Constraining twin stars with *ab initio* calculations

Sofia Blomqvist 12.3.

PAP301 Seminar in Particle Physics and Astrophysical Sciences

Contents

Quantum Chromodynamics (QCD)

Neutron stars (NS) & twin stars

Constructing equation of state (EoS)

Results

Summary & Conclusions

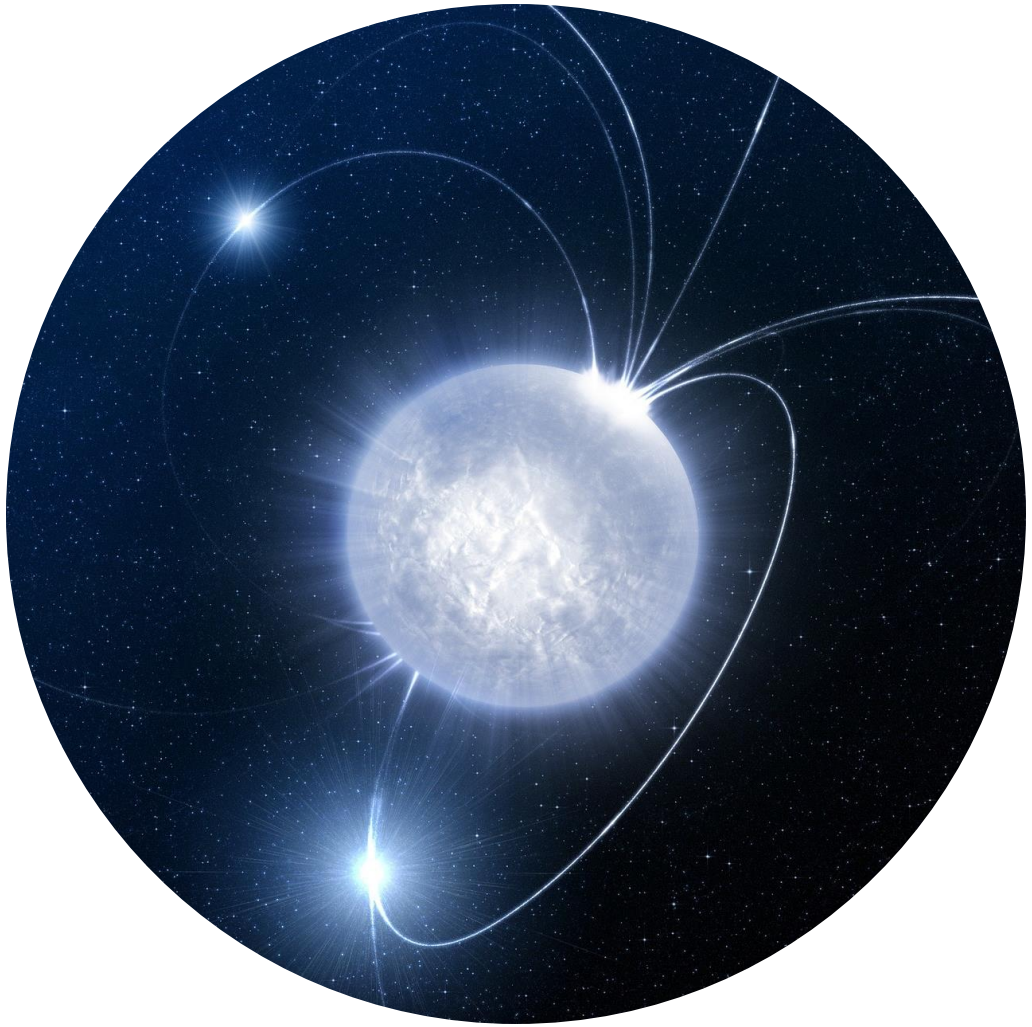

Image by Nidhi Yashwanth from Pixabay

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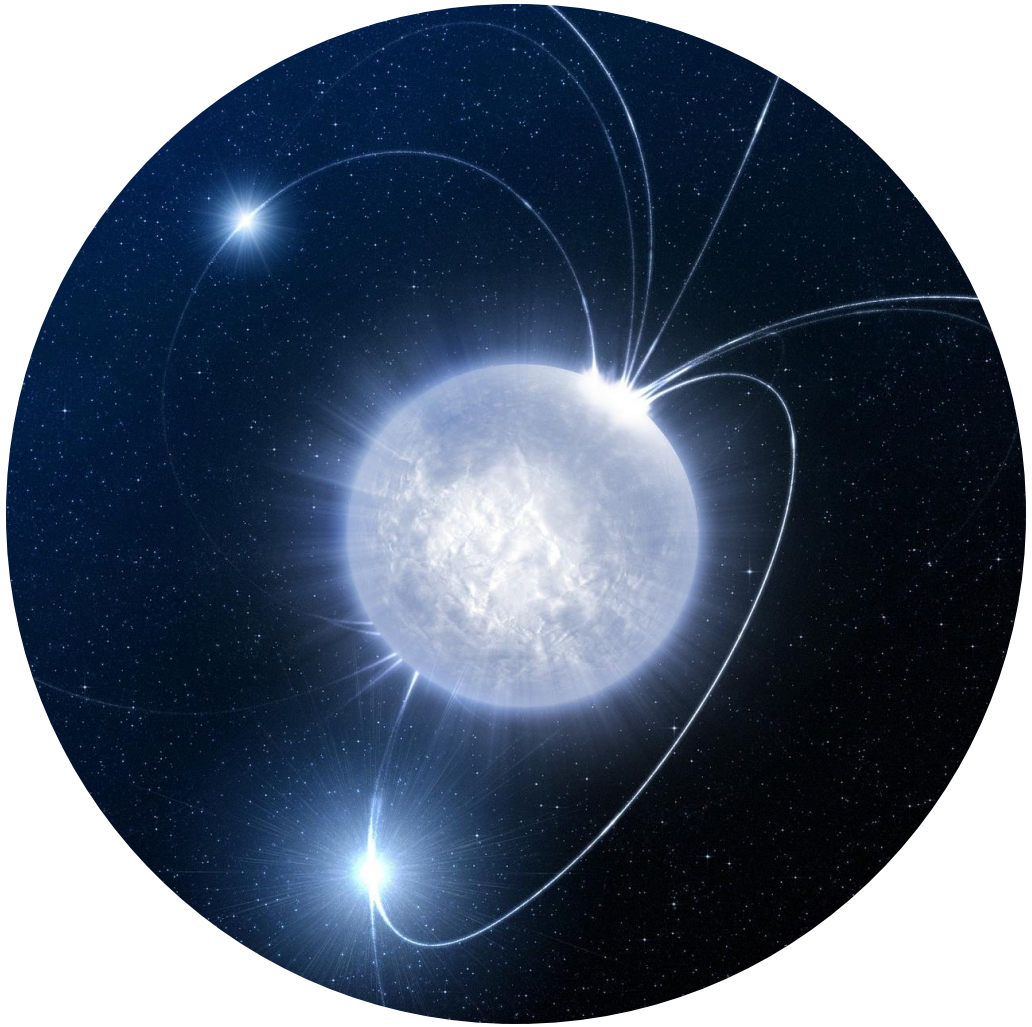
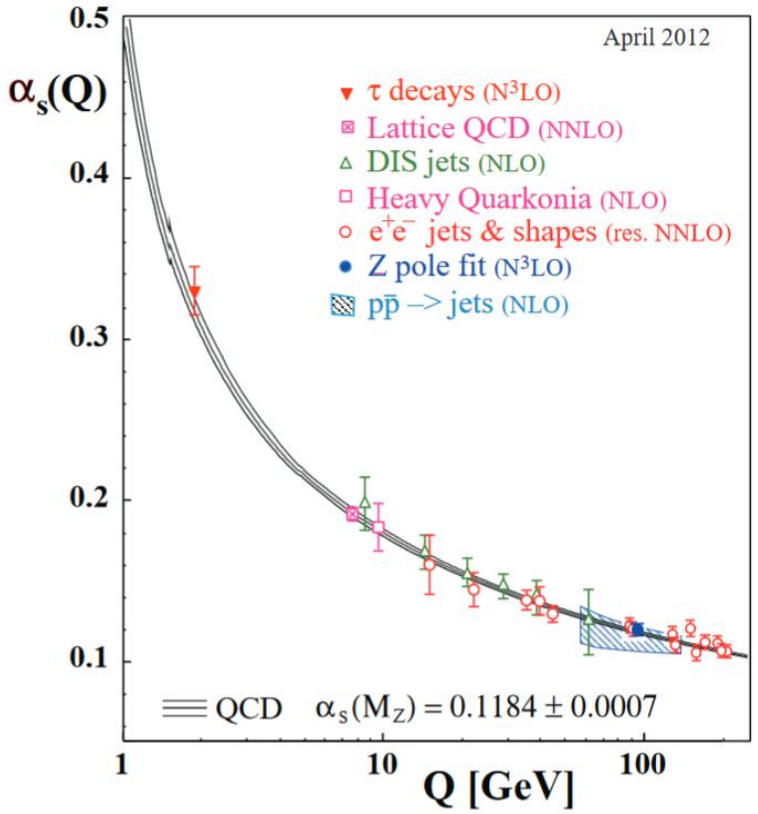


QCD is the theory of strong interaction

- SU(3) non-Abelian gauge field theory
- Quarks and gluons
- Asymptotic freedom
  - Coupling decreases for increasing energy

