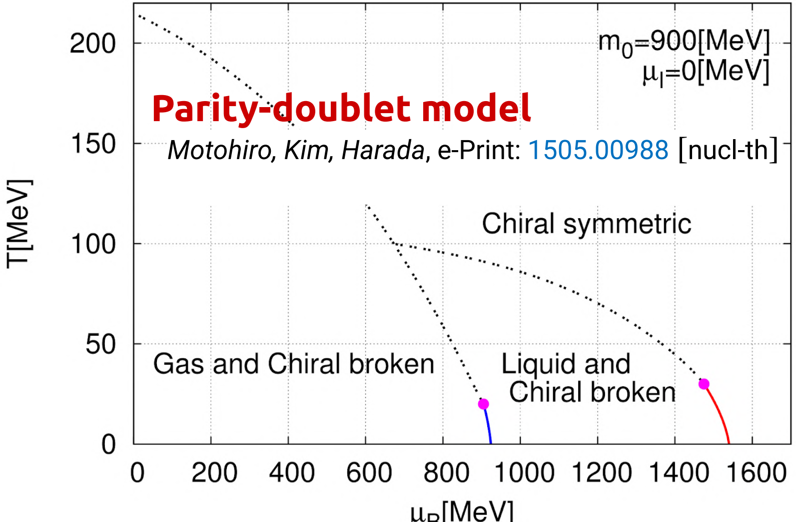
Glozman, Philipsen, Pisarski, e-Print: 2204.05083 [hep-ph]

Lattice QCD inspired phase diagram



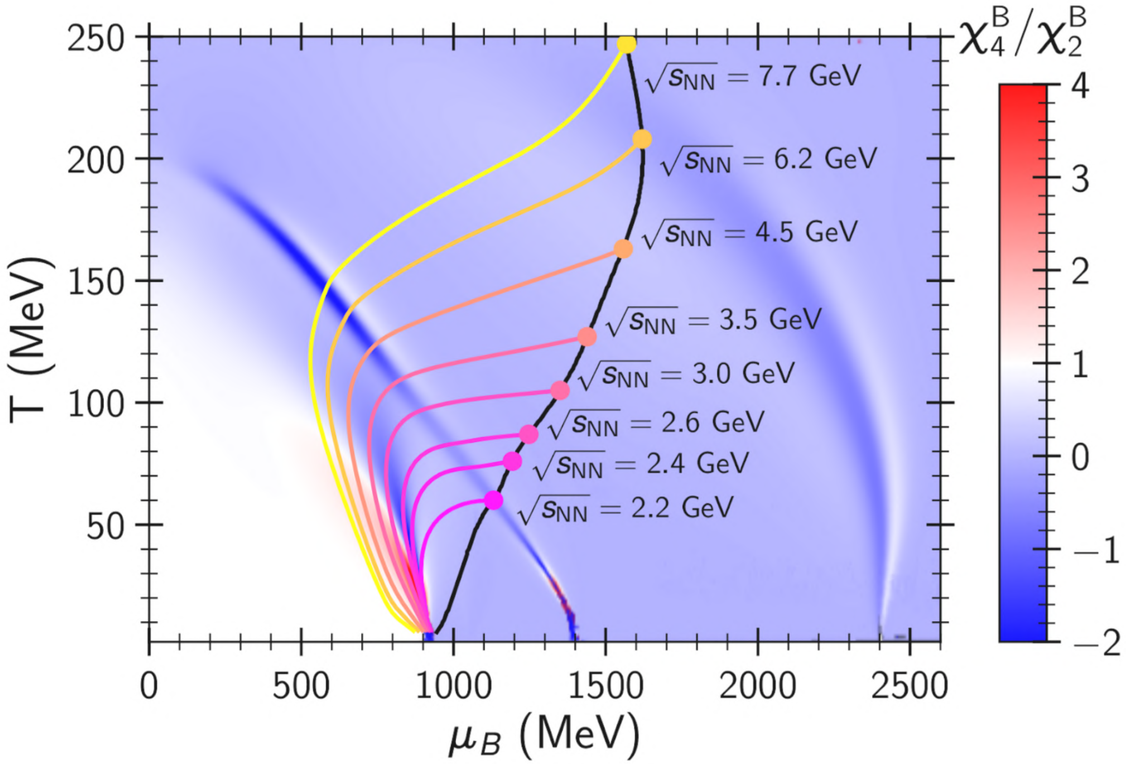
Parity-doublet model

Motohiro, Kim, Harada, e-Print: 1505.00988 [nucl-th]



Probing the phase diagram by heavy ions

AM, Steinheimer, Vovchenko, Schramm, Stoecker, *Phys. Rev.* C 101, no.3, 034904 (2020)

