AI for Supernova Neutrinos:
Implementation of Neutrino Flavor Conversions in Core-Collapse Supernova Simulations

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$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

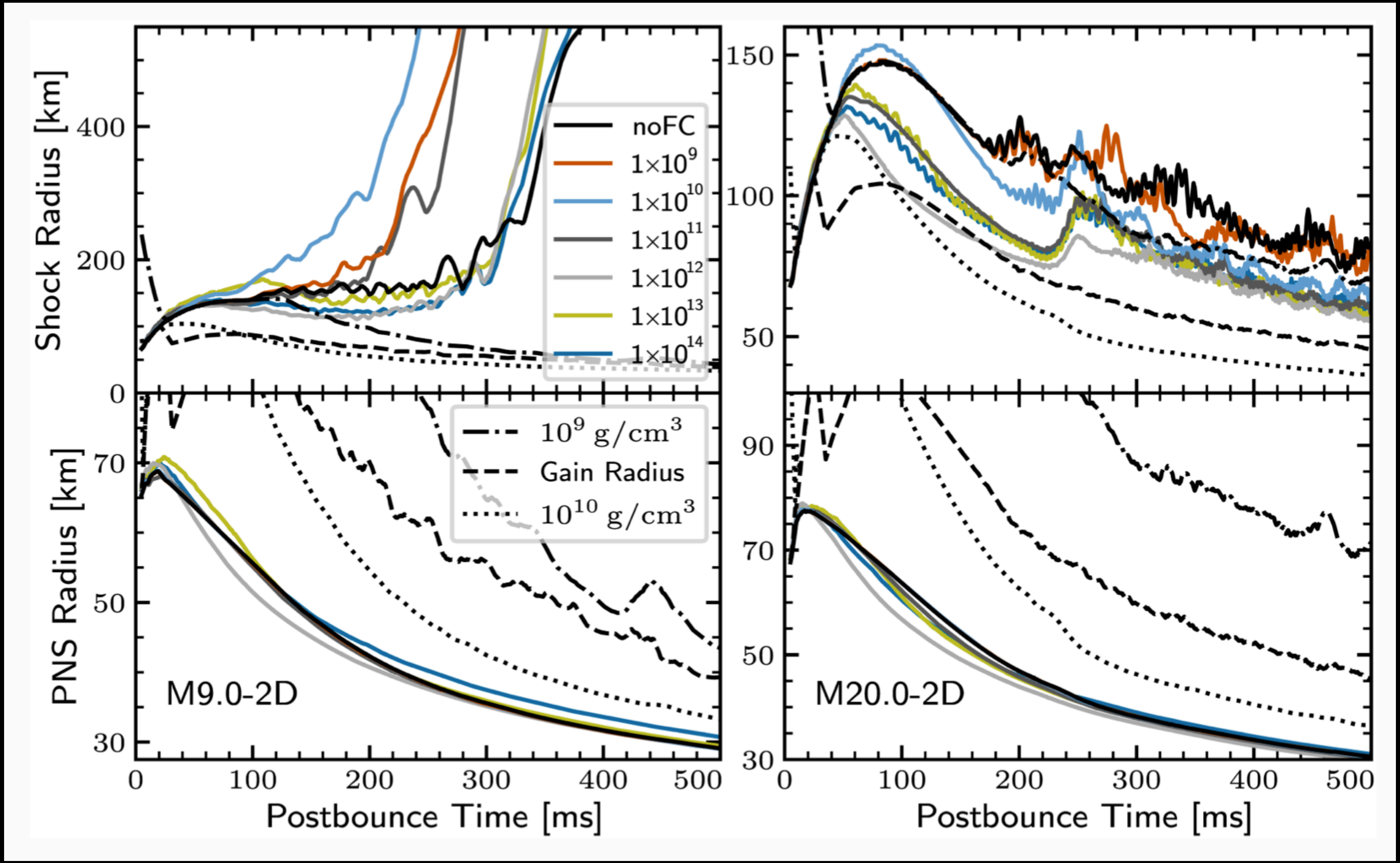
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

SFB 1258 | Neutrinos Dark Matter Messengers

Including Neutrino Flavor Conversions in CCSNe

- We performed the first SN simulations including neutrino flavor conversions for 2D models, in a parametric way