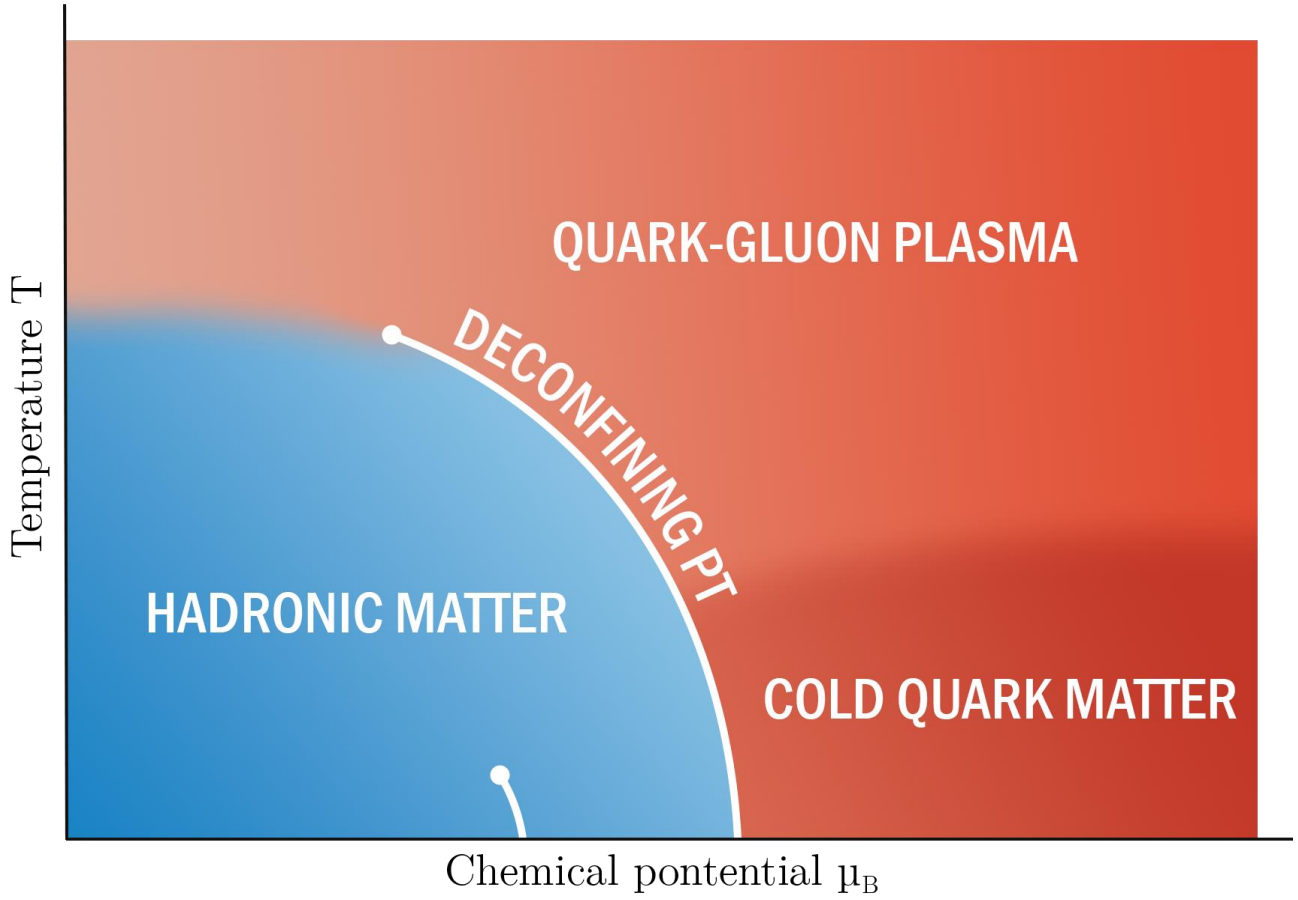
→ Deconfining phase transition (PT)



Beringer et al., PRD 86 (2012)

The phases of QCD are shown in the phase diagram

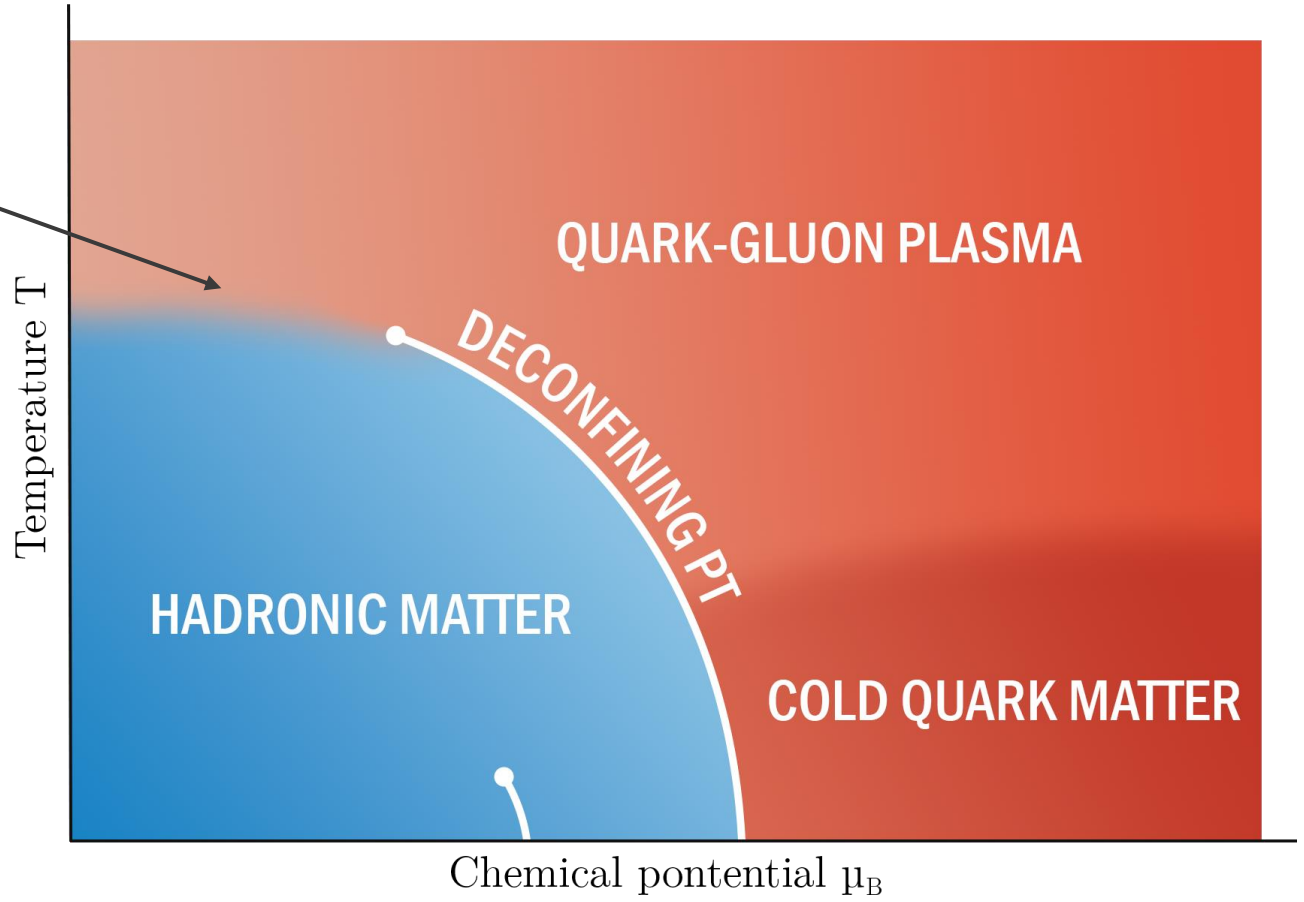
- **Confined matter**
  - → Hadrons
- **Deconfined matter**
  - → Quarks and gluons



The phases of QCD are shown in the phase diagram

Crossover

(lattice simulations)



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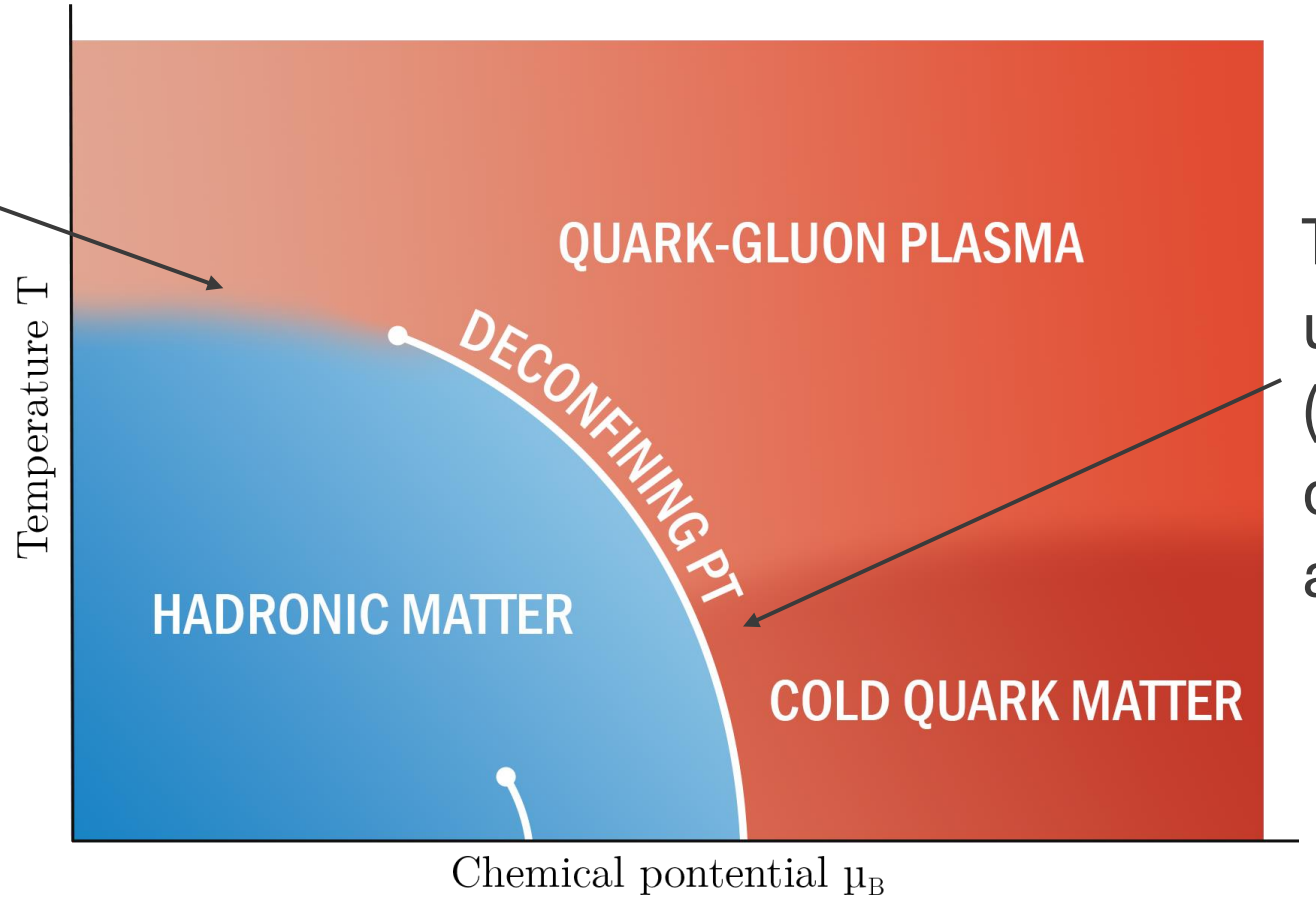
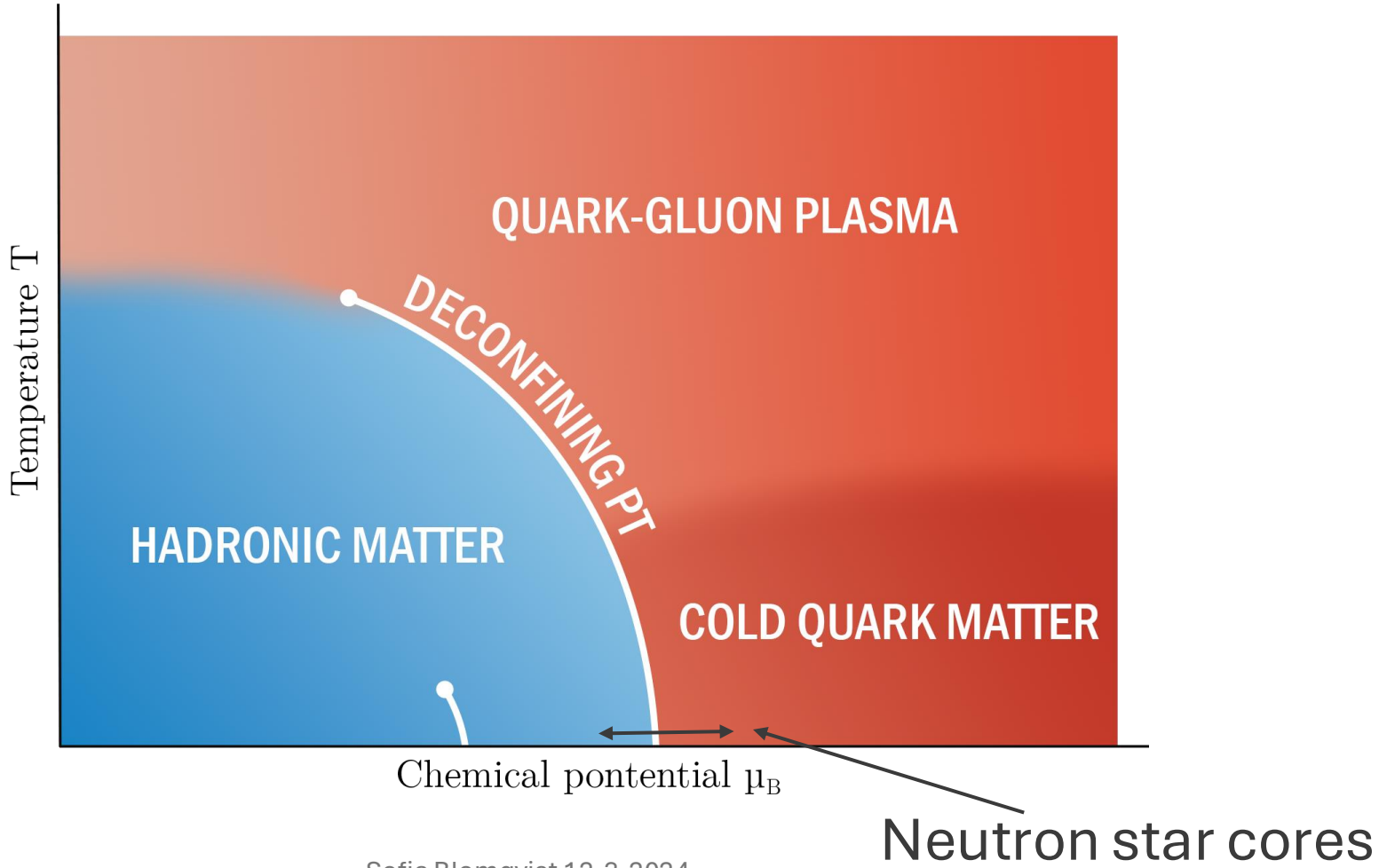


