Applications of Machine Learning to Detecting Fast Neutrino Flavor Instabilities

Focus workshop on collective oscillations and chiral transport of neutrinos
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Sajad Abbar
Max Planck Institut für Physik (MPP)

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

SFB 1258 Neutrinos Dark Matter Messengers

Neutrino Oscillations in Dense Media

- Neutrino evolution in dense neutrino media is very different from the one in vacuum and matter

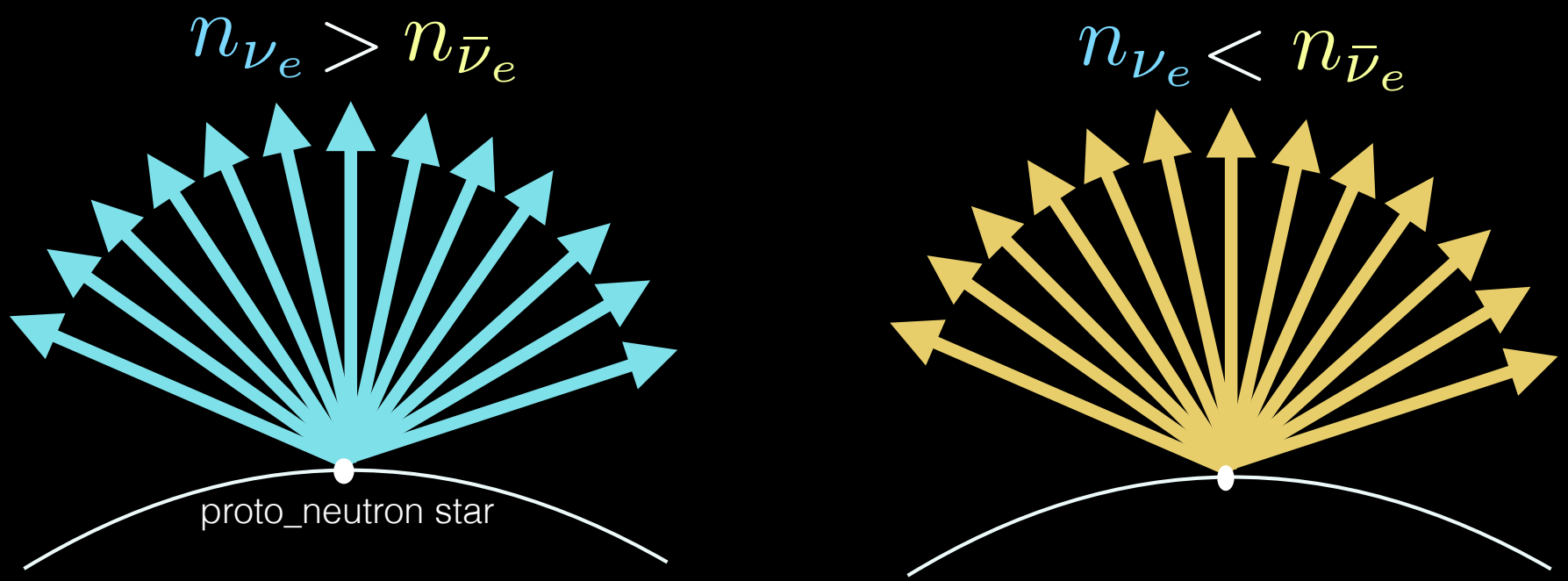
$$i(\partial_t + \mathbf{v}\cdot\nabla)\rho = [H, \rho]$$

$$H = \frac{1}{2}\begin{bmatrix} -\omega\cos 2\theta + \sqrt{2}G_{\rm F}n_e & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta - \sqrt{2}G_{\rm F}n_e \end{bmatrix} + H_{\nu\nu}$$

$$\sqrt{2}G_{\rm F}\int \underbrace{d^3q}_{\text{coupling}}(1-\mathbf{v_P}\cdot\mathbf{v_q})(\underbrace{\rho_\nu - \rho_{\bar\nu}}_{\text{nonlinearity}})$$

Fast Flavor Conversions

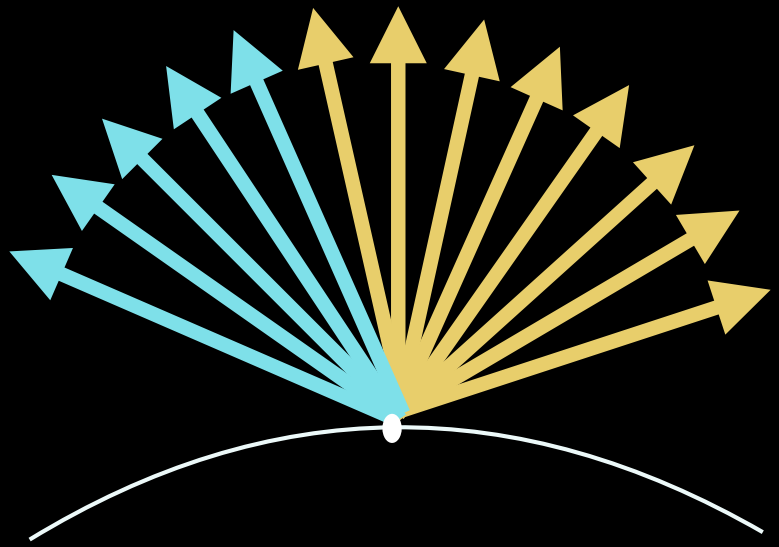
- In our traditional understanding, we assumed that neutrinos are emitted isotropically from the surface of the neutrino source
- $f_{\nu_e}(\theta) - f_{\bar{\nu}_e}(\theta)$ is either always positive or negative



- This implies that the scales on which flavor conversion could occur are determined by vacuum frequency $\Delta m^2/2E \sim 1\ \mathrm{km}^{-1}$

Fast Flavor Conversions

- FFC could occur when there is crossing in $f_{\nu_e}(\theta) - f_{\bar{\nu}_e}(\theta)$



- Scales on which flavor conversion can occur is now proportional to n_ν and could be < 10 cm

- Neutrino oscillations can now occur at densities that had been long thought to be the realm of collisional and scattering processes

Fast Flavor Conversions

- The angular distributions are not available, instead we have only access to their moments

$$I_n = \int \mathrm{d}\cos\theta_\nu \;\; \cos^n\theta_\nu \;\; f_\nu(\cos\theta_\nu)$$

- In M1 closure scheme only the evolution of zeroth and first moments are followed directly
- We can still make progress! Dasgupta+2018; Abbar2020; Johns+2021; Richers2022;
- But these methods are normally inefficient and very slow
- FFC can not be detected on the fly

Application of Machine Learning

- Question: Given I_0 and I_1, do ELN crossings exist?