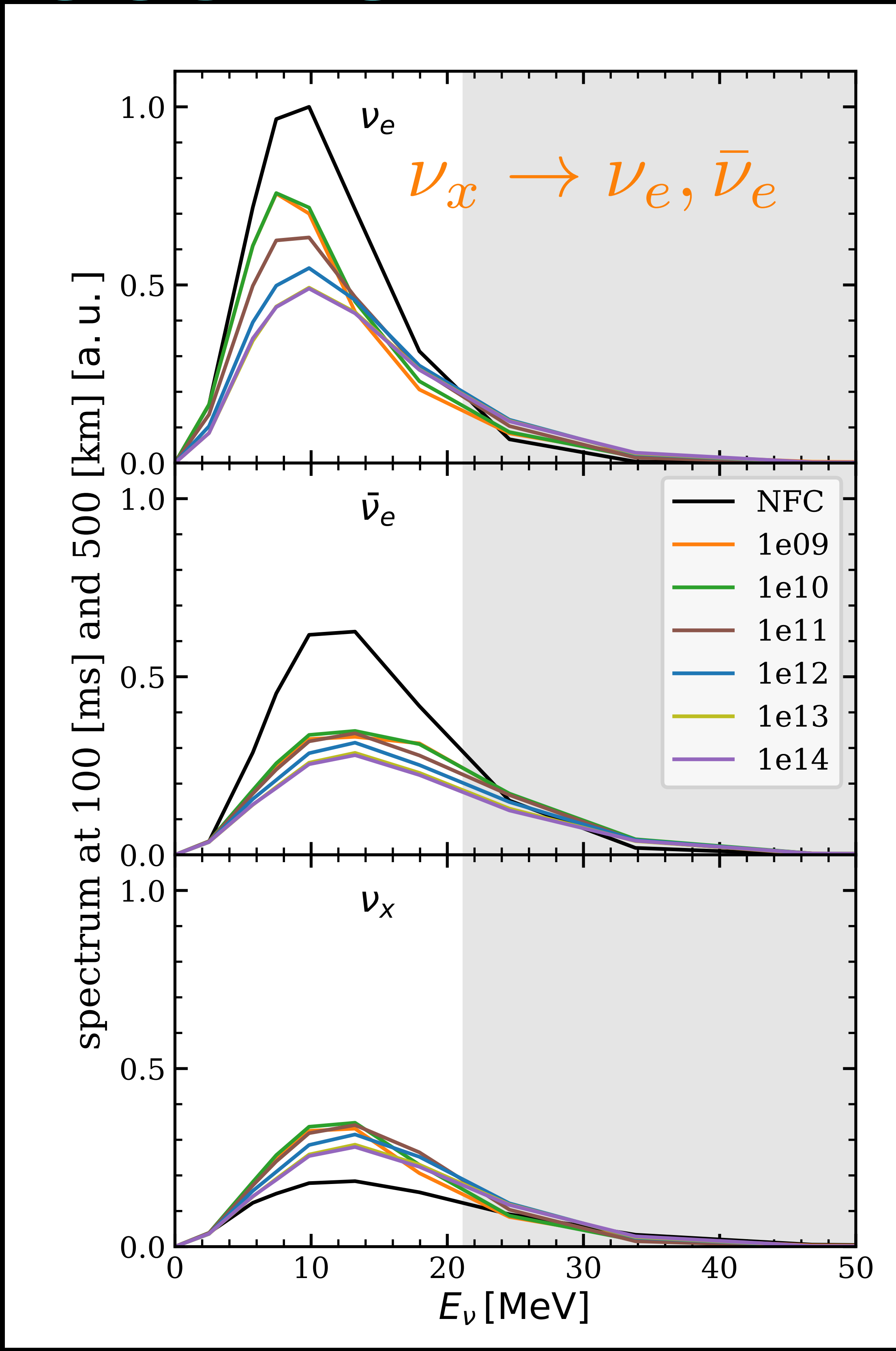
Ehring+2023



Including Neutrino Flavor Conversions in CCSNe

Ehring+(2023)

- Two competing effects here
  - $\nu_x \rightarrow \nu_e, \bar{\nu}_e$ at the tail increases heating

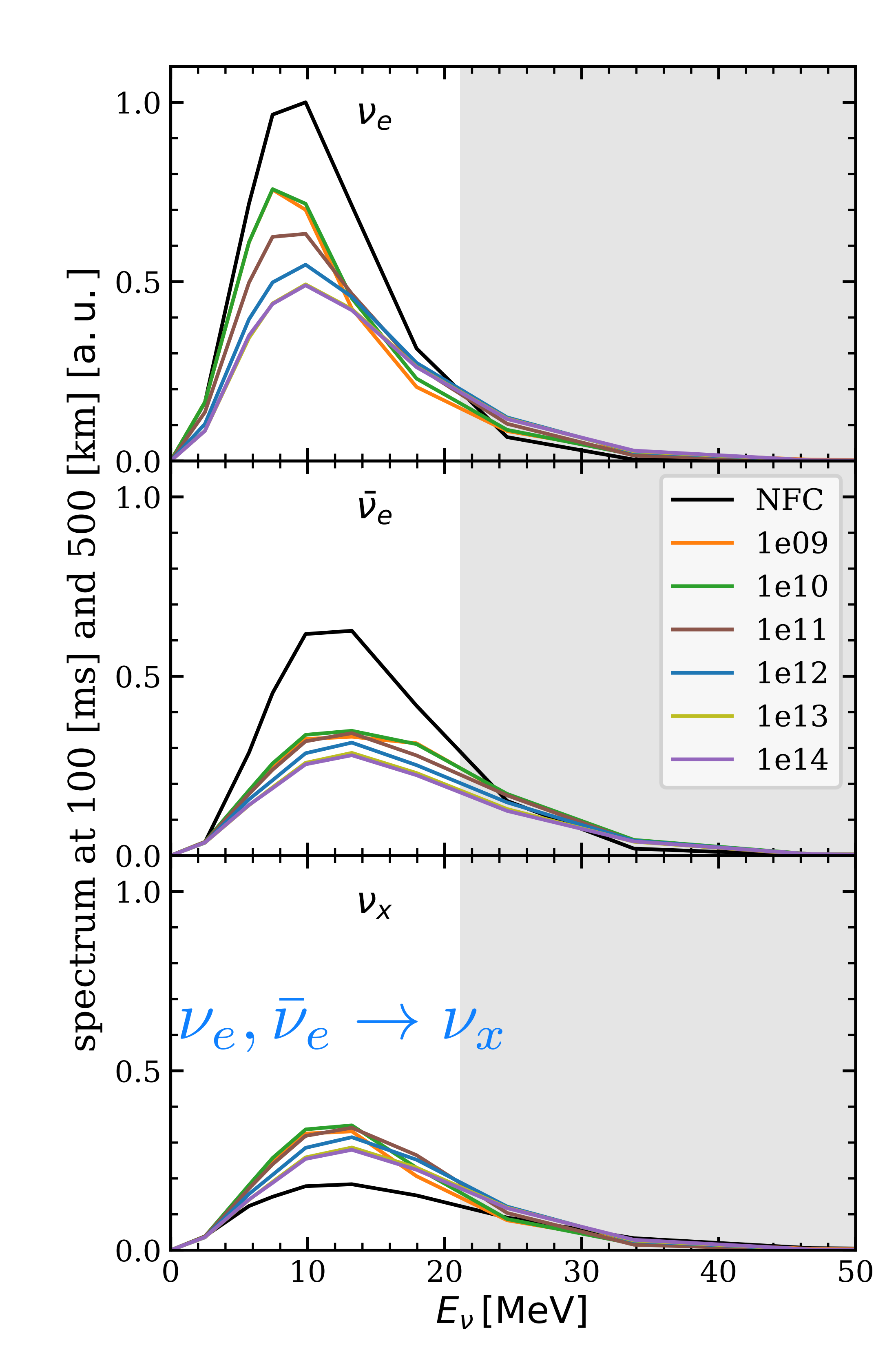


Including Neutrino Flavor Conversions in CCSNe

Ehring+(2023)

- Two competing effects here
  - $\nu_x \rightarrow \nu_e, \bar{\nu}_e$ at the tail increases heating