Type and onset unknown (no first-principle calculations available)

The phases of QCD are shown in the phase diagram



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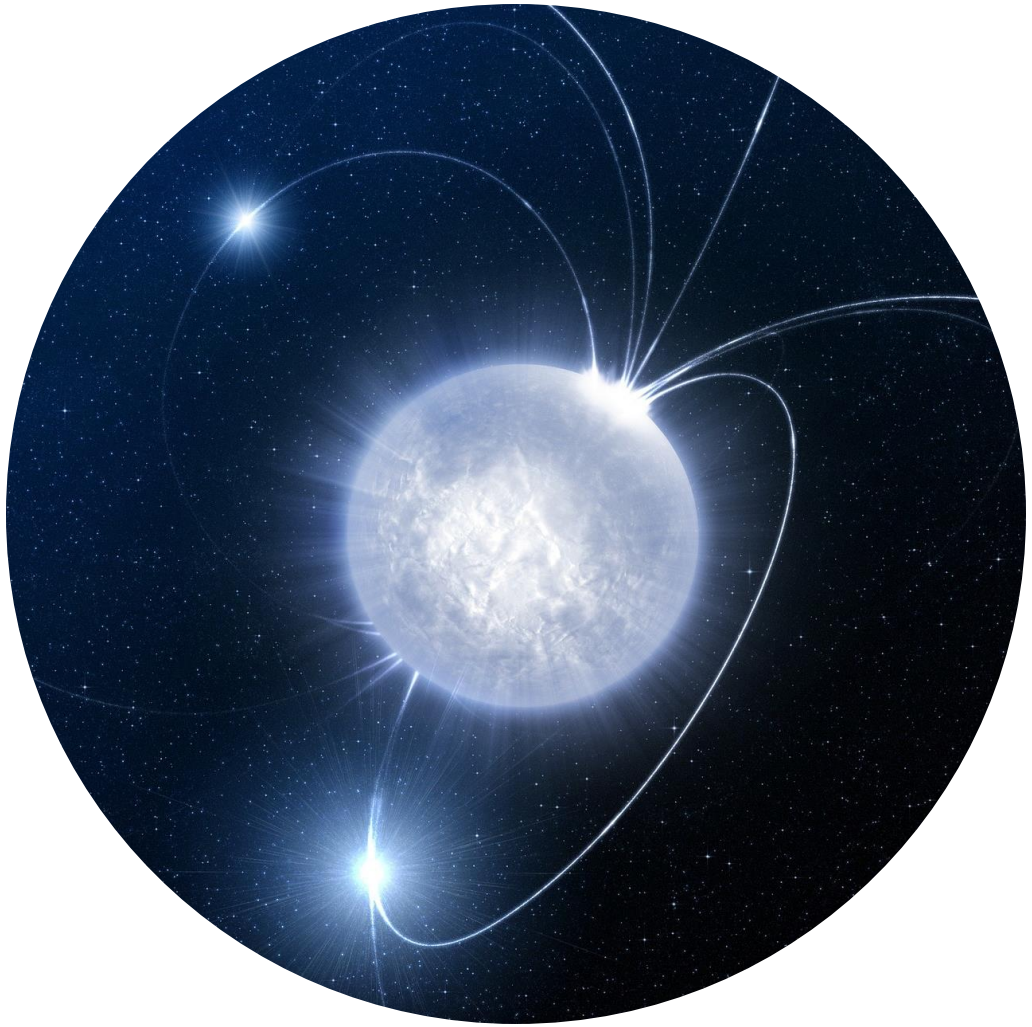
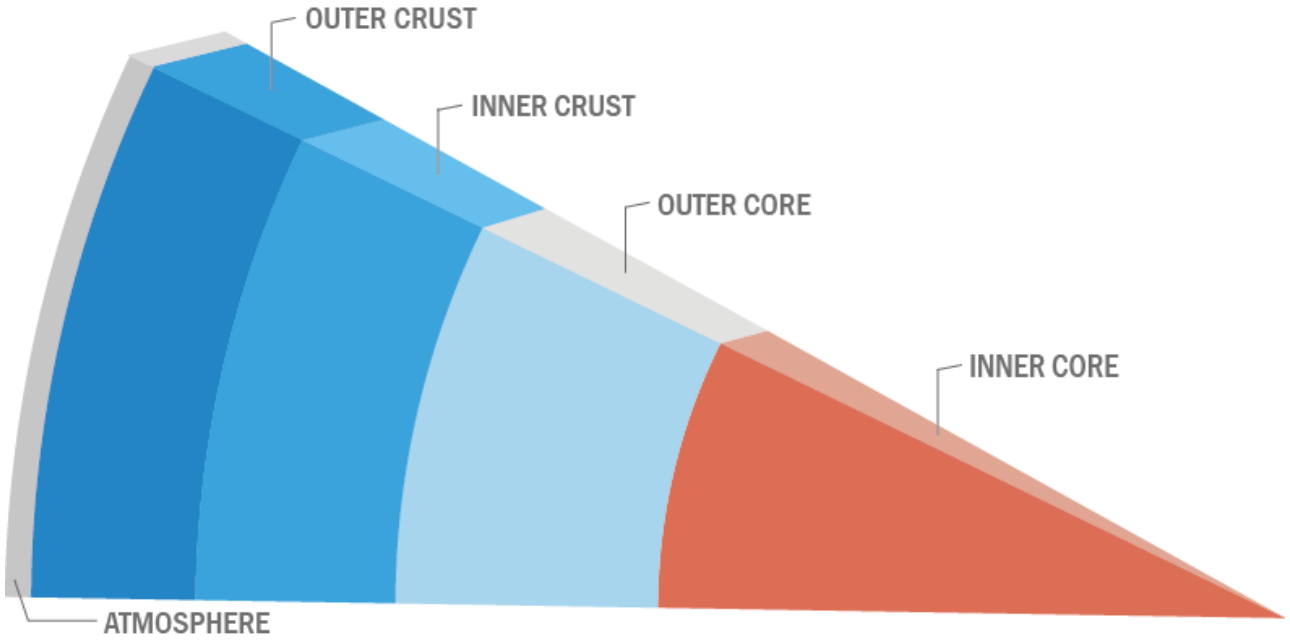


Neutron stars: Matter under extreme conditions

- Mass ~ 1.1-2.1$M_\odot$, radius ~ 9-14km
- Densities extend beyond nuclear saturation density $n_0 \approx 0.16\,\mathrm{fm}^{-3}$
  - At core maximum 5-10 n_0
- Good approximation: T = 0



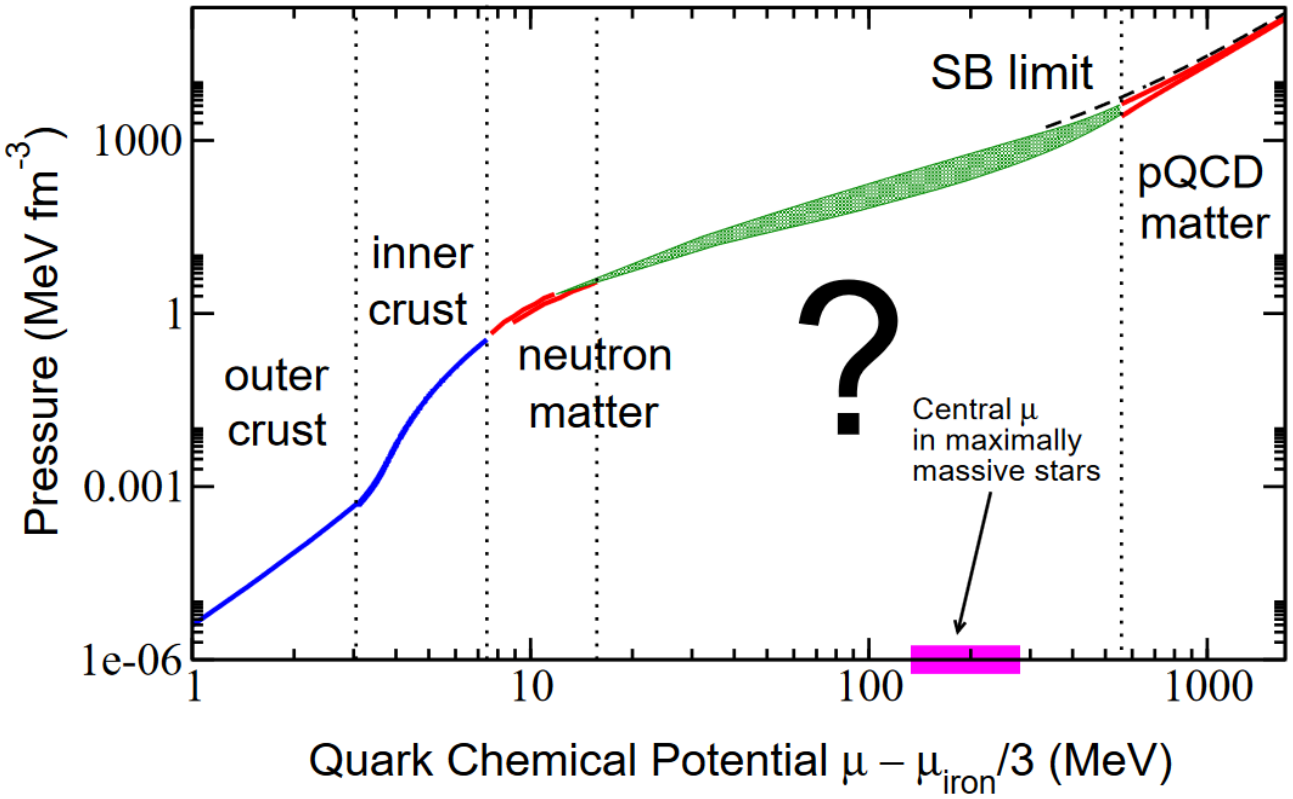
Equation of state determines the inner structure of neutron stars

- NS equation of state (EoS) e.g. p(ε)
- Structure equations from general relativity:
  - dp/dr & dm/dr
  - Solve for given EoS to obtain e.g. mass-radius (MR) curve

$$p(\varepsilon) \Rightarrow M(R)$$

What do we know about the EoS?

