Collective Neutrino Oscillations in Supernovae and Neutron Star Mergers Workshop
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Supernova Neutrinos on Quantum Computers

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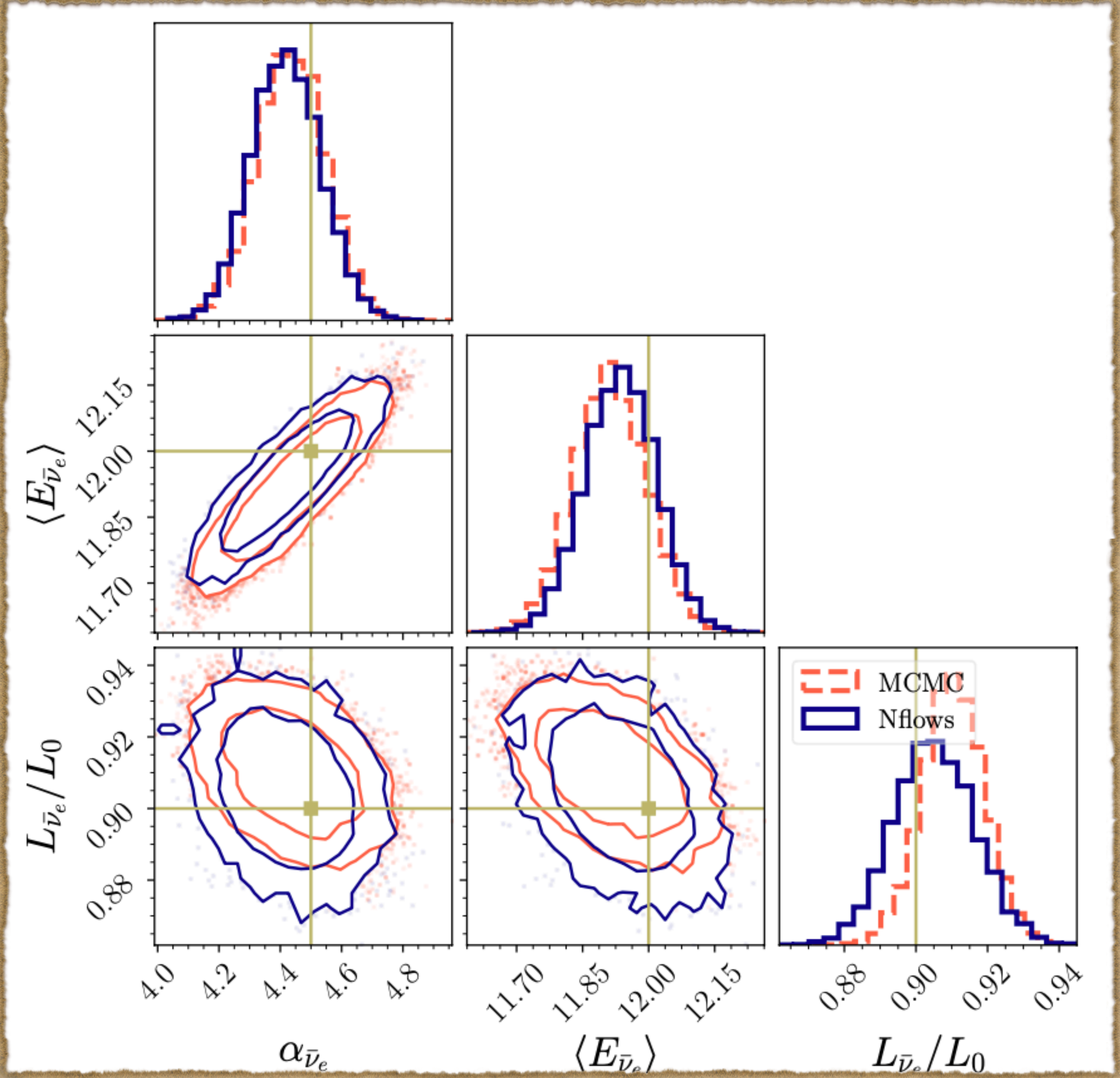
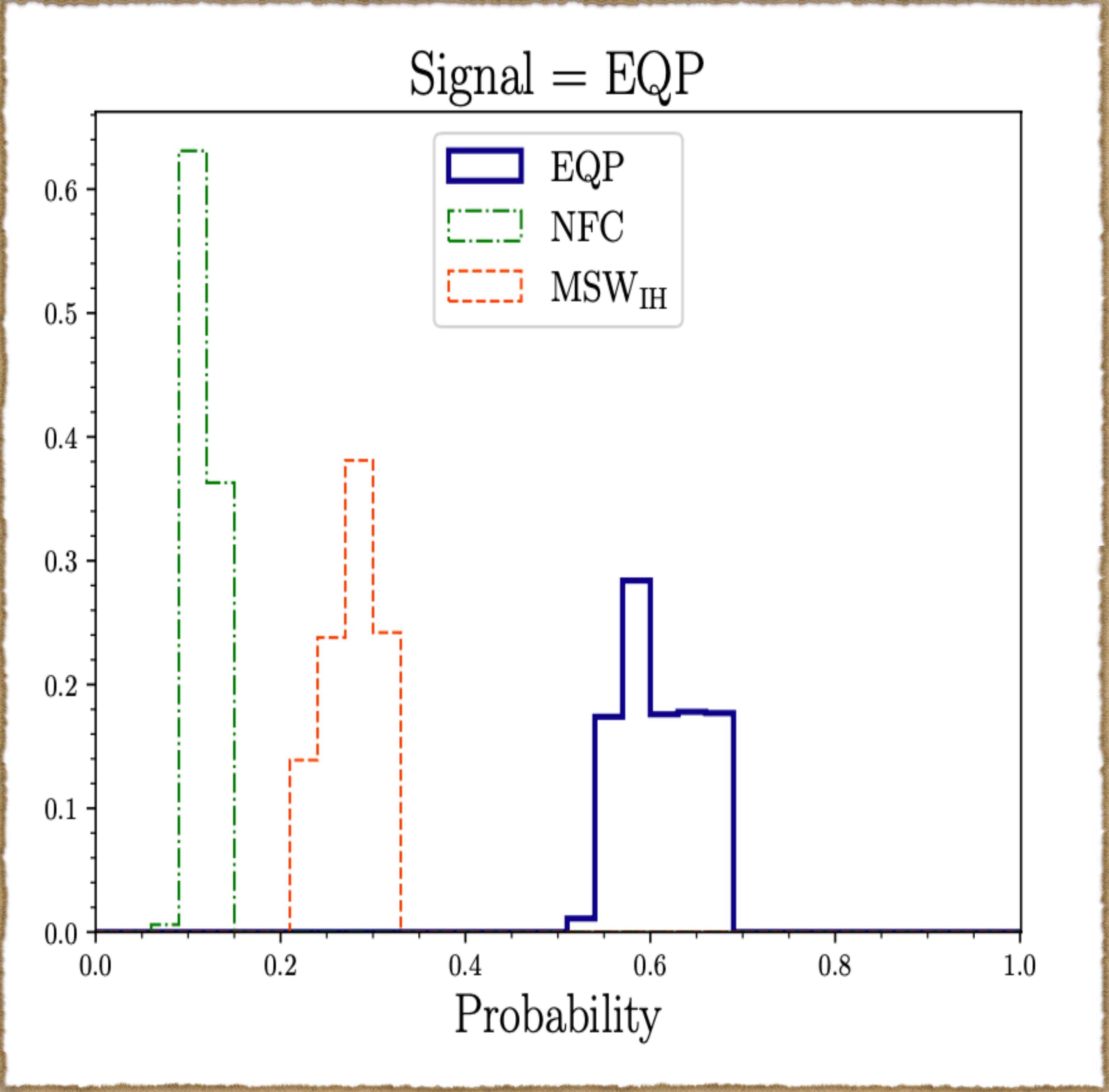
Generative AI for Supernova Neutrinos