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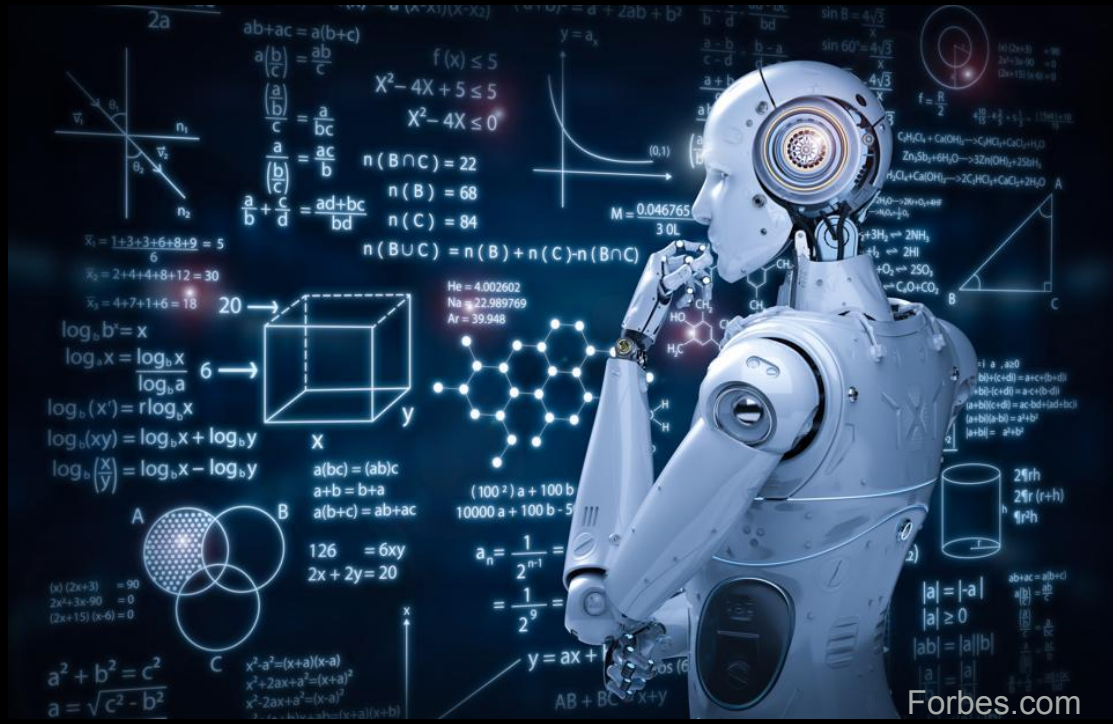
- Machine learning can help us
- We have four feature here: I_0 and I_1 for neutrinos and antineitrnonos



