



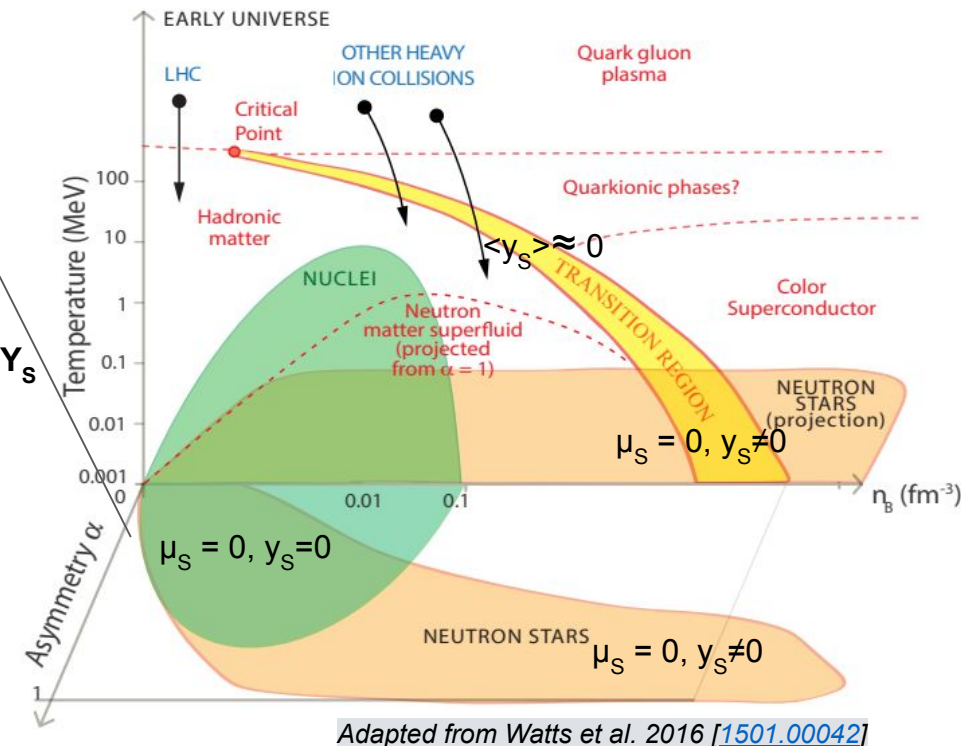
Strange Effects at Finite Temperature Hyperons and Phase Transitions

Mateus Reinke Pelicer

University of Illinois Urbana-Champaign



Phase diagram: degrees of freedom

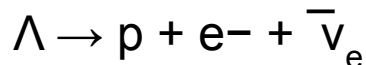
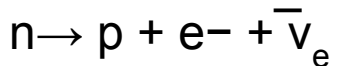


Strong interaction is fast.

Strong equilibrium $\rightarrow P(T, \mu_B, \mu_Q, \mu_S)$

$$\mu_i = B_i \mu_B + Q_i \mu_Q + S_i \mu_S$$

Long weak-interaction timescales set:

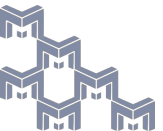


$$\mu_Q = -\mu_e = -\mu_\mu$$

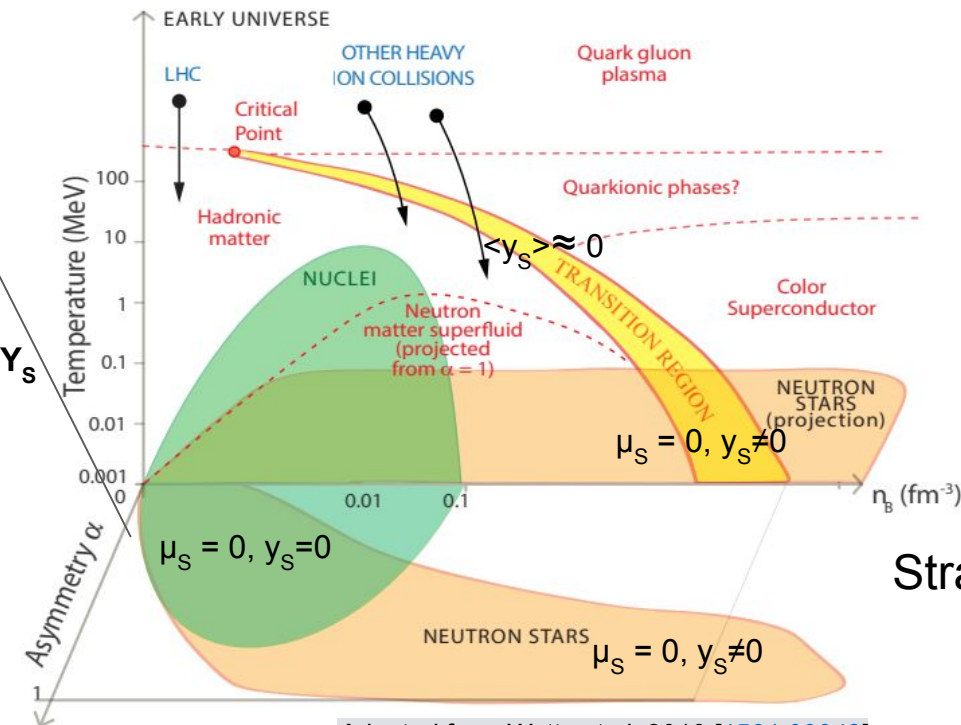
$$\mu_S = 0$$

$$n_{Q, \text{net}} = 0$$

Weak Equilibrium + CN $\rightarrow P(T, \mu_B)$



Phase diagram: degrees of freedom



Adapted from Watts et al. 2016 [1501.00042]

Heavy-ions: probe $\langle y_S \rangle \approx 0, \langle y_Q \rangle \approx 0.4$

NICER + GW inspiral: probe $T=0, \mu_S = 0$

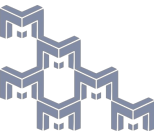
BNS Mergers: out-of-equilibrium;

$$\mu_Q \neq \mu_e \neq \mu_\mu$$

$$\mu_S \neq 0$$

Strangeness is not *just* extra particle species

It is a thermodynamic direction

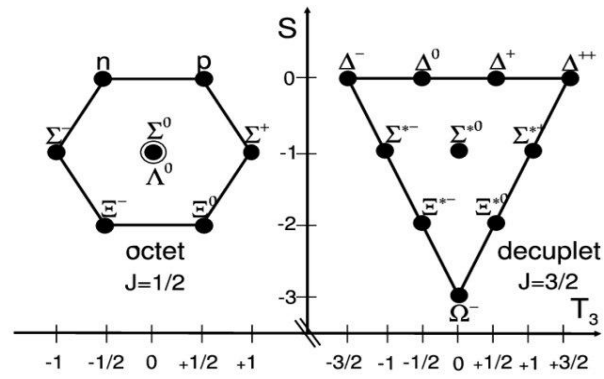


The Chiral Mean Field model

- Baryon octet and decuplet enter as SU(3) multiplets
- Deconfinement is modeled by a Polyakov-like field
- Meson multiplets mediate the interactions
- *Dynamic* mass generation
- Interactions built with SU(3) flavor symmetry
- Calculable in the full $\{T, \mu_B, \mu_Q, \mu_S\}$ space

Papazoglou+ [9706024,9806087]
 Dexeimer+ [0802.1999,0901.1748]
 Cruz Camacho+ [2409.06837,2603.16019]

What is the phase structure of the model in the (T, μ_B, μ_Q, μ_S) space?