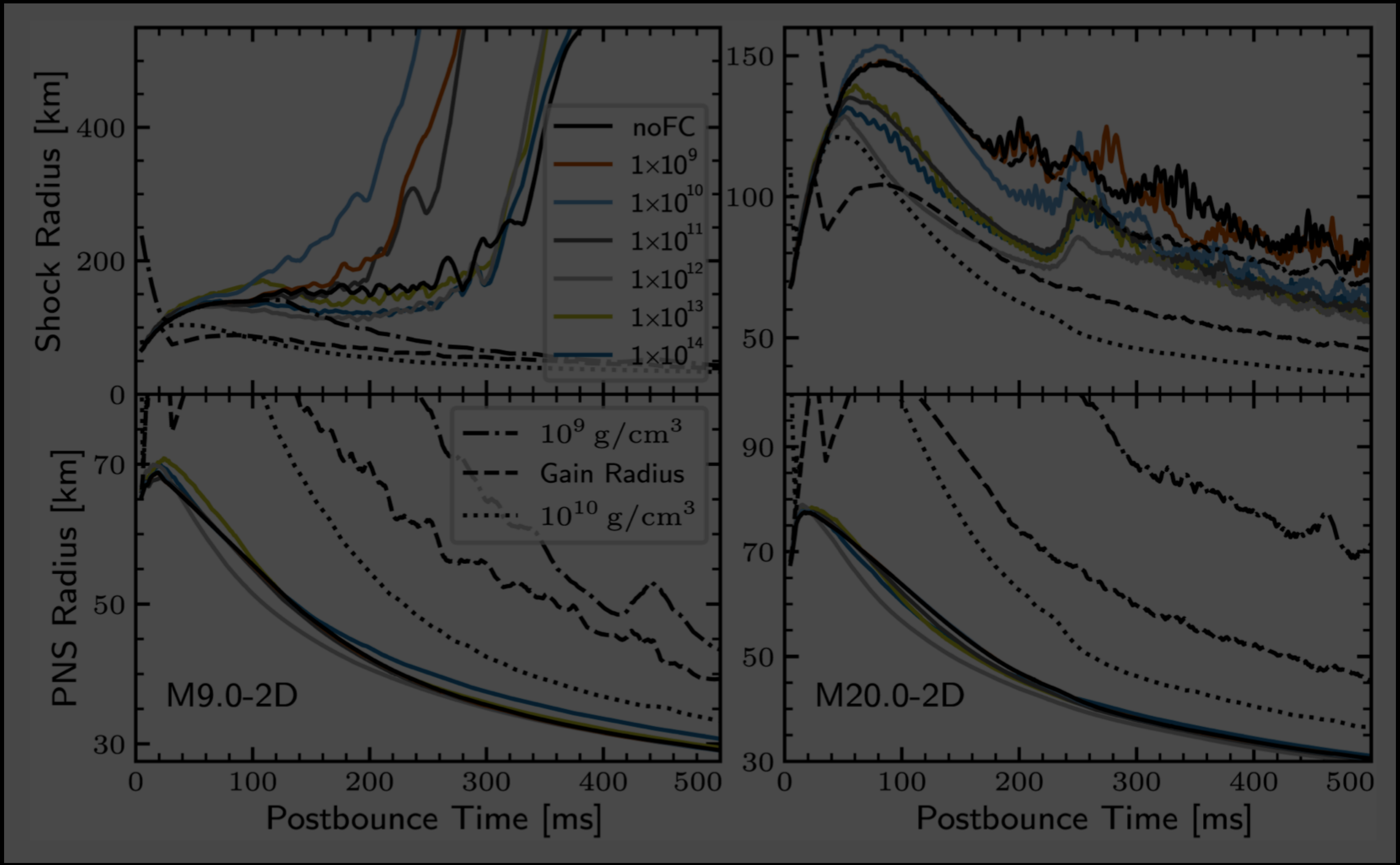
- $\nu_e, \bar{\nu}_e \rightarrow \nu_x$ at the peak increases total neutrino luminosity



Including Neutrino Flavor Conversions in CCSNe

- Neutrino FC cannot be ignored blindly in CCSN simulations!

Ehring+2023



Including Neutrino Flavor Conversions in CCSNe

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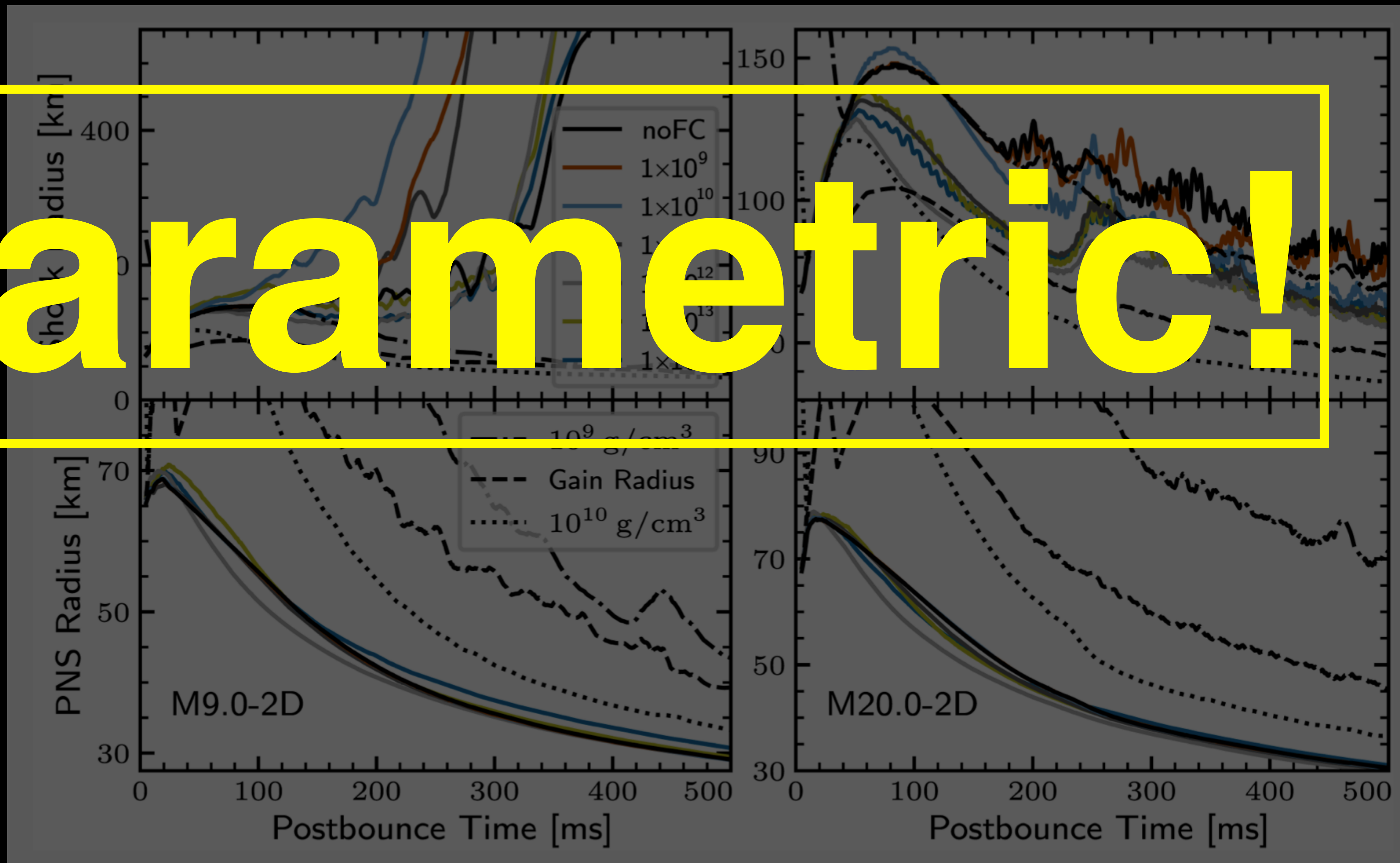