Application of Machine Learning

- For training, we use analytical maximum-entropy and gaussian distributions

$$f_\nu(\cos\theta_\nu) = \exp(-\eta + a\cos\theta_\nu)$$

$$f_\nu(\cos\theta_\nu) = \exp[-a(1-\cos\theta_\nu)^2 + b]$$

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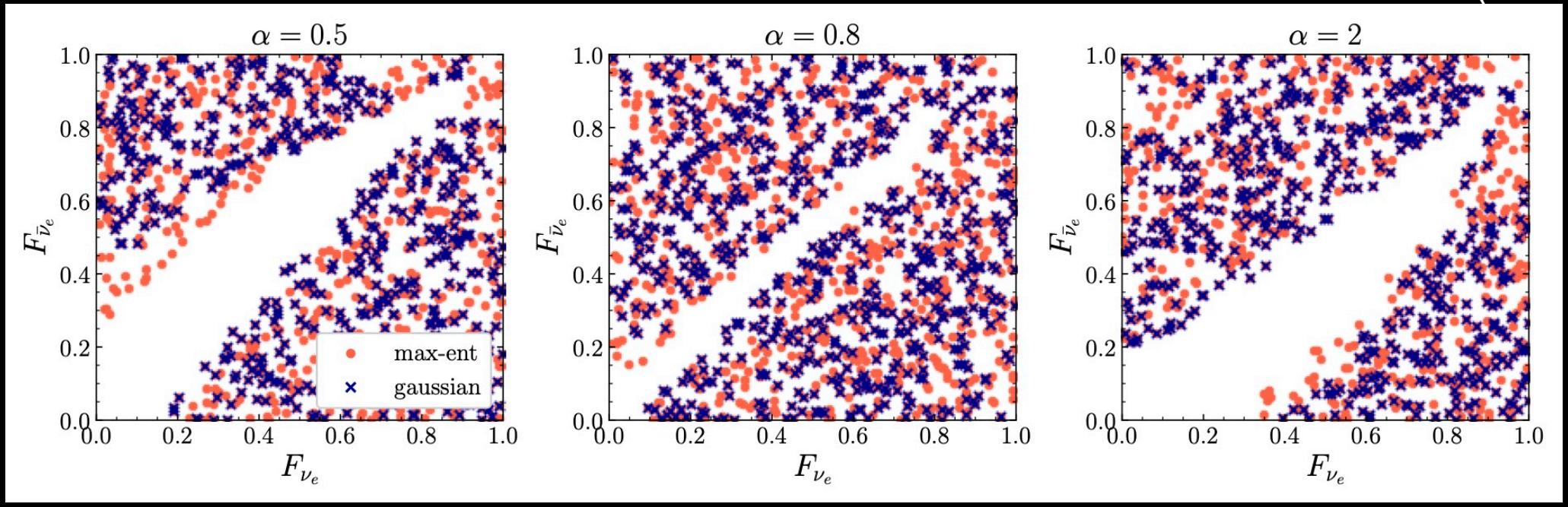
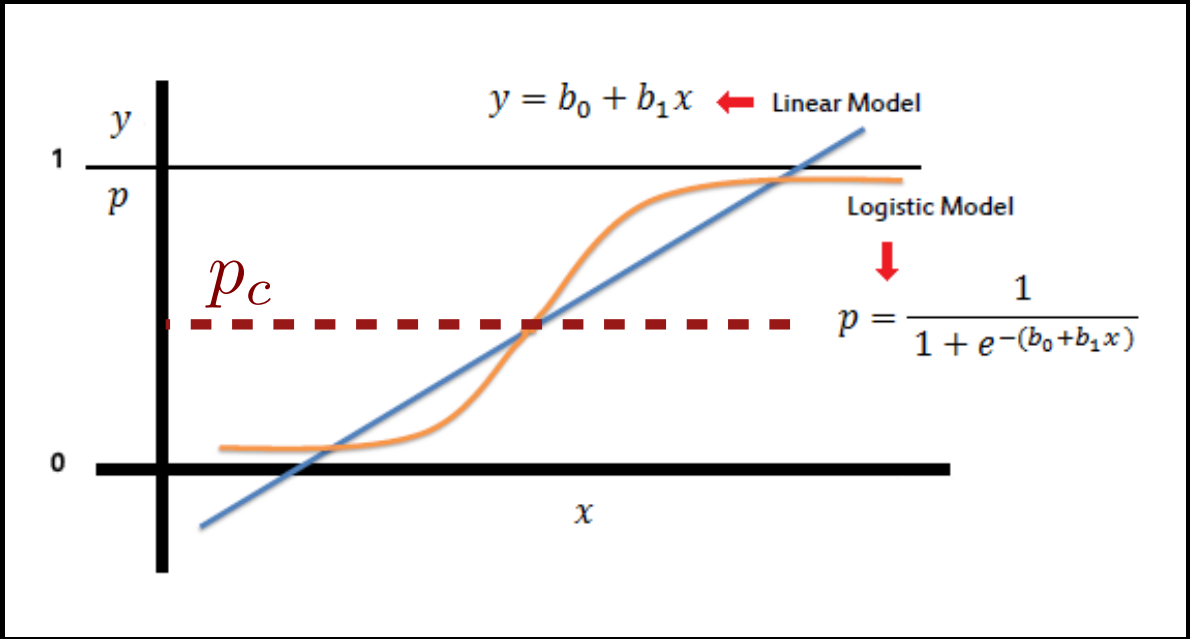


Logistic Regression

- Based on finding a line that separates the data points, in which a logistic function is applied on the top of the linear one so that one can decide on the basis of some final values which are in (0,1)



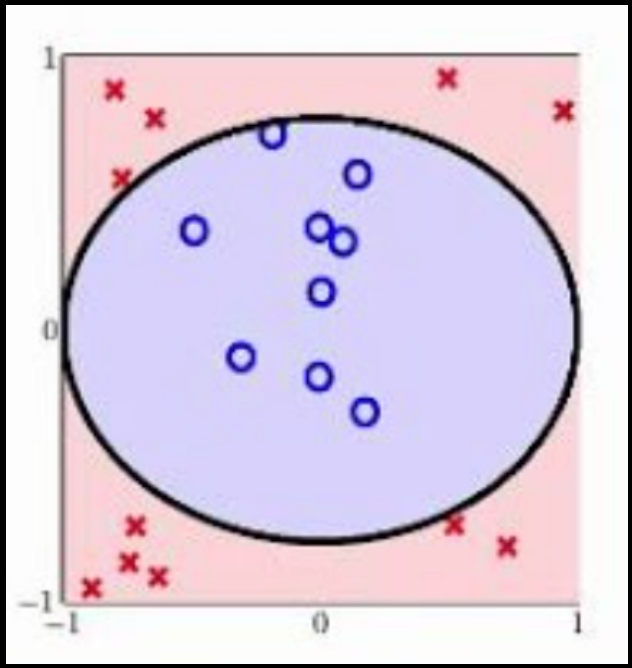
http://www.elusives.eu

Figure from Wikipedia

Logistic Regression

- one should first make non-linear transformations

$$x, y \rightarrow x, y, x^2, y^2$$



Abu Mostafa

Figure from Wikipedia

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- In our problem, maximum accuracy is reached for n = 9

