

## I. GENETIC PROGRAMMING

### A. Introduction

We use a supervised ML algorithm called genetic programming (GP) [3]. A detailed introduction to this method is beyond the scope of the paper, so we only present essential information pertaining to our work.

GP is evolutionary computation that employs naturally occurring genetic operations, a fitness function, and multiple generations of Darwinian evolution to resolve a user-defined task [4]. GP can be used to discover a mathematical relationship between the input variables, also called features, in data (regression) or group data into categories (classification). Similar to biological natural selection, GP learns how well the program functions by comparing the output of its multivariate expression to a *fitness score*. Programs with high fitness score are most likely, but not certain, to propagate to next generation. With subsequent generations, programs are more likely to get better at solving the task at hand [7].

GP multivariate expressions are classically represented as a syntax tree, where the trees have a root (top center), nodes (mathematical operators), and leaves (operands). Operators can be arithmetic, trigonometric, boolean, etc. and the operands are place-holder variables related to the problem. The tree depth can be varied aiding in evolution of more complex multivariate expression. GP initially generates a stochastic population of trees, computes fitness scores and randomly selects trees for comparison. The lead scoring trees are selected and one of the genetic operators (reproduction, mutation, crossover) is randomly applied to carry them forward to next generation. The process repeats until user-defined conditions are met. The run-time parameters like initial population size, tree depth, tournament size for competing trees, number of generations, and termination criterion can be tuned for better algorithmic performance.

The unique aspect of GP algorithm used here is the transparency of its internal workings. Unlike many black box ML algorithms, the evolutionary process can be reviewed at each step which might be quite important to many researchers. [2]

For our analysis, we used an open source python code, Karoo GP [5]. Karoo GP package is scalable, with multicore and GPU support enabled by the TensorFlow library and has capacity to work with very large datasets. The latest version of Karoo GP can be found in PyPI [6].

### B. Methodology

After the dataset creation ...

The end of each Karoo GP training produces a multivariate expression with highest fitness score. We repeat the training process 200 times to get 200 expressions for each label (hasNS and hasRemnant). Due to the stochastic nature of the GP algorithm, the expressions mostly tend to be unique depending upon the complexity of the classification problem. Each expression can then be used to classify the reconstructed source parameters to determine the labels hasNS and hasRemnant by substituting the values in the expression. If the result is greater or equal to zero, we classify the reconstructed set of parameter as true and false otherwise. The performance of each of the expressions against the testing set for one EoS is shown in Fig 1. As seen in the plots, the average performance of hasRemnant expressions is better than hasNS expressions. Also the winning expressions are more dispersed in case of hasRemnant. **Shall we explain the reasons: hasNS being simpler classification but contaminated by poor reconstructions by the pipeline. HasRemnant is more complex leading to more variable winning trees.** **Calculation of Probability:** Using testing set, we compute probabilities using bayesian method. HasNS and hasRemnant are not inherently independent quantities since there can be no hasRemnant without hasNS. Hence, we utilize both hasNS winning expressions and hasRemnant winning expressions for quantifying probabilities  $p(hasNS)$  and  $p(hasRemnant)$ . If XREM denotes the number of hasRemnant winning trees which classifies given set of parameter as true and XNS denotes the number of hasNS winning trees which classifies as true, we compute the probability on the testing set as:

$$p(HasNS|XREM \cap XNS) = \frac{p(XREM \cap XNS|HasNS).p(HasNS)}{p(XREM \cap XNS)} \quad (1)$$

$$p(HasRemnant|XREM \cap XNS) = \frac{p(XREM \cap XNS|HasRemnant).p(HasRemnant)}{p(XREM \cap XNS)} \quad (2)$$