- Chiral effective field theory (cEFT), e.g. conservative result at $1.1n_0$
- Perturbative QCD, state-of-the-art result at $40n_0$



Kurkela et al. ApJ 789 (2014)

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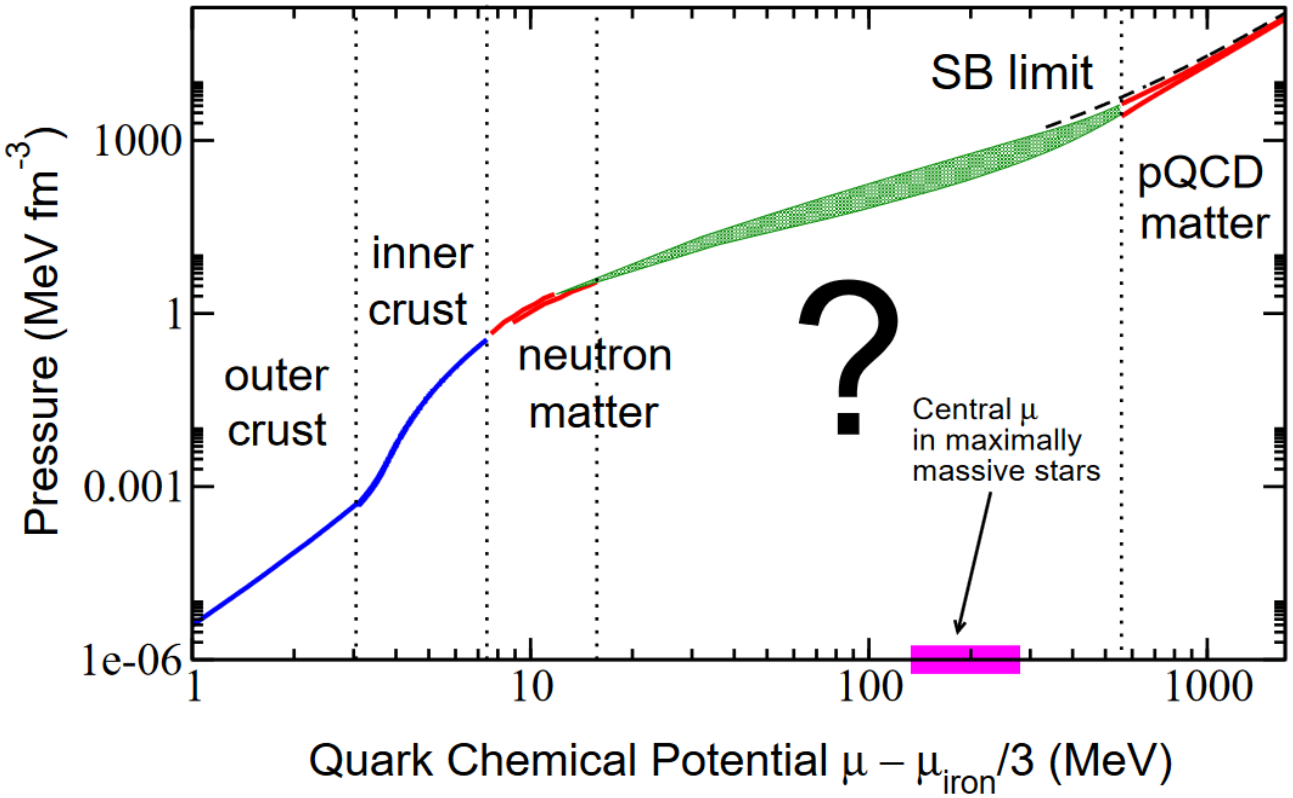
Intermediate densities:

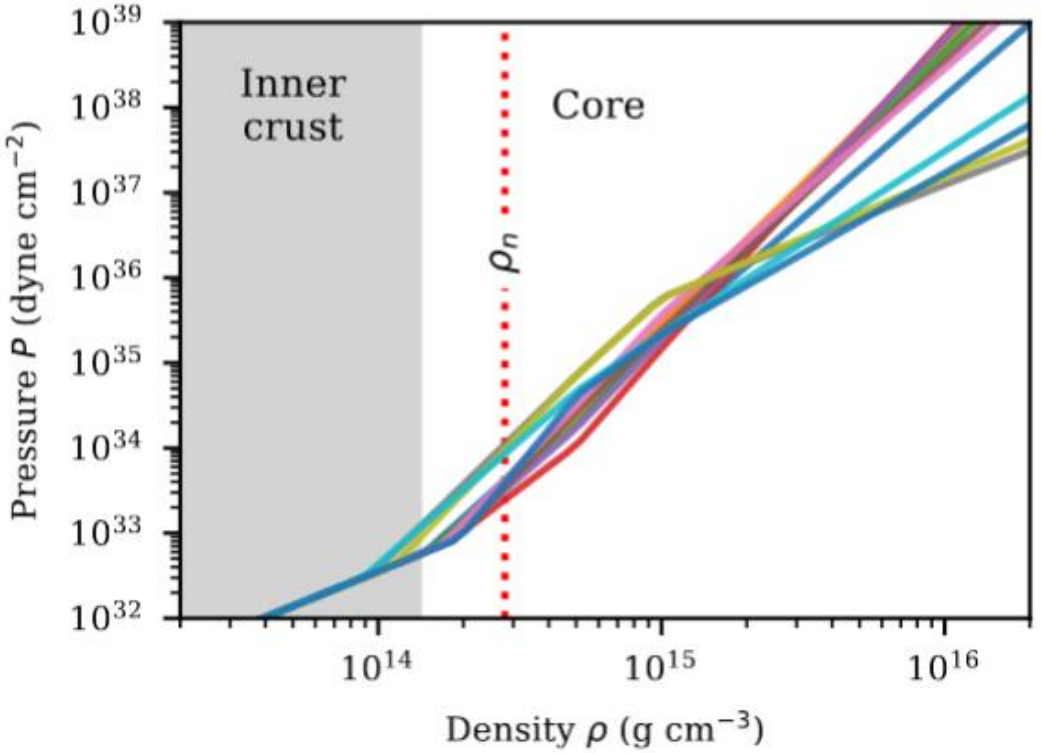
→ Microscopic models or interpolation



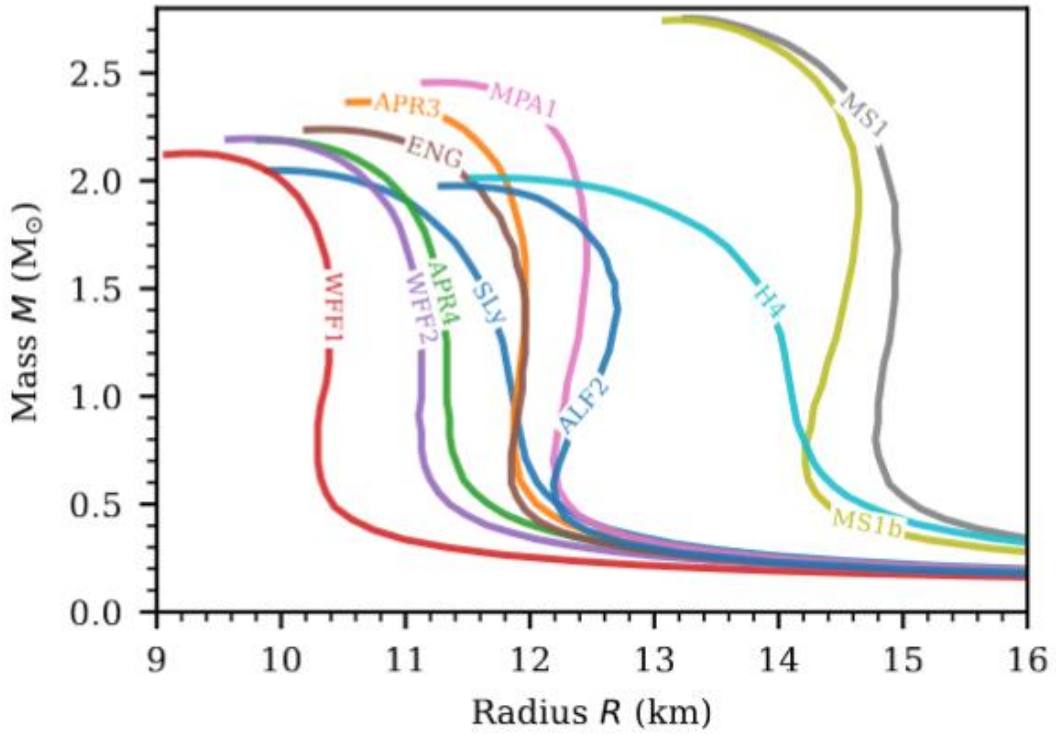
Kurkela et al. ApJ 789 (2014)