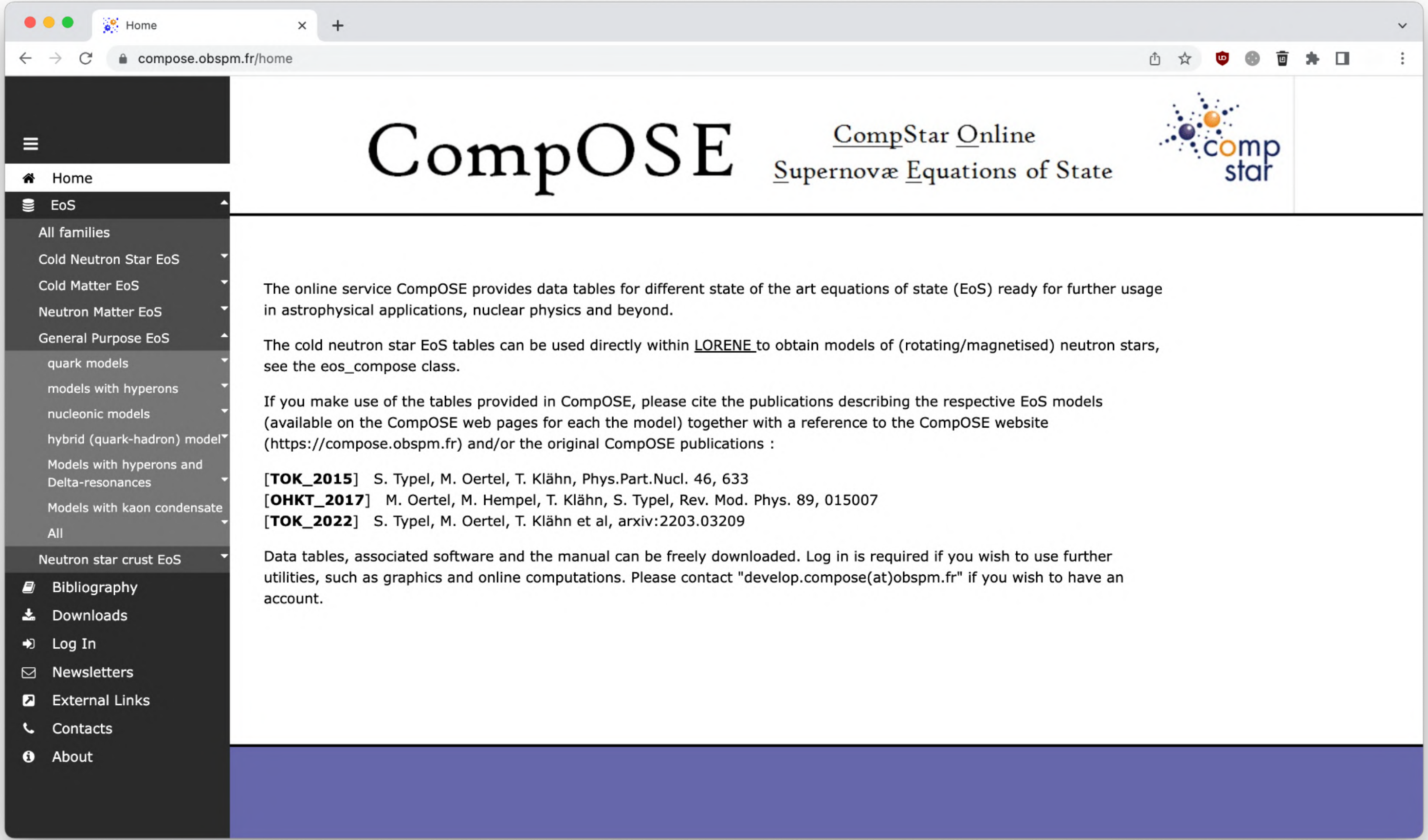


Entropy per baryon, S/A = const: hydrodynamic evolution of heavy ion collision

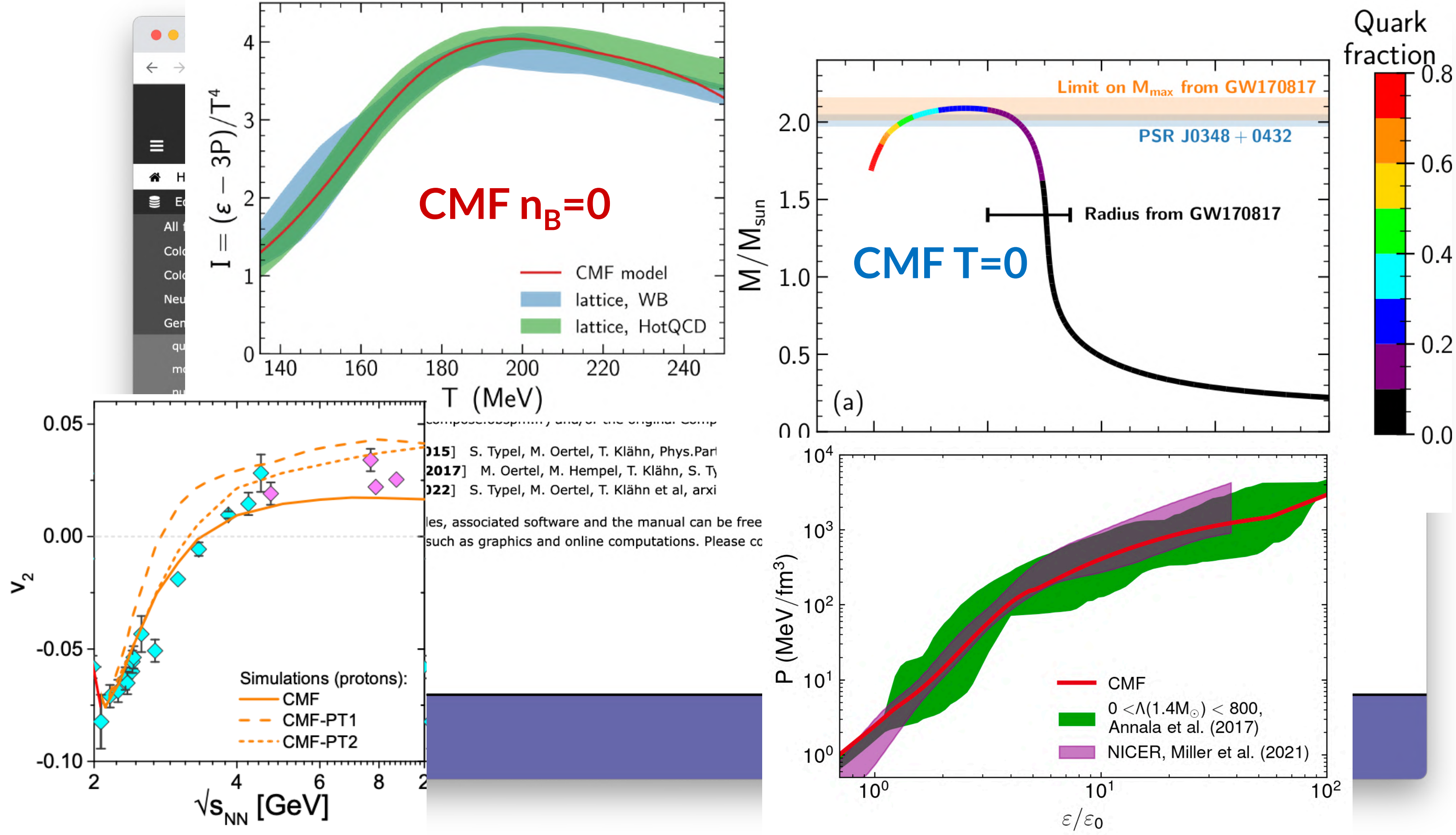
Relation to initial entropy by 1D shock wave solution (Taub adiabat).