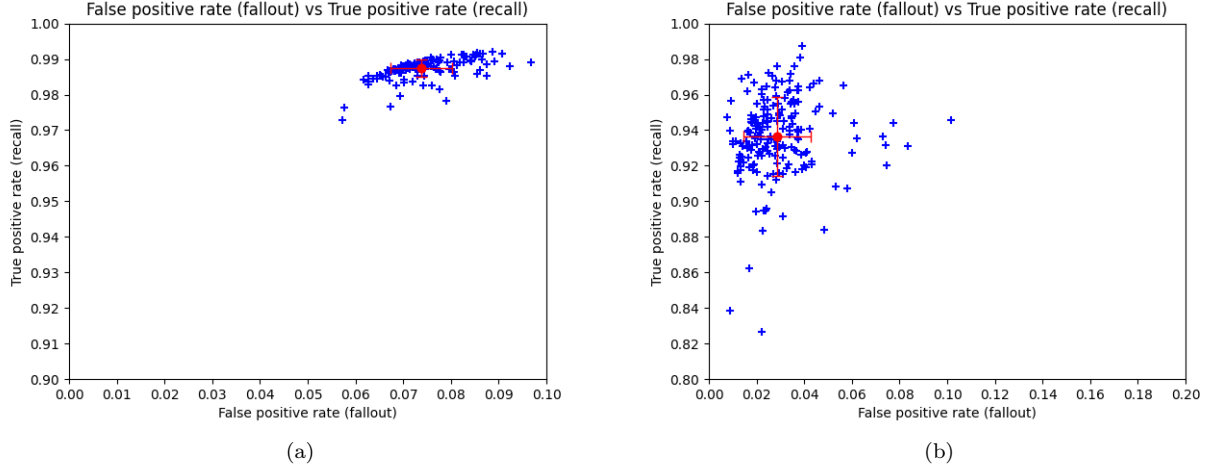


FIG. 1: The plot on the left is a FPR (False Positive Rate) vs (True Positive Rate) plot for all 200 winning expressions for hasNS classification on MS1-PP EoS. The red dot is the average of TPR and FPR of the expressions and the vertical and horizontal spread are the one sigma values for TPR and FPR respectively. The plot on the right is similar but for hasRemnant classification.

There are some caveats to this calculation. Given a finite testing set, we cannot fully compute the entire parameter space ( $201 \times 201$  cases) of the probability since there are some cases which are highly unlikely to occur, like  $p(\text{hasNS} | XNS = 0 \cap XREM = 200)$ . Also, our probability computations might also suffer due to the finite testing set size. The resulting probability distribution is highly rugged and **discontinuous or incomplete**. Hence, in order to span the entire parameter space of the probability, we use Gaussian process regression (GPR).

**Gaussian Process Regression:** We implement GPR using a python package gpytorch [1]. Using the Rational Quadratic(RQ) kernel of the gpytorch, we compute a smooth probability distribution over all possible combination of XREM and XNS as shown in Fig 2. The selection of the parameters for GPR was motivated by two major factors. The first being that probability had to be confined between interval  $[0,1]$  and the case  $P(\text{hasNS})$  or  $P(\text{hasRemnant})$  1 when XNS and XREM approaches maximum number of trees. The second being the condition  $p(\text{hasNS} | XREM \cap XNS) \geq p(\text{hasRemnant} | XREM \cap XNS)$ . After multiple trials, we found that using 200 winning expression and using length scale interval  $[1 \times 10^{-5}, 1 \times 10^5]$  and alpha parameter interval  $[1 \times 10^{-5}, 10]$  for GPR, we can obtain desired probability distribution.

