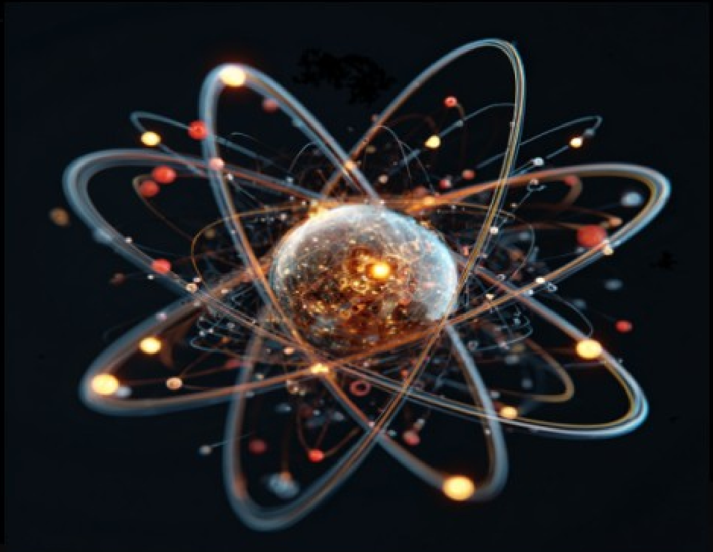
The role of isospin asymmetry in the onset of quark matter

Violetta Sagun
University of Southampton

In collaboration with Pavlo Panasiuk, Alexander Ayriyan, Oleksii Ivanytskyi, David Blaschke, and Tim Dietrich