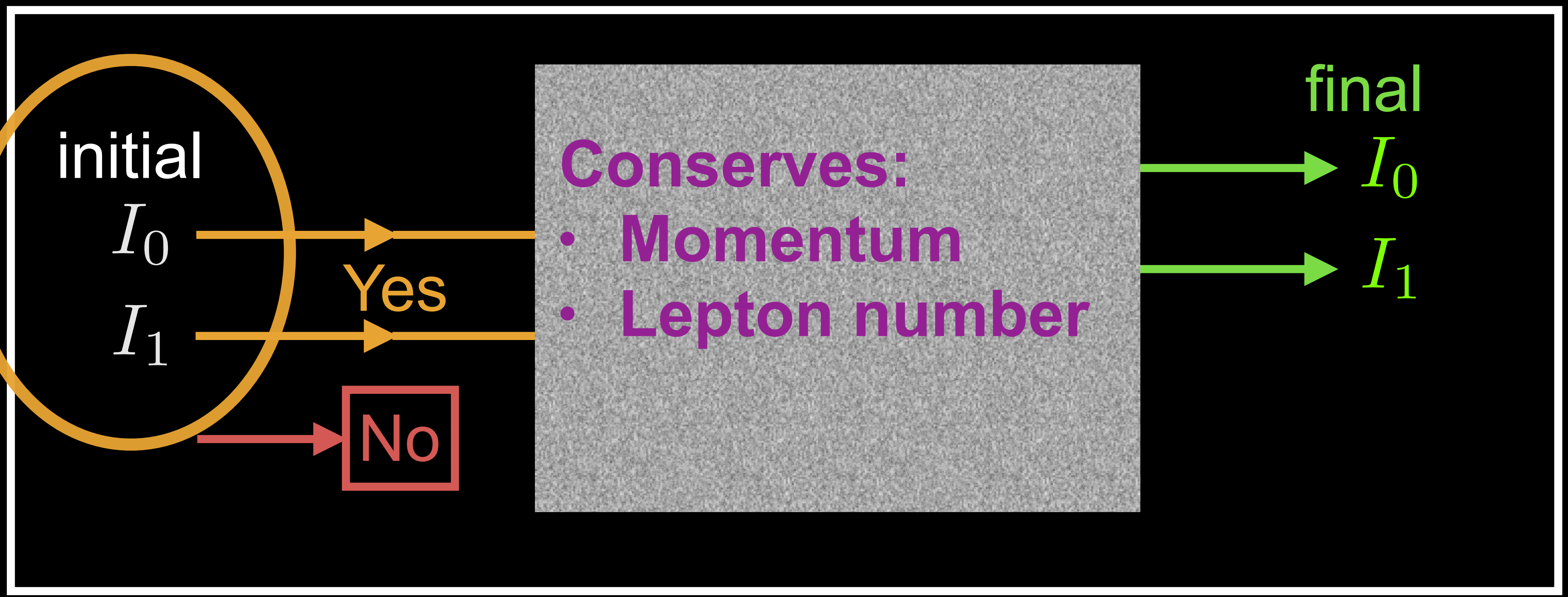
Parametric!

Including Neutrino Flavor Conversions in CCSNe

- We didn’t check the criteria for the occurrence of FCs

- Assuming instantaneous flavor equilibrium (FFCs), the equilibrium state was chosen to maximize the impact of FC

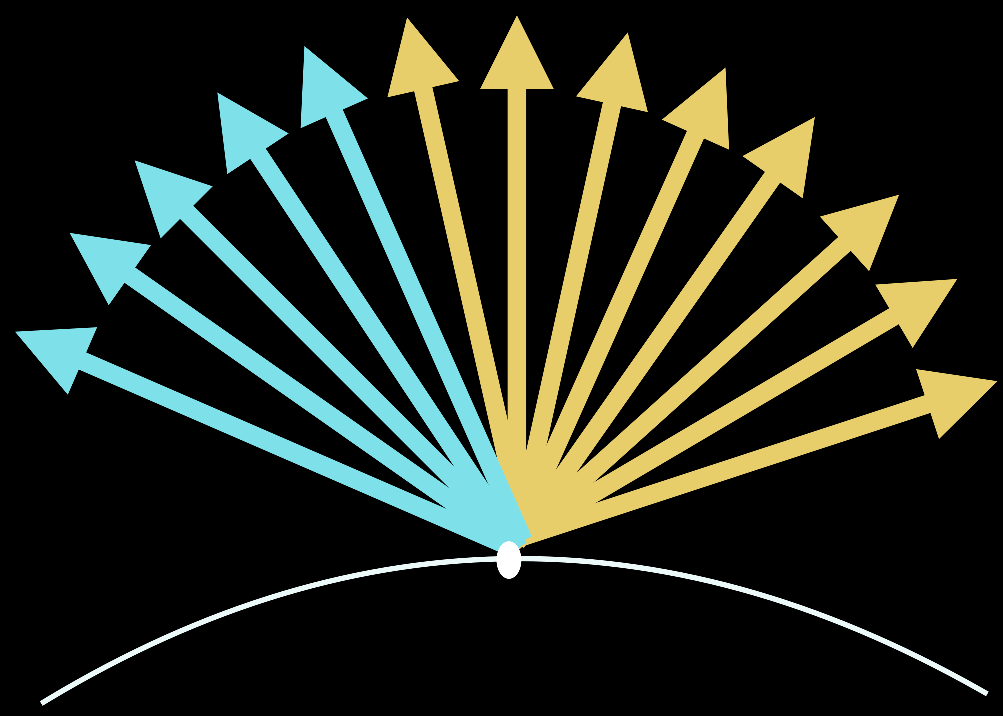
AI for Neutrino Flavor Conversions



- Checking criteria for the occurrence of FCs
- Finding equilibrium state for given initial quantities