U_Φ

Buchmann A. [0712.4383]

$$X = \text{diag} \left(\frac{\sigma + \delta}{\sqrt{2}}, \frac{\sigma - \delta}{\sqrt{2}}, \zeta \right)$$

$$V = \text{diag} \left(\frac{\omega + \rho}{\sqrt{2}}, \frac{\omega - \rho}{\sqrt{2}}, \phi \right)$$

$$\mathcal{L}_{\text{int}} = -\sqrt{2}g_8^M \left(\alpha_M [\bar{B}OBM]_F + (1 - \alpha_M) [\bar{B}OBM]_D \right) - \frac{1}{\sqrt{3}}g_1^M \text{Tr}(\bar{B}OB)\text{Tr}(M),$$

$$\mathcal{L}_{\text{pot}}^H = -m_3^H \text{Tr}(\bar{B}B - \bar{B}[B, S]) \text{Tr}(X - X_0)$$

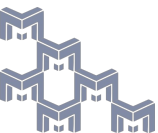
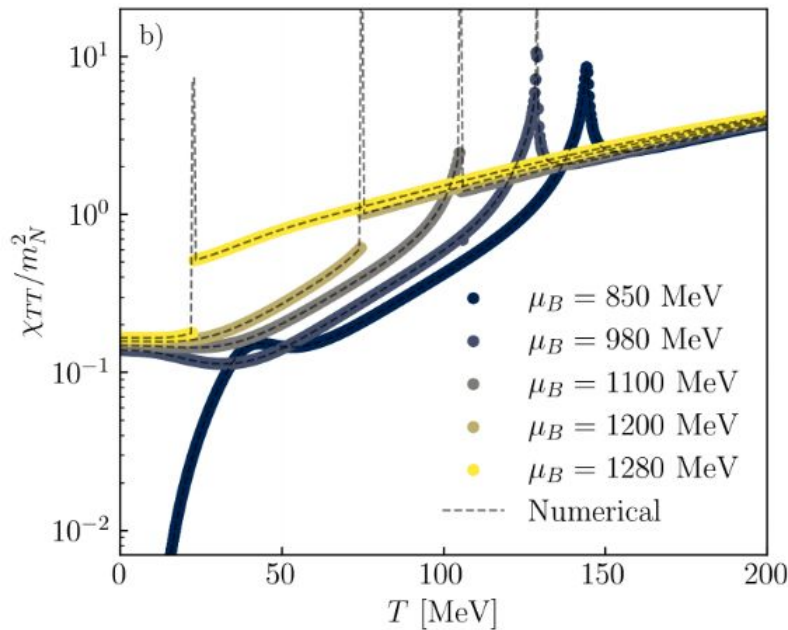
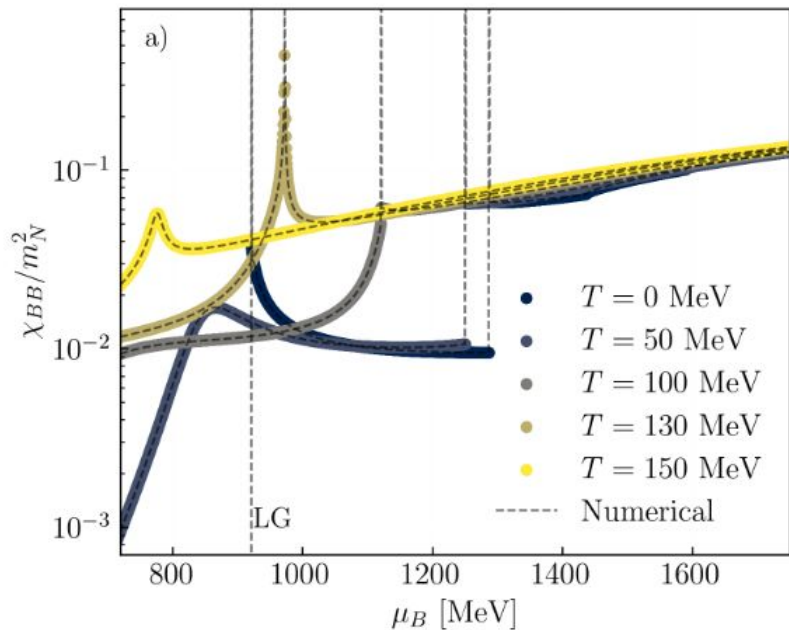
Stability of the EOS

Gholami, [2501.05192]

Stability requires: $d^2p = d\mathbf{x}^T \chi d\mathbf{x} \geq 0$ $\chi_{ab} = \frac{\partial^2 p}{\partial x_a \partial x_b}$ $d\mathbf{x}^T = (dT \ d\mu_B \ d\mu_Q \ d\mu_S)$

Jacobian method: $\chi_{ab}(T, \mu) = [\tilde{\chi}_{ab}(T, \mu, \xi(T, \mu))]_{\partial_\xi \Omega^{\text{eff}}=0} = H_{ab}/D$ $H_{ab} = \frac{\partial(\chi_a, \partial_{\xi_1} \Omega, \dots, \partial_{\xi_N} \Omega)}{\partial(X_b, \xi_1, \dots, \xi_N)}$
 $D = \frac{\partial(\partial_{\xi_1} \Omega, \dots, \partial_{\xi_N} \Omega)}{\partial(\xi_1, \dots, \xi_N)}$