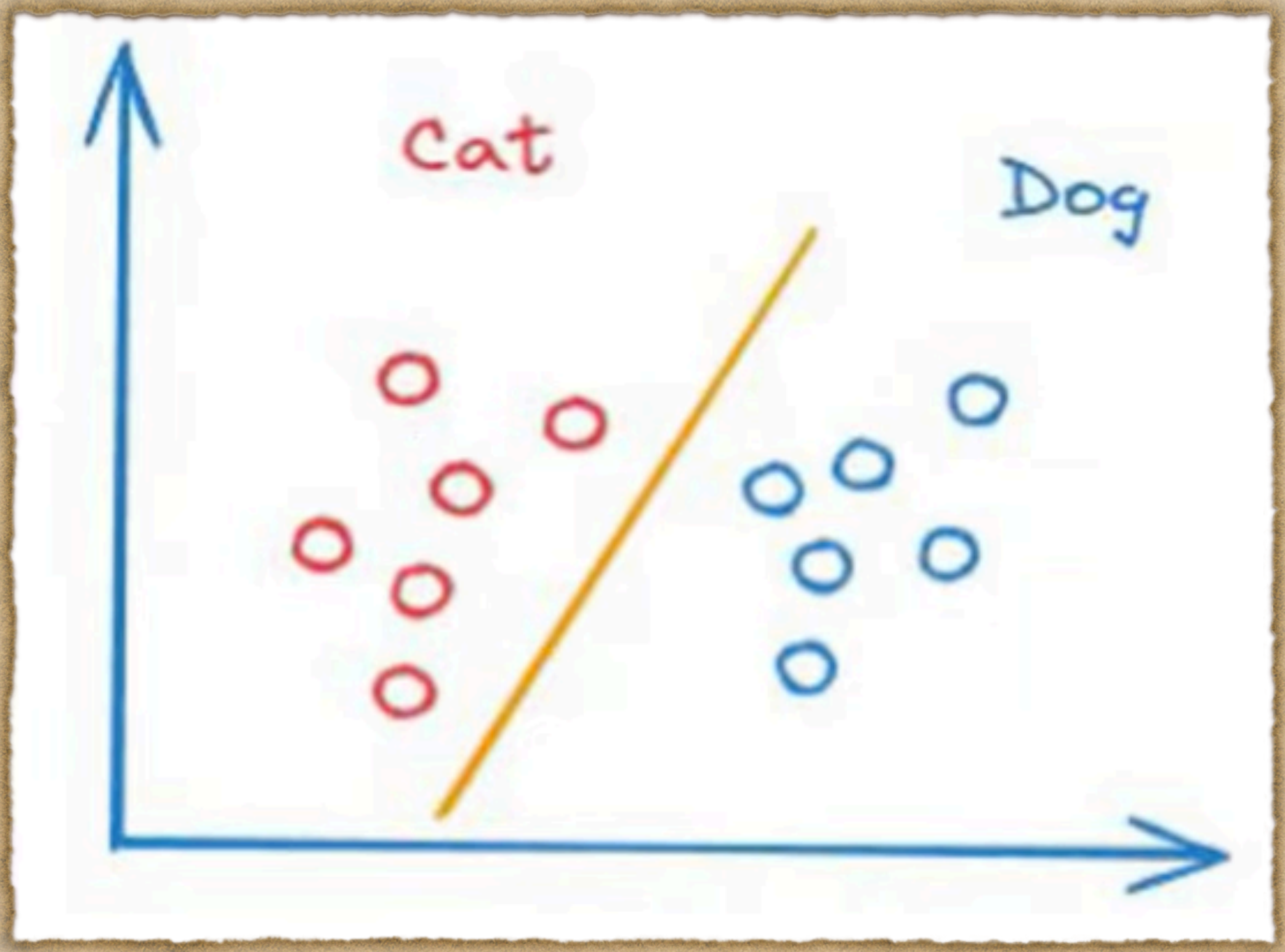
Ana Roshan (Master)

