

# Bayesian Inference of Hybrid Stars with Large Quark Cores

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# The Central Question

## 01. Density Extremes

Neutron star cores achieve densities far exceeding nuclear saturation density, creating an extreme physical environment at the center of these compact objects.

## 02. The Hybrid Star Hypothesis

Does extreme density lead to the deconfinement of quarks? If deconfined quark matter exists at the core, these stars are classified as **Hybrid Stars**.

## 03. Multi-Messenger EOS Constraints

Combined data from NICER (X-rays), GW170817 (GWs), and HESS (gamma-rays) now tightly constrain the Equation of State (EOS) of dense nuclear matter.

# Objectives & Approach

## Primary Research Goal

Perform a Bayesian inference analysis of the Equation of State (EOS) for hybrid stars, specifically focusing on configurations that may contain large quark cores.

## Quark Model Comparison

Systematically compare two distinct quark matter frameworks: the chiral NJL model versus the gluon mean-field MFTQCD model to assess their impact on the EOS.

## Five EOS Ensembles Design

Isolate and quantify the effects of prior assumptions, the inclusion of gravitational wave data, and the fundamental quark model choice.

# Theoretical Models

Phase	Model	Key Features
Hadron	RMF	$\sigma, \omega, \rho$ mesons + nonlinear self-interaction terms
Quark A	NJL	Dynamical mass generation, vector repulsion, 6 free parameters
Quark B	MFTQCD	MIT bag constant + vector interaction term, 2 free parameters
Transition	Maxwell	Sharp phase interface condition, pressure equilibrium ( $P_h = P_q$ )

# Bayesian Framework

## Prior Definition

A non-informative uniform distribution is applied for all free model parameters to avoid biasing the posterior space.

## Likelihood Function (10 Constraints)

- Nuclear matter properties & chiral EFT ( $\chi$ EFT)
- NICER mass–radius observations (3 pulsars)
- GW170817 tidal deformability (NJL-GW only)
- Causality & pQCD bounds at  $7\rho_0$  density
- Thermodynamic phase-transition construction terms

## Sampling Engine: PyMultiNest

Generates  $\sim 5,000$ – $7,000$  posterior samples per ensemble for robust statistical inference.

# Five Ensembles

Ensemble	Hadronic	Quark	Special Condition
RMF	RMF	—	Nucleonic baseline
NJL	RMF	NJL	Broad priors
NJL-GW	RMF	NJL	+ GW170817 constraint
r-NJL	RMF (tight)	NJL	Hadronic prior = RMF posterior
MFTQCD	RMF	MFTQCD	Early transition model