HIC do not reach quark dominated phase

Separate EOS for astrophysics



~~Separate~~ Universal EOS for astrophysics and HIC



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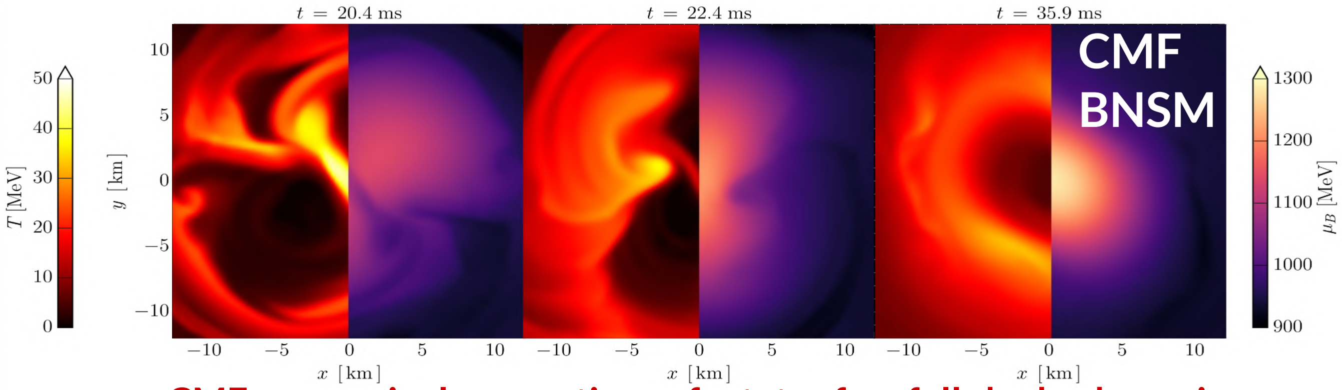
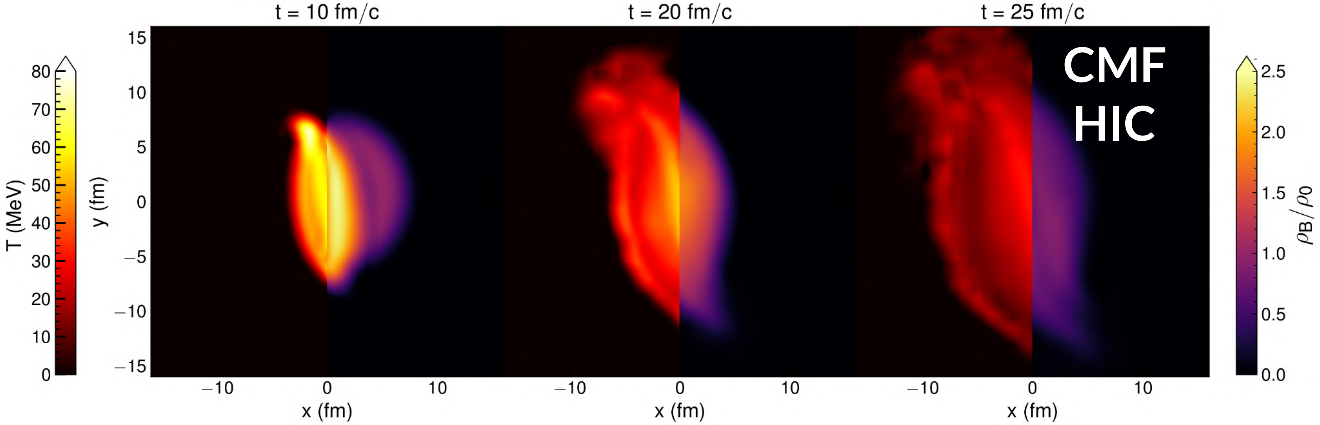


CMF — a single equation of state for full hydrodynamic modeling of both heavy ion collisions and neutron star mergers!



HIC vs BNSM: comparison

In the following we use **ideal** relativistic hydrodynamics, no viscosity and dissipations

Binary Neutron Star Mergers

General-relativistic magneto- hydrodynamics
Frankfurt/IllinoisGRMHD (FIL) code
with Einstein Toolkit

Etienne, Paschalidis, Haas, Mosta, and Shapiro, 1501.07276 [astro-ph.HE]
Most, Papenfort, and Rezzolla, 1907.10328 [astro-ph.HE]
F. Loffler et al., 1111.3344 [gr-qc].

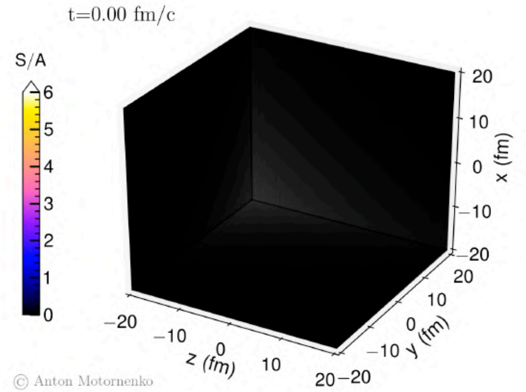
Heavy Ion Collisions

Relativistic flux-corrected SHASTA code

Boris, and Book, J. Comput. Phys. 11, 38 (1973)
Rischke, Bernard, and Maruhn, arXiv:nucl-th/9504018