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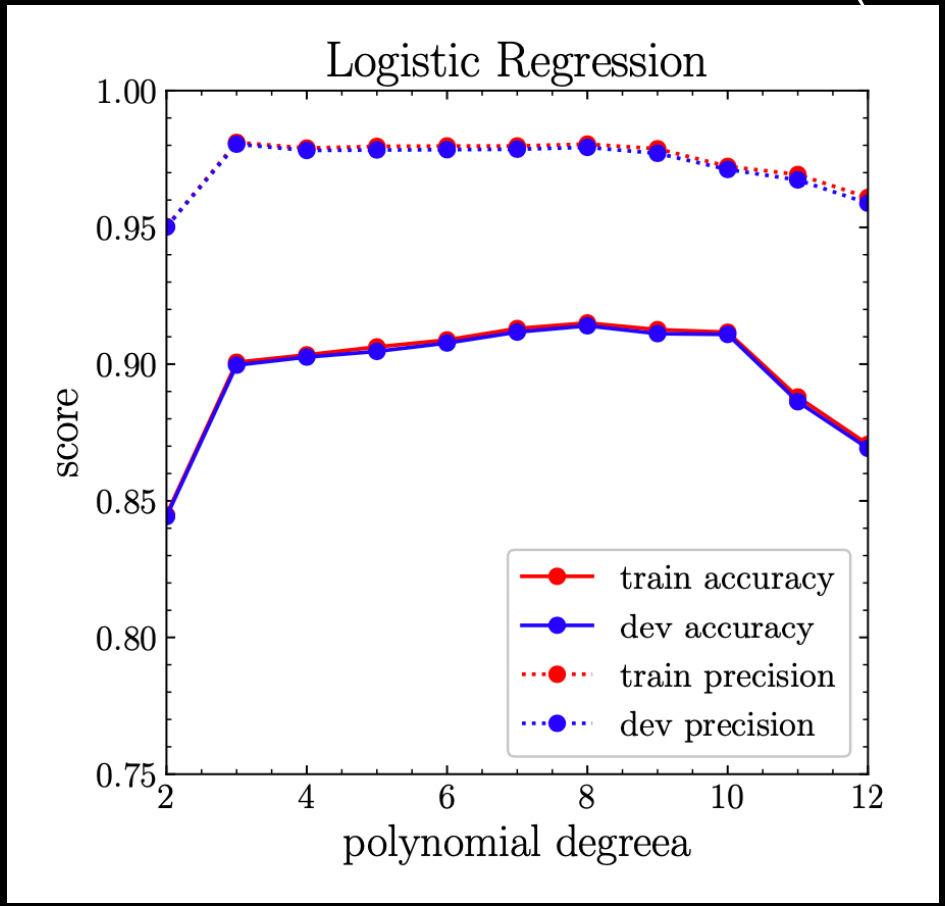
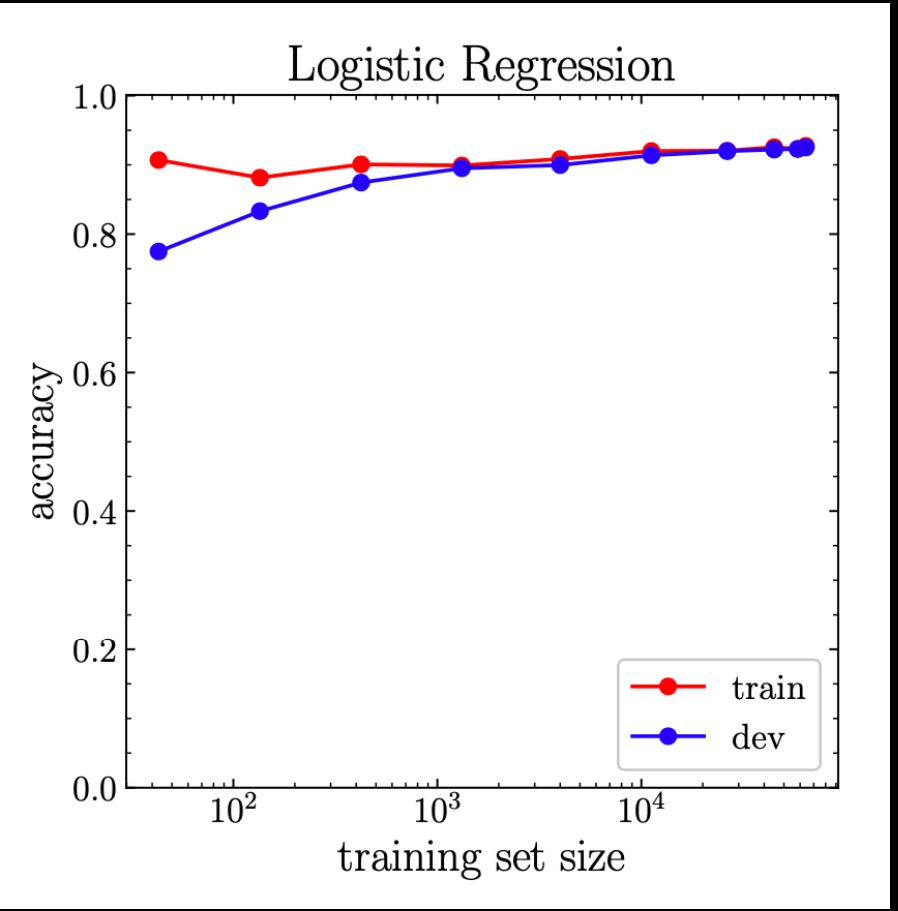


Logistic Regression

- In order to overcome the overfitting, one needs at least a few thousand points



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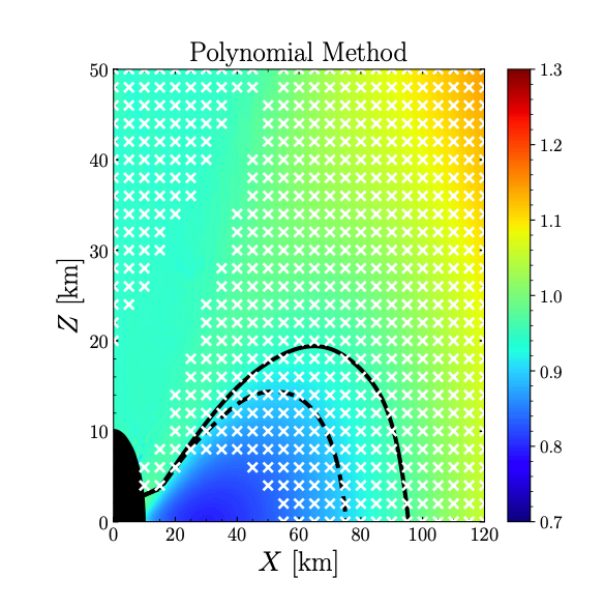
Logistic Regression