Criteria for FFCs

- 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

Criteria for FFCs

- 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

- AI can detect FFCs based on I_0 and I_1 on the fly
  - A classification problem!
  - We have four feature here: I_0 and I_1 for neutrinos and antineutrinos

Criteria for FFCs

- The error is the same as the error in the noisy labels

Parametric distributions

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%

Abbar2022

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Realistic data

LR (n = 2) (94%)			
	precision	recall	F_1-score
no crossing	96%	95%	95%
crossing	91%	93%	92%
KNN (n=3) (98%)			
	precision	recall	F_1-score
no crossing	98%	99%	99%
crossing	98%	97%	98%
SVM (97%)			
	precision	recall	F_1-score
no crossing	98%	98%	98%
crossing	96%	97%	97%
Decision tree (99%)			
	precision	recall	F_1-score
no crossing	99%	99%	99%
crossing	98%	98%	98%

Abbar&Nagakura2023

Criteria for FFCs

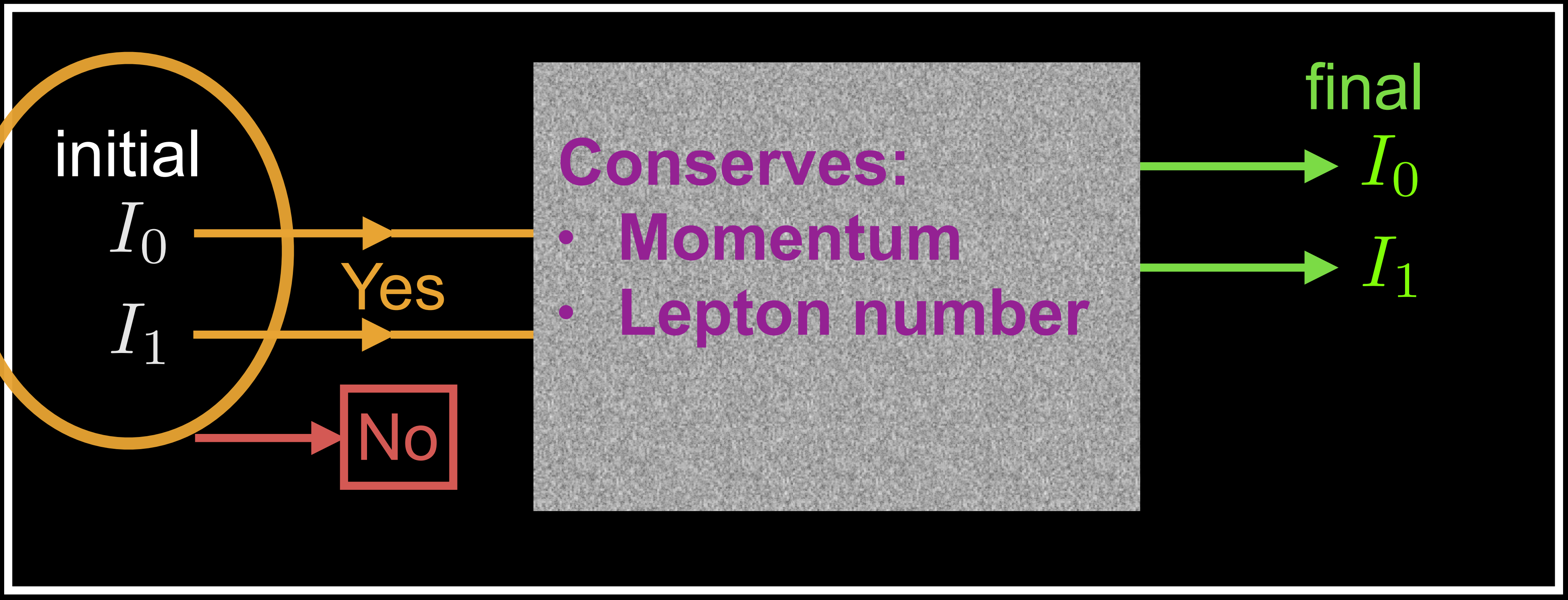
- In the case of the crossings in the azimuthal angle, we have 7 input features

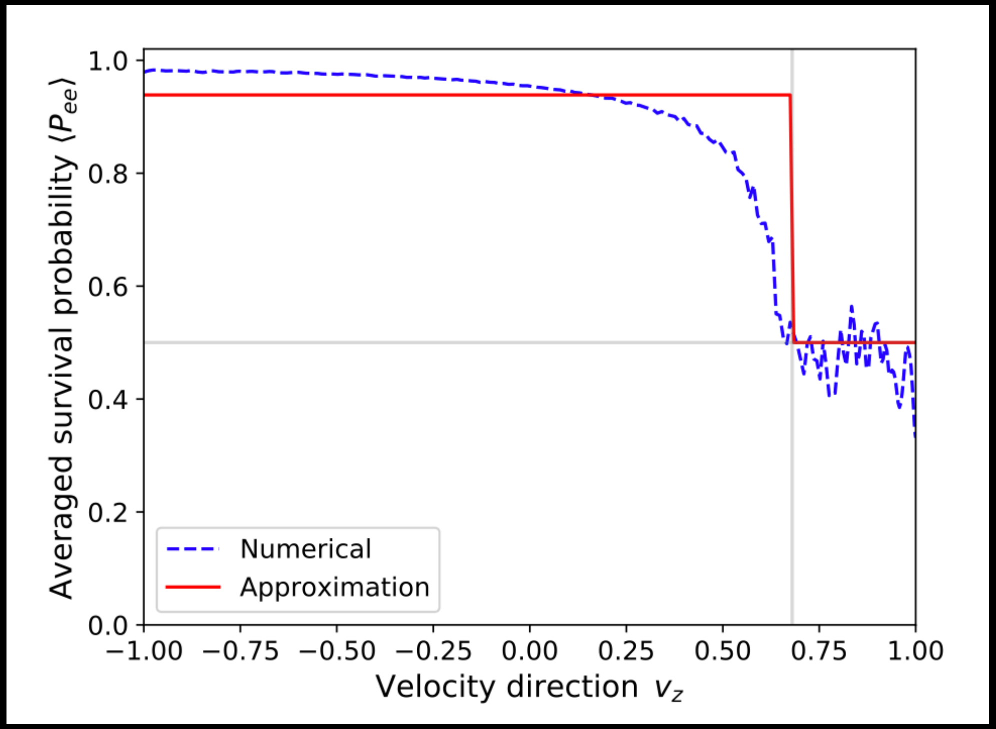
	precision	recall	F_1-score
LR (n = 2) (95%)			
no crossing	97%	95%	96%
crossing	93%	96%	94%
KNN (n=3) (100%)			
no crossing	100%	100%	100%
crossing	100%	100%	100%
SVM (95%)			
no crossing	97%	95%	96%
crossing	93%	96%	94%
DT (100%)			
no crossing	100%	100%	100%
crossing	100%	100%	100%