Abbar, to be submitted

Generative AI

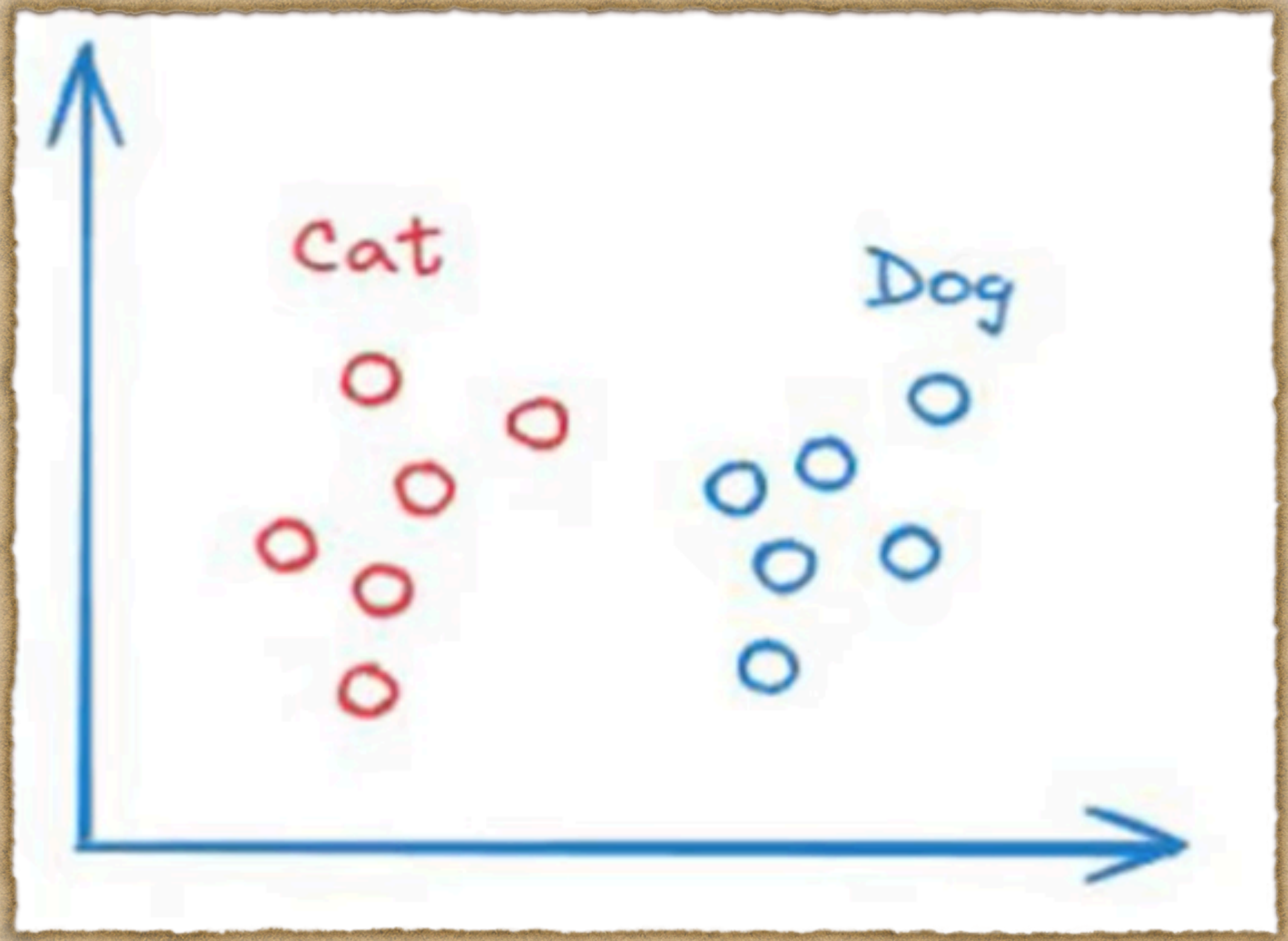
- **Generative AI** creates synthetic but realistic outputs!
- In Generative AI, we try to model a probability distribution.

