Exploring the effect of rotation on the deconfinement phase transition in hybrid stars

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EREP, Coimbra

Are Neutron Stars (NSs) worth to discuss in a Relativity Meeting?

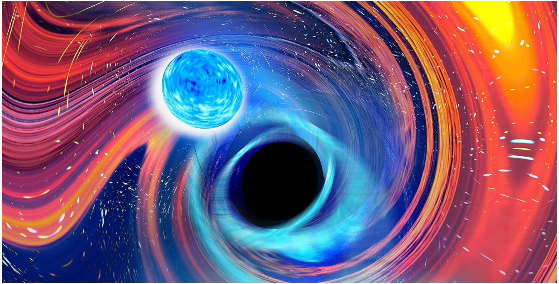
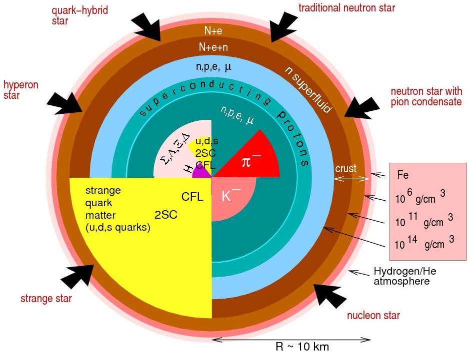


Illustration of NS-BH merger

Compactness of objects $\mathcal{C} = M/R$

- Black Holes (BHs) $\Rightarrow$ Schwartzschild radius $\Rightarrow \mathcal{C} = 1/2$
- maximum mass NSs $\Rightarrow \mathcal{C} \approx 0.2 - 0.3$

What are these compact objects made of?



Weber+ 2007

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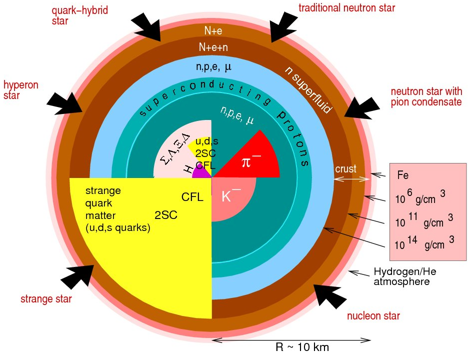

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- different possible composition of Neutron Stars (NS)

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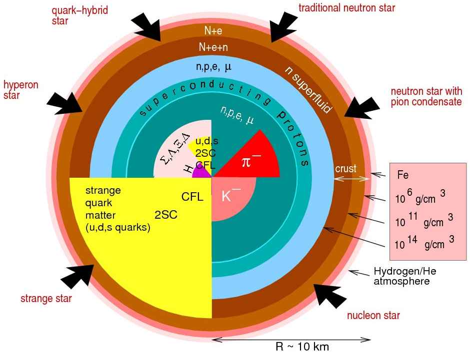

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- one possibility: Quark Gluon Plasma in the core (including phase transition)

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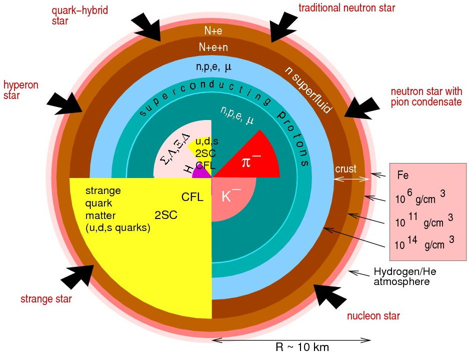

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- different possible composition of Neutron Stars (NS)
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  ⇒ chance to probe QCD phase diagram with NSs

How to build up an NS with Equations of State?

What do we need to obtain possible NS configurations?

⇒ Tolmann-Oppenheimer-Volkoff Equations
(spherical symmetric and gravitational equilibrated objects)

static

$$\frac{dp}{dr} = -(\varepsilon + p)\frac{m+4\pi r^3}{r^2-2rm}$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

⇒ need $p(\varepsilon)$ ⇒ need full EoS ⇒ hybrid EoS

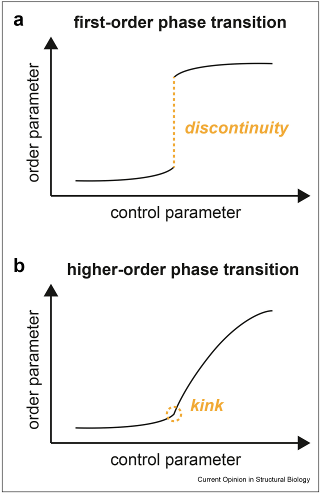
How to build up an NS with Equations of State?