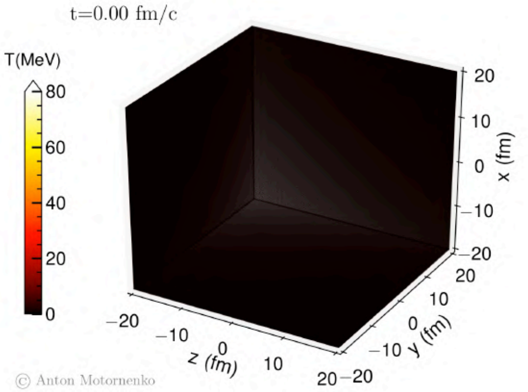
Both codes require equation of state as an input,
HIC — 2d table (T vs n_B)
BNSM — 3d table (T vs n_B vs n_{iso})

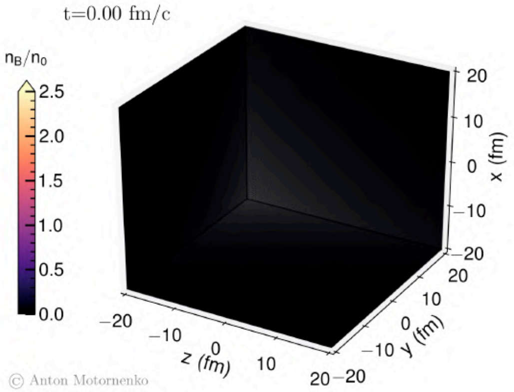
Heavy ion collision evolution



Full 3D hydro evolution of Au+Au collision at E_{lab}=450 MeV
Initial state:
Wood-Saxon Distributions

$$n_{WS} = \gamma_{CM} \frac{n_0}{1 + \exp\left(\frac{\Delta r - R}{a}\right)}$$





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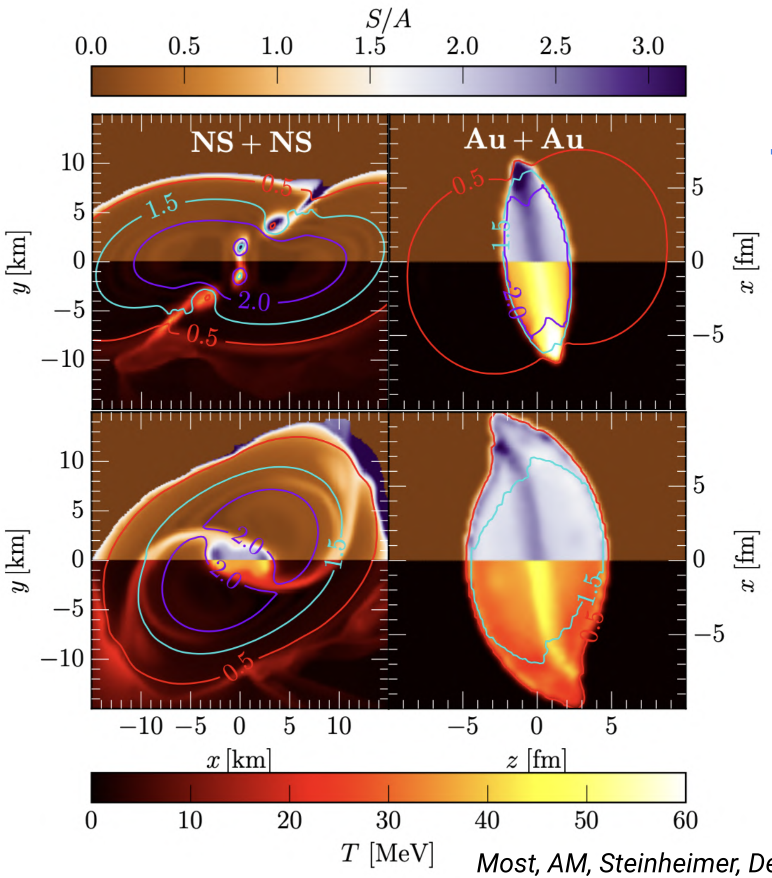


Geometry and scales are drastically different.

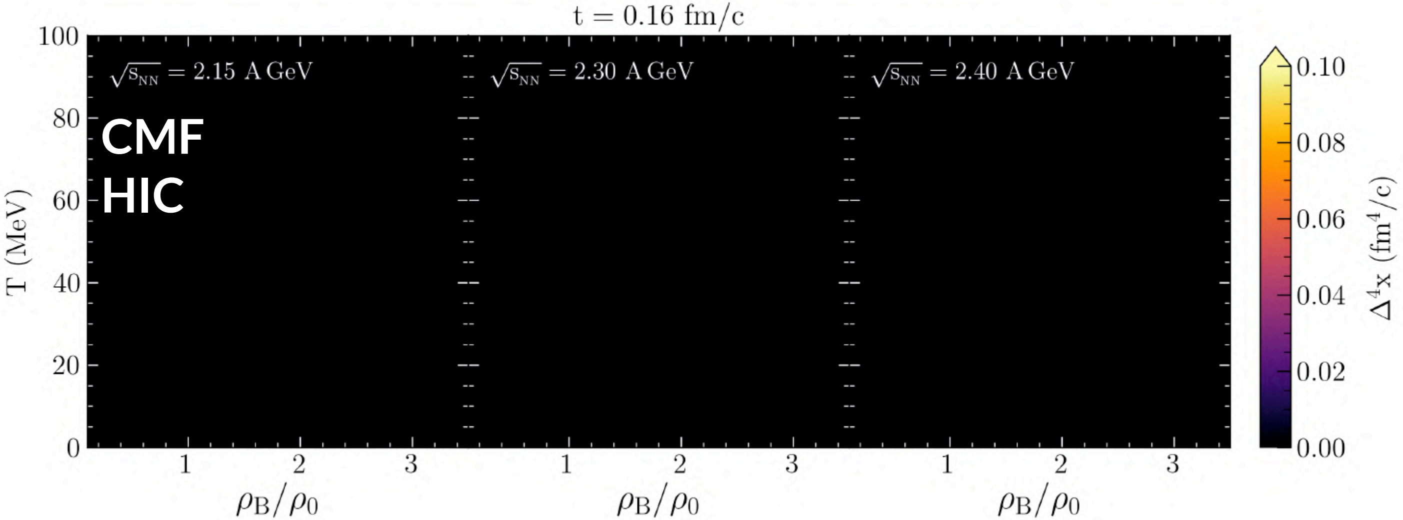
Thermodynamic conditions are similar!