RC4



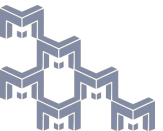
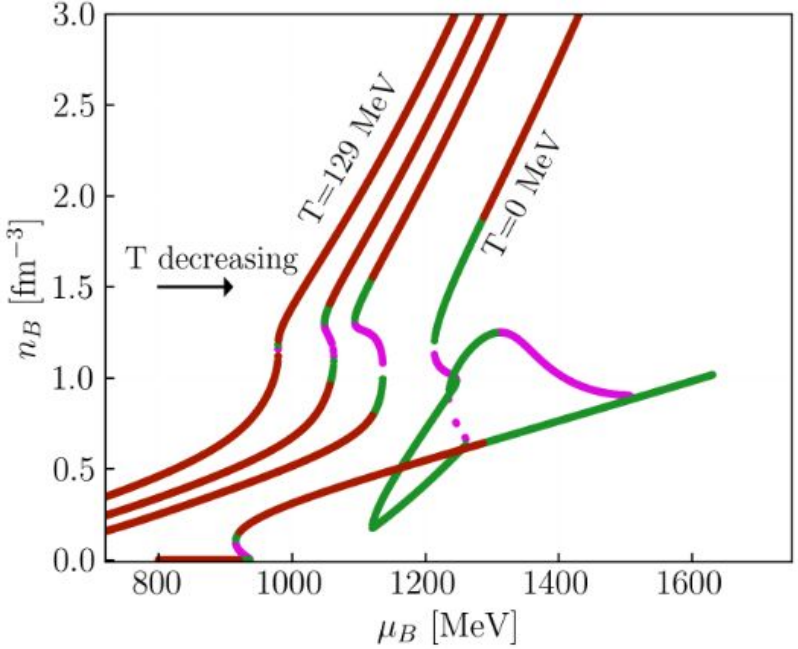
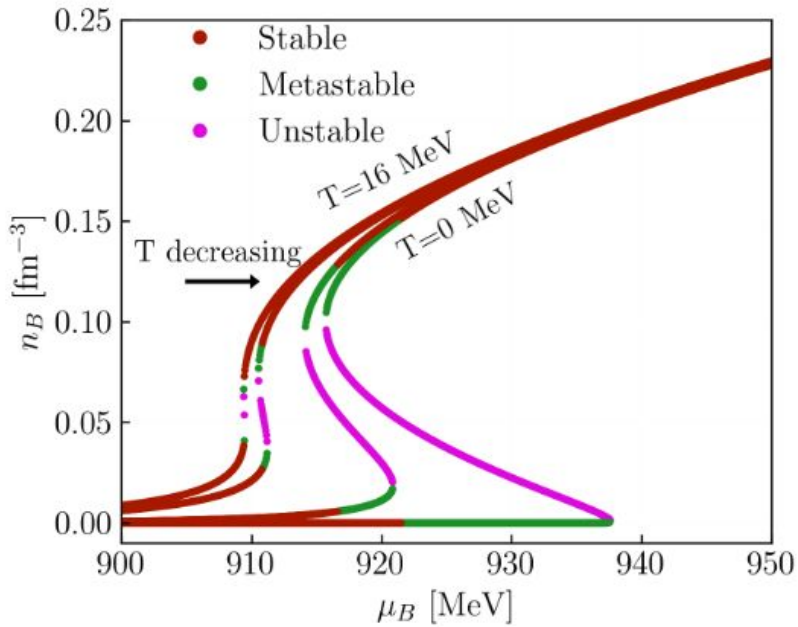
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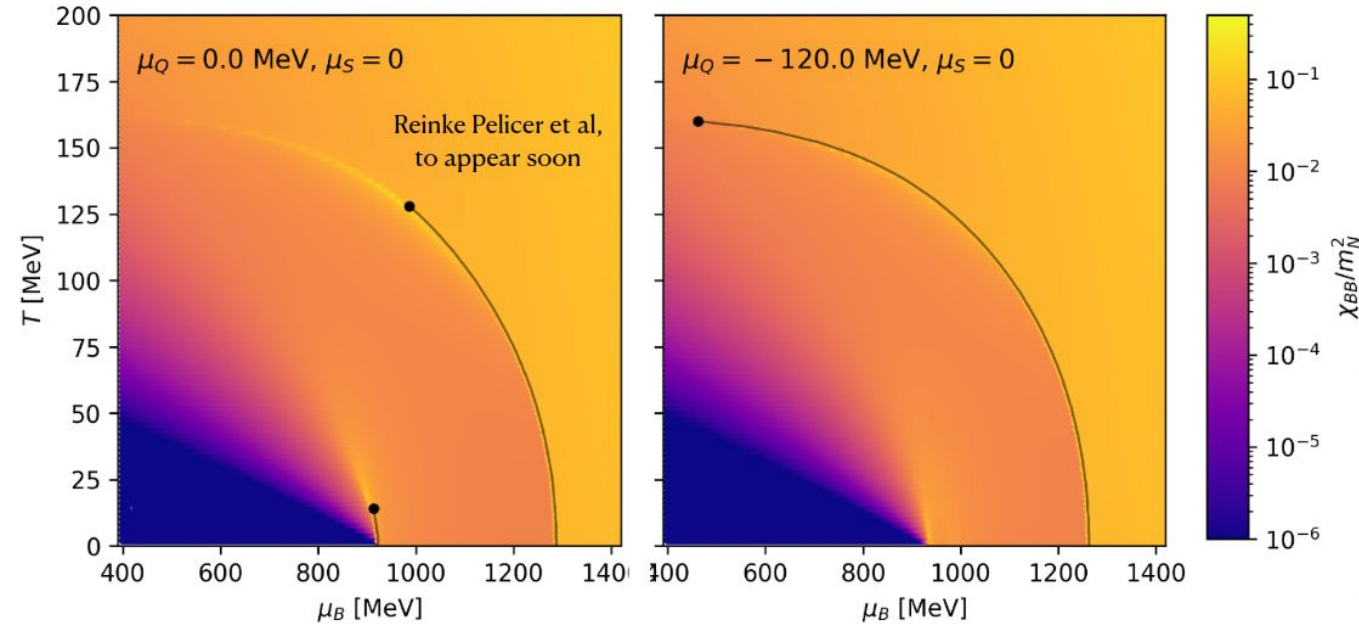
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RC4



The baseline phase diagram



20+ free parameters

Few parametrizations

$$\text{C1: } \mathcal{L}_{\text{vec}}^{\text{SI}} = 2g_4 \text{Tr}(V^4),$$

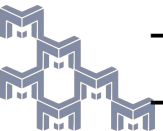
$$\text{C2: } \mathcal{L}_{\text{vec}}^{\text{SI}} = g_4 \left[\frac{3}{2} [\text{Tr}(V^2)]^2 - \text{Tr}(V^4) \right],$$

$$\text{C3: } \mathcal{L}_{\text{vec}}^{\text{SI}} = g_4 [\text{Tr}(V^2)]^2,$$

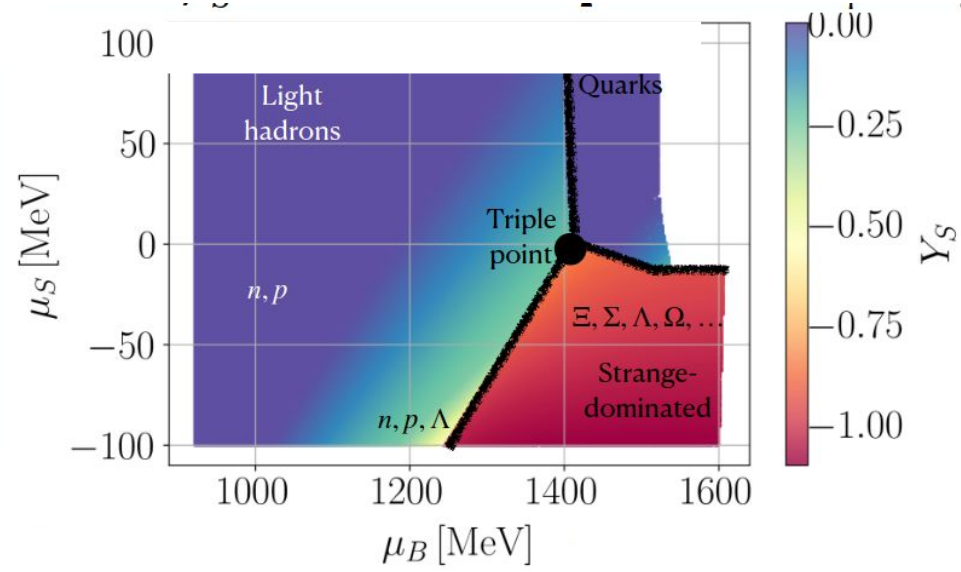
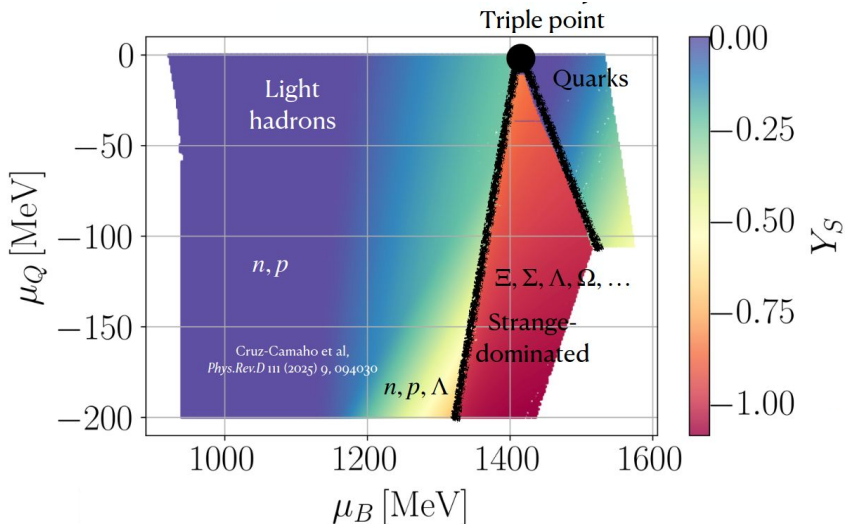
$$\text{C4: } \mathcal{L}_{\text{vec}}^{\text{SI}} = \frac{g_4}{4} [\text{Tr}(V)]^4,$$

