Relativistic neutron stars beyond general relativity

The equations describing a static, spherically symmetric neutron star in general relativity are well known (the TOV equations) and can be readily solved numerically using standard ODE methods. This project explores how neutron-star structure changes in alternative theories of gravity, focusing on metric $f(R)$ gravity as a concrete example. One motivation is that $f(R)$ models can introduce genuinely strong-field effects (while reducing to GR in the appropriate limit), making neutron stars a useful laboratory for testing gravity beyond GR. Specifically, this project has the following sections in mind

1. Starting from the field equations of metric $f(R)$ gravity, derive the coupled system governing a static, spherically symmetric star.
2. Investigate the pros/cons of (i) adaptive explicit Runge–Kutta schemes and (ii) fully implicit solvers (e.g. BDF/Radau-type methods) for coupled non-linear ODE systems that can become stiff for certain parameter choices. Compare performance via robustness, step-size histories, and residual/constraint checks.
3. Putting these ideas into practice by solving the modified TOV-like equations for a chosen equation of state and produce mass–radius curves and additional profiles. Compare directly with the GR solutions and identify parameter ranges where deviations become significant.
4. (Optional extension) Explore how the maximum mass/stability properties shift relative to GR, and/or perform a small parameter scan to map out where the numerics become challenging or qualitatively new behaviour appears.

The student must be comfortable with (or willing to learn) stiff systems of ODEs and the shooting method for boundary-value problems, and must be proficient in writing code (in any programming language of choice). Linux experience is helpful (a short setup guide can be provided). Overall, this project is best suited for students who enjoy computational physics, numerical ODE experimentation (accuracy vs robustness), and want a project with a clear astrophysical payoff.

Some references:

1. T. P. Sotiriou and V. Faraoni. $f(R)$ theories of gravity. *Rev. Mod. Phys.*, 82:451–497, 2010. doi:10.1103/RevModPhys.82.451.
2. A. De Felice and S. Tsujikawa. $f(R)$ Theories. *Living Reviews in Relativity*, 13:3, 2010. doi:10.12942/lrr-2010-3.
3. A. Cooney, S. DeDeo, and D. Psaltis. Neutron stars in $f(R)$ gravity with perturbative constraints. *Phys. Rev. D*, 82:064033, 2010. doi:10.1103/PhysRevD.82.064033, arXiv:0910.5480 [astro-ph.HE].

4. A. V. Astashenok, S. Capozziello, and S. D. Odintsov. Further stable neutron star models from $f(R)$ gravity. *JCAP*, 12:040, 2013. doi:10.1088/1475-7516/2013/12/040, arXiv:1309.1978 [gr-qc].