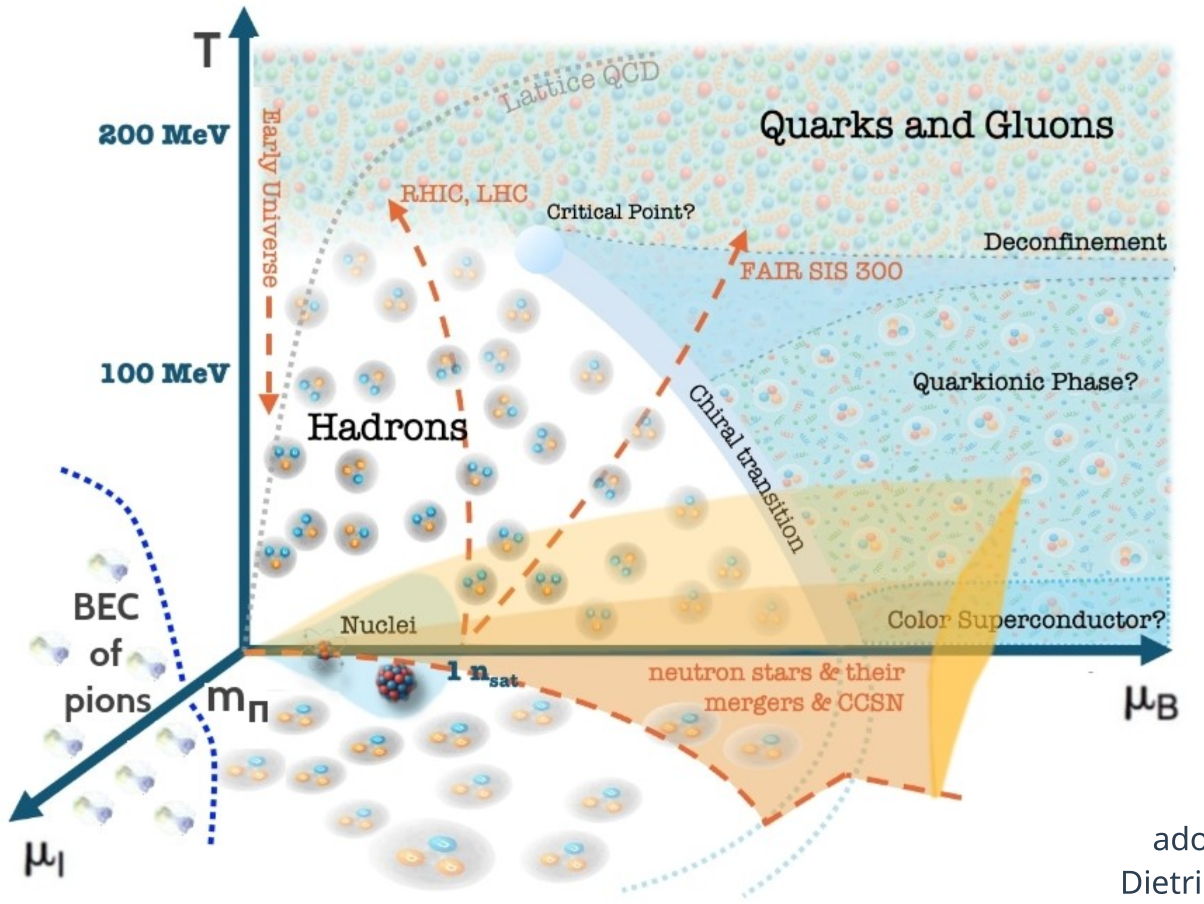


University of Southampton

STAG RESEARCH CENTRE

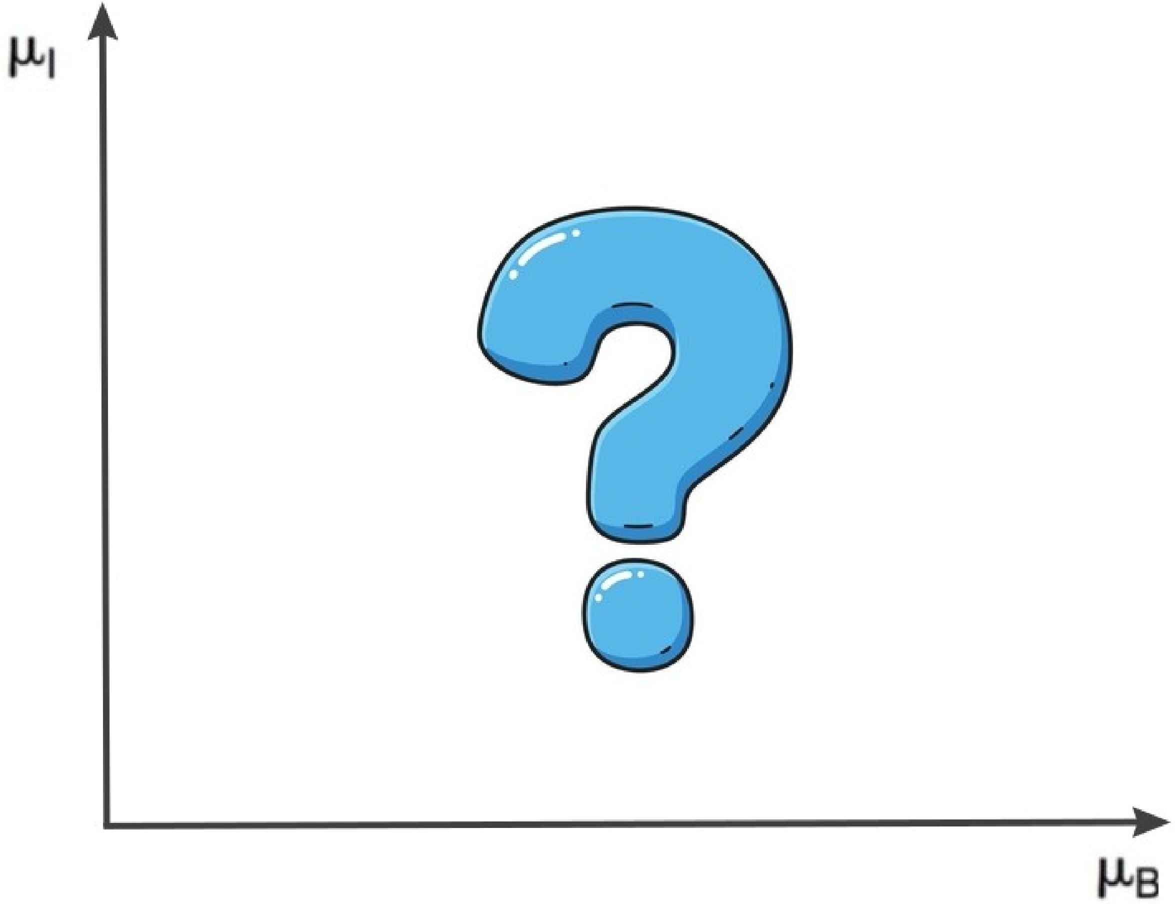
19 May, CSQCD2026