Assumption: We work with a **First order Phase Transition** between Hadronic and Quark Gluon Plasma Phase

- Hadronic Phase: **DD2npY-T model** including n, p, e, μ and hyperonic degrees of freedom Shahrbaf,Blaschke+(2022)
- Quark matter: confining relativistic density functional approach Ivanytskyi,Blaschke (2022)

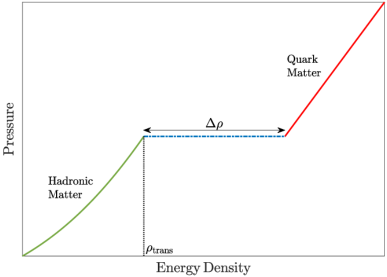
$\Rightarrow$ encoded in underlying Lagrangian

Interlude on phase transitions



Erdel 2023

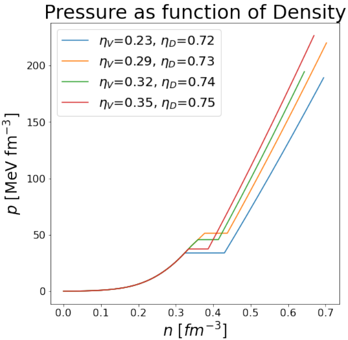
Short answer: Discontinuity of order parameter ⇒ First order phase transition



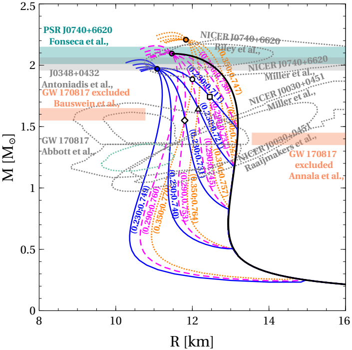
Jump in energy density for hybrid EoS

- sharp interface between two phases

From EoSs to M-R curves



TOV

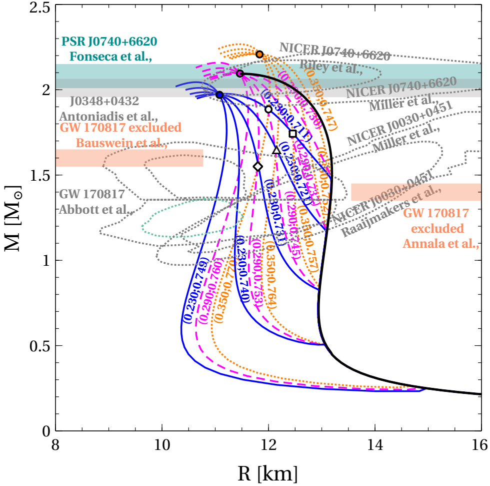


TOV equations:

$$\frac{dp}{dr} = -(\varepsilon + p)\frac{m + 4\pi r^3}{r^2 - 2rm},$$
$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

Remember interesting properties as

- Special Points (SPs) and
- the deconfinement phase transition



Gärtlein+ 2023

Summary of published paper

1. Hybrid EoS with specific quark matter description

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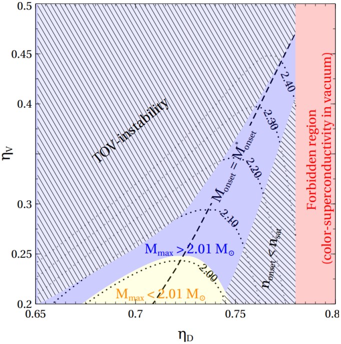

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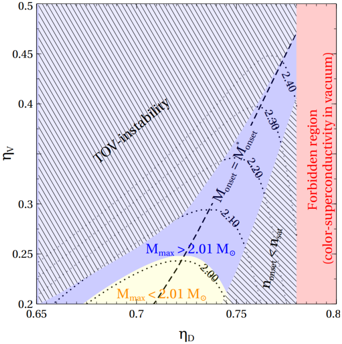

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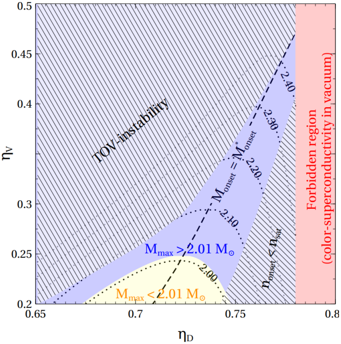

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4. 10.1103/PhysRevD.108.114028

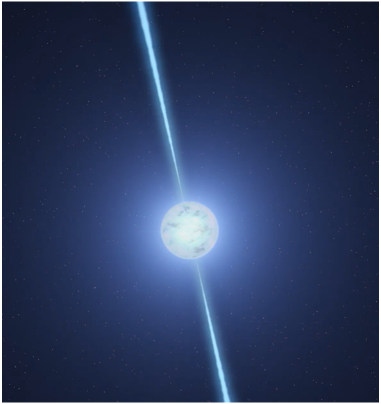
What about rotating NSs?