Abbar+20223

FFC equilibrium state

- Assuming instantaneous equilibration



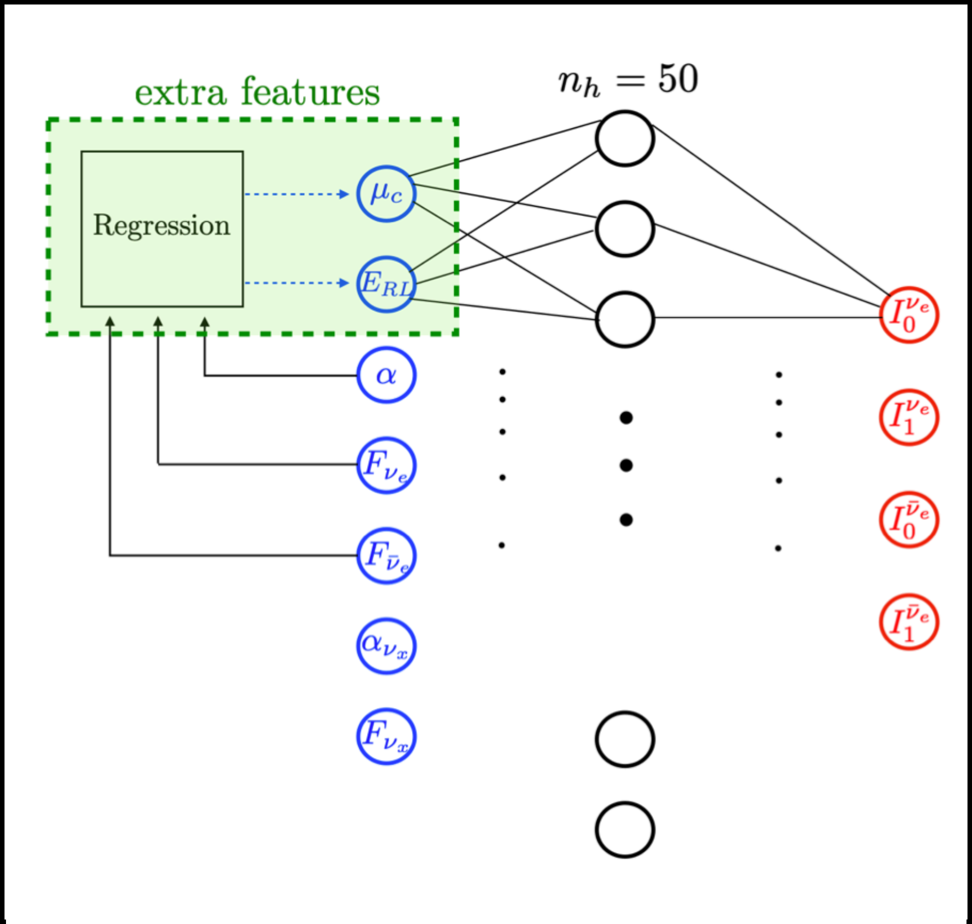


- Assuming the periodic box solution, the survival probability can be found analytically

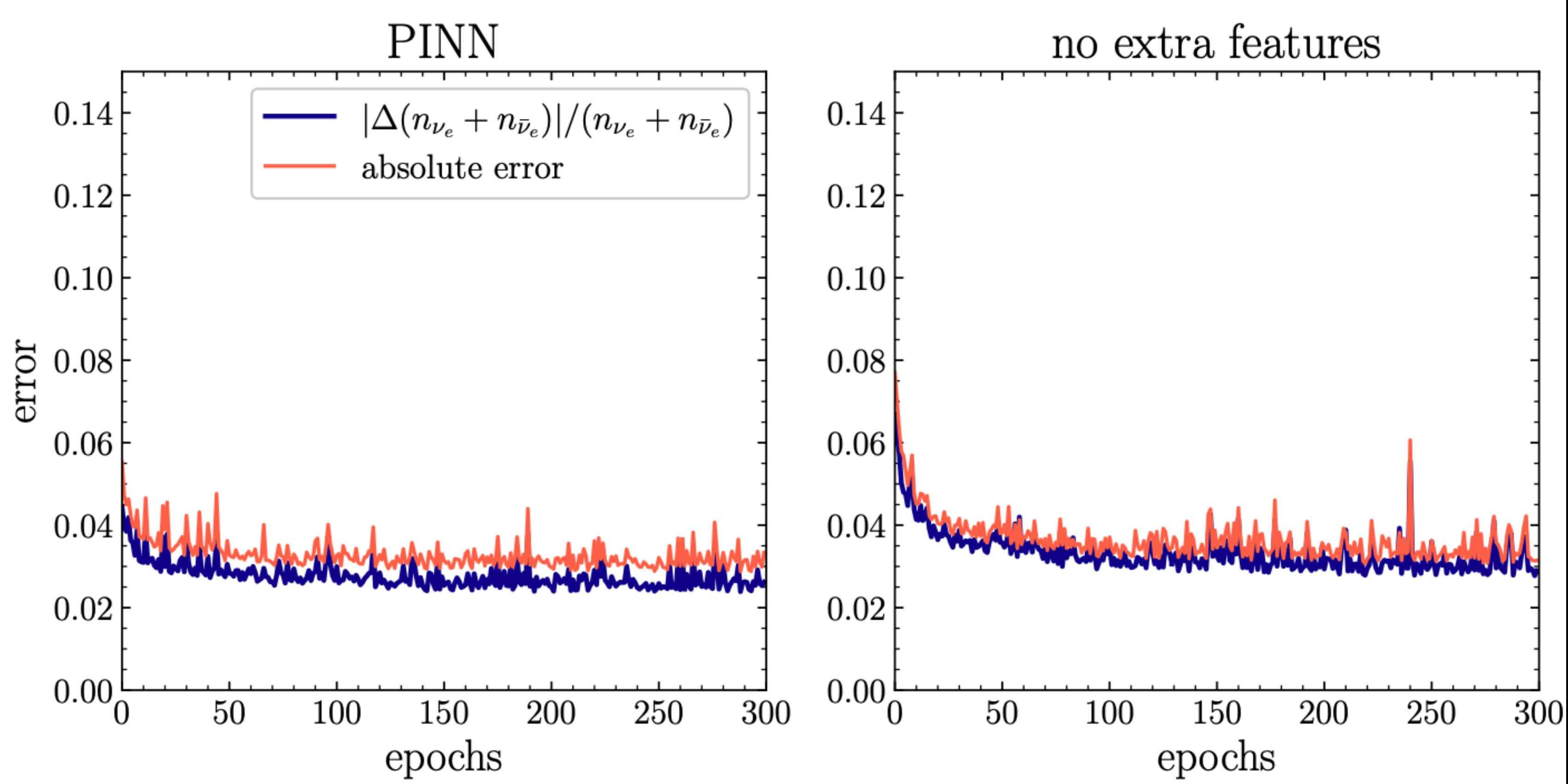
Nagakura+,Wu+(2022)