The C4/RC4 couplings have significantly **less** strangeness

- Finite bare mass term m_0
- Weaker coupling to the scalar (attractive) mesons



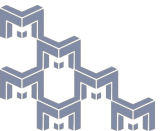
A strangeness-dominated phase transition



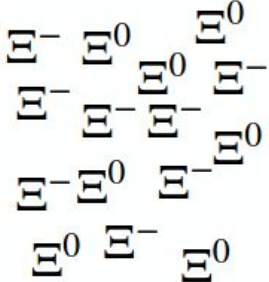
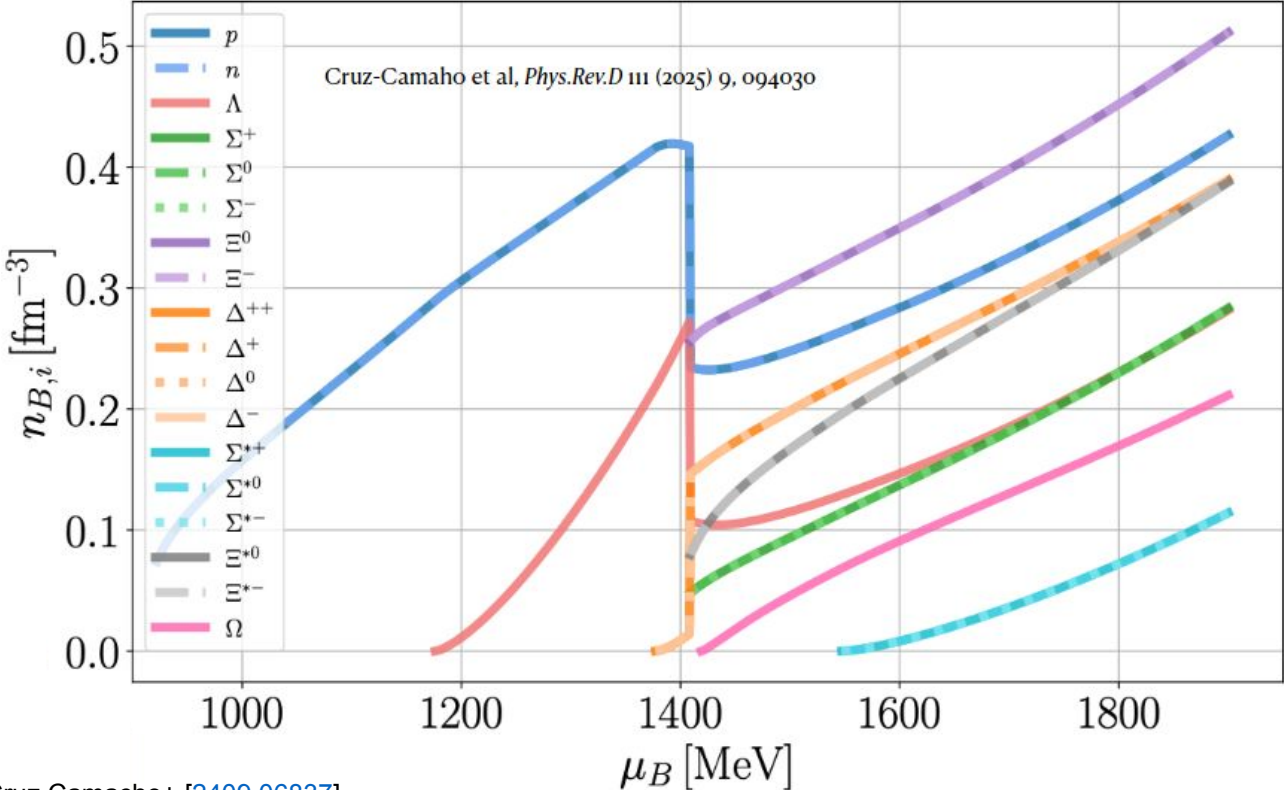
Cruz Camacho+ [[2409.06837](#)]

The C3/RC3 couplings have significantly **more** strangeness;

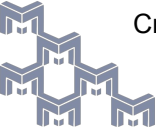
- Zero bare mass term m_0
- Stronger coupling to the scalar (attractive) mesons