- LR performs well on NSM remnant simulation data



Just+2022

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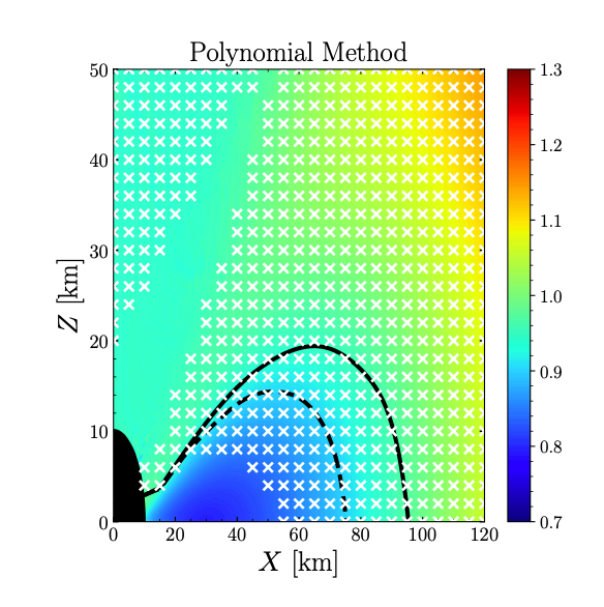
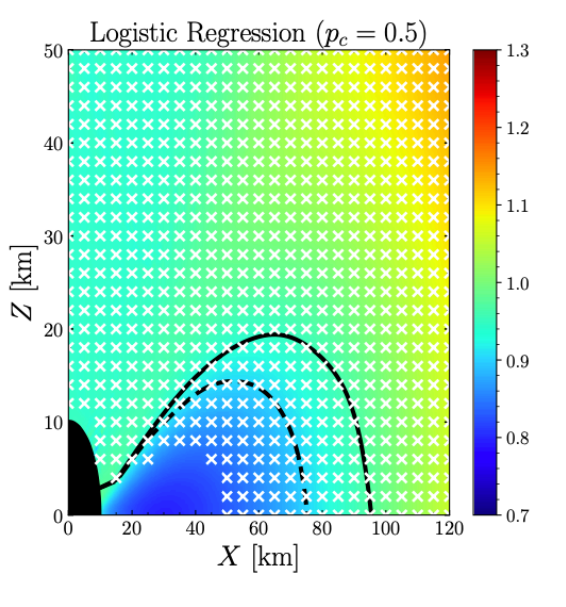


Just+ (2022)



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- Another justification for using parametric angular distributions

Logistic Regression

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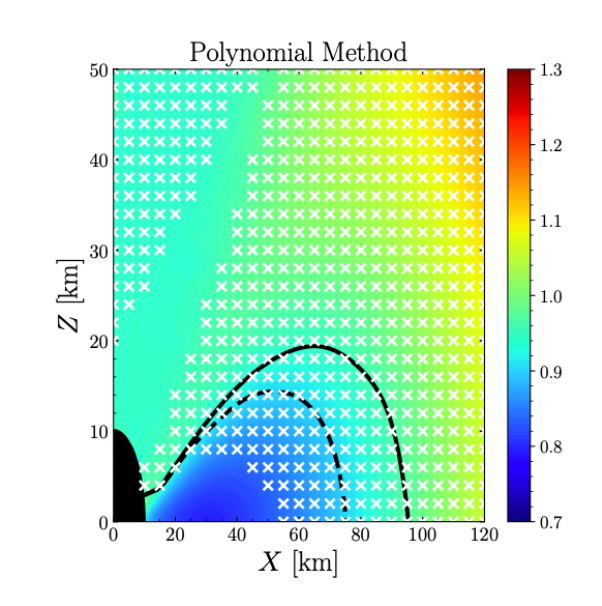
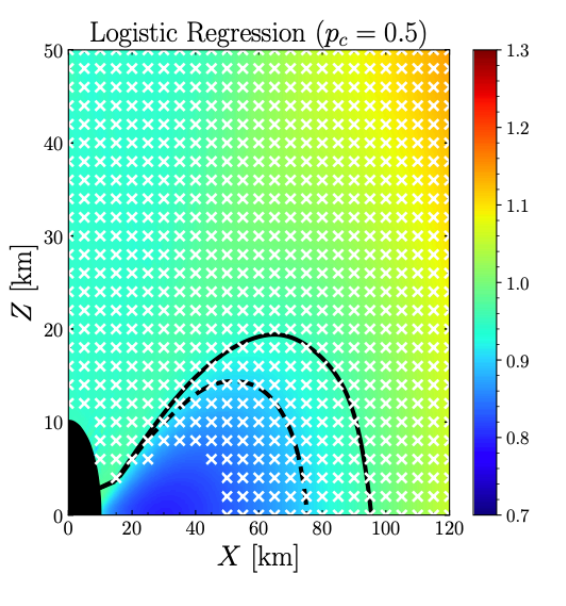
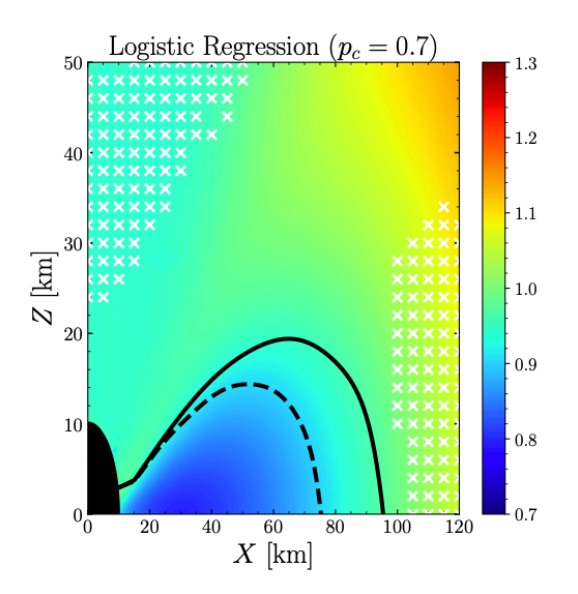
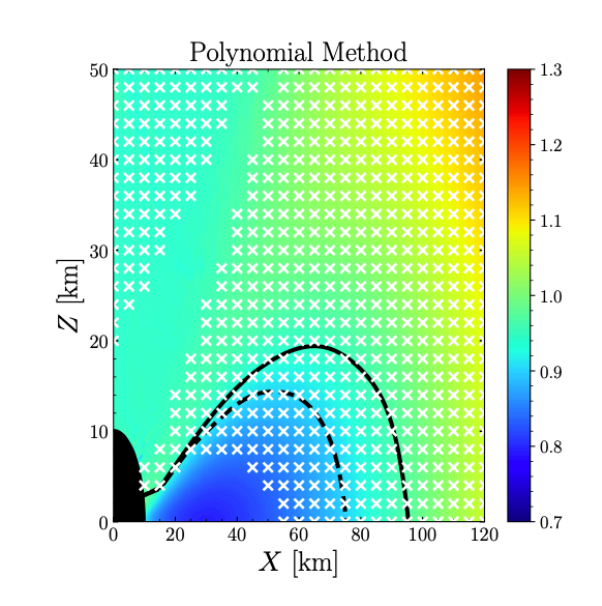