QCD phase diagram

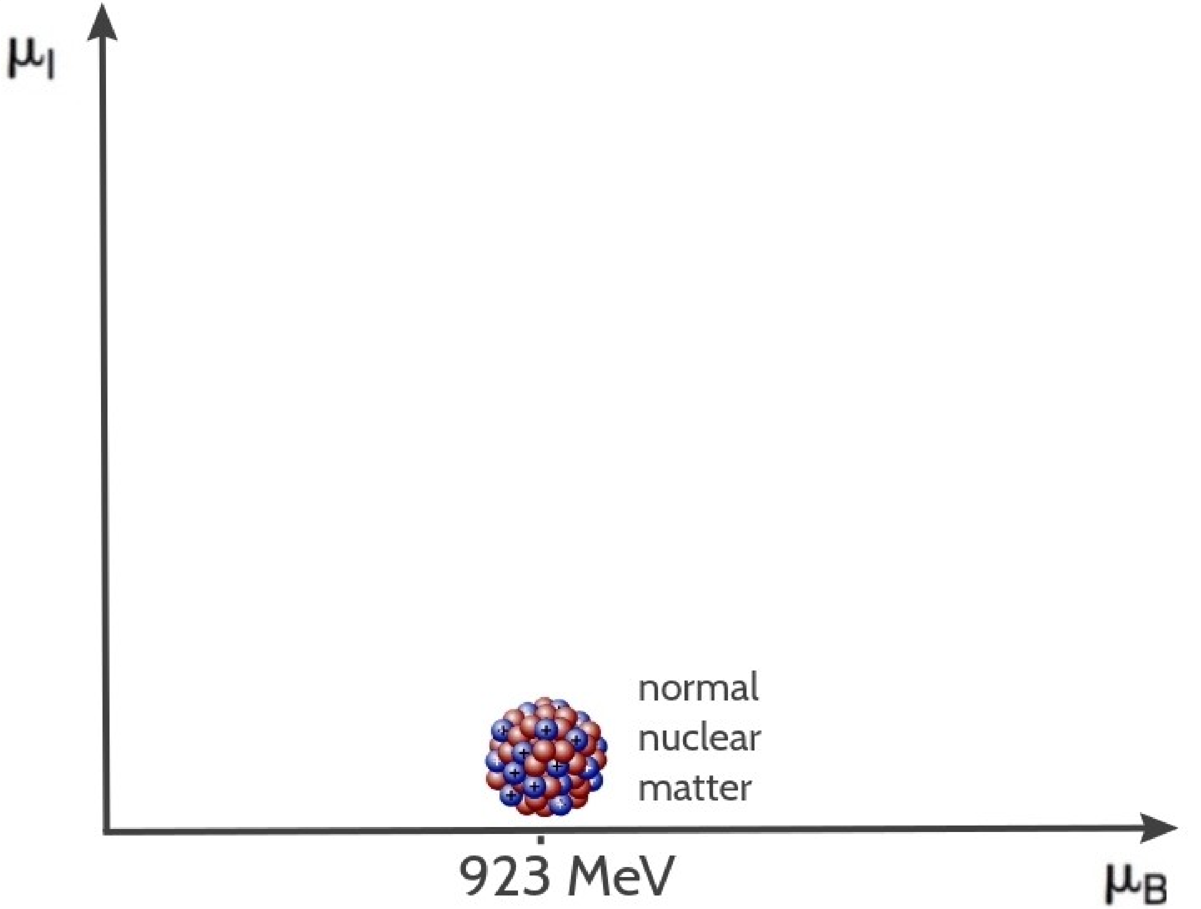


adopted from
Dietrich et al. 2025

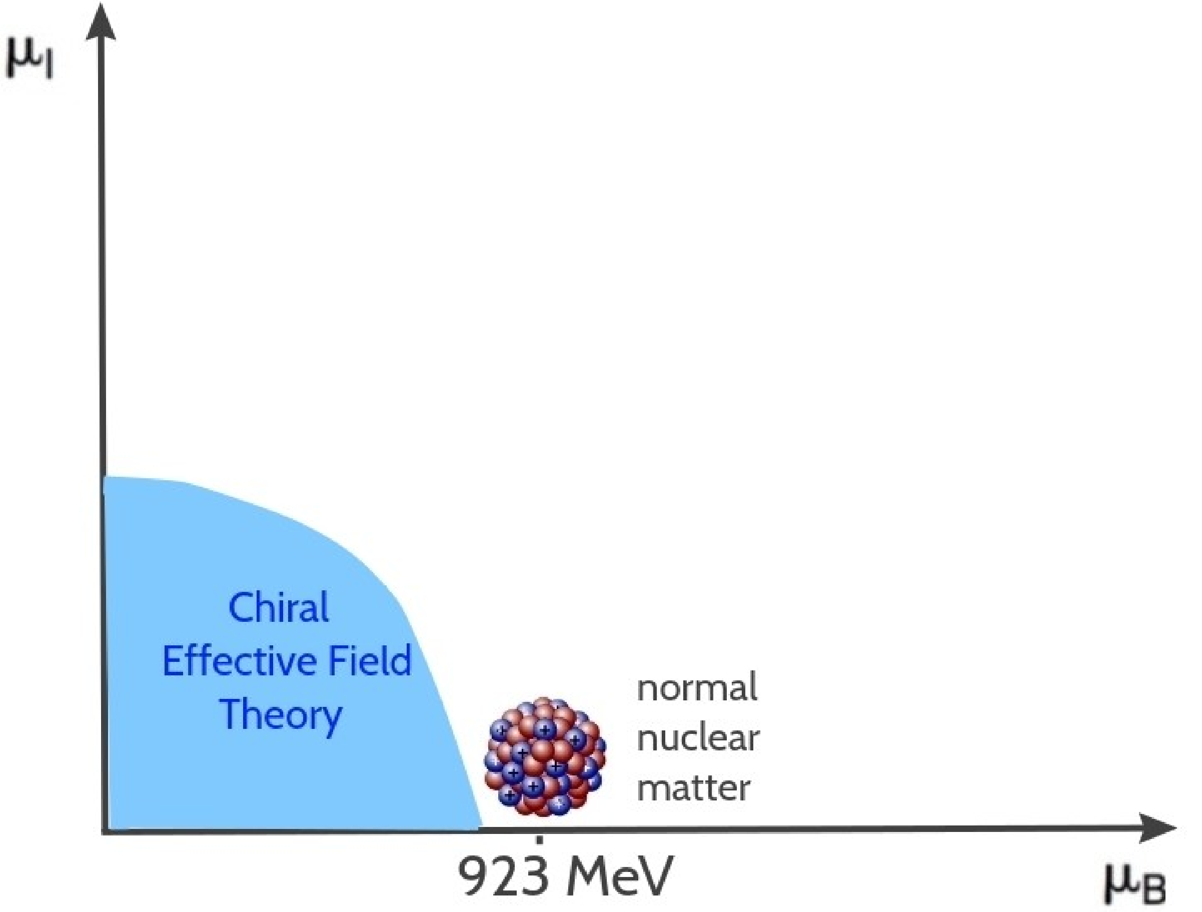
Phase diagram (T=0)