Composition of the strangeness-rich phase

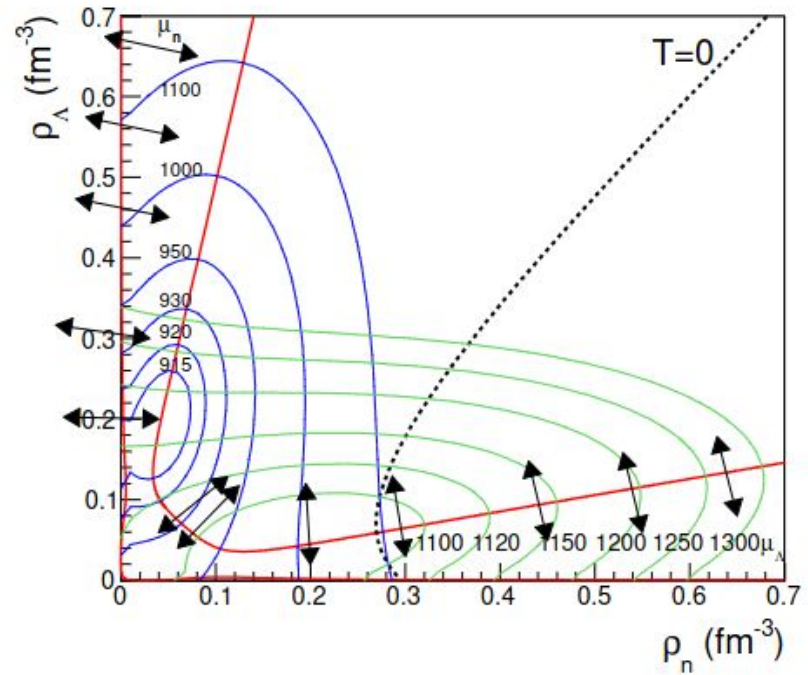


$S = -2, Q = 0, -1$

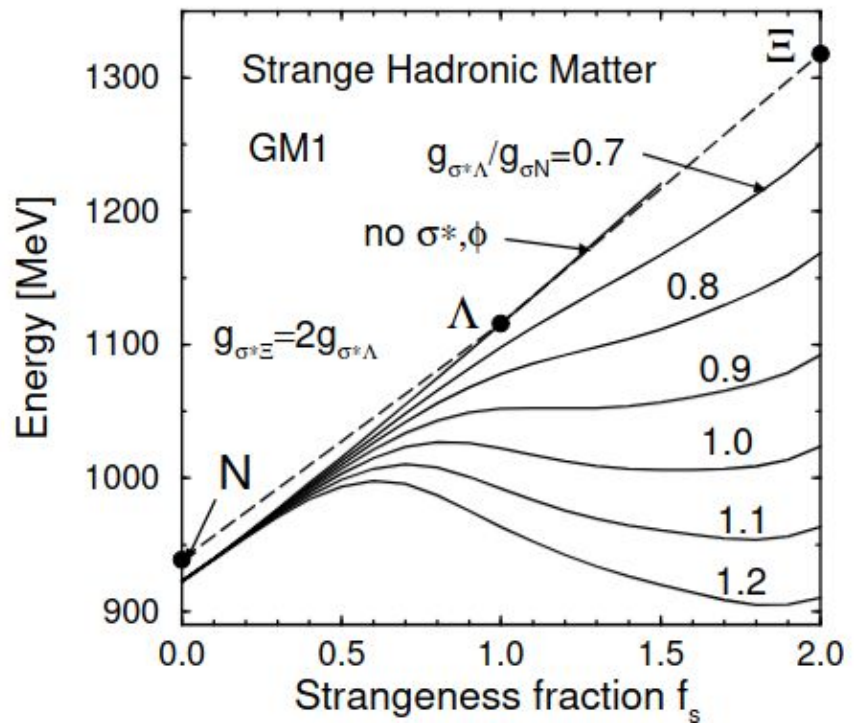


Composition as an order parameter

Gulminelli+ [1206.4924]



Schaffner-Bielich+ [0005490]

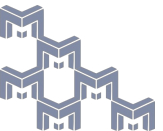


Eigenvectors dictate the order parameter.

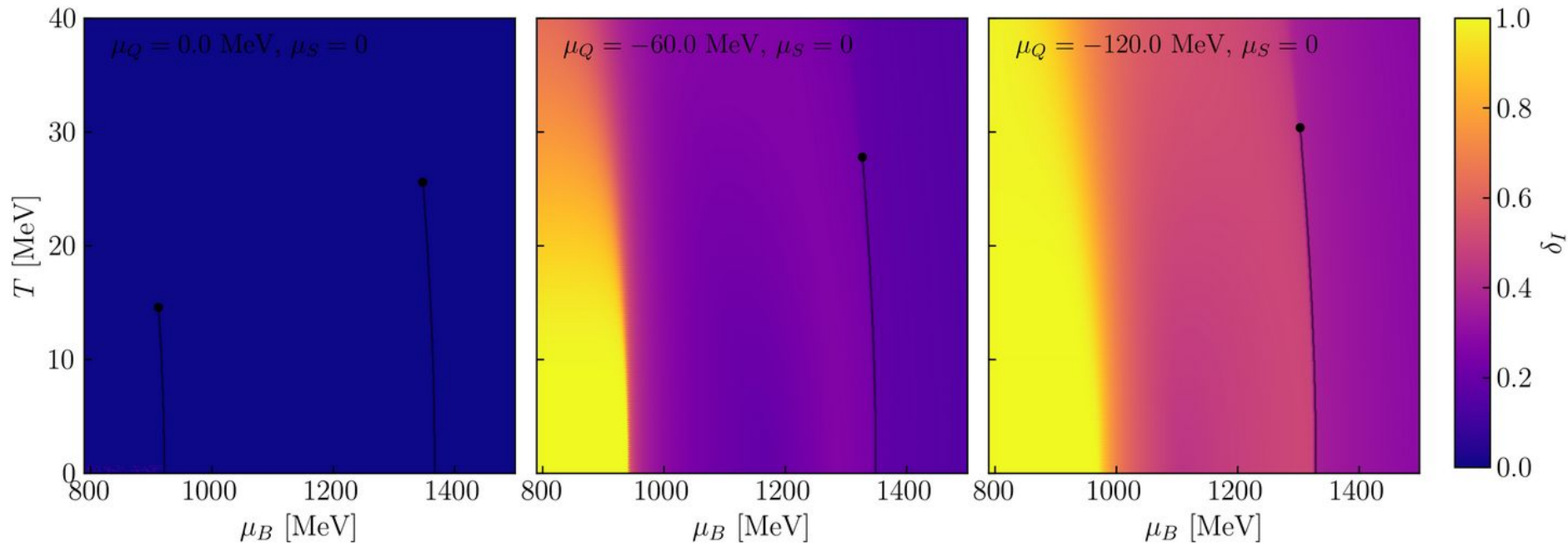
In ordinary nuclear matter it is n_B .

In strange matter the eigenvector can rotate toward the strangeness direction.

Composition-driven instability

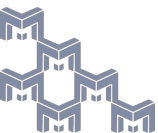


(Semi) Restoration of isospin symmetry

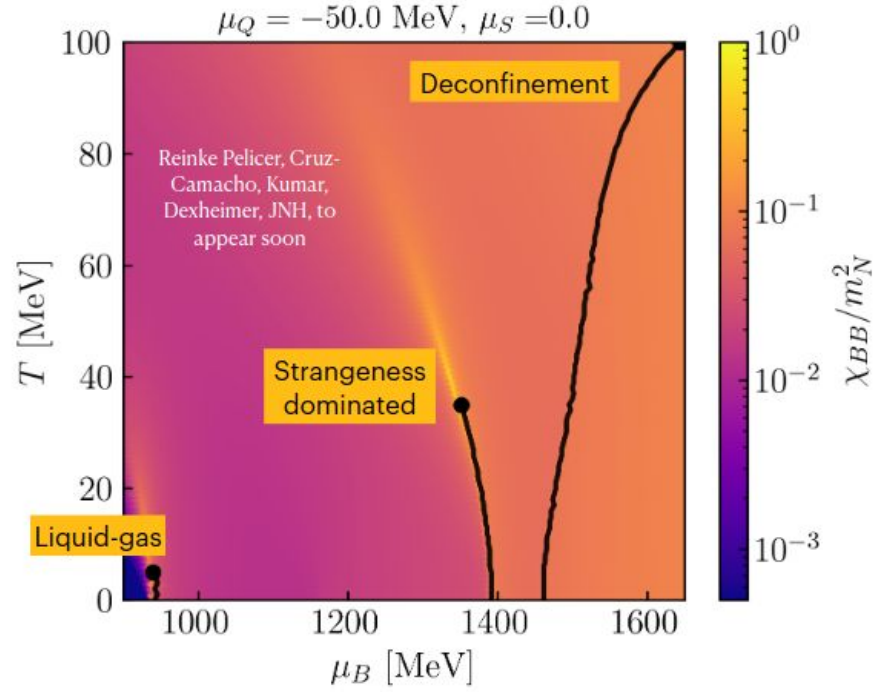
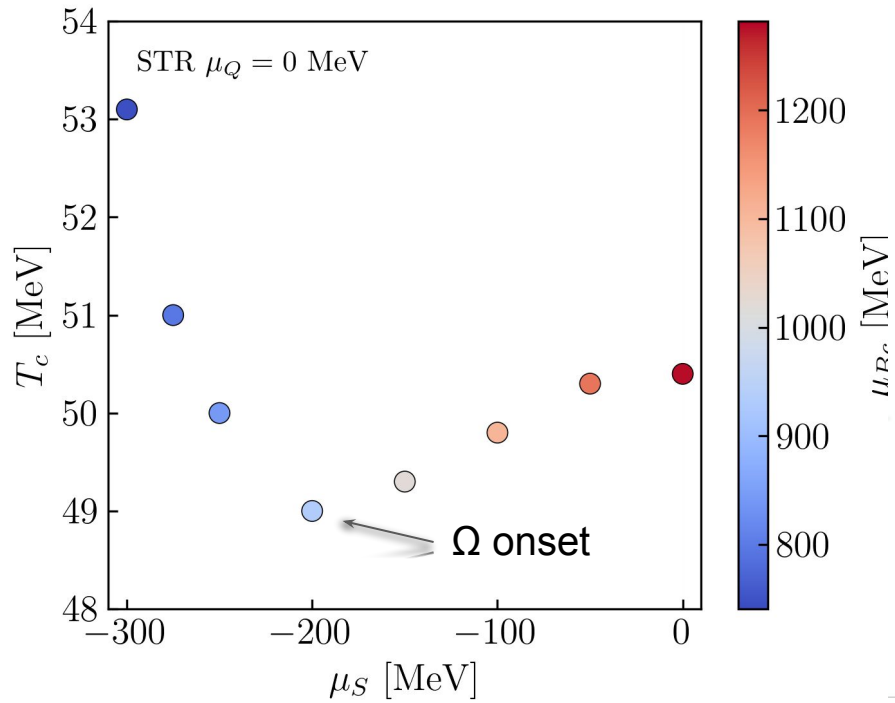