# EOS & Sound Speed

## MFTQCD Model Prediction

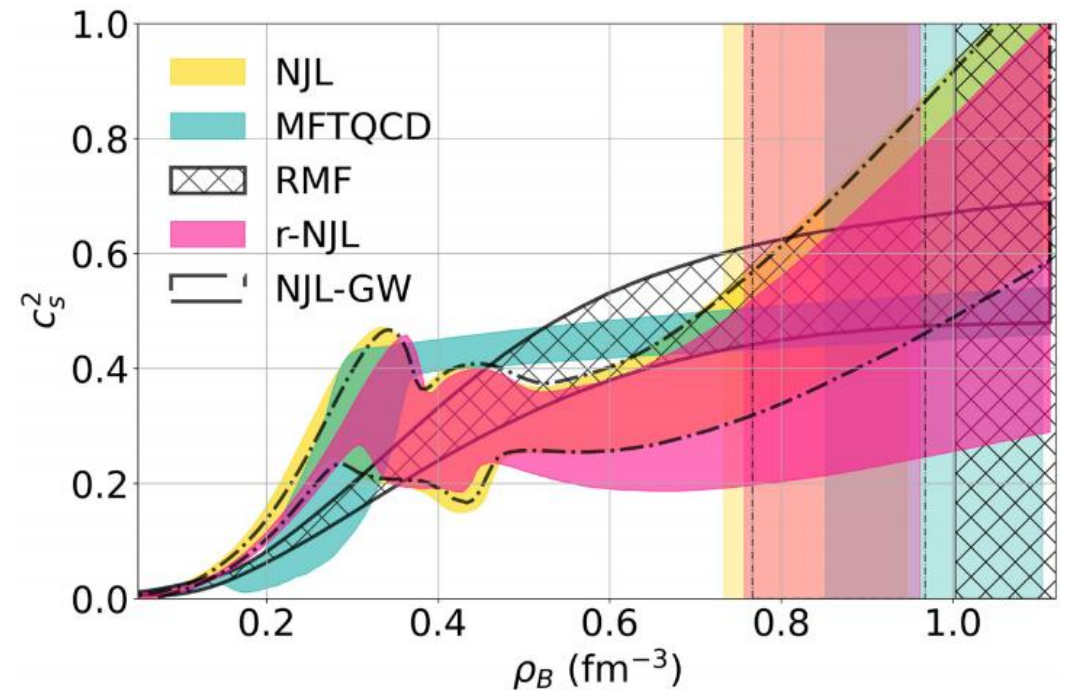
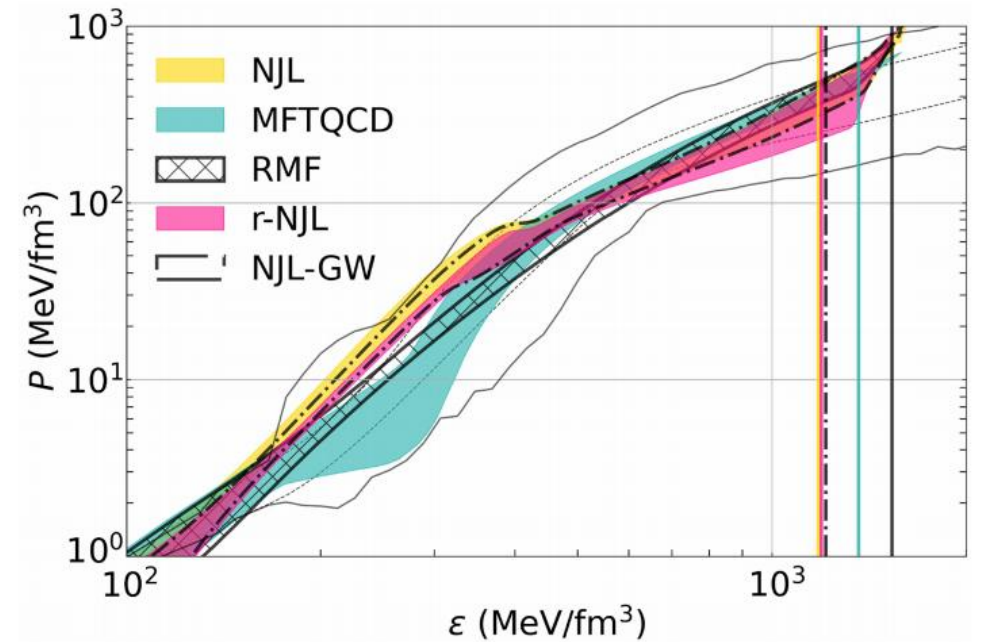
Exhibits a phase transition at densities as low as  $\sim 0.17 \text{ fm}^{-3}$ . Its EOS is notably softer and consistently lies below the "agnostic band" defined by other theoretical analyses.

## NJL Model Characteristics

Features a significantly stiffer hadronic EOS component. The chiral phase transition is predicted to occur at super-saturation densities, specifically above  $2\rho_0$  (twice nuclear saturation).

## Sound Speed ( $c_s^2$ ) Profile

NJL displays a double peak (linked to deconfinement & strange quarks), while MFTQCD/RMF show a smooth, monotonic rise to  $c_s^2 \approx 0.5$ .