One-to-one mapping between EoS and MR-curves

Equation of state



Mass-radius curves



Nättilä & Kajava (2022), 2211.15721

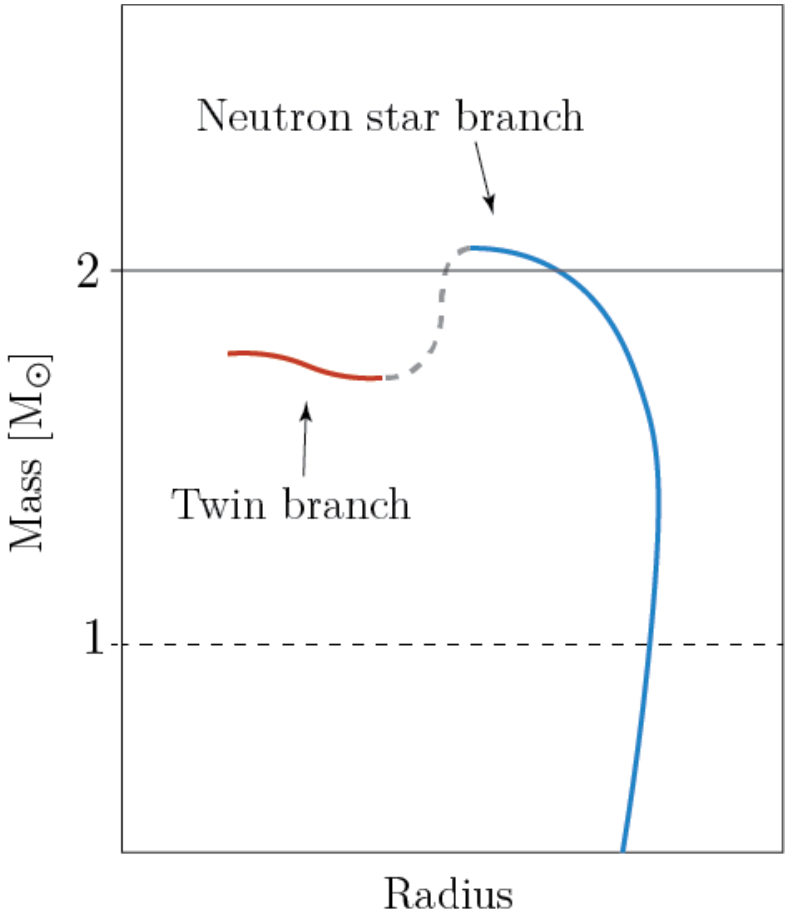
Twin stars are hypothetical compact objects

- Strong first order phase transition (PT)

  Hadronic matter → quark matter

  → Mass twin phenomenon

- Cores of quark matter on twin branch
- Instability region caused by the PT
  - Visible in e.g. mass-radius curve



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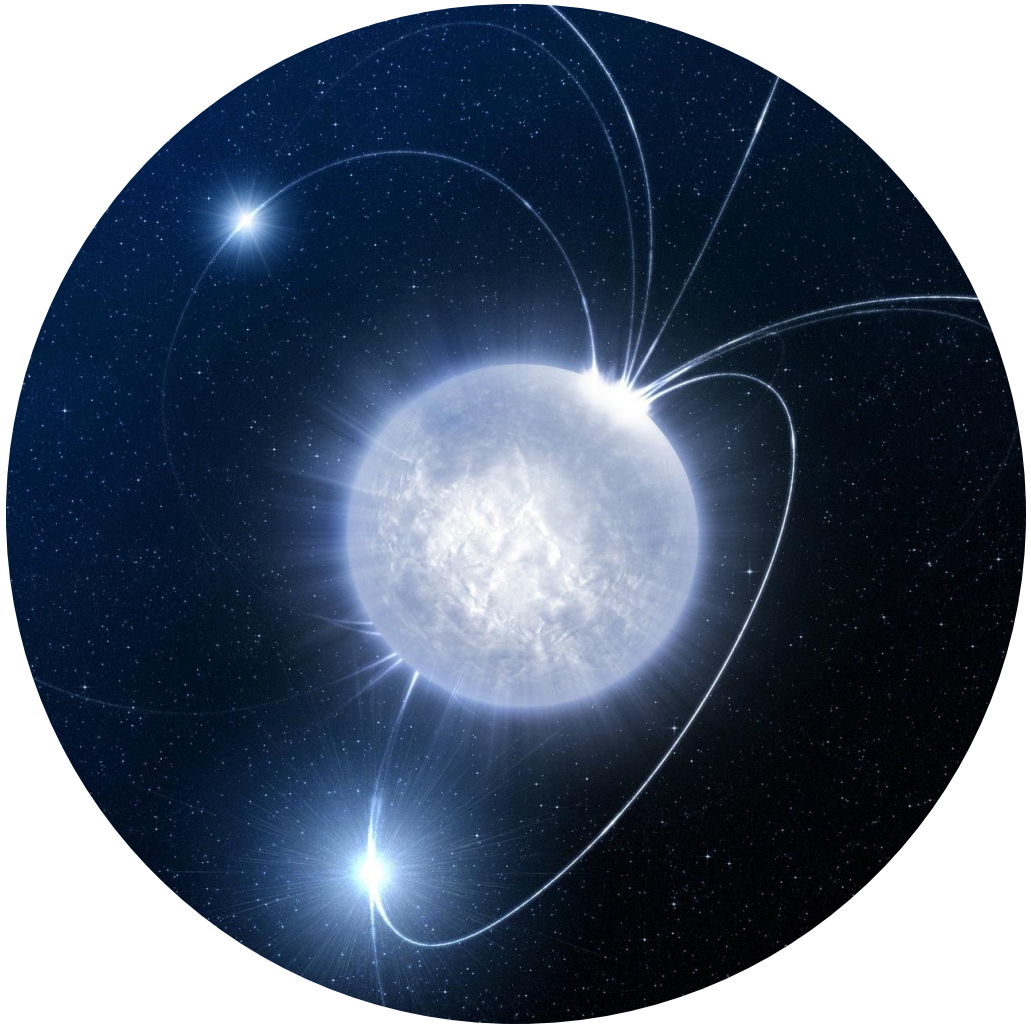


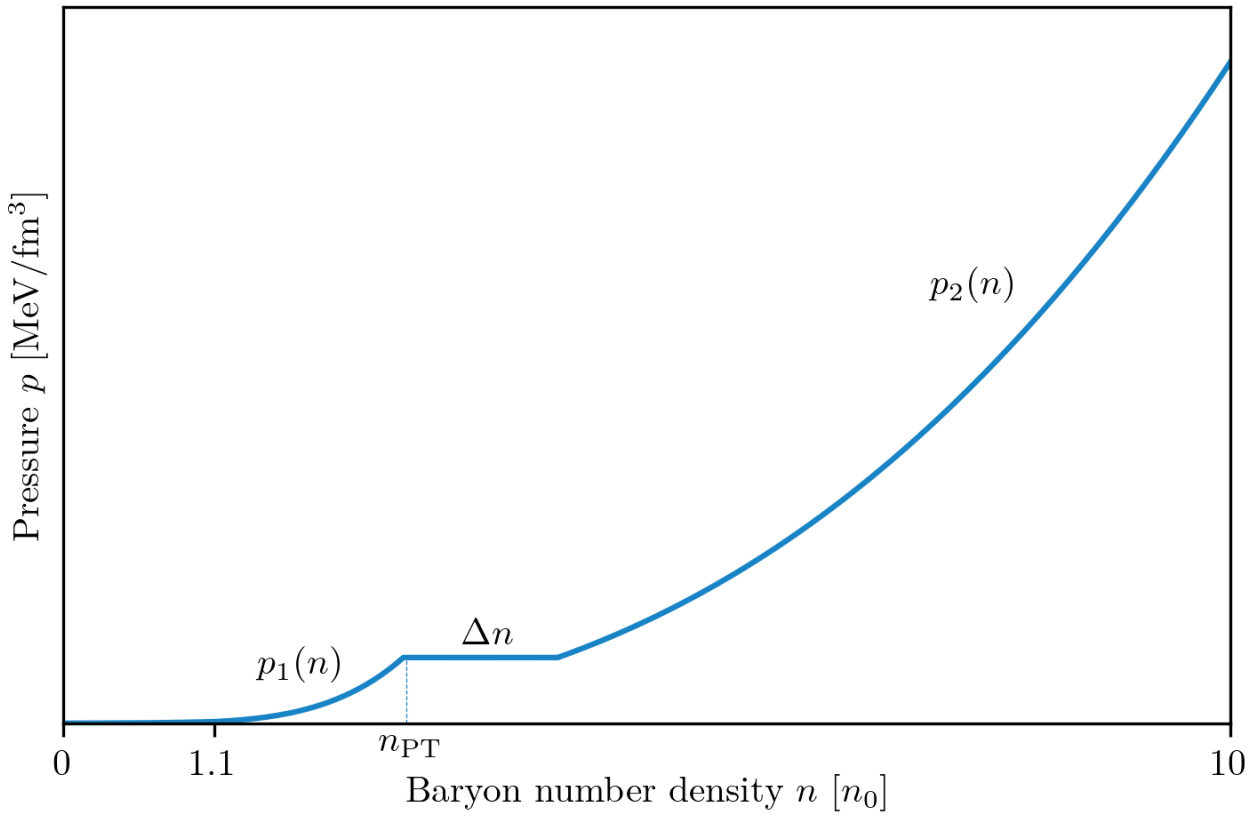
Piecewise interpolation with polytropic EoS

Construct the EoS for 1.1-10n_0:

1. Polytropic EoS $p_1(n)$
2. Phase transition Δn
3. Polytropic EoS $p_2(n)$

Transform $p(n) \rightarrow p(\varepsilon)$

Δn: Strength of the PT
n_{PT}: PT onset



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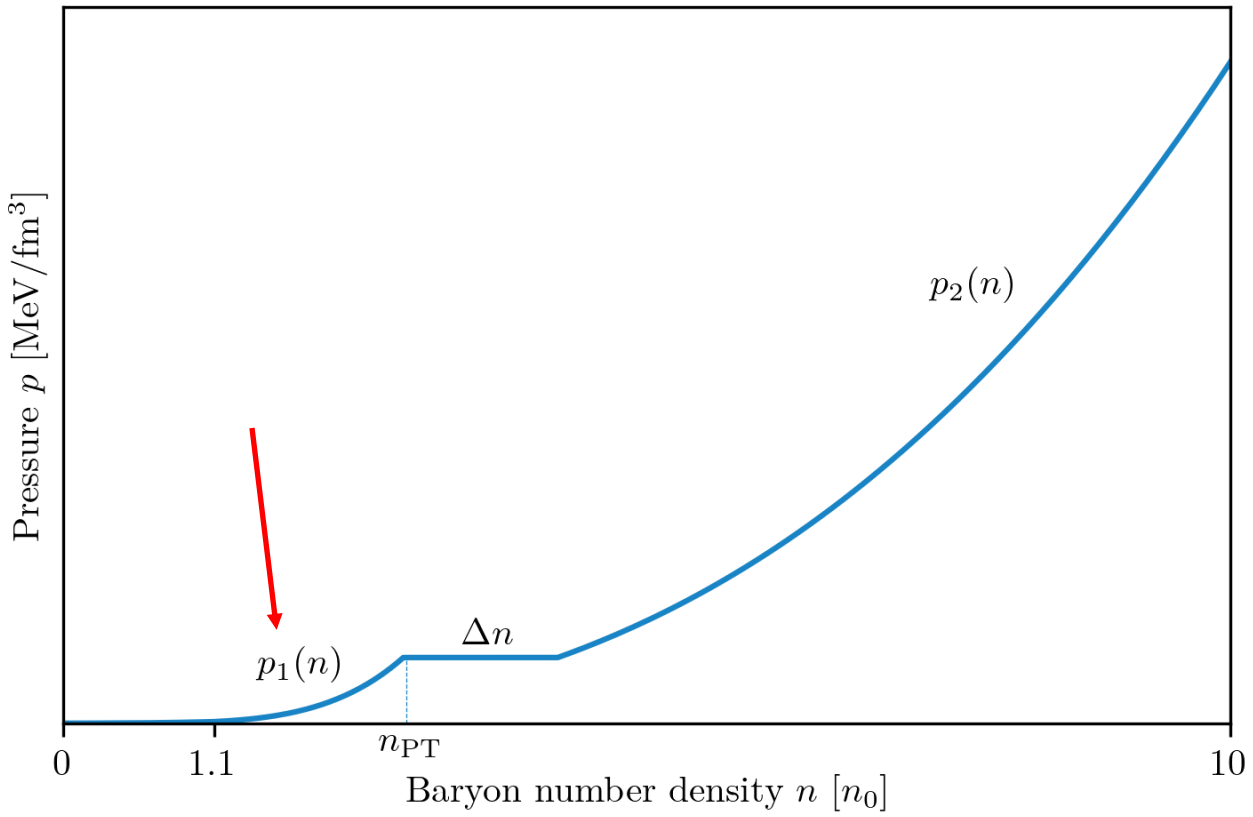