Entropy per baryon S/A (top colormaps) and temperature T (bottom colormaps) for a BNS merger of mass M_{tot} = 2.8 M_{sun}, and a Au + Au HIC at E_{lab} = 450 MeV.

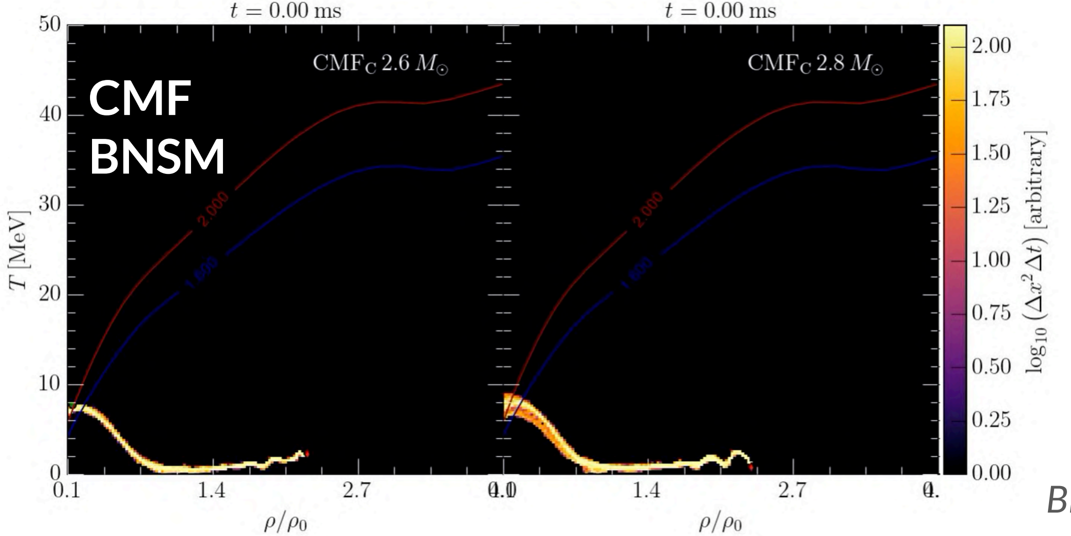
Colored lines mark density contours in units of n_{sat}.

The snapshots in refer to t = −2, 3 ms before and after merger for the BNS, respectively, and to t = ±5 fm/c before and after the full overlap for the HIC.

Most, AM, Steinheimer, Dexheimer, Hanauske, Rezzolla, Stoecker
e-Print: 2201.13150 *[nucl-th]*



HIC:
The whole system expands with approx. constant entropy



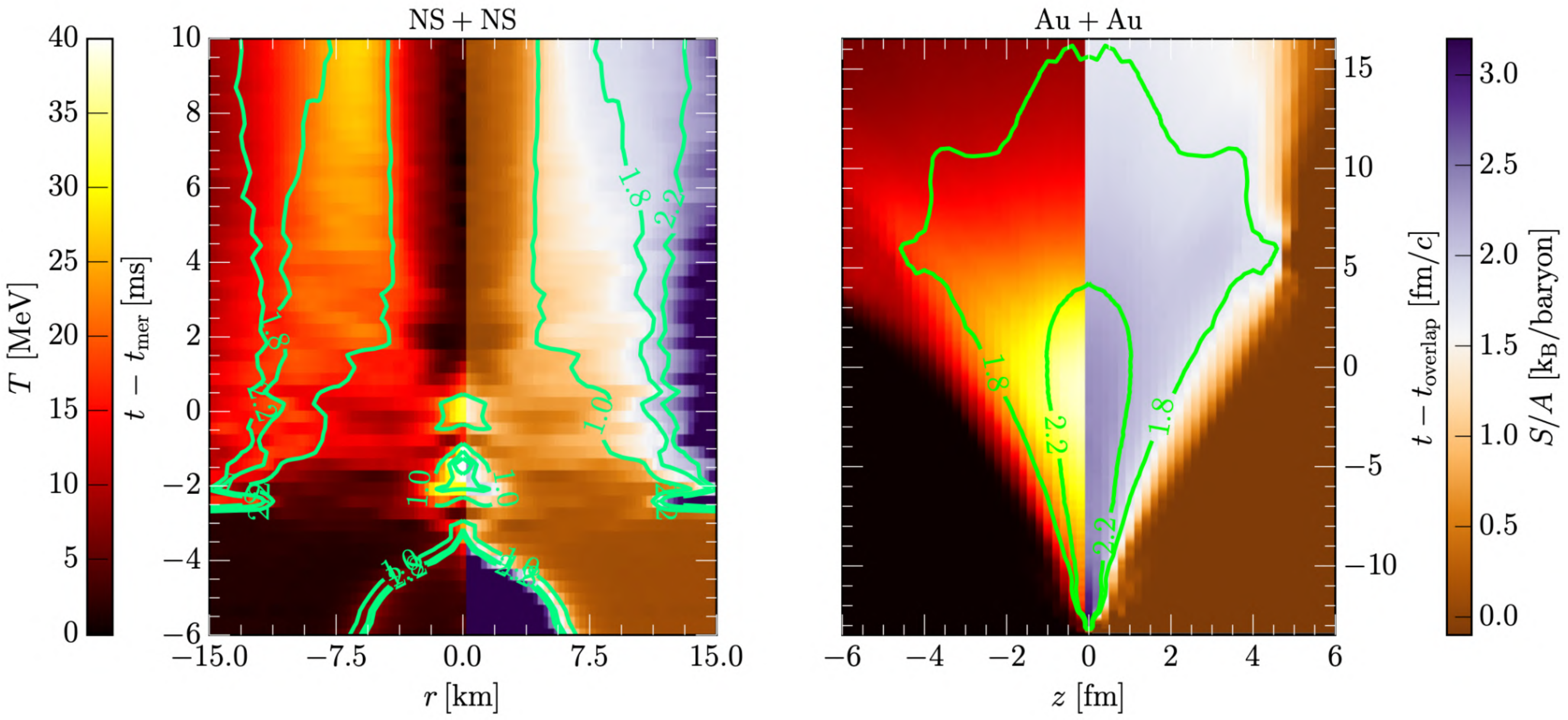
BNSM:
Entropy is localized in a "ring" structure