Discriminative AI



P(y|x)

Generative AI

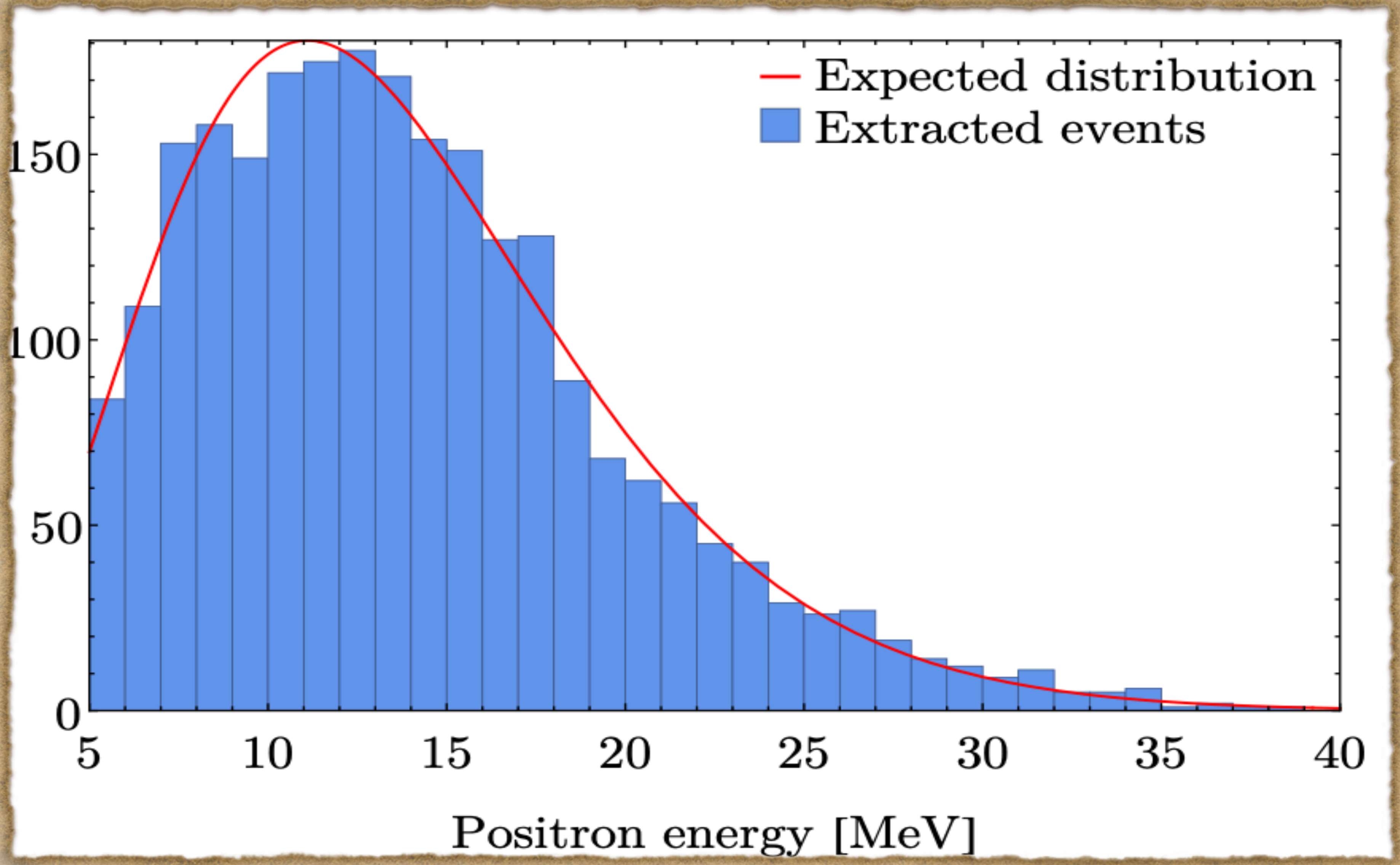


P(x)