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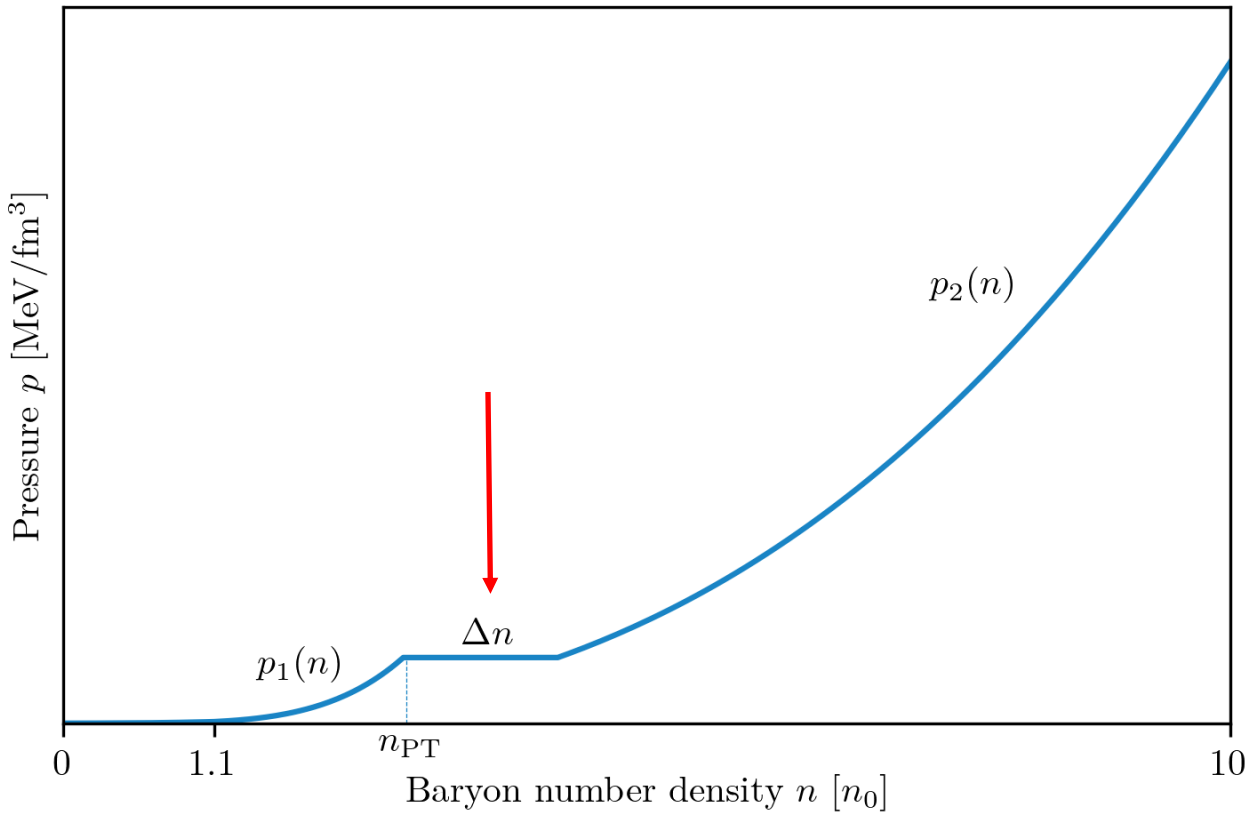

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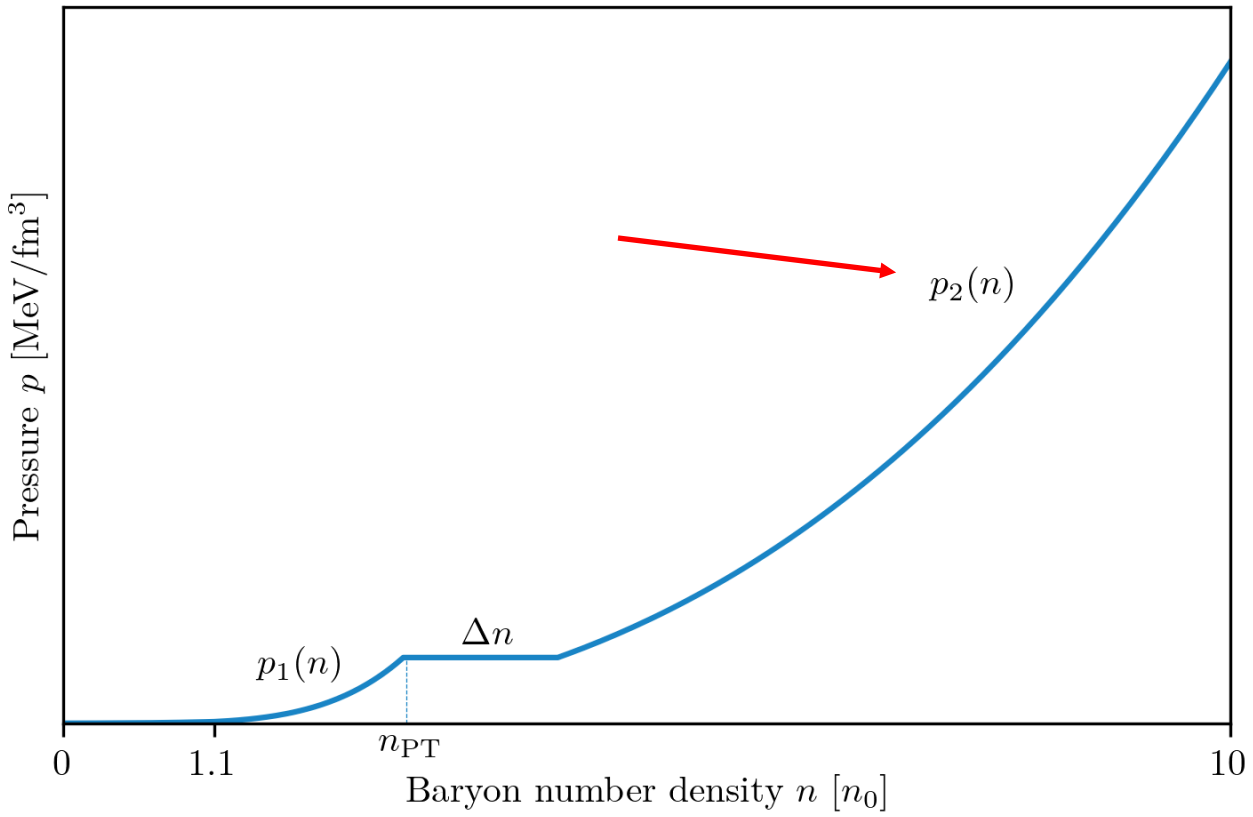
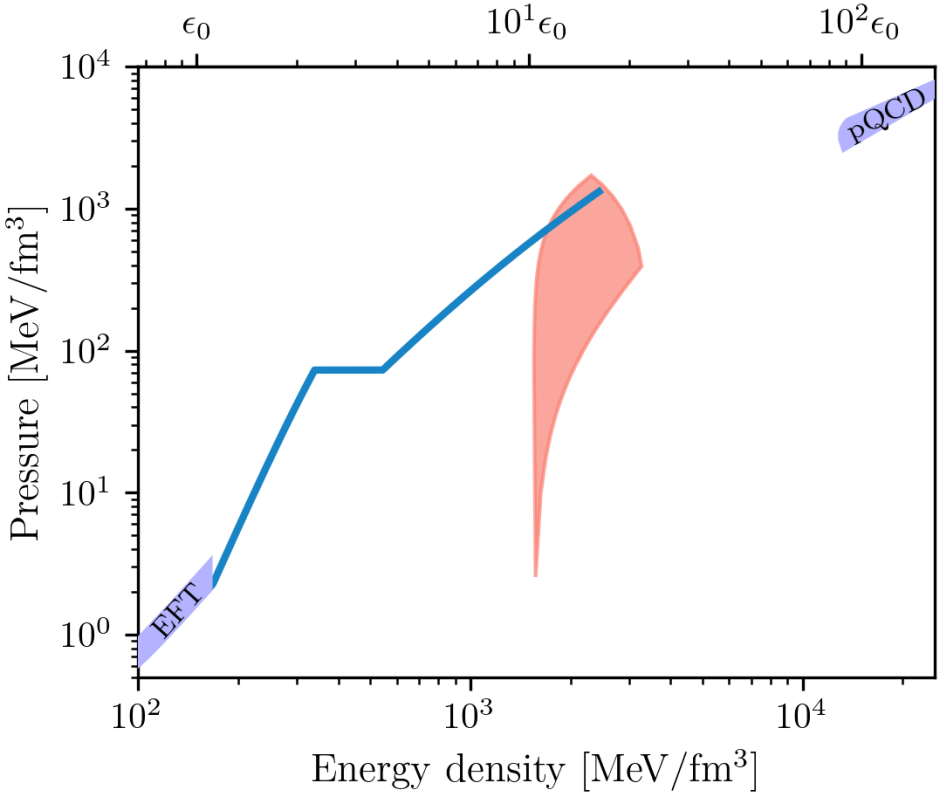


The EoS is connected to known results at high and low densities

- **cEFT EoS** at $1.1n_0$
  [Hebeler et al., ApJ 773 (2013)]

- **Extrapolated pQCD** result at $10n_0$
  [Komoltsev, Kurkela, PRL 128 (2022)]