BNSM movie by Elias Most

HIC vs BNSM: comparison

Spacetime diagrams for the evolution of the temperature and entropy.

The green contours correspond to lines of constant entropy per baryon S/A.



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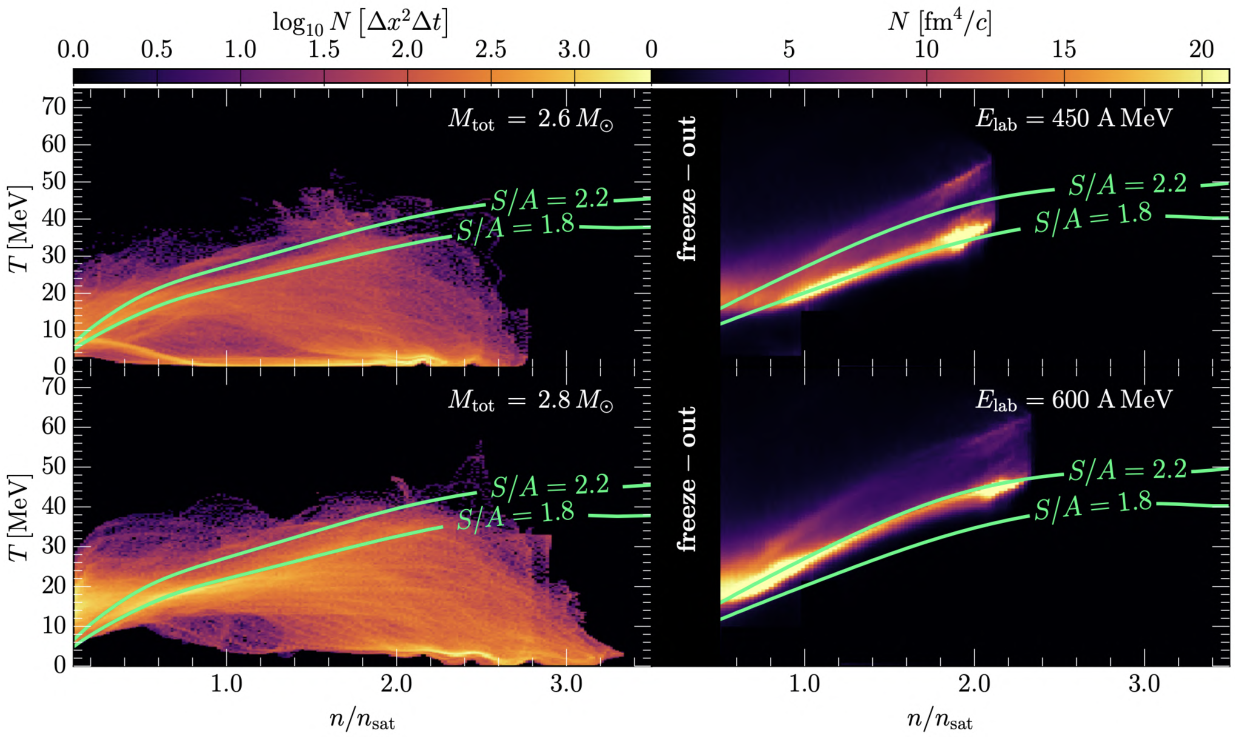
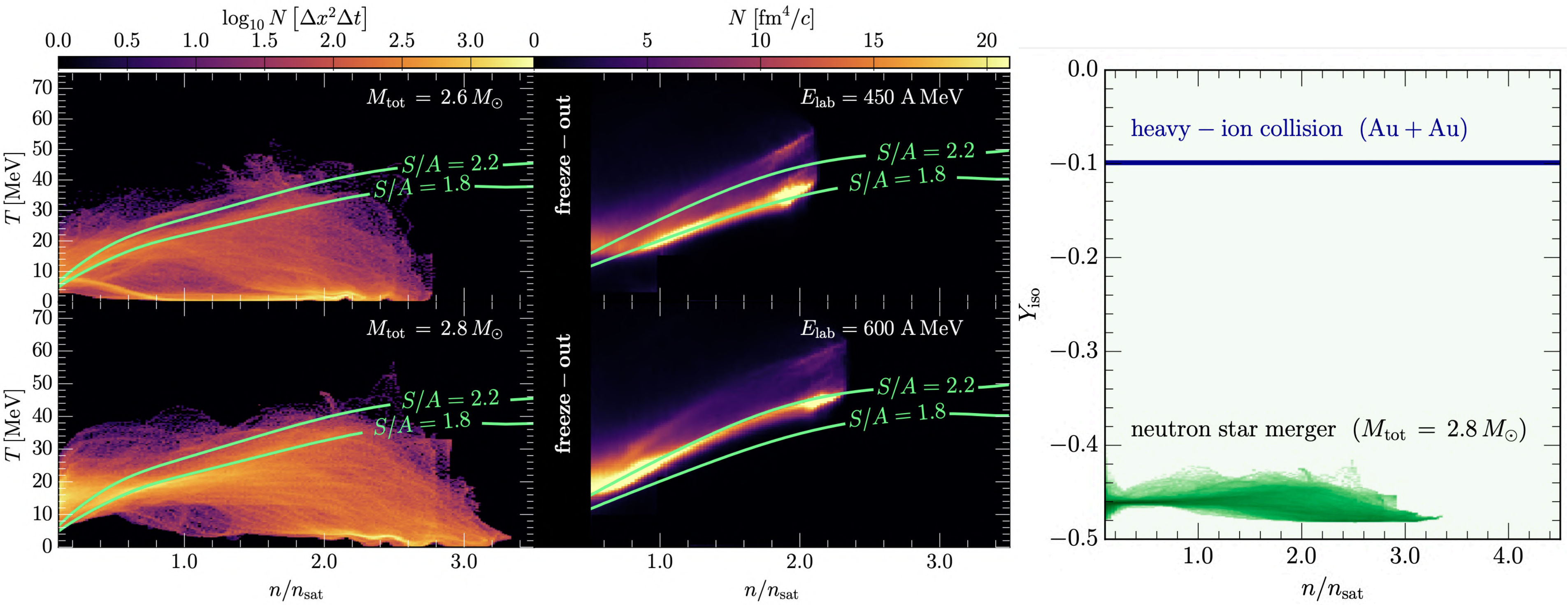
e-Print: *2201.13150 [nucl-th]*