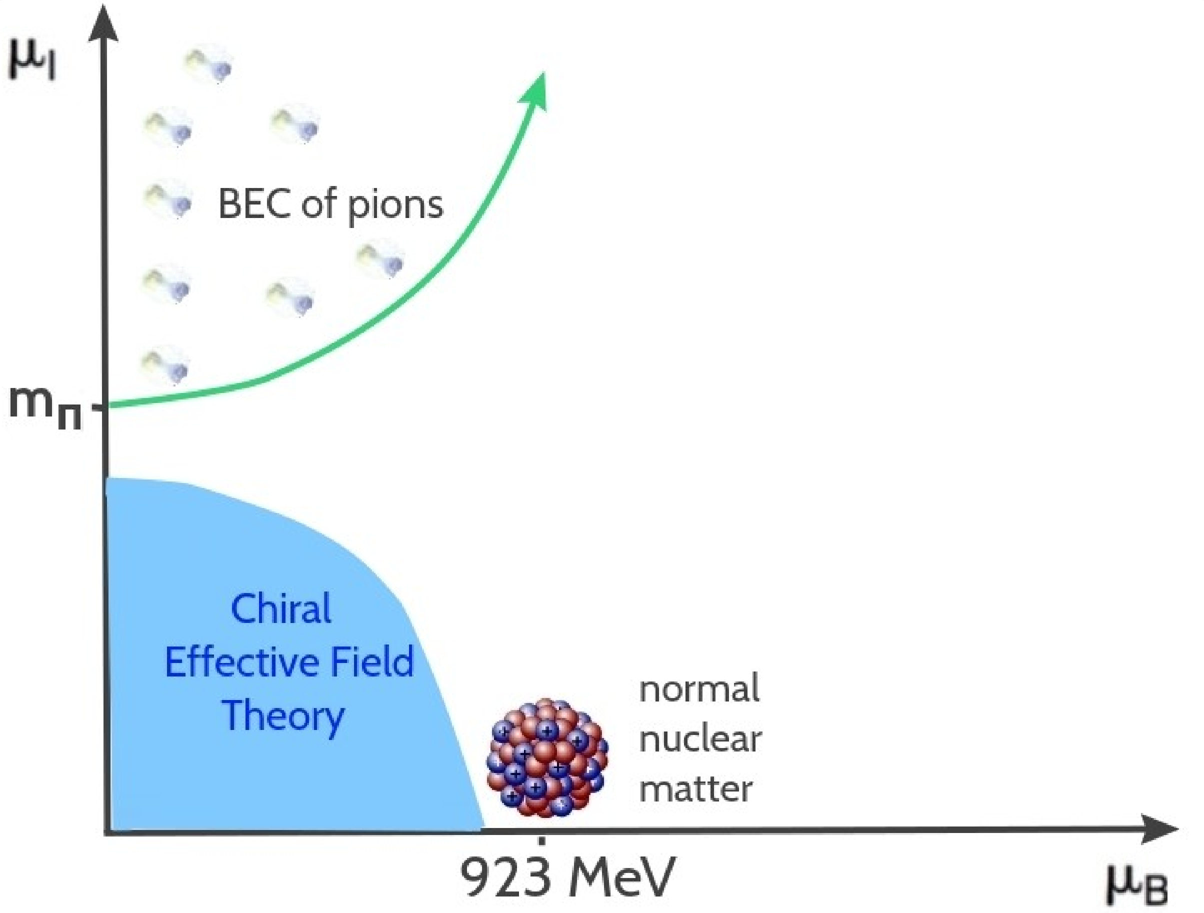
Phase diagram



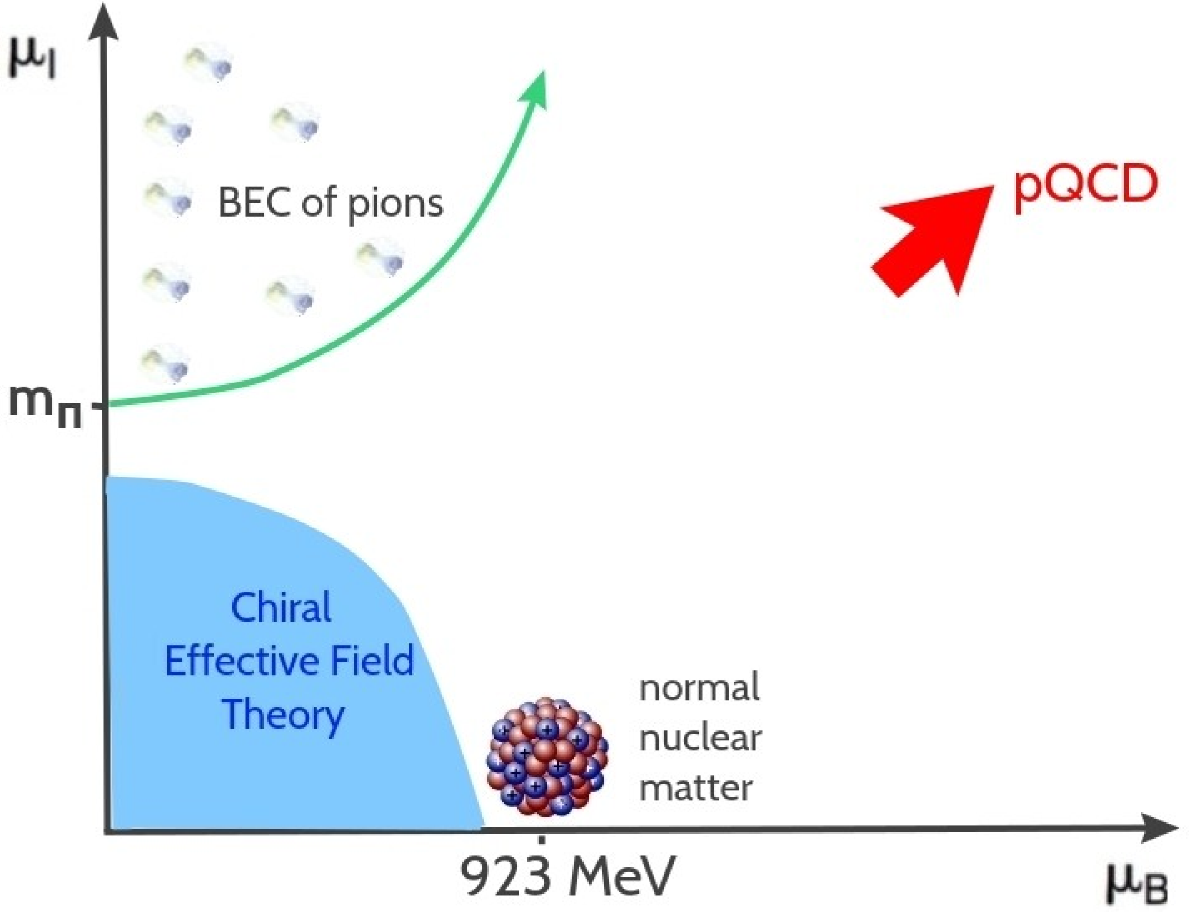
Phase diagram



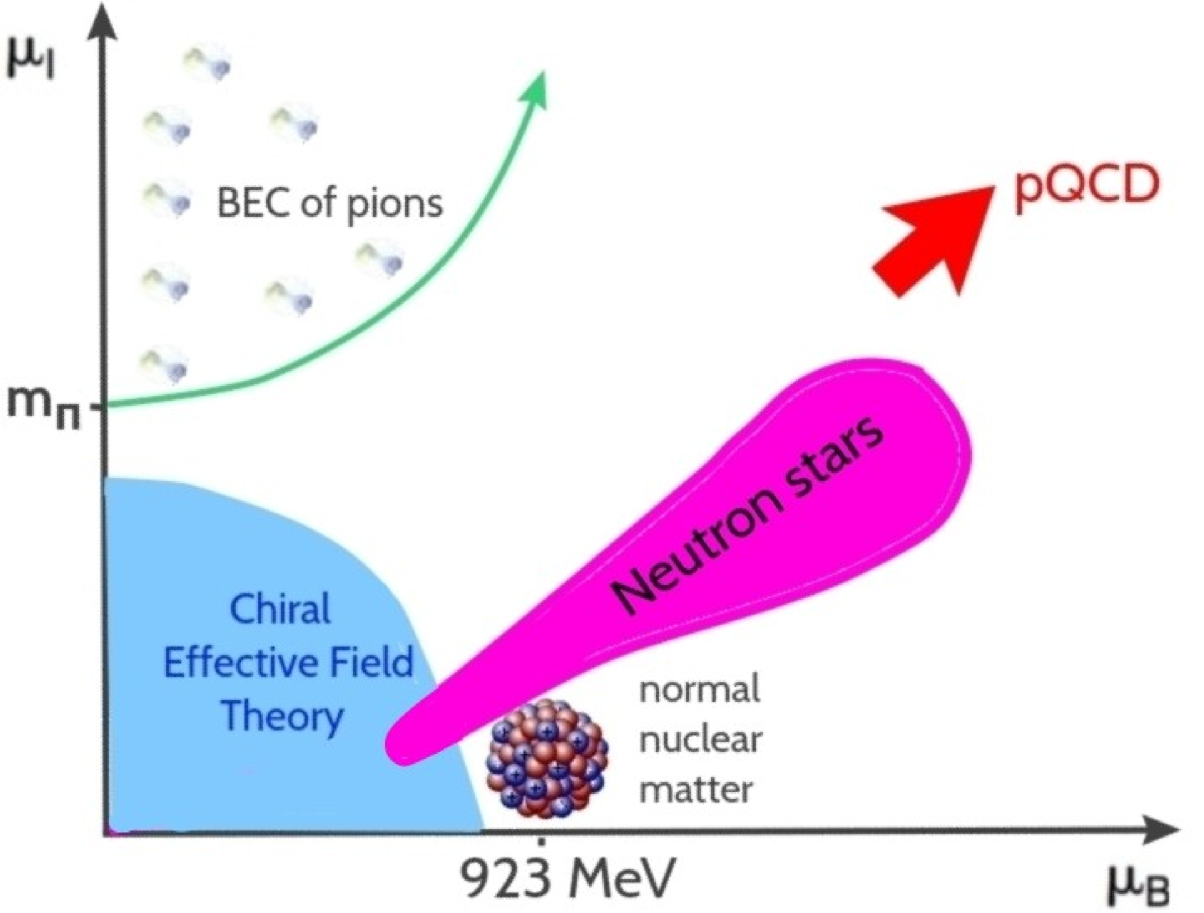
Phase diagram



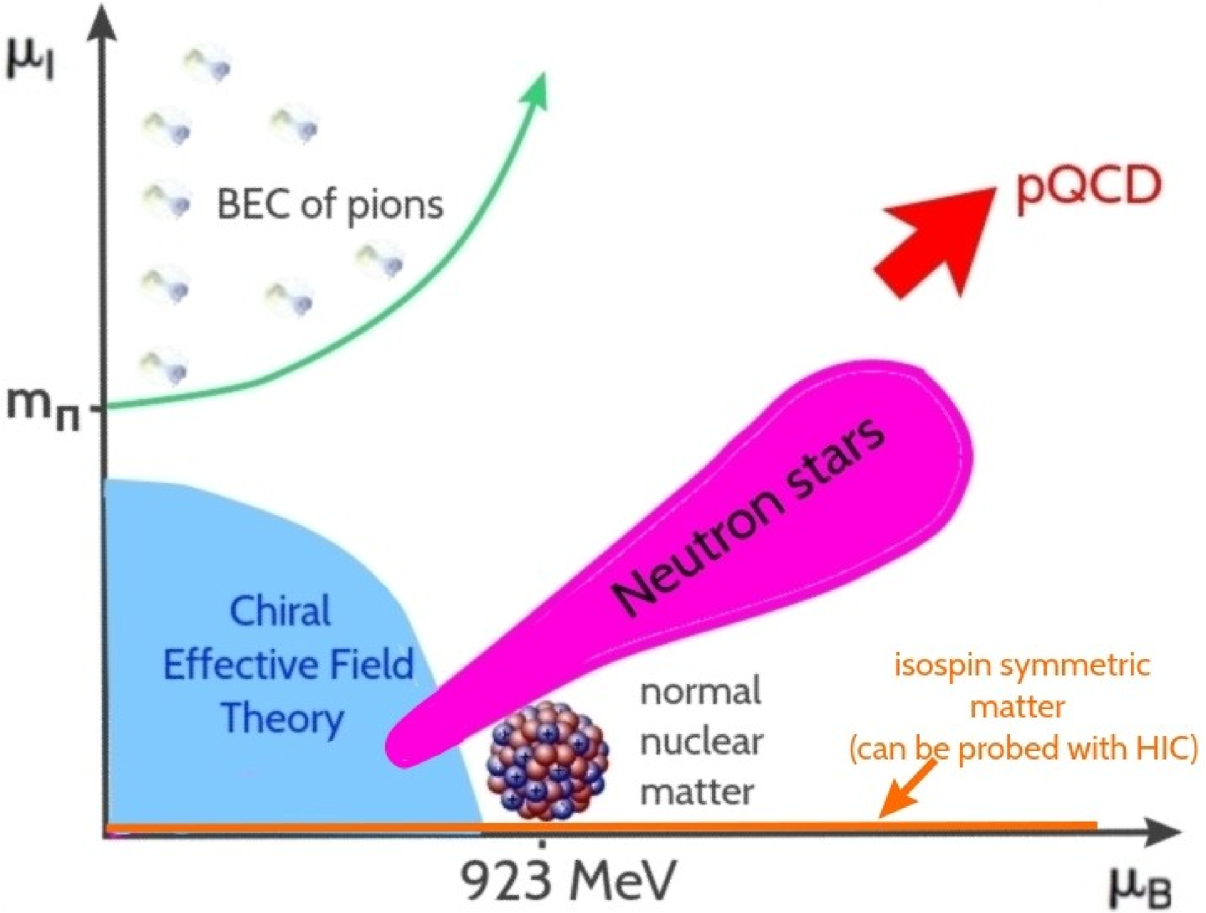
Phase diagram



Phase diagram



Phase diagram



Open questions

- At what density the deconfinement phase transition occurs? (in my talk T=0)

- How it depends on the isospin asymmetry?

Pavlo Panasiuk

Motivation

- What is the impact of asymmetry on the onset of quark matter?
- How are nuclear physics and heavy-ion collision data related to the properties of neutron star matter?

The nuclear Equation of State (EoS) at T=0