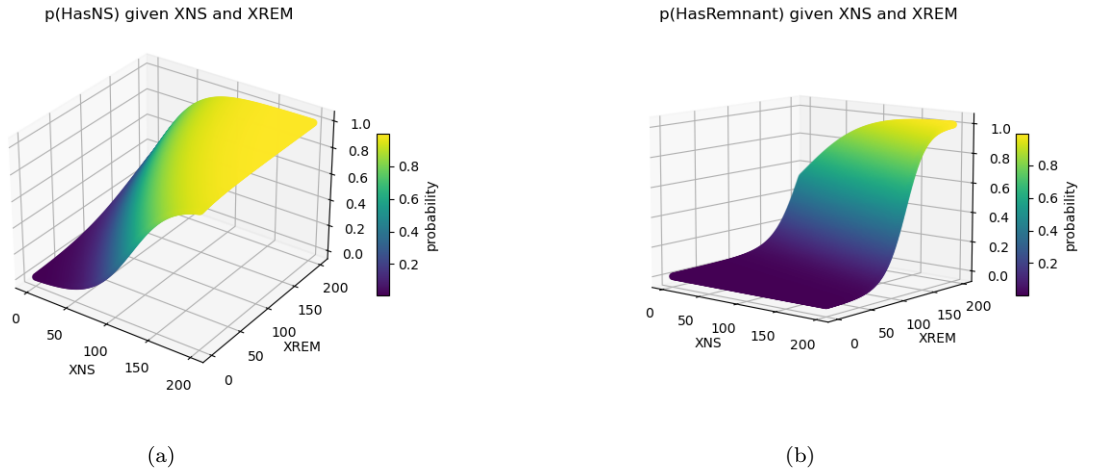


FIG. 2: The plot on the left is the probability distribution of equation 1 after GPR implementation for MS1-PP EoS. The plot on the right is a similar plot of equation 2

Using this probability, we make the ROC curve using the testing set for all the EoS as shown in 3.

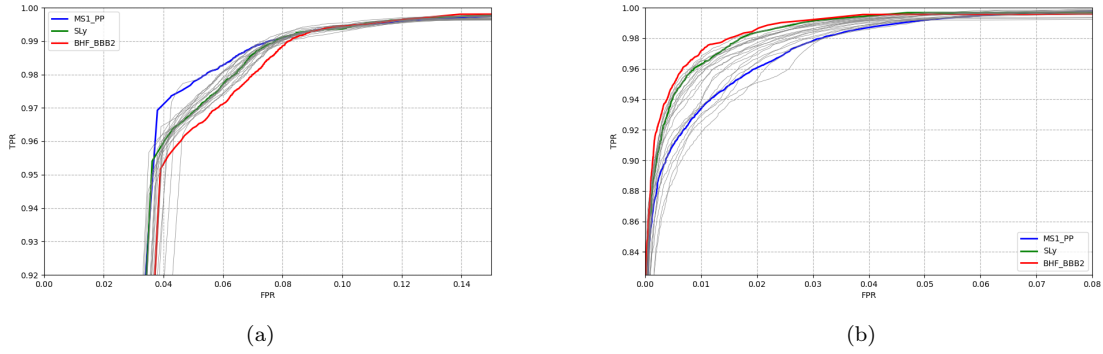


FIG. 3: The plot on the left is the ROC curve for hasHS label evaluated on the testing set whereas the plot in the right is for hasRemnant for all 23 EoS.

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- [1] Gpytorch. <https://gpytorch.ai/>.
  - [2] M. Cavaglià, S. Gaudio, T. Hansen, K. Staats, M. Szczepańczyk, and M. Zanolin. Improving the background of gravitational-wave searches for core collapse supernovae: a machine learning approach. *Machine Learning: Science and Technology*, 1(1):015005, feb 2020.
  - [3] J. Koza and J. Rice. *Genetic Programming: On the Programming of Computers by Means of Natural Selection*. A Bradford book. Bradford, 1992.
  - [4] R. Poli, W. B. Langdon, and N. F. McPhee. *A Field Guide to Genetic Programming*. Egham, UK: Lulu Enterprises, Mar 2008.
  - [5] K. Staats. Karoo gp. [https://github.com/kstaats/karoo\\_gp](https://github.com/kstaats/karoo_gp).
  - [6] K. Staats. Karoo-gp-pypi. <https://pypi.org/project/karoo-gp/>.
  - [7] K. Staats. Genetic programming applied to rfi mitigation in radio astronomy. Master’s thesis, 2016.