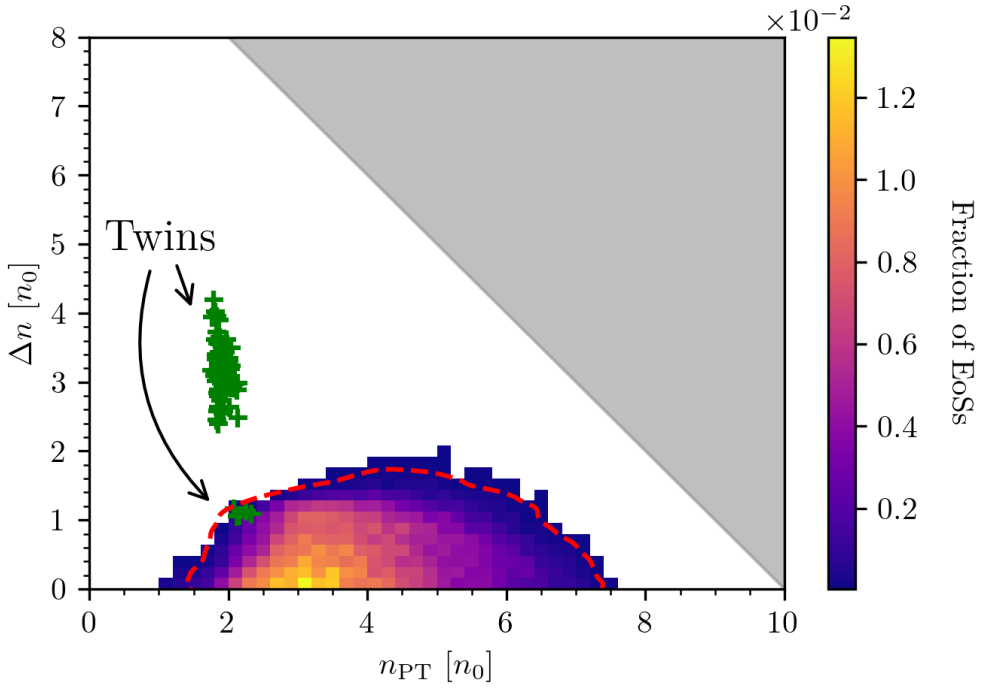
The EoS must fulfil constraints to be considered viable

- Theoretical constraints at low- and high-density limits
- Subluminality: $c_s < 1$
- Supports at least $2M_\odot$ stars
- Tidal deformability $\tilde{\Lambda} < 720$
  - Obtain from NS-NS merger GW170817
  - Related to the tidal properties of the binary components

Generating twin star solutions

- Continuation to work by Gorda et al., ApJ 955 (2023)
- 1st ensemble: without any restrictions
- 2nd ensemble: 1,000,000 EoS with $1.1n_0 \leq n_{PT} \leq 2.5n_0$
  - Pick only solutions with twin branch
  - Impose astrophysical constraints

  → **171 twin star solutions remain**



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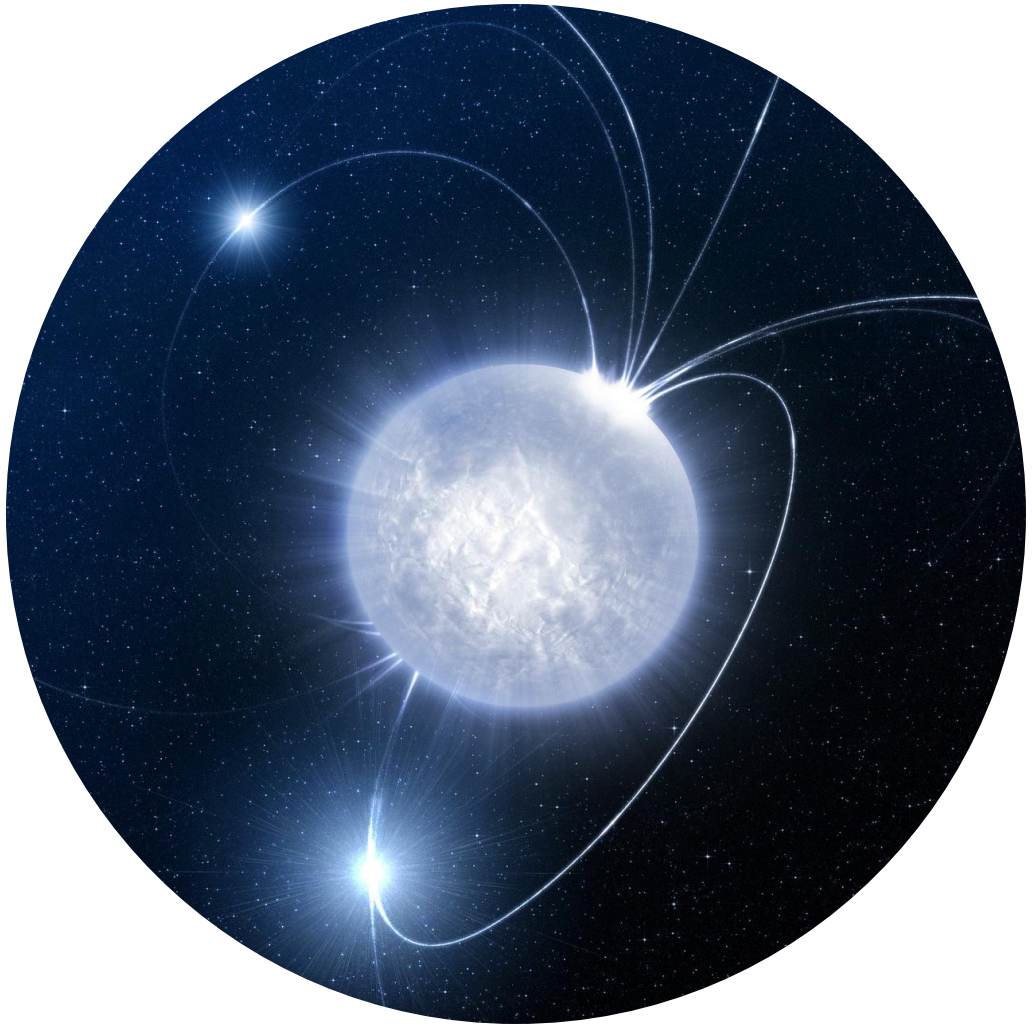
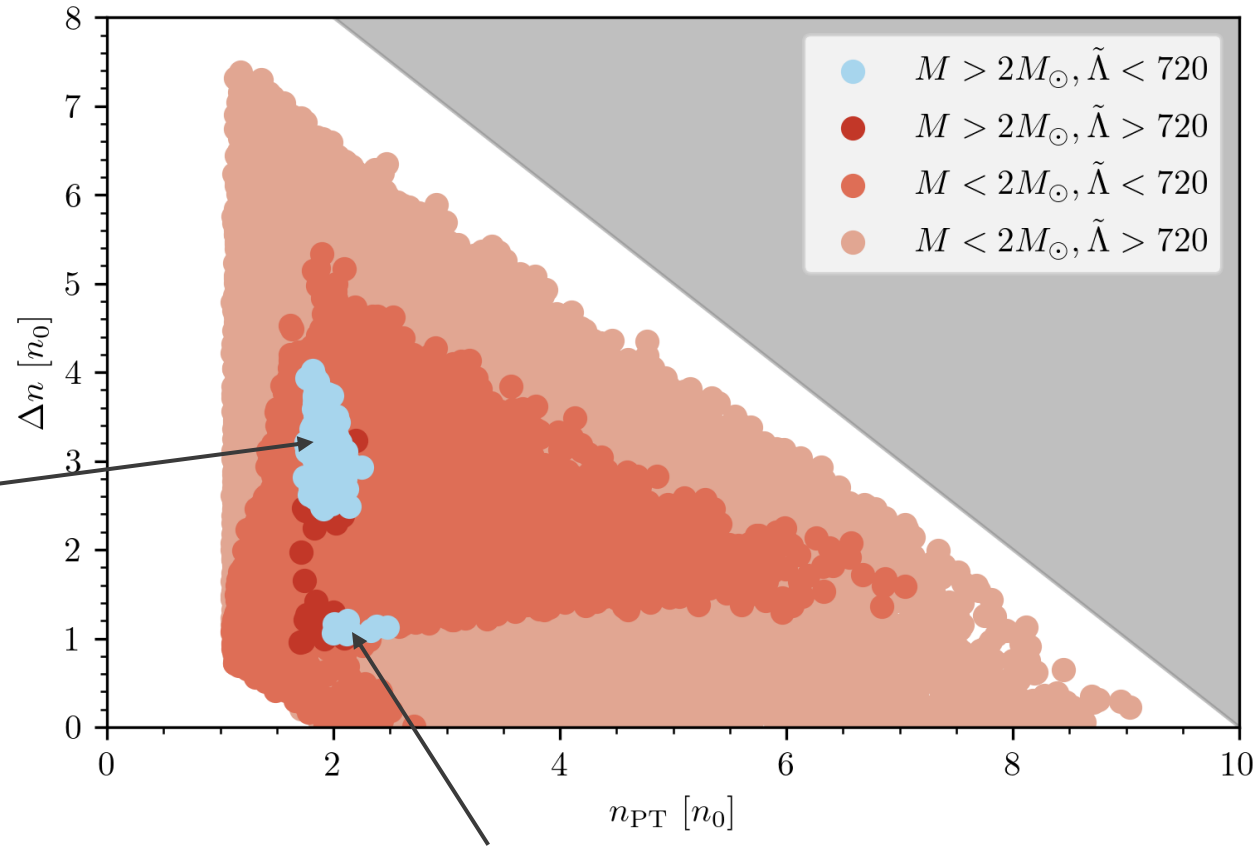


Twin stars originate from a small parameter space



Low-mass twins

High-mass twins

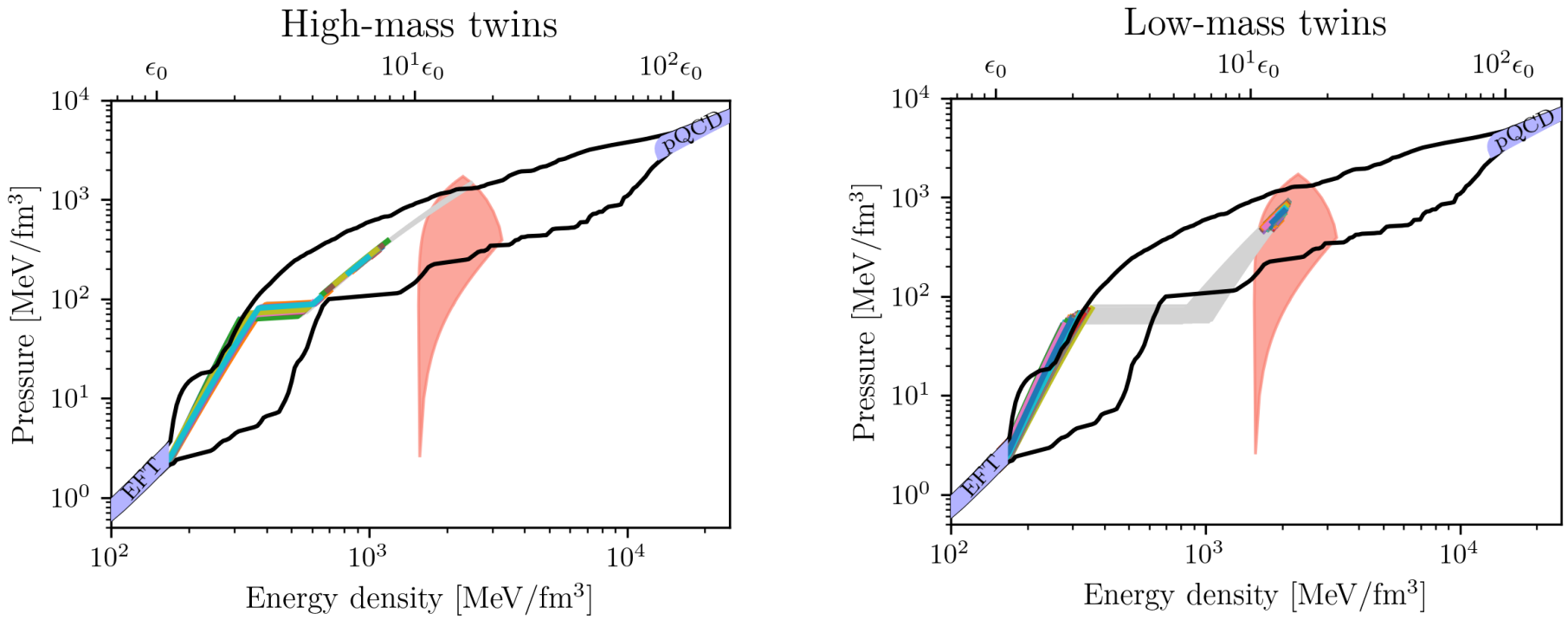
Solutions from 1st ensemble

(do not pass astrophysical constraints, only for comparison)