This is mostly a $N \rightarrow \Xi \rightarrow \Xi + \Omega$ transition

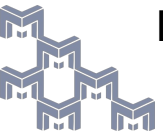
$Y_Q \lesssim 0, Y_S < 0$



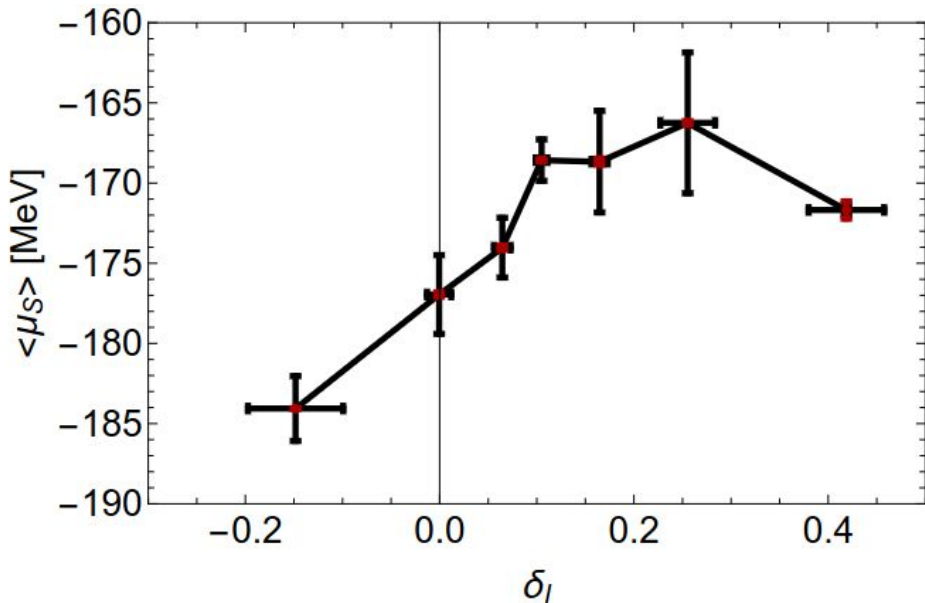
How the critical point moves with μ_S ?



The Ω baryons appear firstly in the dense phase
 Drives the critical temperature up by re-opening a different strangeness channel



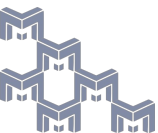
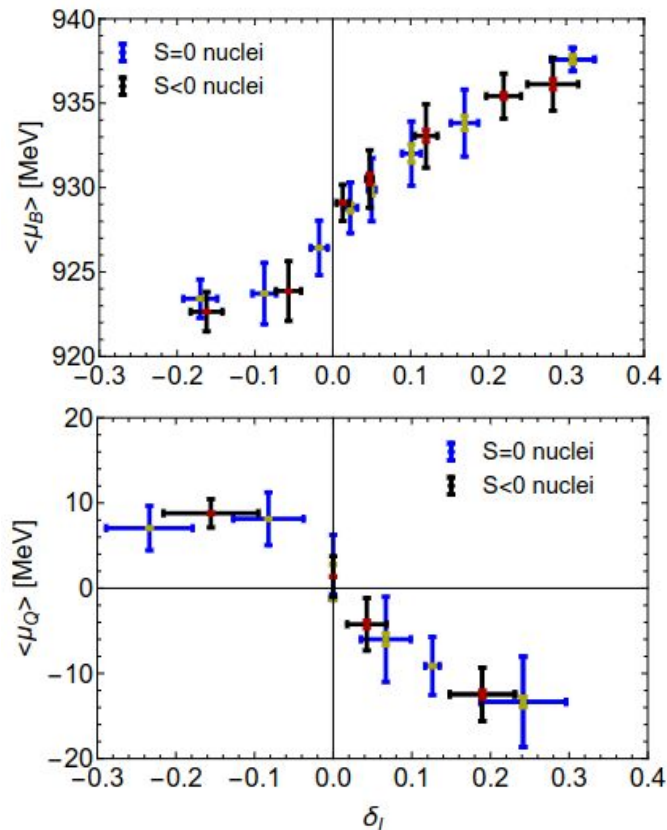
Where to anchor the μ_S dimension? Hypernuclei



Noronha-Hostler [2602.05824]