Supernovae Neutrino Spectra

Based on Hudepohl et al. 2010

- Nontrivial: what are the spectral parameters given the event distribution at the detector?
- Mathematically speaking, we want to calculate P(parameters)
- Traditionally one would use MCMC
- AI has transformed this field: Generative AI

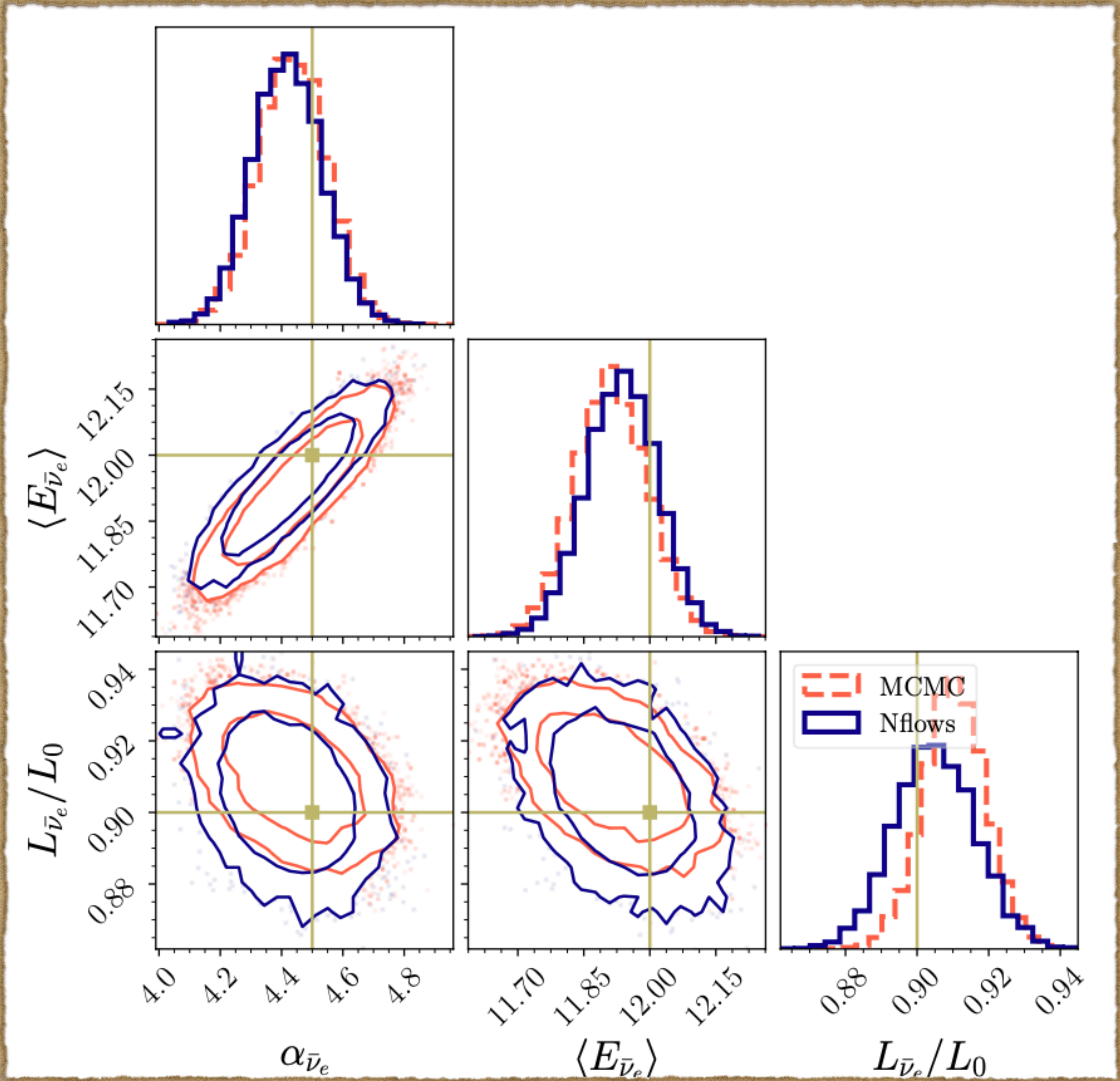


Rosso et al. 2018

Generative AI for SN neutrinos

Abbar, to be submitted

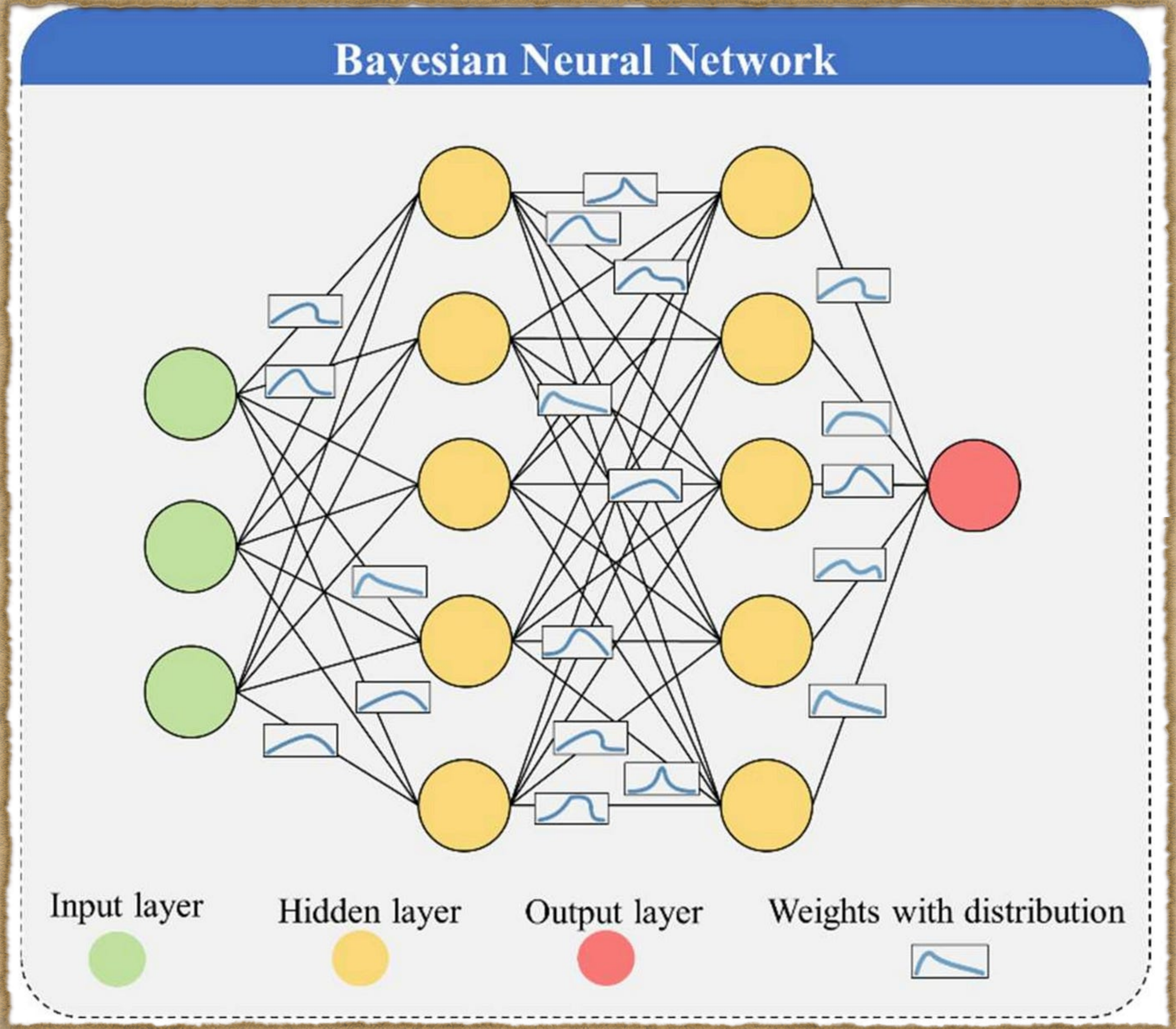
- We used generative AI for measuring spectral parameters, assuming IBD channel at SK.