HIC vs BNSM: comparison



Regions of the QCD phase-diagram probed by BNS mergers and by HICs. The colorcode reports the number of cells N in the various spacetimes having a given value of temperature and density. The green lines show contours of constant entropy per baryon. Only cells with density above freeze-out, n > 1/2 n_{sat}, are shown for the HIC.

HIC vs BNSM: comparison



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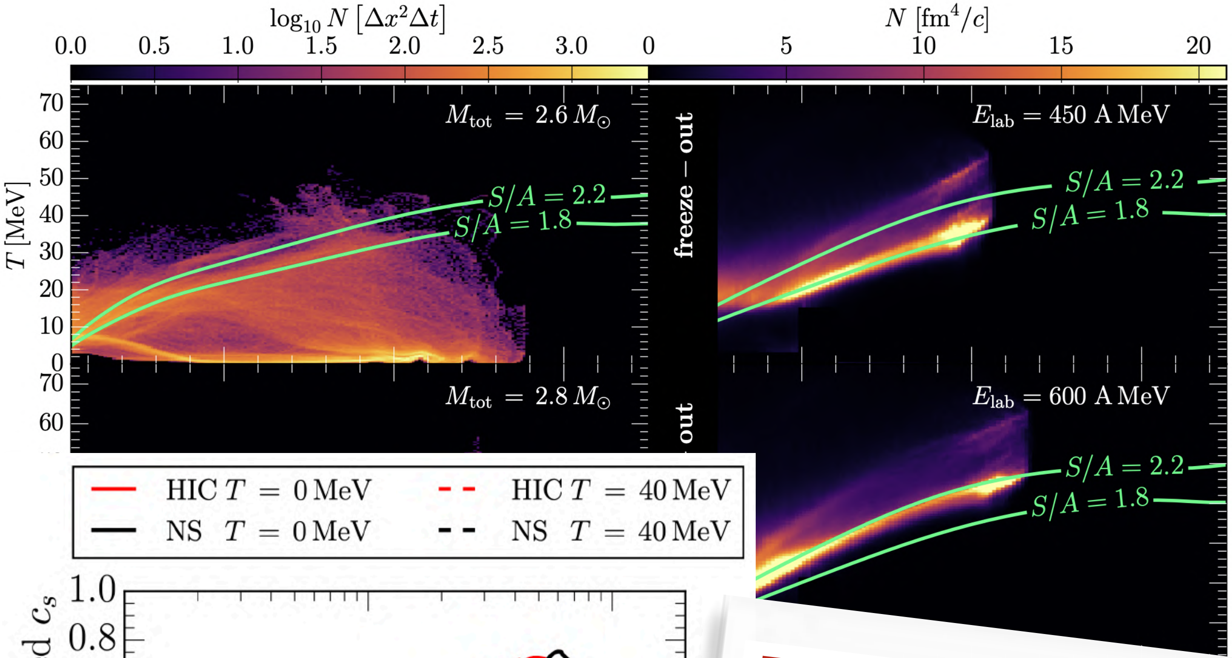
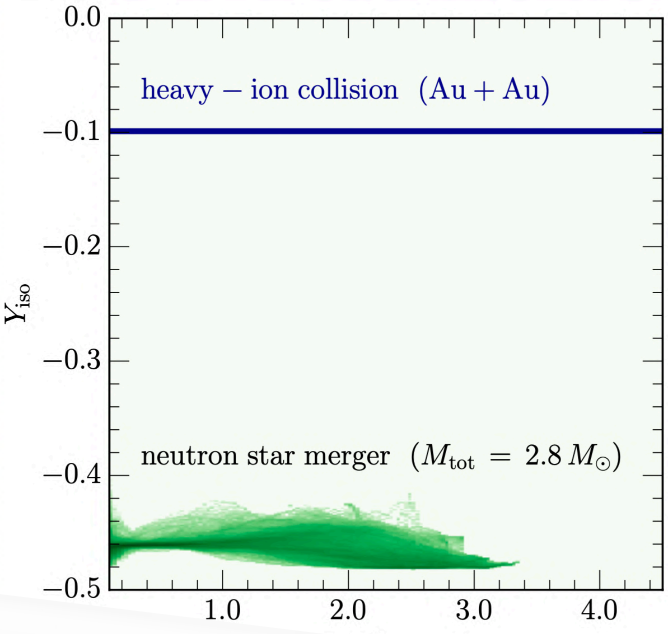
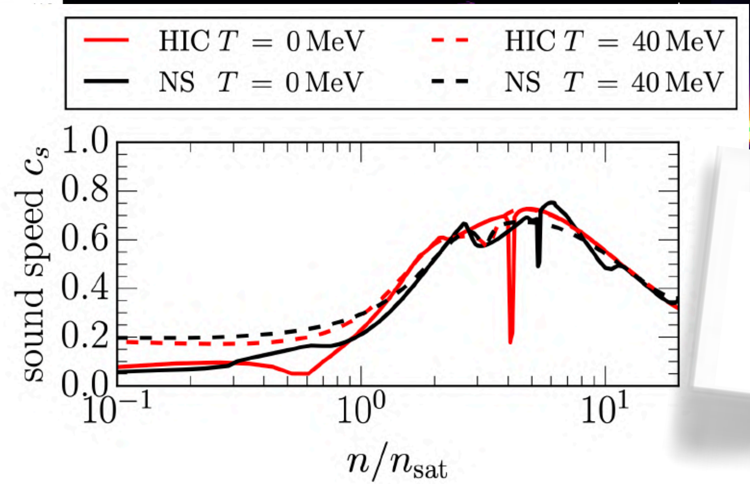
HIC vs BNSM: comparison