$$\mu_S = -177.39 \pm 0.07 \pm 3 \text{ MeV}$$

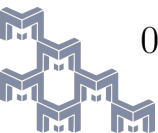
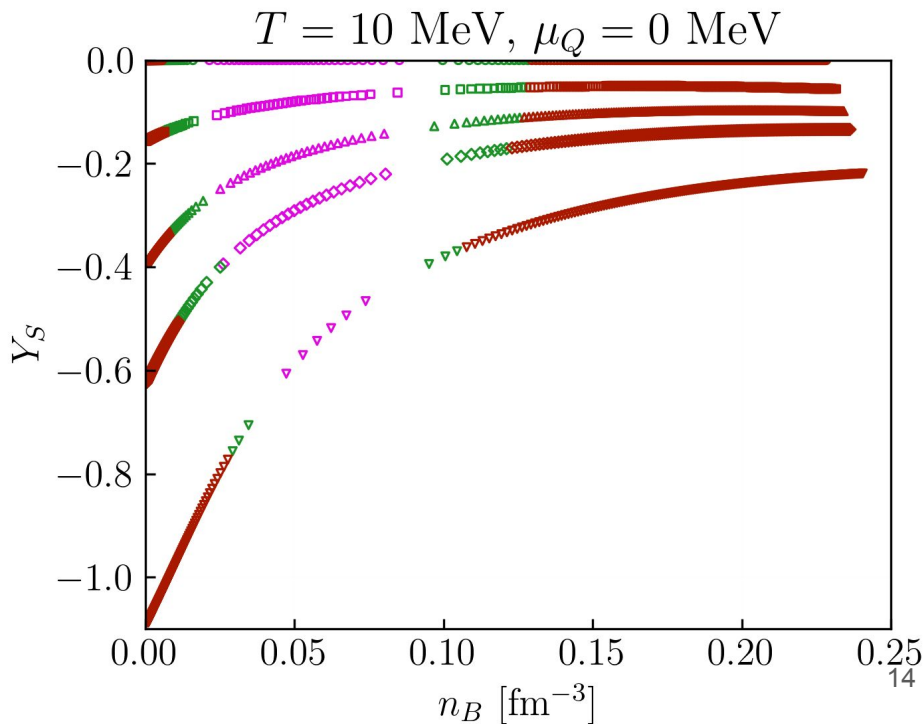
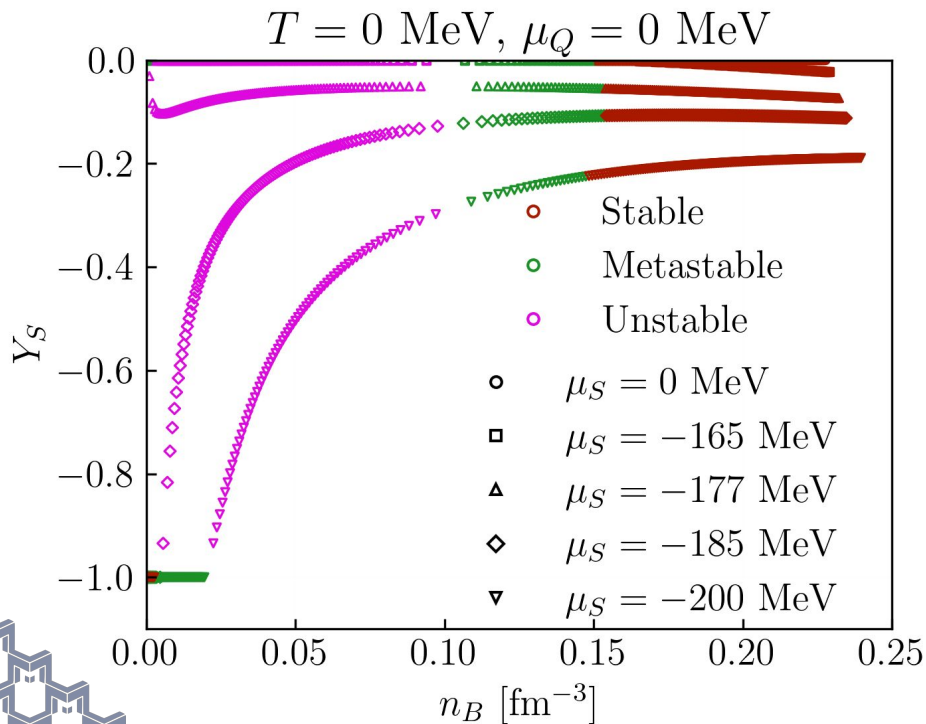
$$\langle \mu_X \rangle (\delta_I^{\min}; \delta_I^{\max}) \equiv \frac{\sum_{\delta_I^{\min}}^{\delta_I^{\max}} A^{1/3} \mu_X}{\sum_{\delta_I^{\min}}^{\delta_I^{\max}} A^{1/3}}$$



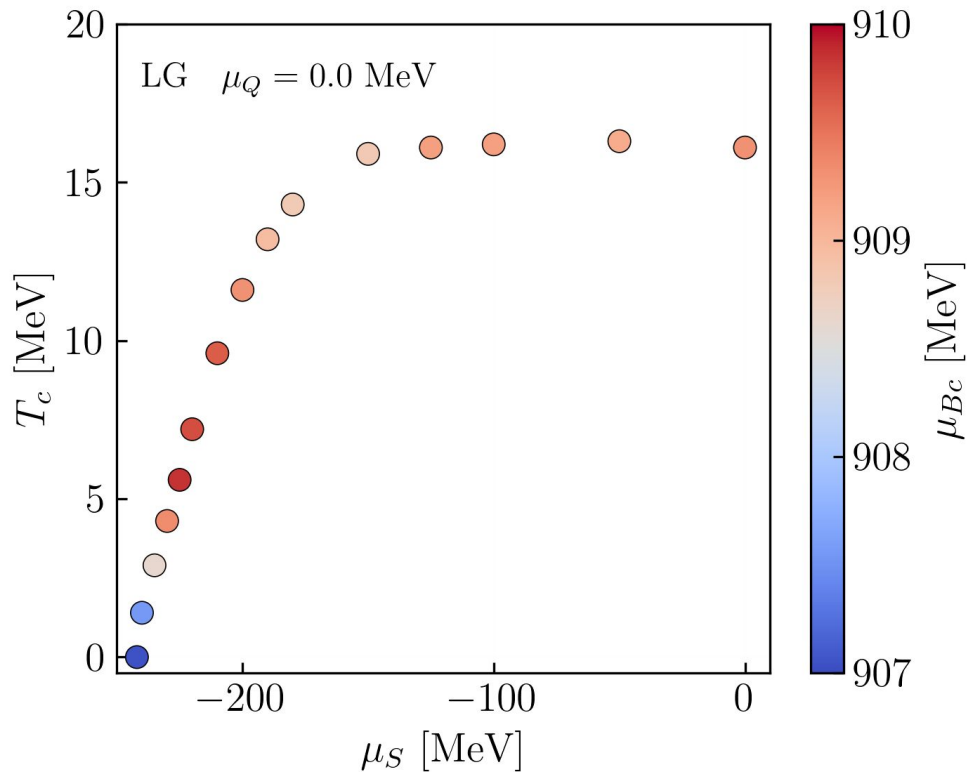
The Liquid-Gas at finite μ_S

The gas phase becomes strange.

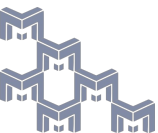
$$\frac{n_\Lambda}{n_N} \sim \left(\frac{m_\Lambda}{m_N}\right)^{3/2} \exp\left[\frac{-\mu_S - (m_\Lambda - m_N)}{T}\right]$$



The Liquid-Gas at finite μ_s



- The LG is strongest before the hyperon onset
- More negative μ_s implies
 - Λ s appear in the gas phase
 - Shifts the density instability
 - Weakens the LG
 - T_c decreases



Coupled electroweak rate equations in mergers

Storbacka, Wu, Dong, Cruz Camacho, Haber, Reinke Pelicer, Dexheimer, Most, Noronha-Hostler, to appear

Rate equations:

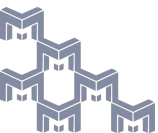
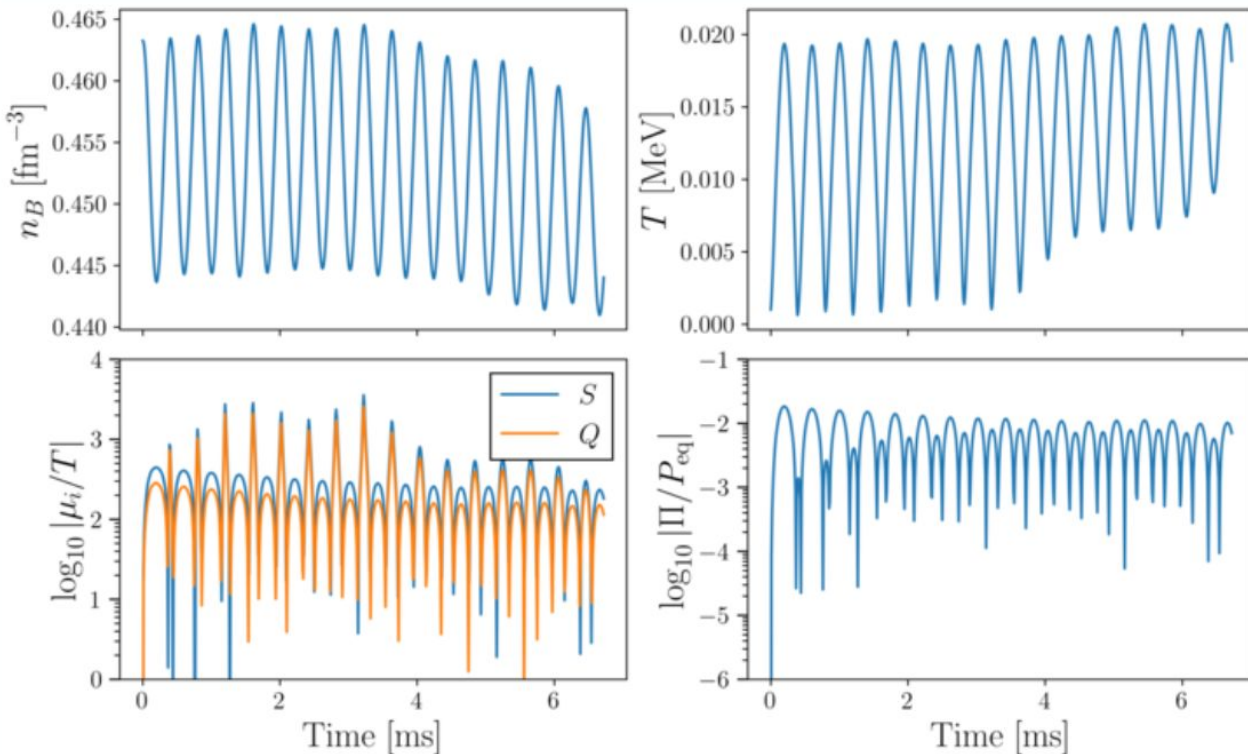
$$\dot{n} = \Gamma [\text{gain} - \text{loss}] + \dots$$

for each particle

In medium reaction rates

Equation of state

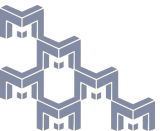
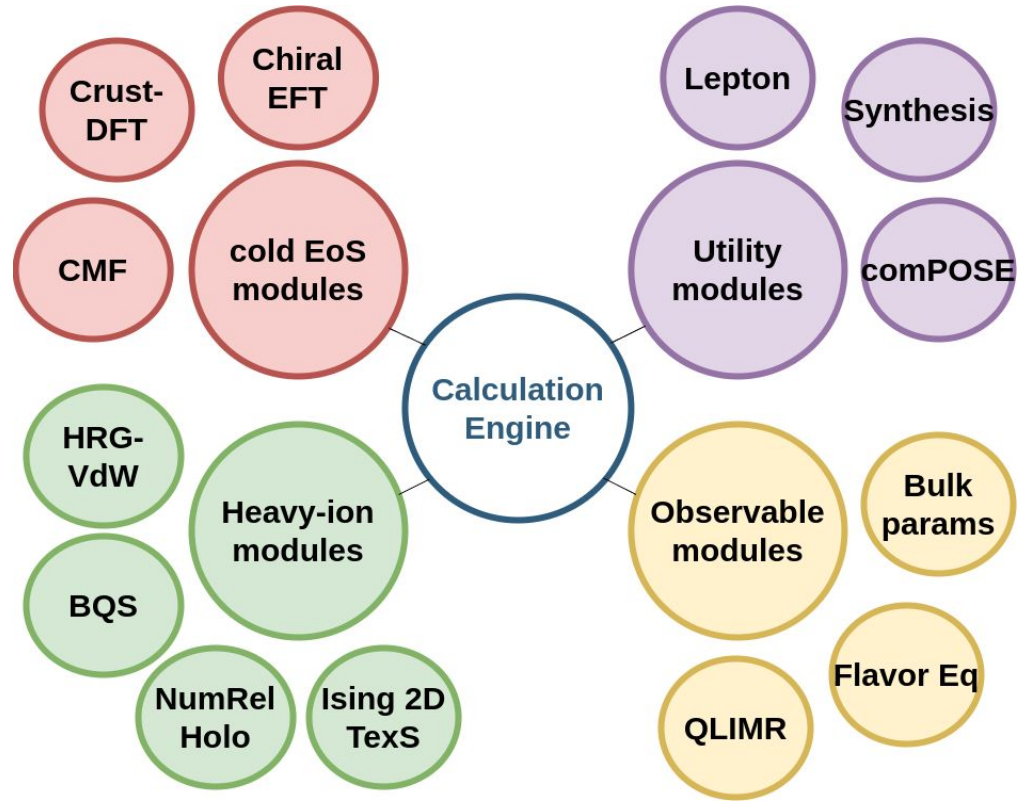
$$\left\{ T, \mu_B, \mu_S, \mu_Q \right\}$$



MUSES Calculation Engine

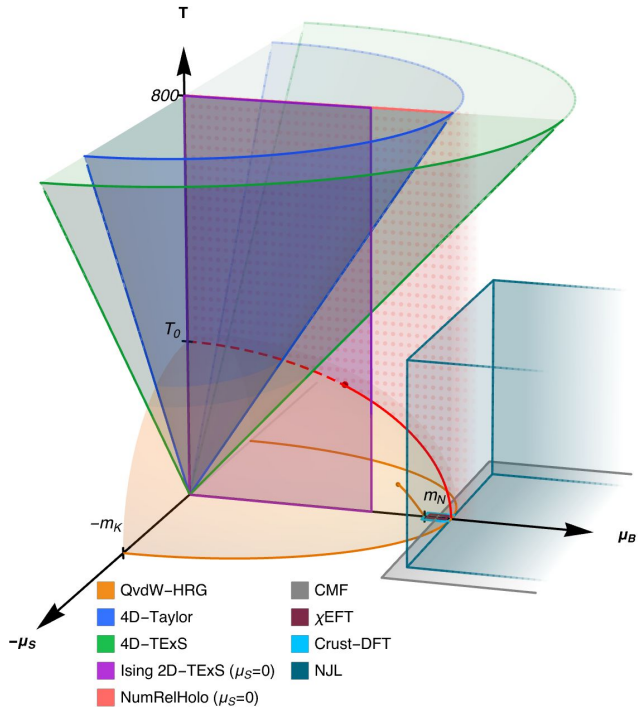
Modular Unified Solver of the
Equation of State

- **Workflow management system**
- Workflows are a way to orchestrate and connect the execution of modules.
- Modules are self-contained software that
 - generate and manipulate EOS
 - use the EOS to compute observables



MUSES Calculation Engine

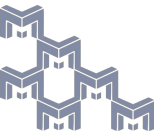
<https://ce.musesframework.io/>



[Tutorial](#)



Jahan+, soon.



Summary

- **Strangeness is a thermodynamic direction:** out-of-weak-equilibrium matter lives in $P(T, \mu_B, \mu_Q, \mu_S)$.
- Using a chiral mean field model, we find a first order transition to strangeness-rich phase matter at large densities.
- This phase of matter is associated with isospin symmetry restoration
- Depending on the parameters of the equation of state, this phase may either be a metastable phase between light hadrons and deconfinement or a first-order phase transition with a triple point and critical point
- Now possible to explore coupled out-of-electroweak equilibrium in binary neutron star mergers, find large fluctuations in μ_Q, μ_S .