FFC equilibrium state

- For a single-energy neutrino gas, NN can predict the outcome of FFCs
- Introducing novel features could help a bit

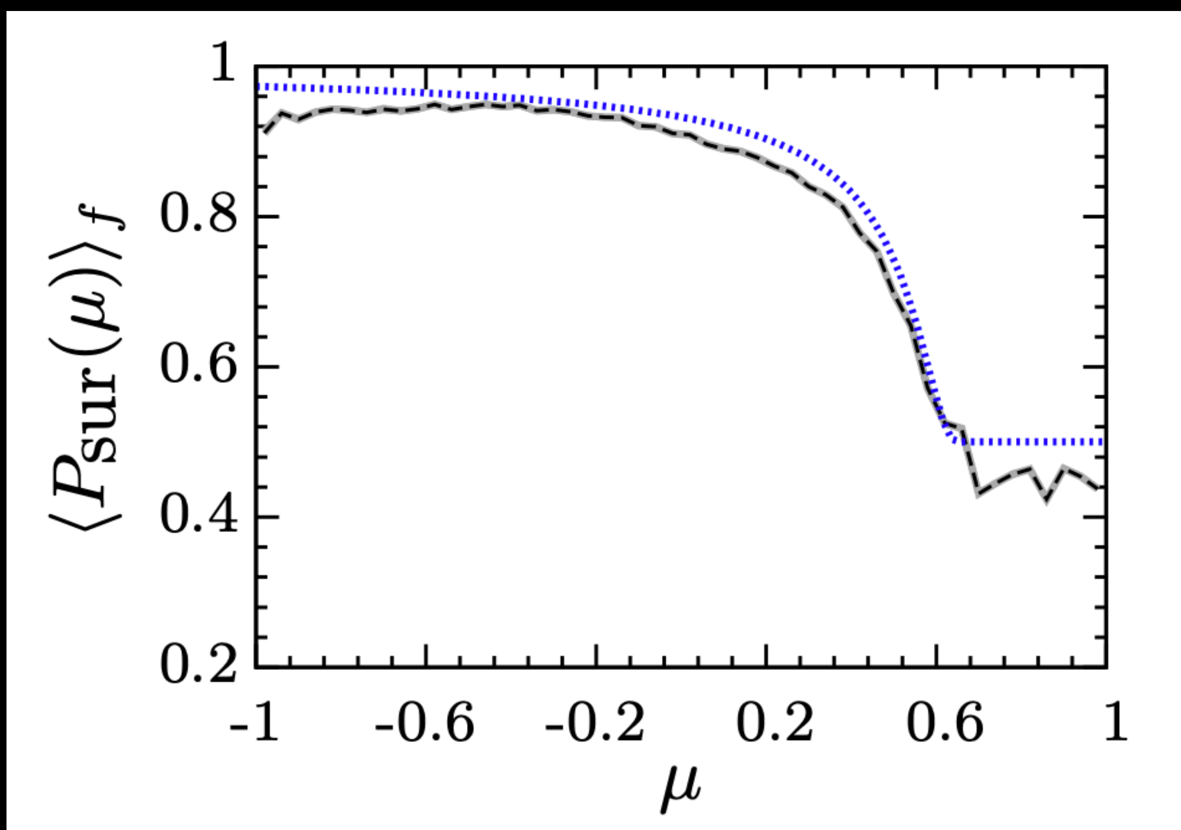


$$\alpha = \frac{n_{\bar{\nu}_e}}{n_{\nu_e}}, \quad \alpha_{\nu_x} = \frac{n_{\nu_x}}{n_{\nu_e}}, \quad \text{and} \quad F_\nu = \left(\frac{I_1}{I_0}\right)_\nu .$$



FFC equilibrium state

- For a multi-energy neutrino gas, all the energy bins follow the same survival probability (if FFC is really fast!)