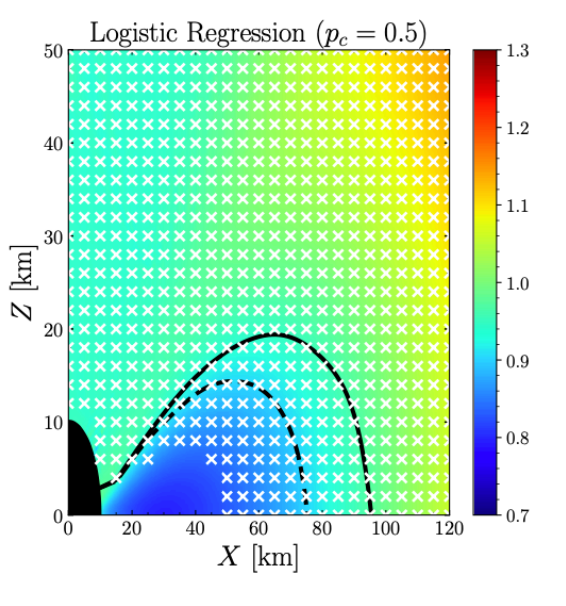


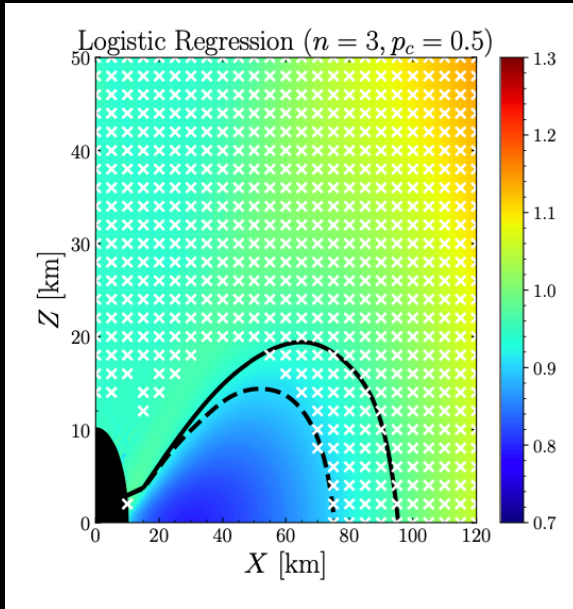


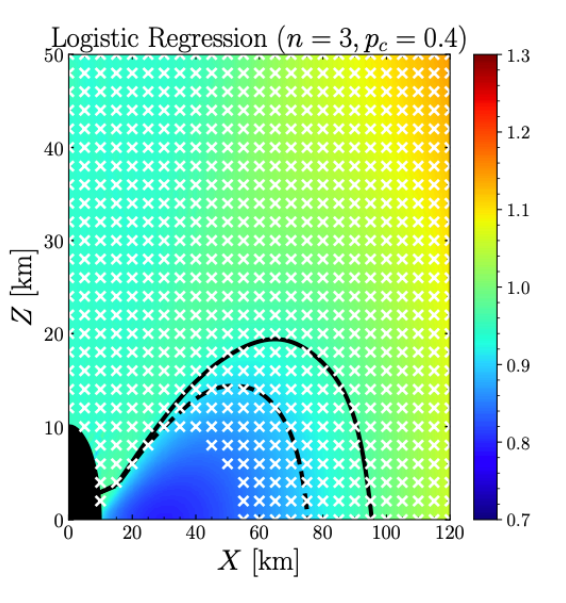
Logistic Regression

- Calculations with n = 3 also perform relatively well









Application of Machine Learning

- All our ML algorithms can reach good accuracies

Logistic Regression (93%)			
	precision	recall	F_1-score
no crossing	83%	93%	88%
crossing	97%	93%	95%
KNN (n=3) (95%)			
	precision	recall	F_1-score
no crossing	90%	90%	90%
crossing	96%	96%	96%
SVM (95%)			
	precision	recall	F_1-score
no crossing	92%	90%	91%
crossing	96%	97%	97%
Decision tree (94%)			
	precision	recall	F_1-score
no crossing	89%	88%	89%
crossing	96%	96%	96%