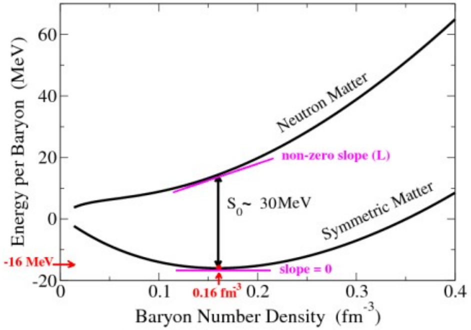
$$\frac{E(n_B,\delta)}{A} = \frac{E(n_B,0)}{A} + S(n_B)\delta^2 + O(\ldots^4)$$

symmetric matter (a)symmetric matter

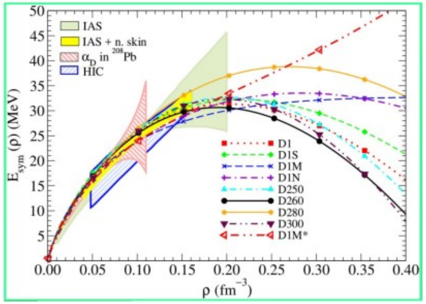
$$\delta = \frac{n_n - n_p}{n_B}$$

$$n_B = n_n + n_p$$

$$\epsilon = \frac{n_B - n_0}{n_0}$$



$$\frac{E(n_B,0)}{A} = \frac{E(n_0)}{A} + \frac{1}{18}K_0\epsilon^2$$



Credits: C. Gonzalez-Boquera

$$S(n_B) = S(n_0) + \frac{1}{3}L\epsilon + \frac{1}{18}K_{sym}\epsilon^2$$

$\frac{E(n_0)}{A} \equiv \frac{E_0}{A} = -16 \pm 1MeV$ **binding energy per nucleon at saturation density** $n_0 = 0.16 \pm 0.01 fm^{-3}$