Do they exist and if yes...

- How to observe them?
- How do they behave under rotation?
- Do characteristics change “dramatically” under rotations?

⇒ Consider a “phase diagram” of rotating hybrid stars ω-M space

Justification



Pulsars - Showing a "beam of light"

- multiple detected pulsars including rotations over 700Hz $\Rightarrow$ millisecond pulsars

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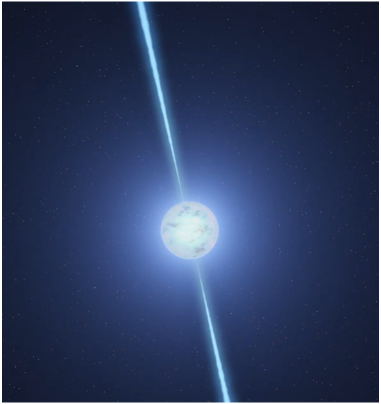

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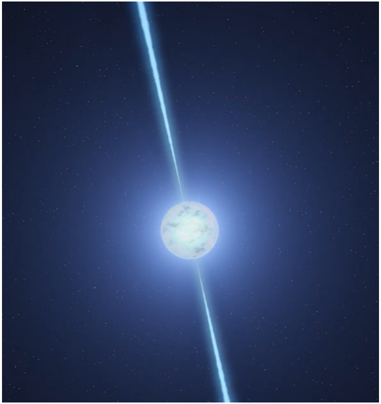

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- changing of spherical shape (**flattening**) and frame-dragging
- phase transition inside and maximum mass $\Rightarrow$ how does it change?

What does it mean mathematically?

- Rotational metric (ZAMO frame - observer at same ω)

$$ds^2 = -e^{2\nu}dt^2 + e^{2\psi}(d\phi - \omega dt)^2 + e^{2\lambda}(dr^2 + r^2 d\theta^2)$$

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- **process:**
  - input: EoS, central density ε_c, frequency ω
  - output: R, M, oblateness (R_p/R_e), etc.

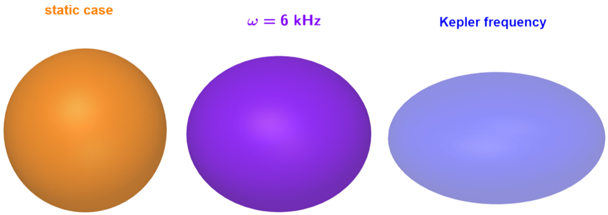
Kepler frequency

NSs rotating at Kepler frequency

- hypothetical highest rotation of NSs
- higher rotations will lead to mass shedding
- $\omega_{Kepler} \propto \sqrt{\frac{M}{R^3}}$

- ω_{Kepler} will play the role of a phase boundary in our discussion

Neutron stars under rotation



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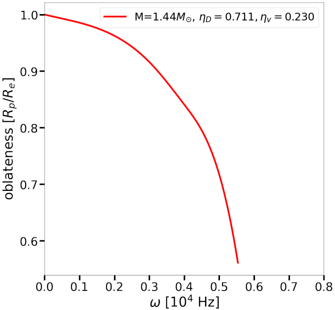
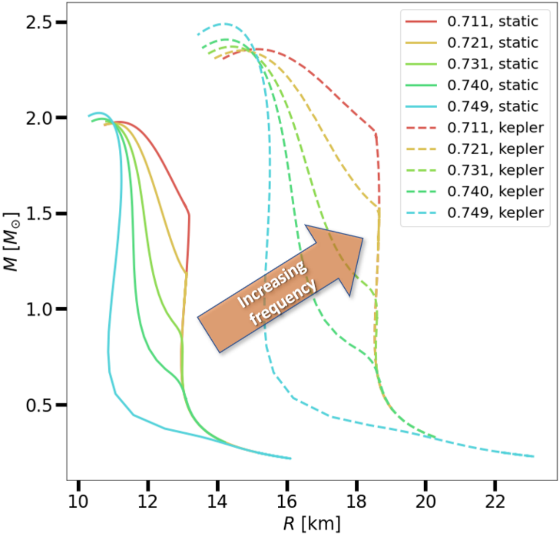


- oblateness as a function of the rotational frequency ω
- depending on EoS/couplings $\Rightarrow$ oblateness goes down to ca. 55%