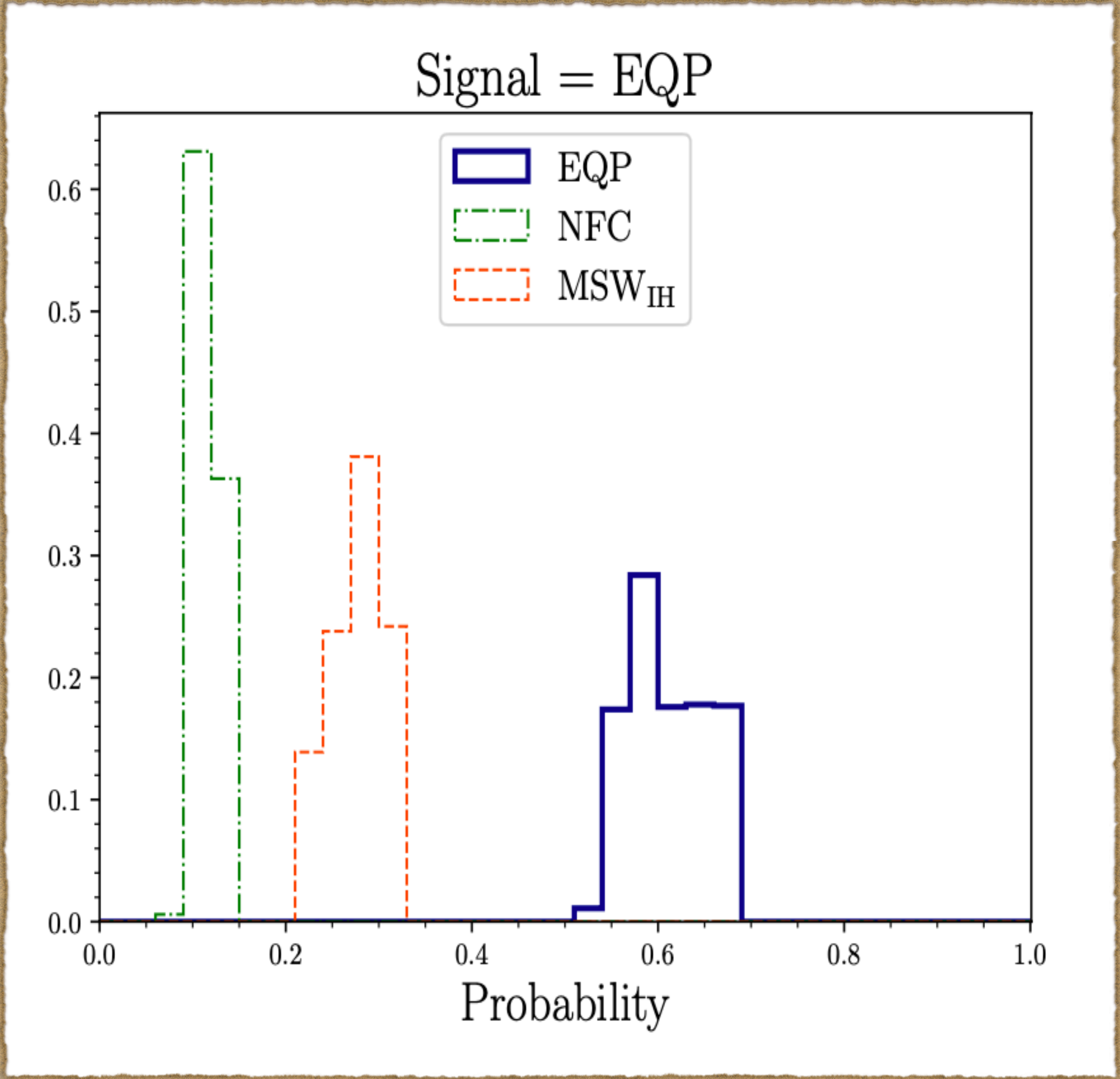


Generative AI for SN neutrinos

Abbar, to be submitted

- We also Bayesian neural networks to classify neutrino flavor conversion scenarios.





Impact of Neutrino Flavor Conversion in Supernovae

- In the mean-field approximation:

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

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

$$\sqrt{2}G_{\mathrm{F}}\int d^3q(1-\mathbf{v_p}\cdot\mathbf{v_q})(\rho_\nu - \rho_{\bar{\nu}})$$

- It can be modelled exactly within the full many-body picture.

$$H = H^\nu + H^{\nu\nu} = \sum_i \mathbf{b}\cdot\boldsymbol{\sigma}^{(i)} + \frac{1}{N}\sum_{i<j} J_{ij}\boldsymbol{\sigma}^{(i)}\cdot\boldsymbol{\sigma}^{(j)},$$

$$J_{ij} = \sqrt{2}G_F\rho_\nu(1-\cos\theta_{ij}),$$

$$\mathbf{b} = \frac{\Delta m^2}{4E}[\sin(2\theta_v), 0, -\cos(2\theta_v)],$$

Trotter error

$$e^{A+B} \neq e^A e^B$$

- This is exactly where **quantum computers** can help!