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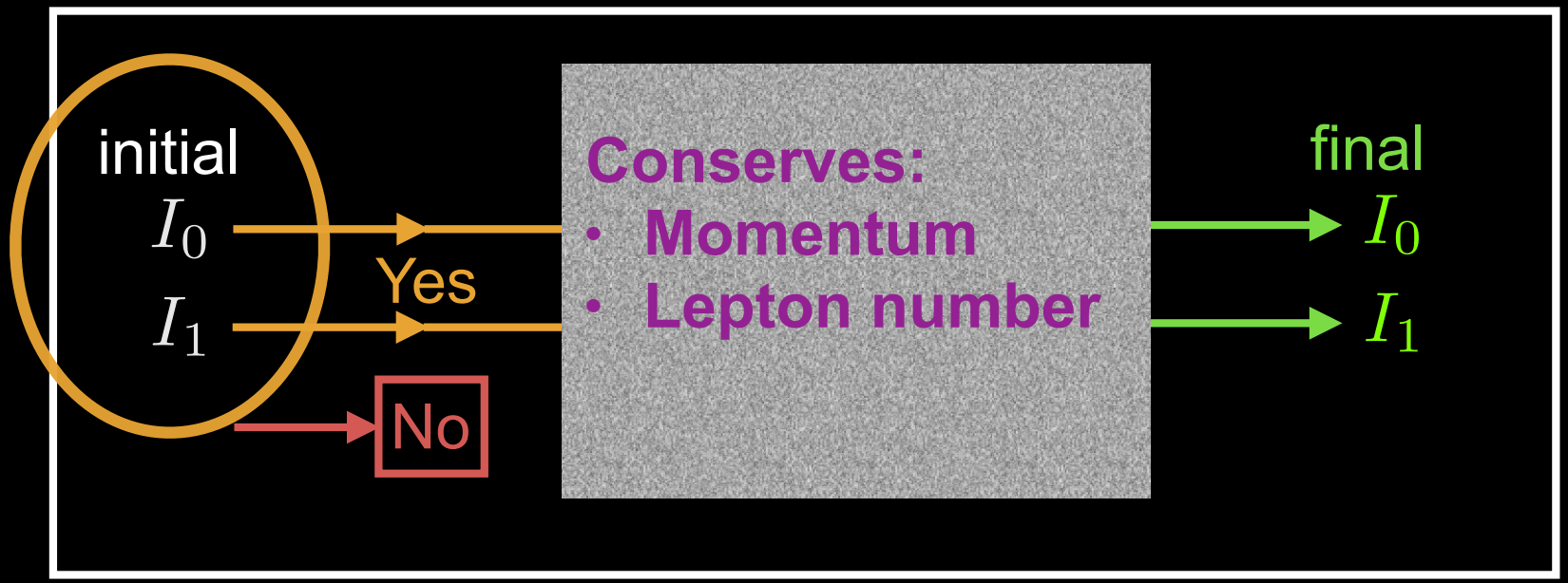
Future Directions

- Improve the ML algorithms with more realistic data
- Three-flavor effects: muon creation
- Machine learning methods prove to be very promising regarding the detection of FFI

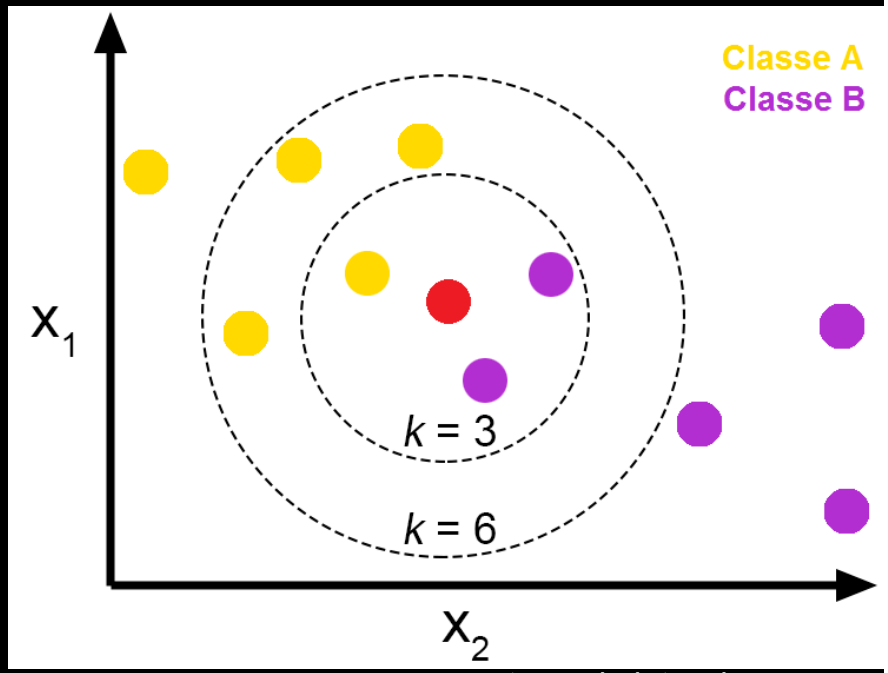


Summary

- Machine learning is fascinating!