# Mass–Radius & Observations

## MFTQCD Model Analysis

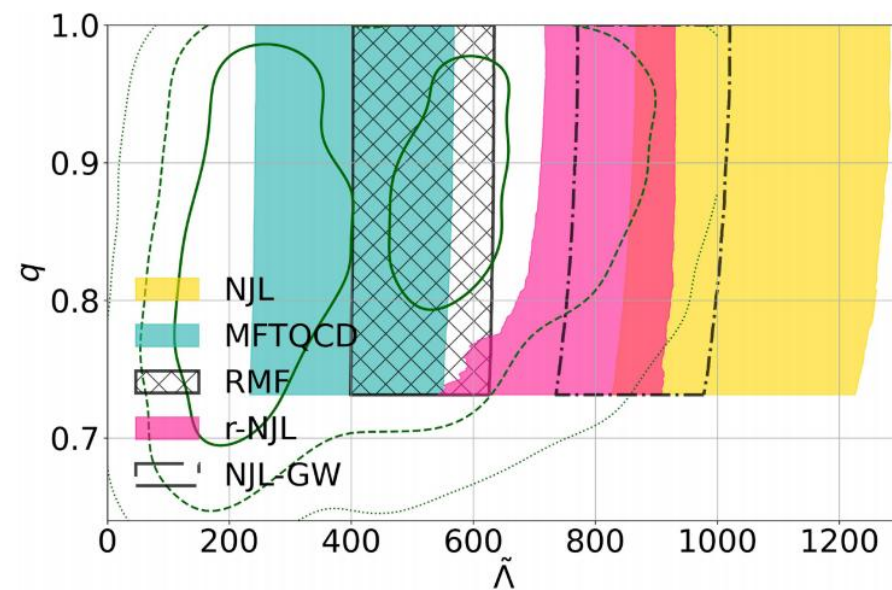
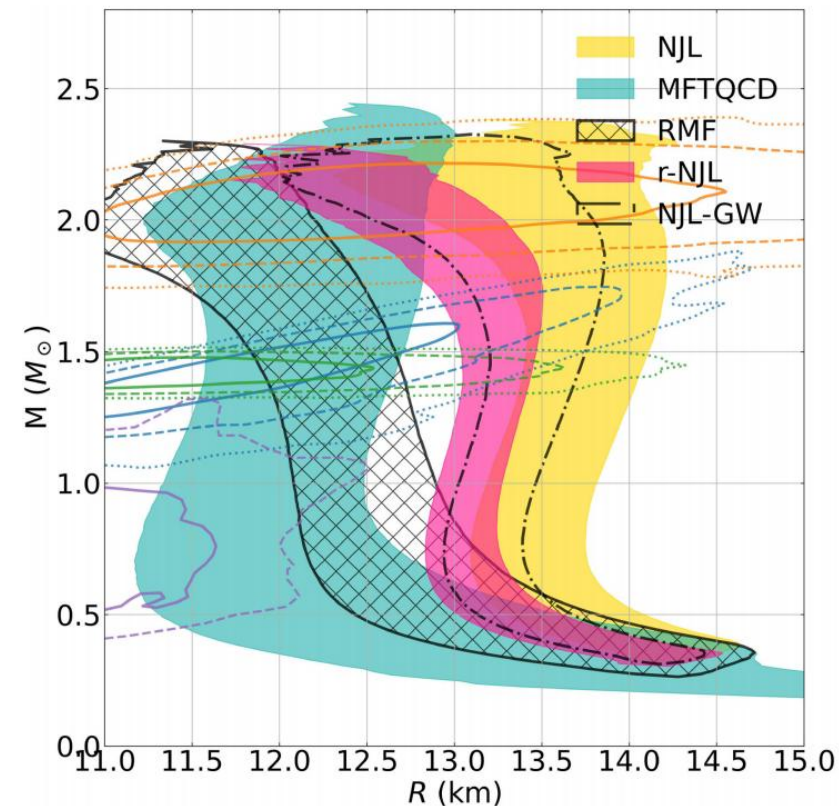
Predicts small radii for compact stars. Critically, it is the **only model** that is statistically compatible with the HESS J1731-347 observations at the 68% confidence level (CL).

## NJL Model Limitations

Characterized by larger predicted radii. The calculated tidal deformability values for this model exceed the upper limit of the 90% confidence interval (CI) derived from GW170817.

## Hybrid Star Configurations

Across all hybrid EOS sets, we find that a deconfined quark core is physically possible even in massive pulsars like PSR J0740+6620, which has a mass of approximately 2 solar masses.