Collective Neutrino Oscillations on Quantum Computers

Hall et. Al; PRD (2021)

Aydeniz et. al.; Quantum Information Processing (2022)

Siwach et. al.; PRD (2023)

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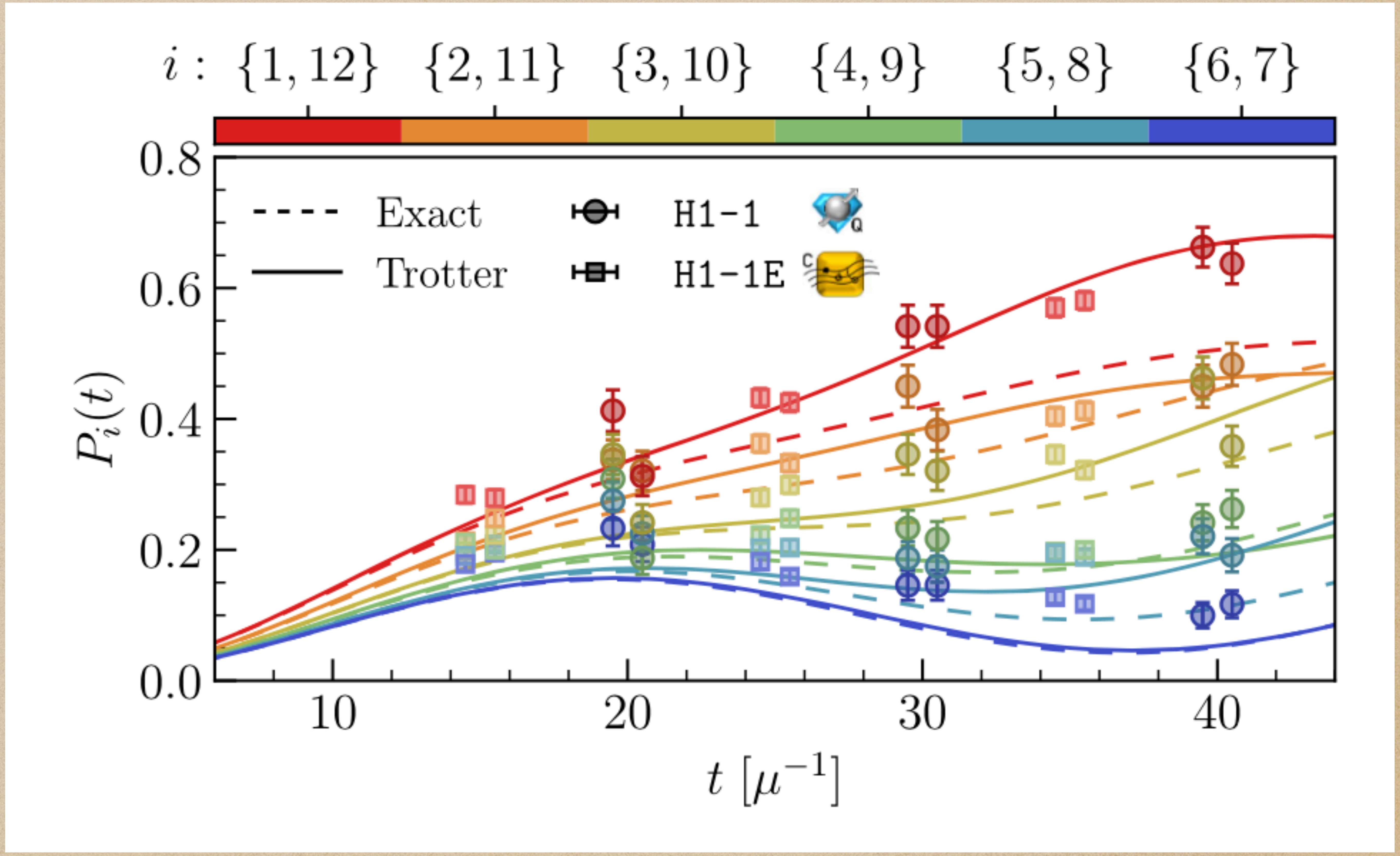

Marc Illa and Martin J. Savage; PRL (2023)

Hybrid Quantum-Classical Approach

- We choose a trial wavefunction:

$$|\Psi(\vec{\theta}(t))\rangle$$

- McLachlan's EoM:

$$\mathrm{M}(\vec{\theta})\ \dot{\vec{\theta}} = \mathrm{V}(\vec{\theta})$$

- M and V components can be calculated on QC, then $\dot{\vec{\theta}}$ can be solved on HPC devices.

- Hybrid methods can help with the circuit depth and propagating error!

Collective Neutrino Oscillations on Quantum Computers

- Our projects have been selected for the pilot phase of two of Europe’s most advanced quantum computing systems at the LRZ.

  - **Euro-Q-Exa:** a 54-qubit superconducting quantum computer system inaugurated just in March. It is tightly integrated with supercomputers for hybrid workflows

  - **MAQCS** (planqc): 1000-qubit device based on neutral atom technology; all-to-all connectivity!

Quantum Computers Beyond Quantum Chemistry

- Quantum Computers could also be used for solving problems beyond quantum chemistry.

- One needs to take advantage of the principles of quantum mechanics:
  - **Superposition**
  - **Quantum Interference**
  - **Entanglement**