Solutions from 2nd ensemble

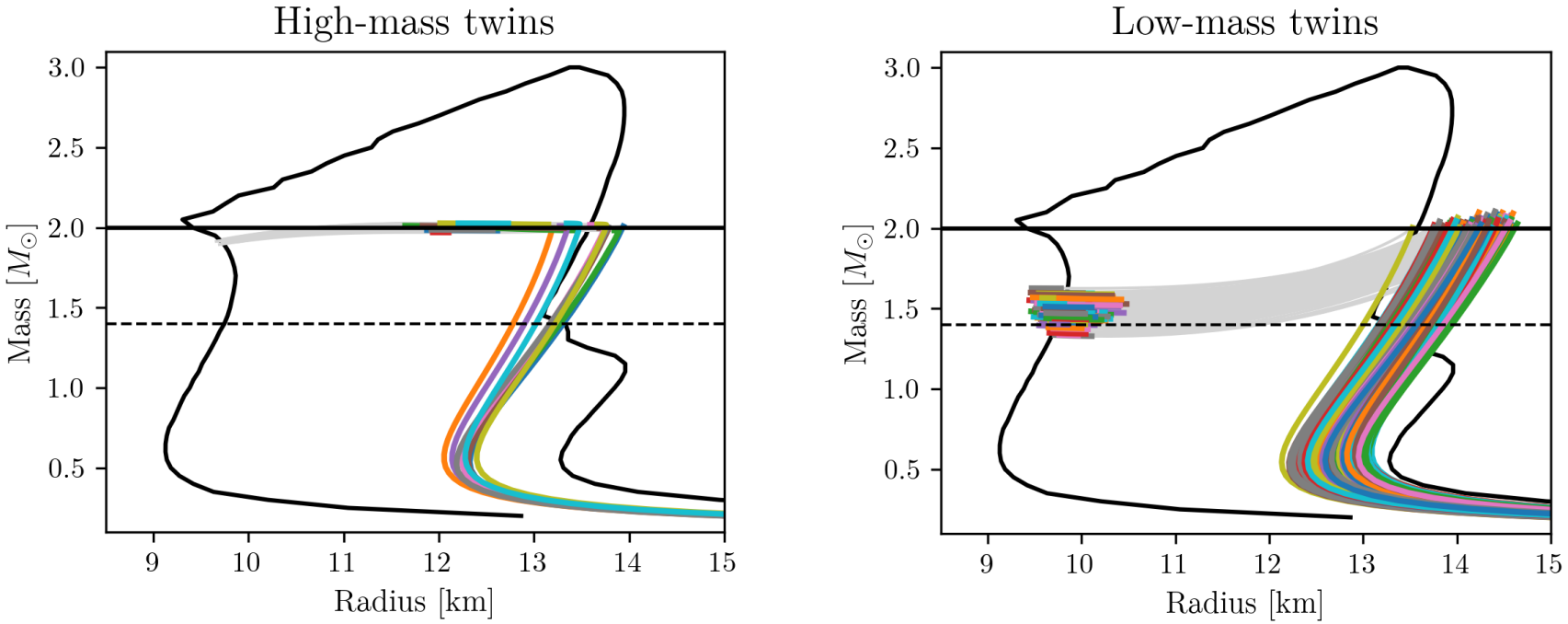
(pass astrophysical constraints)

EoSs exhibit differences in the size of the PT



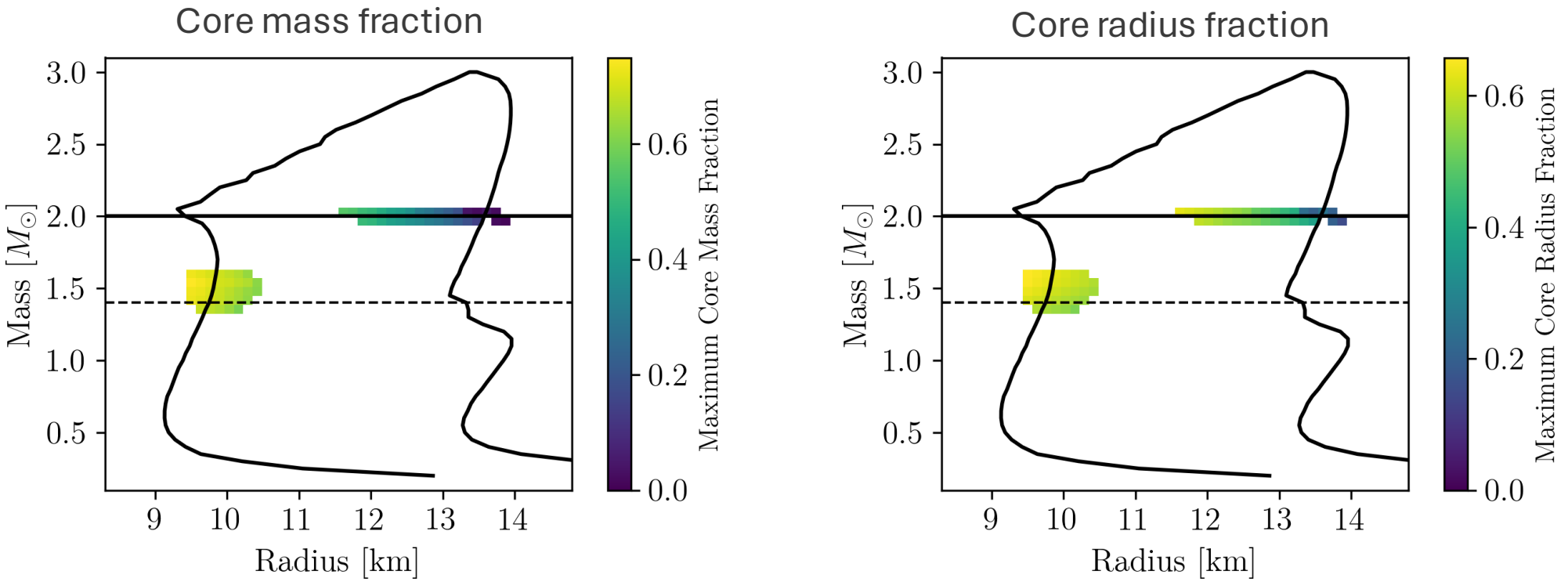
- Compare to NS ensemble by Annala et al., PRX 12 (2022) (black outlines)
- Differences e.g. in the PT size and instability region (grey color)

Twin stars only marginally pass the astrophysical constraints



- Maximum masses 2-2.1$M_\odot$
- Large radii on NS branch → leads to large $\tilde{\Lambda}$

Twin stars obtain sizable cores of quark matter



- Largest cores typically obtained for low-mass twins

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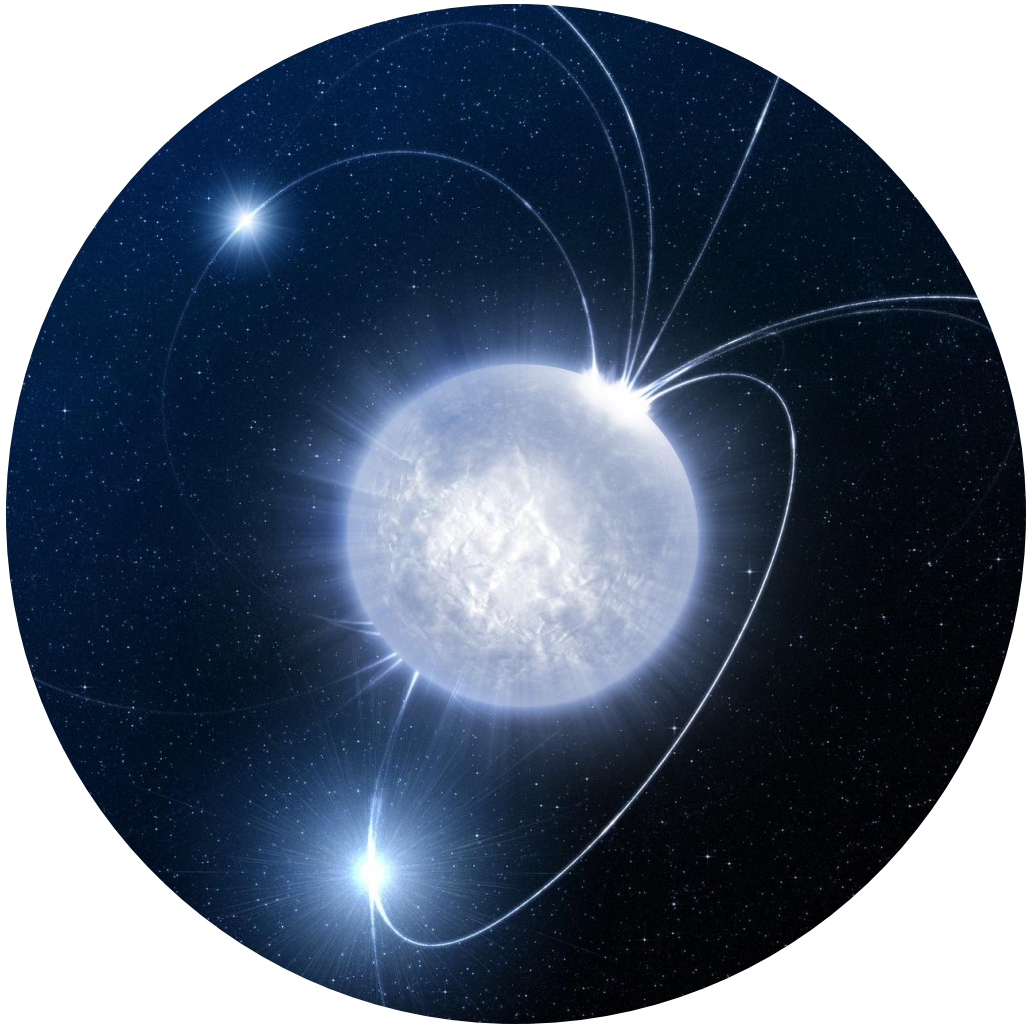

Summary & Conclusions

- Systematic study of twin stars
  - Interpolation with polytropic EoS including an explicit first-order PT
  - Known results at high- and low densities and astrophysical constraints
- Twin stars
  - Obtain small parameter space
  - Marginally pass astrophysical constraints

→ Do not seem to be a very probable scenario

Summary & Conclusions

- Polytropic EoS does not replace realistic EoS
  - Serves as heuristic guidance
- Use different approach in a future study (e.g. c_s^2 interpolation)
- Observation of twin stars would serve as a signal of a first-order PT in the QCD phase diagram

Thank you!