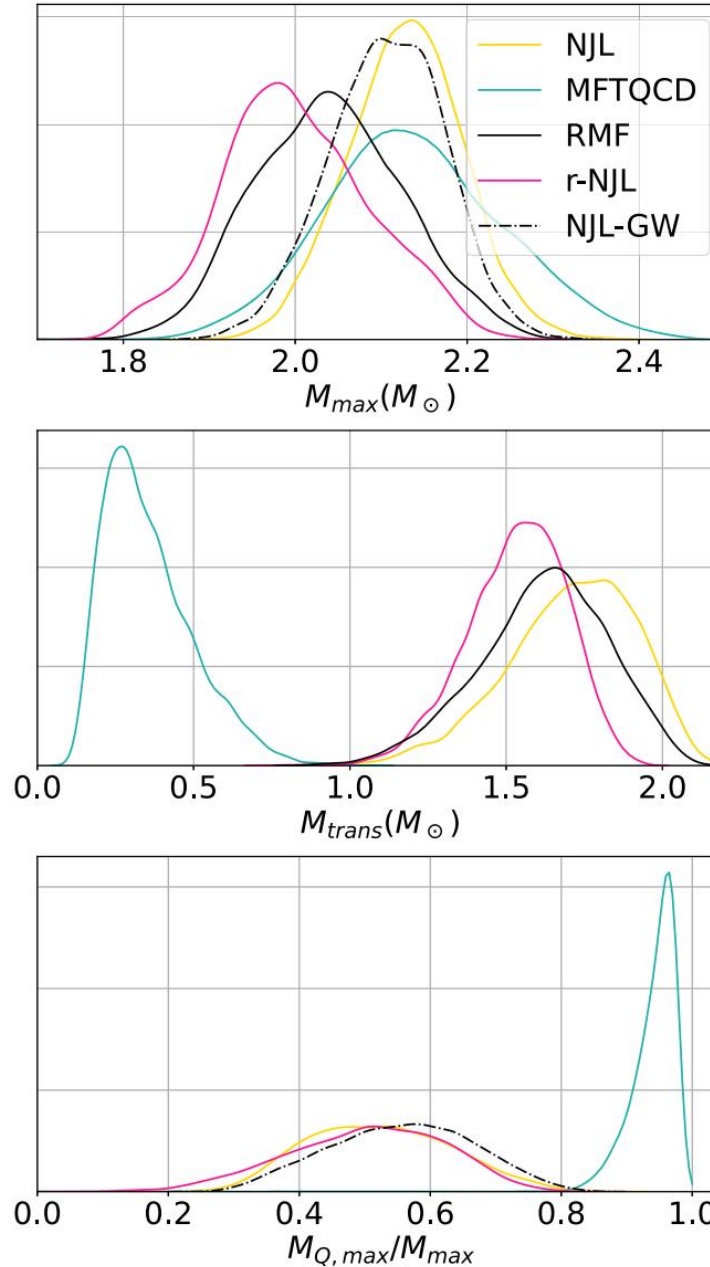
# Transition Mass & Quark Core Size

## MFTQCD Model: Early Transition

Median transition mass ( $M_{\text{trans}}$ ) =  $0.33 M_{\odot}$ . The quark core is allowed to grow significantly, reaching sizes up to  $2 M_{\odot}$ .

## NJL Model: Late Transition

Median transition mass ( $M_{\text{trans}}$ )  $> 1.5 M_{\odot}$ . This high threshold limits the maximum quark core size to approximately  $1.1 M_{\odot}$ .



# Diagnostic: Slope of $M(R)$

## RMF Models (Pure Hadronic)

Slope is consistently negative for >97% of Equations of State (EOSs) at a canonical mass of  $1.4 M_{\odot}$ , reflecting standard nuclear matter properties.

## Hybrid Star Configurations

The slope transitions to positive for >90% of EOSs within the mass range  $1.2\text{--}1.6 M_{\odot}$ , a key discriminant distinguishing hybrid stars from pure hadronic models.

## Physical Interpretation

A positive slope at high mass is interpreted as a robust observational signature, strongly suggesting the presence of exotic quark matter in the star's core.

# Conclusions

## **Large quark cores are viable.**

- MFTQCD: Early transition provides a good fit to HESS J1731-347 data.
- NJL: Requires a stiff hadronic EOS, predicting significantly larger radii.

## **A positive M–R slope at high masses is a strong signature of exotic cores**

The mass-radius relation's slope is a highly promising indicator to identify hybrid star candidates.

## **Future precision radius measurements will be decisive.**

High-precision astrophysical observations are crucial to confirm the nature of compact stars.

# Thank You