$S(n_0) \equiv S_0 \equiv J = 30 \pm 4MeV$

$S(n_0) \equiv \frac{1}{2}\left(\frac{\partial^2 E}{\partial \delta^2}\right)_{n_B=n_0,\ \delta=0}$ **symmetry energy at** n_0

$K_0 \equiv 9n_0^2\left(\frac{\partial^2 E}{\partial n_B^2}\right)_{n_B=n_0,\ \delta=0} = 200 - 260MeV$ **incompressibility at** n_0

$L \equiv 3n_0\left(\frac{\partial S(n_B)}{\partial n_B}\right)_{n_B=n_0,\ \delta=0} = 20 - 115MeV$ **symmetry energy slope at** n_0

Hybrid stars: DDTCY-NJL3f model

DDTCY model of hadron matter

- nucleonic and hyperonic degrees of freedom
- accounts for the tensor-meson-mediated interaction important at high densities
- reproduce the properties of the nuclear matter ground state, chiEFT
- $M_{max}=1.995M_\odot$

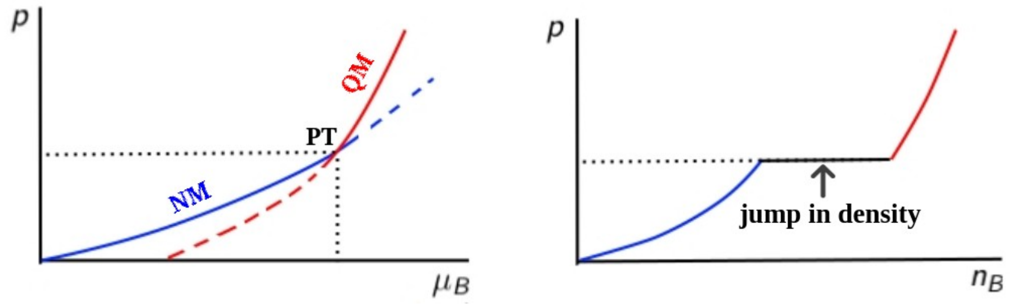
Credits: S. Typel

NJL3f model of quark matter

- three-flavor chiral quark model of the Nambu-Jona-Lasinio (NJL) type with nonlocal interaction
- coupling constants: scalar G_S , vector G_V and diquark pairing G_D channels
- $\eta_V=G_V/G_s$ determines the stiffness of the quark EoS
  $\eta_D=G_D/G_s$ determines the onset of the quark EoS

Credits: O. Ivanytskyi PRD 111, 3, 3 (2025); PRD 111, 7, 079904 (2025)

Maxwell construction



Method

Uniform grid in the coupling space $(\eta_V, \eta_D) \in [0.10, 1.00] \times [0.12, 0.50]$

for each combination of the coupling constants

construct the quark EoS for symmetric matter

construct the β-equilibrated electrically neutral quark matter EoS

Maxwell construction with the symmetric DDTCY EoS

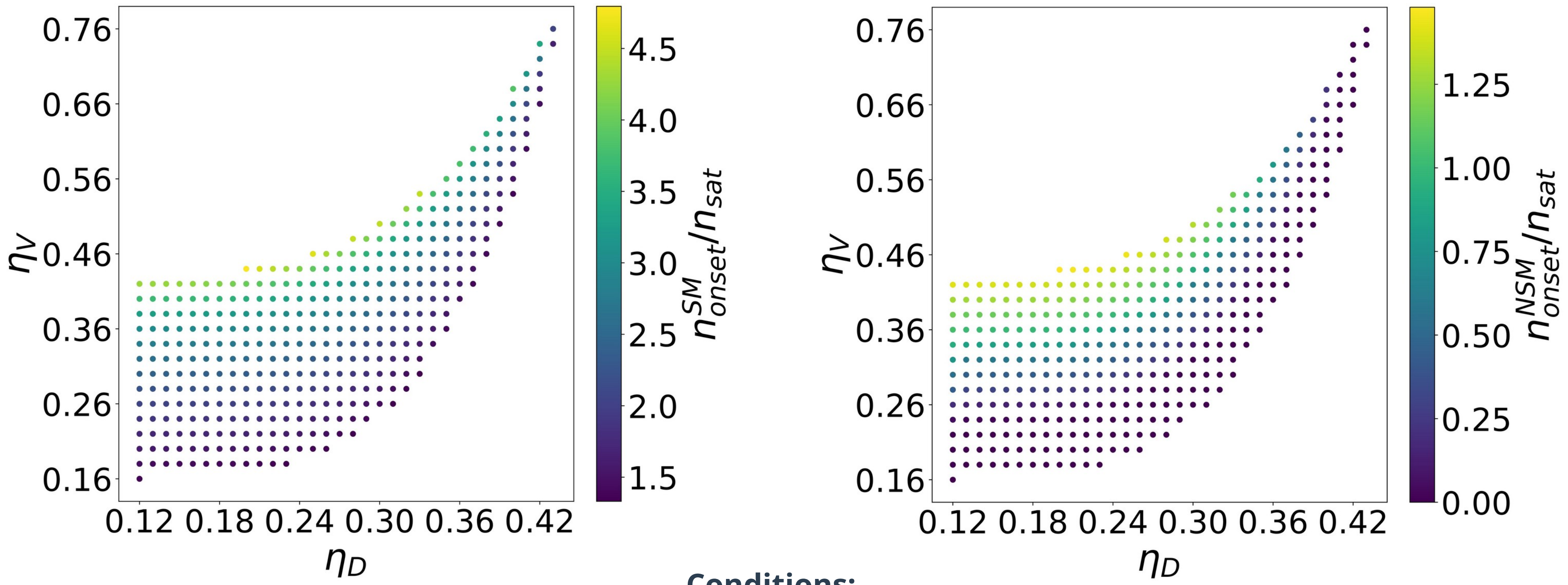
Maxwell construction with the β-equilibrated DDTCY EoS

Conditions:

- We restrict our analysis to the subset of (η_V, η_D) values for which both constructions are possible.
- We discard the parameter sets that do not provide the intersection of the hadronic and quark EoSs