Though large differences in isospin, speed of sound stays robust even at finite temperatures.

Supernova explosions: another application for CMF

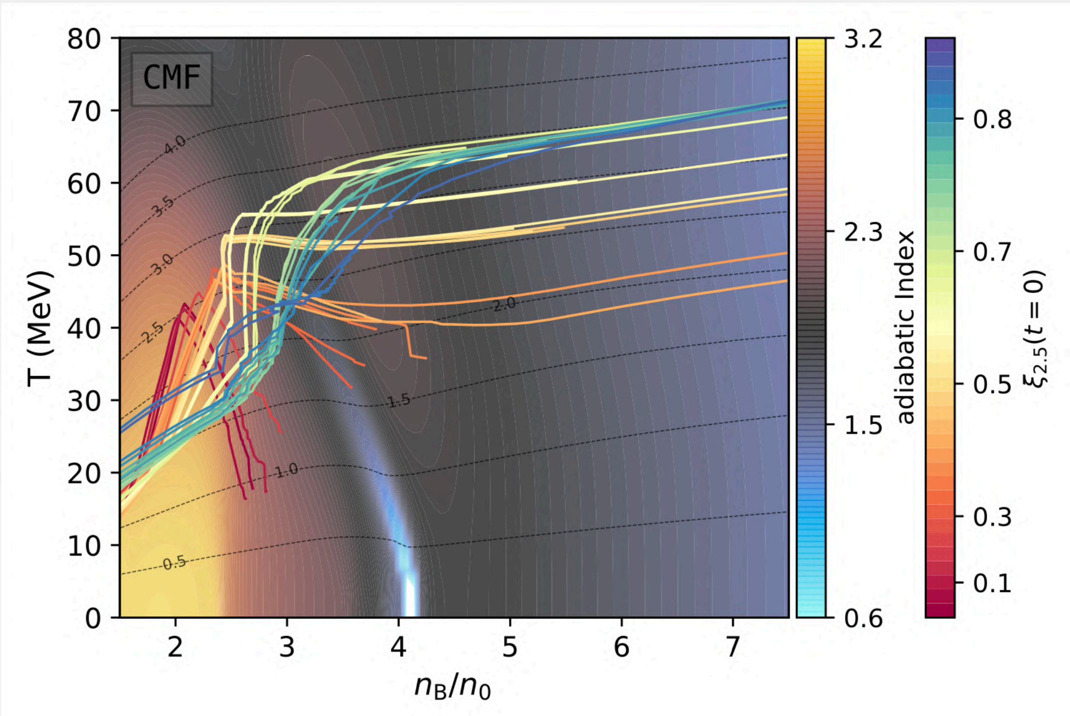


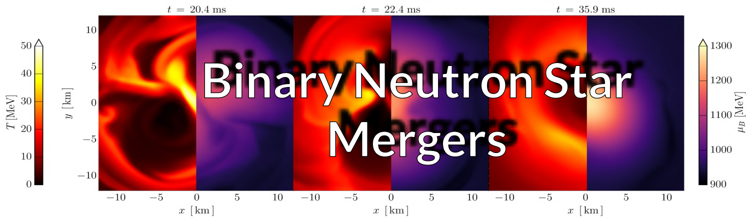
Figure 8. Phase diagram with trajectories of the central density and temperature (thick solid lines) of selected CMF models. The background displays the colour-coded adiabatic index at fixed electron fraction $Y_e = 0.25$ for the CMF EoS. The black dashed lines are isentropes for different entropy values (indicated as contour labels).

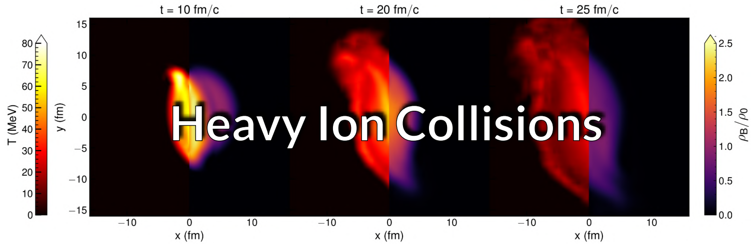
Jakobus, Müller, Heger, AM, Steinheimer, and Stoecker,
e-Print: *2204.10397 [astro-ph.HE]*

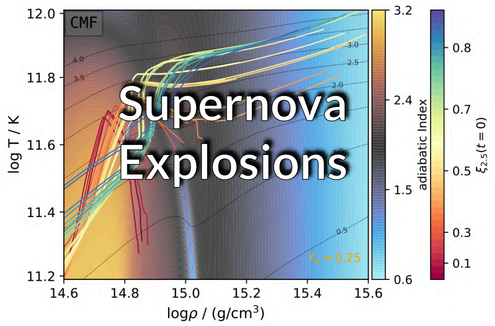
Summary

- EOS models are capable for simulations of:
- Can be used to analyse

- Astrophysical conditions can be probed by low energy nuclear collisions
- Predictions for laboratory experiments can be done by transport with proper interactions
- The interactions can hopefully be tested by (B)NS(M)







Thank you for the attention!