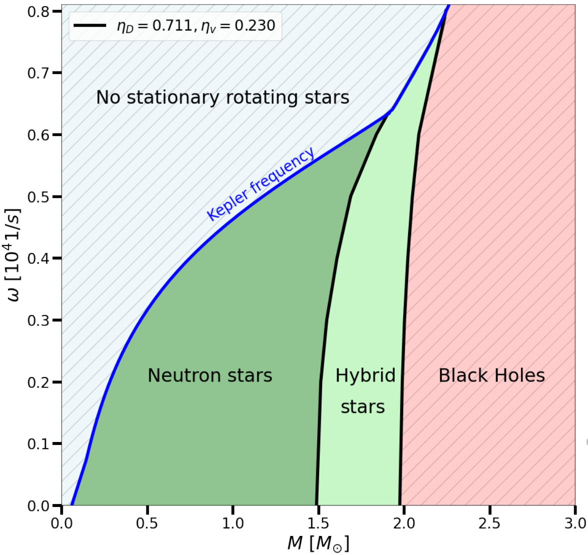
M-R curves and characteristics



- M-R curves are essentially shifted to higher radii and masses
- properties as SP and onset of deconfinement phase transition are shifted in a similar way
- SP still seems to exist!

Gärtlein+ 2024, still in preparation

Phase diagram ω-M



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Still in preparation

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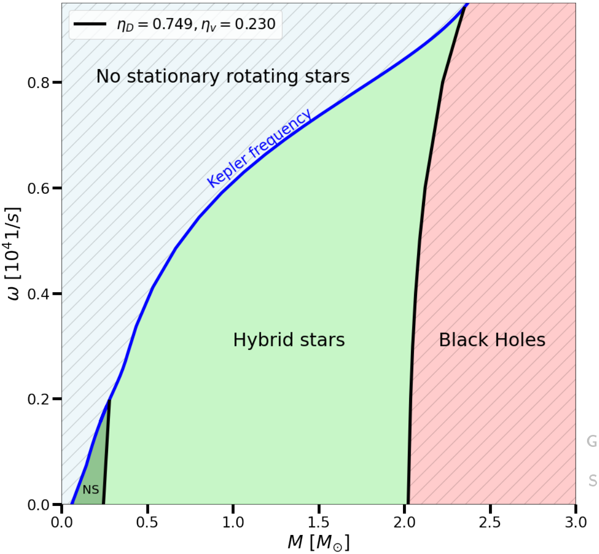

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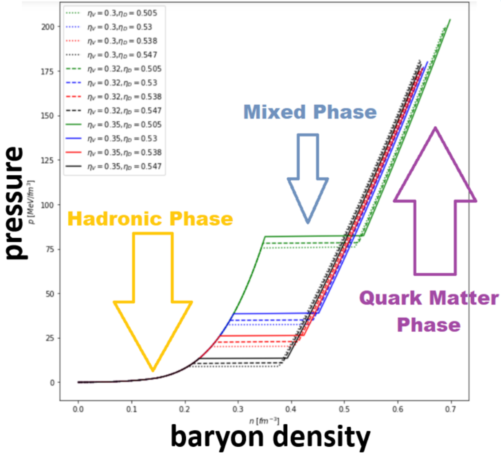
6. observation of rotating stars can put constraints on internal composition

Thanks!

Maxwell construction



Hybrid EoSs

- typical plateau of first order phase transition
- **But:** inside star, no shell of mixed phase ⇒ narrow

Relativistic density functional for quark matter EOS

$$\mathcal{L} = \overline{q}(i\partial\!\!\!/ - \hat{m})q + \mathcal{L}_{PS} + \mathcal{L}_V + \mathcal{L}_D$$

- **Pseudoscalar interaction ⇒ chiral dynamics**

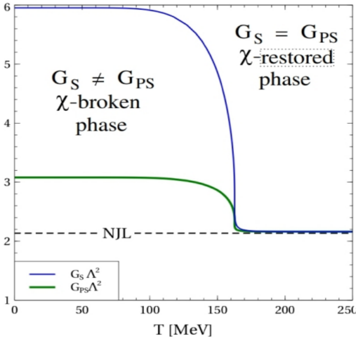
$$\mathcal{L}_{PS} = G_0\left[(1+\alpha)\langle\overline{q}q\rangle_0^2 - (\overline{q}q)^2 - (\overline{q}i\vec{\tau}\gamma_5 q)^2\right]^{\frac{1}{3}}$$

- **Vector interaction ⇒ repulsion**

$$\mathcal{L}_V = -G_V(\overline{q}\gamma_\mu q)^2$$

- **Diquark pairing ⇒ color superconductivity**

$$\mathcal{L}_D = G_D \sum_{A=2,5,7} (\overline{q}i\gamma_5\tau_2\lambda_A q^c)(\overline{q}^c i\gamma_5\tau_2\lambda_A q)$$



Details in:

Ivanytskyi, Blaschke, PRD (2022)

Ivanytskyi, Blaschke, Particles (2022)

- **Comparison to NJL model**
  - medium dependent scalar G_S and pseudoscalar G_{PS} couplings
  - high vacuum quark mass ⇒ phenomenological confinement
  - quark correlations ⇒ mesons: $\pi,\ \sigma\ =$