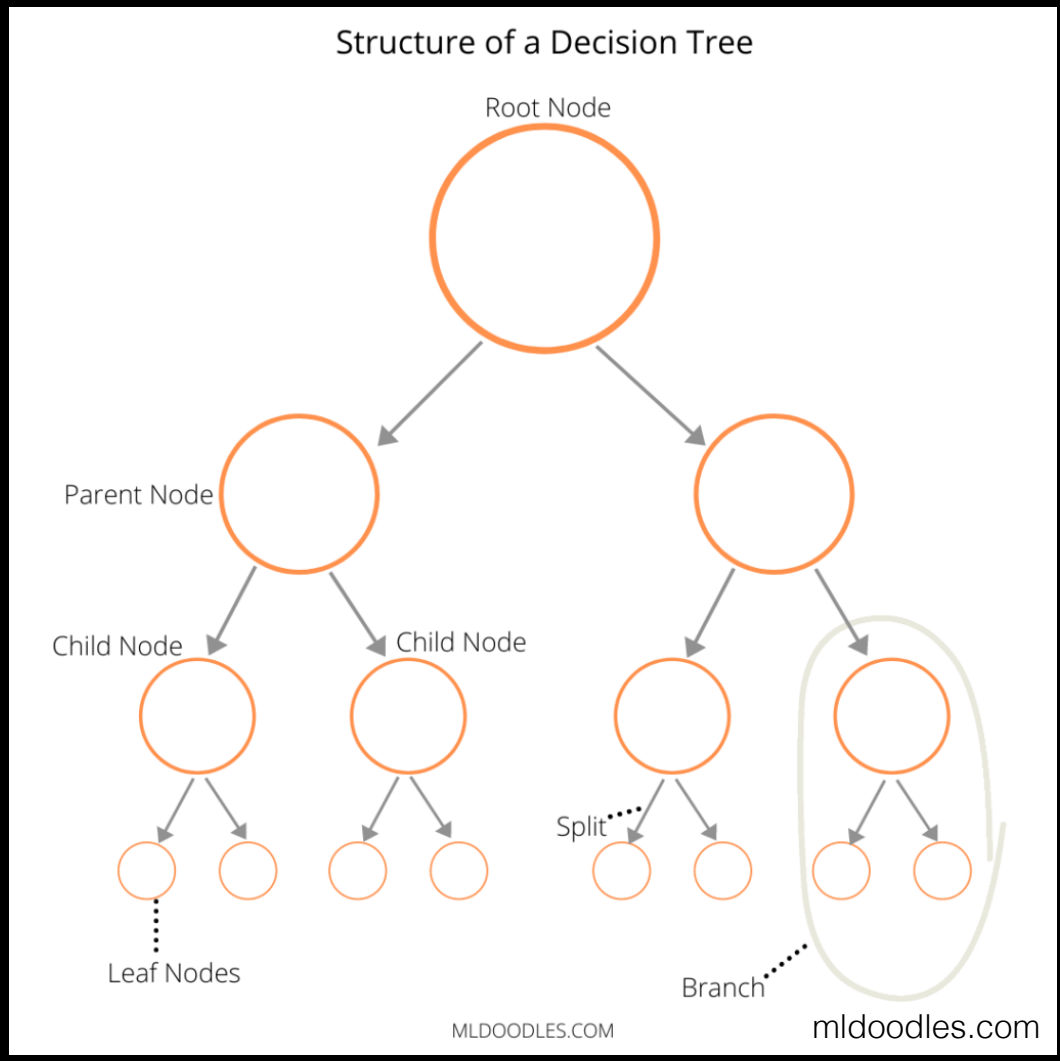
KNN

- KNN is one of the simplest forms of machine learning algorithms mostly used for classification. It **classifies the data point on how its neighbor is classified**.



Decision Tree

- In decision tree, one makes decision using a tree-like structure. At each node, one of the features is selected and the branching occurs.



SVM

- Support Vector Machine is a classification based on finding a line that classifies the data points, maximises the margins

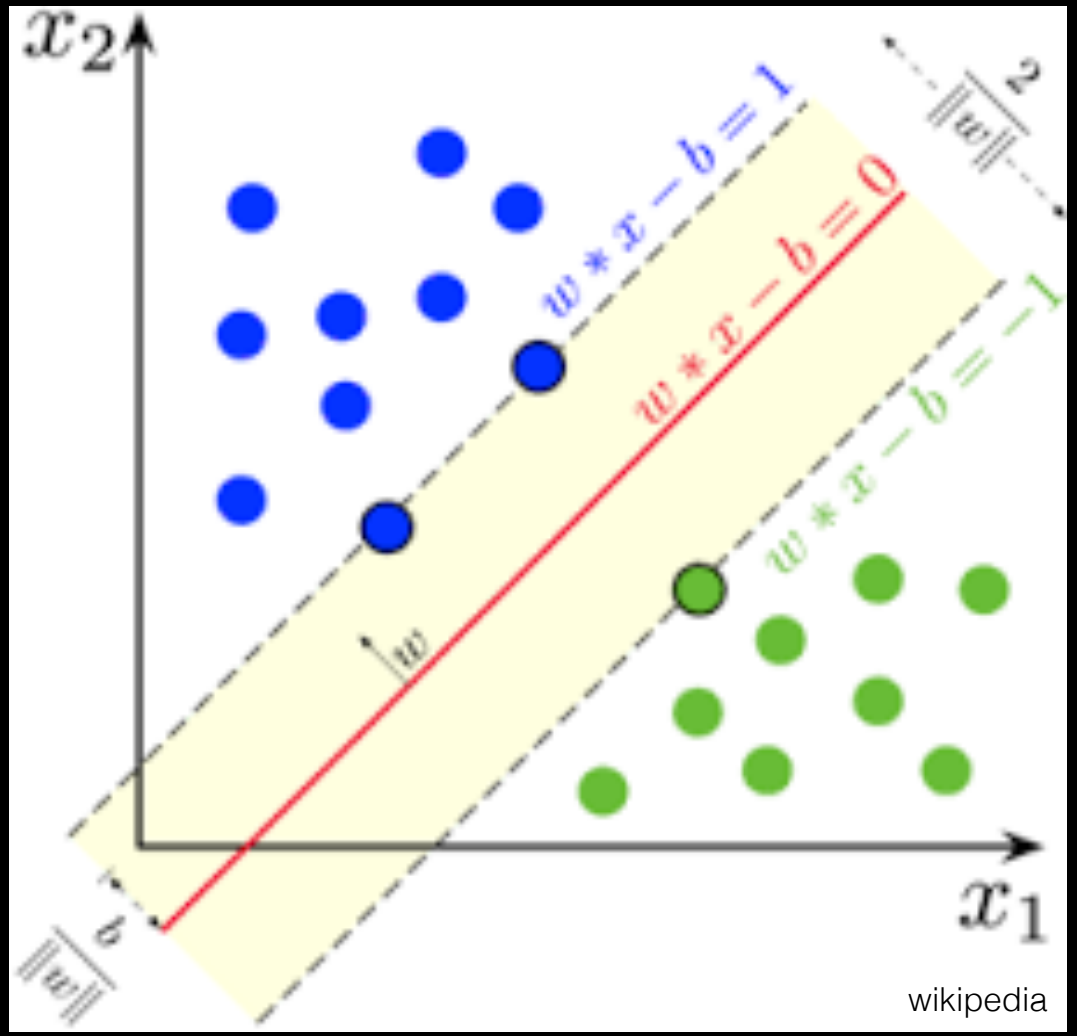


Figure from wikipedia