Phase transition onset

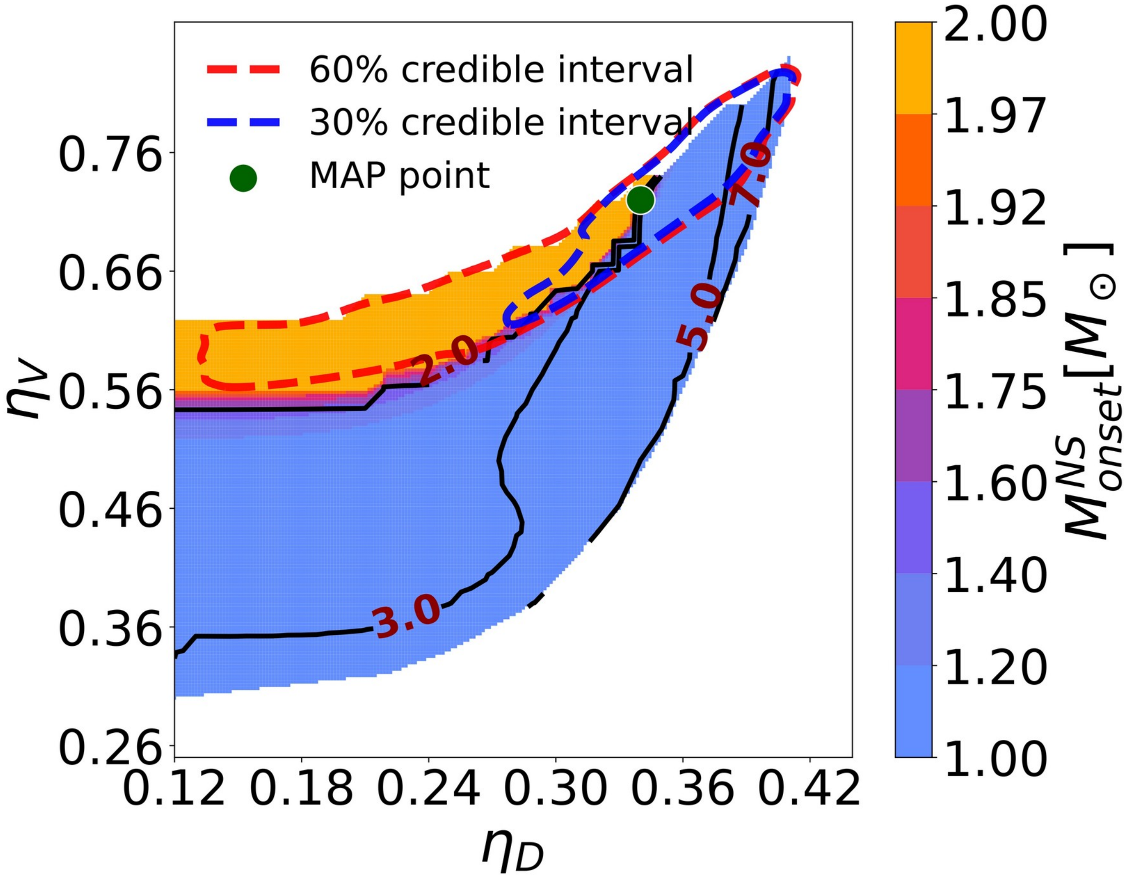
symmetric matter | **β-equilibrated electrically neutral matter**



Conditions:

1. We restrict our analysis to the subset of (η_V , η_D) values for which both constructions are possible.
2. We discard the parameter sets that do not provide the intersection of the hadronic and quark EoSs

Bayesian analysis

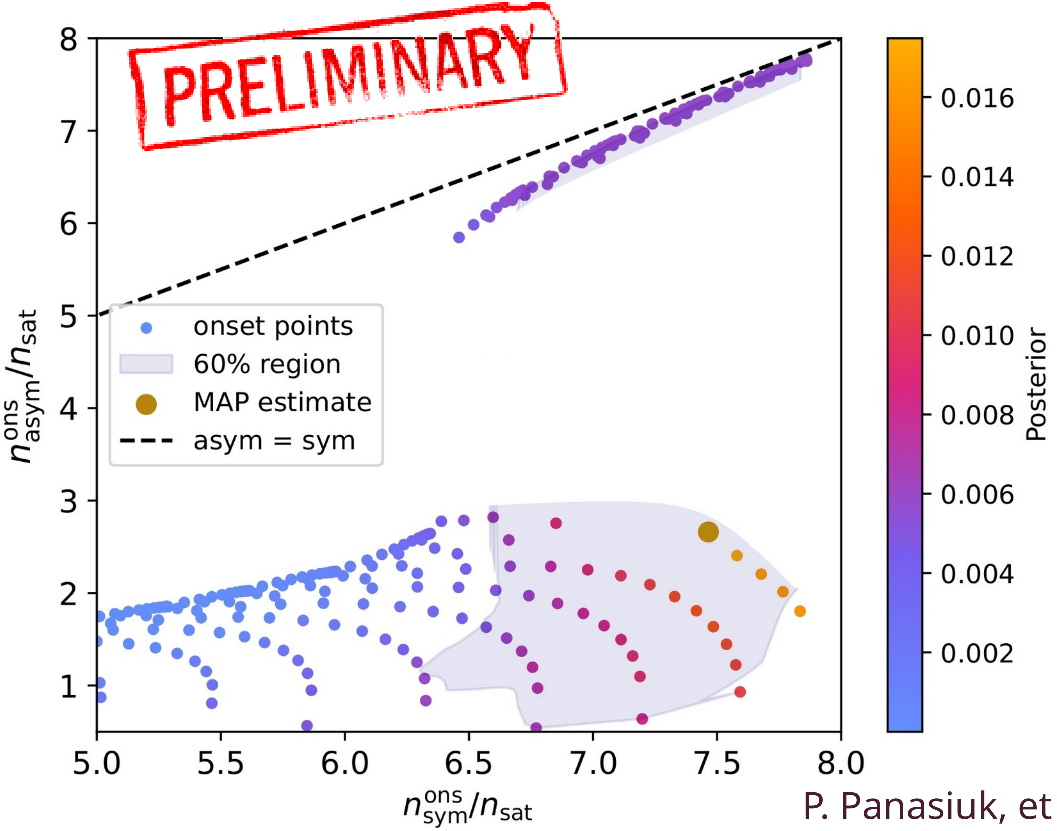


<u>Data utilized</u>

- heavy pulsar PSR J0348+0432
- NICER measurements
  PSR J0030+0451
  PSR J0740+6620
  PSR J0437-471
- GW170817

Countour lines illustrate the constant ratio
$n^{SM}_{onset}/n^{NSM}_{onset}$

Quark onset in asymmetric vs. symmetric matter



P. Panasiuk, et al., In prep (2026)

Toy model for deconfinement

- **Nucleons**

$$\mu_N = E_N + (\mu_0 - E_0)\frac{n_N}{n_0} + I^2\frac{\partial \varepsilon_{sym}}{\partial n_N}$$

$$E_N = \sqrt{m_N^2 + k_N^2}, \quad E_0 \equiv E_N \text{ @ } n_N = n_0$$

- **Quarks with zero momentum**

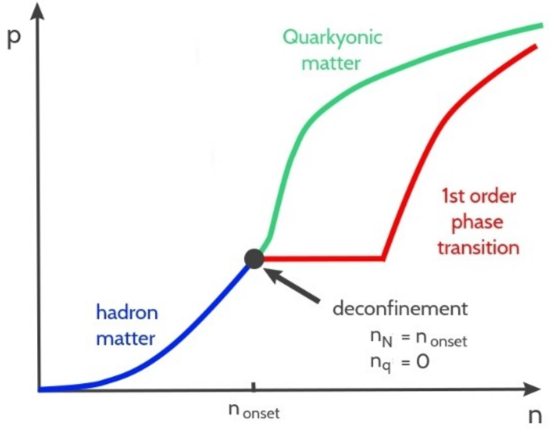
$$\mu_q = m_q$$

- **Criterion of deconfinement:**

$$\mu_N = 3\mu_q$$

- **Onset density:**

$$n_{onset} = \frac{d}{6\pi^2}\left(\left(3m_q - (\mu_0 - E_0)\frac{n_{onset}}{n_0} - I^2\frac{\partial \varepsilon_{sym}}{\partial n_N}\right)^2 - M_N^2\right)^{\frac{3}{2}}$$



Toy model for deconfinement

- **Nucleons**

$$M_N = M_{vac}\left[1+\left(\frac{M_{vac}}{M_0}-1\right)\frac{n_N}{n_0}\right]^{-1}$$

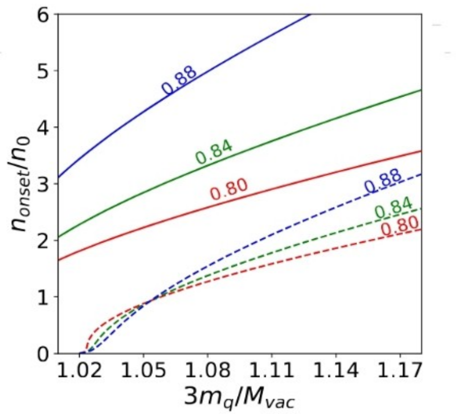
$$M_0 \equiv M_N \ @\ n_N = n_0$$

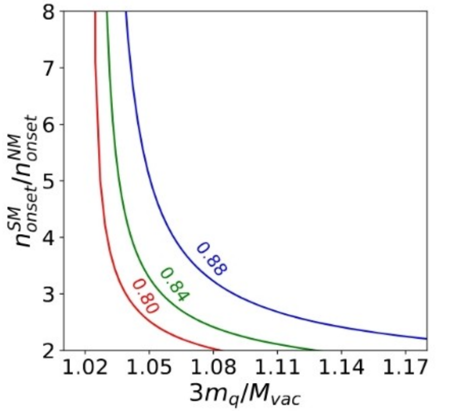
- **Symmetry energy**

$$\varepsilon_{sym} = n_N\left(J_0 + L_0\frac{n_N - n_0}{3n_0}\right)$$

$$J_0 = 32\ MeV, \quad L_0 = 40\ MeV$$

Onset densities of deconfinemet in neutron stars and symmetric matter can be very different





Violetta Sagun University of Southampton

Conclusions

- ✔ We studied the impact of isospin asymmetry on the onset of quark matter.
- ✔ We established a relation between the quark onset density in electrically neutral, beta-equilibrated matter and that in symmetric matter. This relation is demonstrated across a broad class of hybrid EoSs.
- ✔ We showed that the quark onset density in neutron-star matter can be substantially lower than in symmetric matter.
- ✔ We identified two disconnected islands of hybrid configurations that satisfy all constraints. The Bayesian analysis indicates a preference for the region in which the onset density in asymmetric matter lies below 3 $n_{sat.}$

Limitations:

- 1st order phase transition via the Maxwell construction

- subject to variations depending on the hadronic and quark EoSs

P. Panasiuk, A. Ayriyan, O. Ivanytskyi, D. Blaschke, V. Sagun, and T. Dietrich, The role of isospin asymmetry in the onset of quark matter, In preparation (2026)

Dark Matter and Stars: Multi-Messenger Probes of Dark Matter and Modified Gravity

13–15 Jul 2026
University of Southampton
Europe/London timezone

Enter your search term

- Overview
- Registration
- Call for Abstracts
- Participant List
- Timetable
- Fee and key dates
- Financial Support
- Venue
- Public lecture
- Social Events
- Travel, visa and ETA
- Accommodation
- The previous editions of "Dark Matter and Stars"
- Code of Conduct

Contact

icdms26@soton.ac.uk

The International Conference "Dark Matter and Stars: Multi-Messenger Probes of Dark Matter and Modified Gravity" aims to bring together scientists working across the different research fields of astrophysics, cosmology, and modified gravity. We want to look at the dark matter problem from different perspectives, considering it to be of particle nature, as well as modification of gravity. This meeting is intended to initiate cross-field discussions of dark matter searches, their current status, and future prospects.

CONFERENCE TOPICS

- Dark matter in compact stars (neutron stars, white dwarfs, exotic stars)
- Multi-messenger and gravitational wave probes of dark matter
- Supernovae simulations with dark matter
- Stars, Sun-like stars
- Exoplanets and brown dwarfs
- Cosmology
- Primordial black holes
- Modified gravity
- Models of dark matter
- Direct detection of dark matter

Abstract submission deadline 30 May!

In the framework of the conference, we will host a **special session dedicated to gravitational wave probes of dark matter**, with particular emphasis on current and next-generation gravitational wave detectors.

We seek to encourage dialogue between different research groups to enhance collaboration and help to improve our understanding of dark matter. The conference is also planned to introduce the dark matter research field to encourage attendance by young scientists including Ph.D. students.