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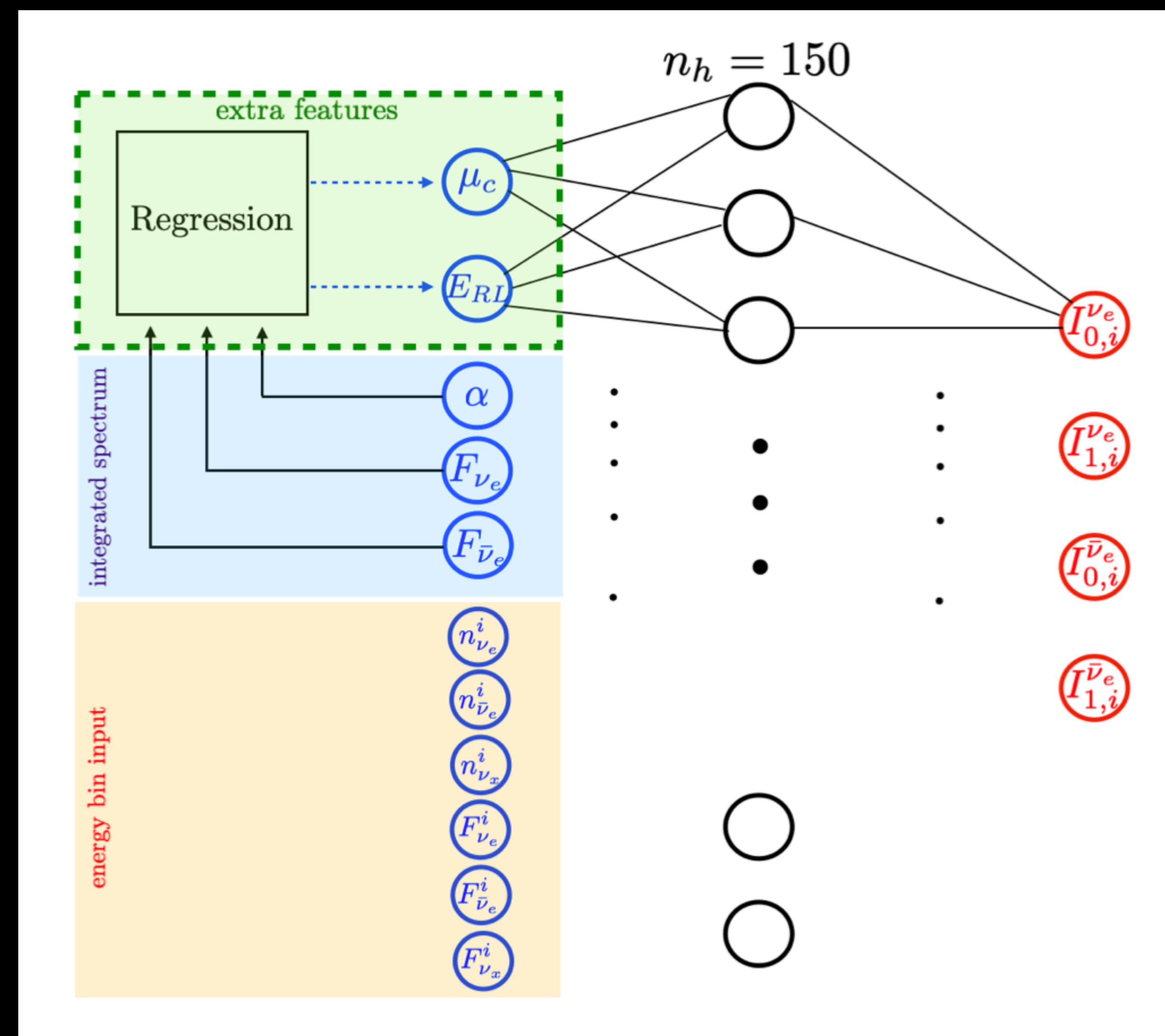

FFC equilibrium state

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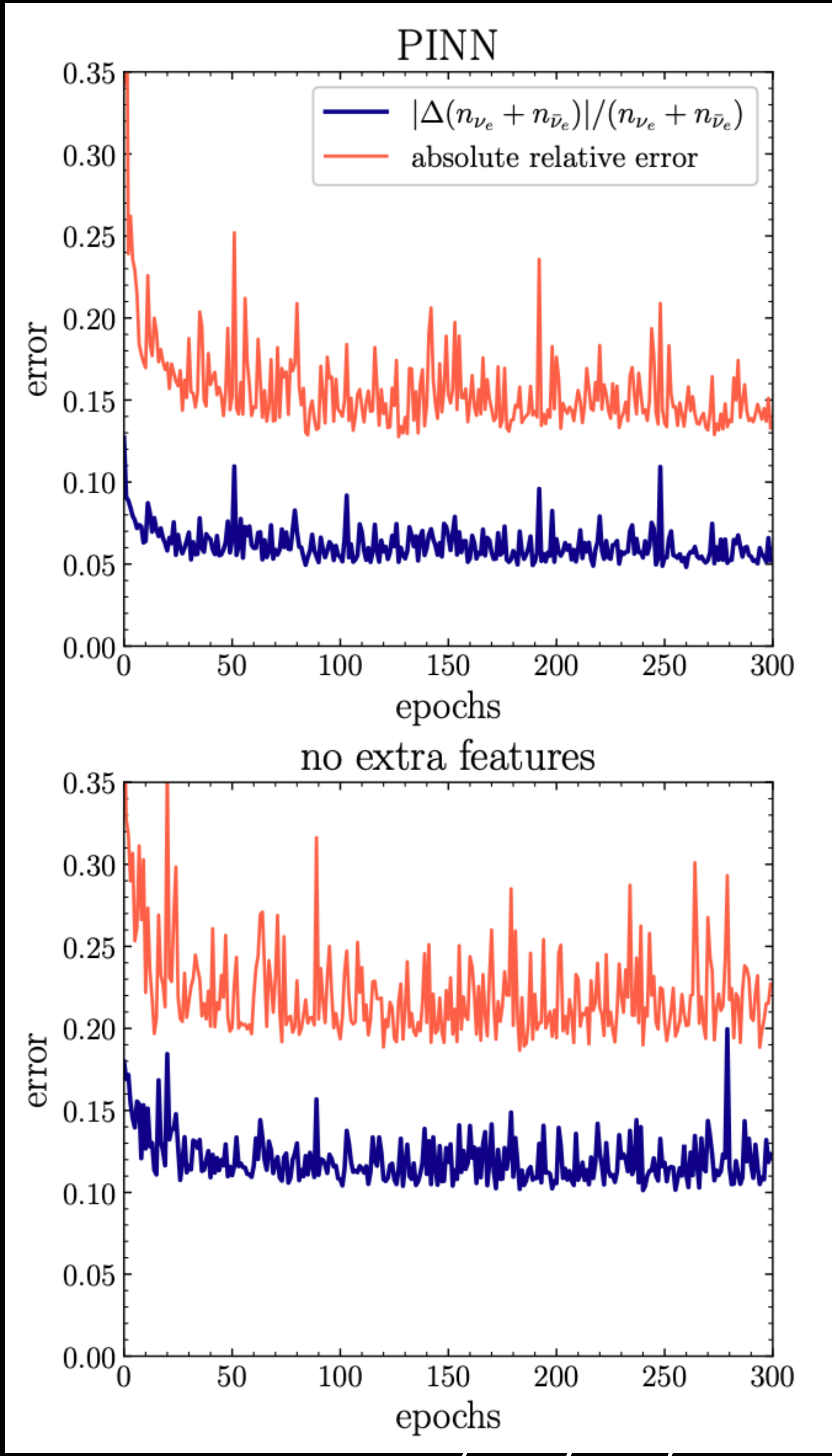
- The error is lager for the multi-energy case

- Feature engineering is important



Summary

- Neutrino Flavor Conversions cannot be ignored blindly in CCSN simulations

- AI can help with this but still lots of issues must be addressed

Discussion

- Should we get back to slow modes?

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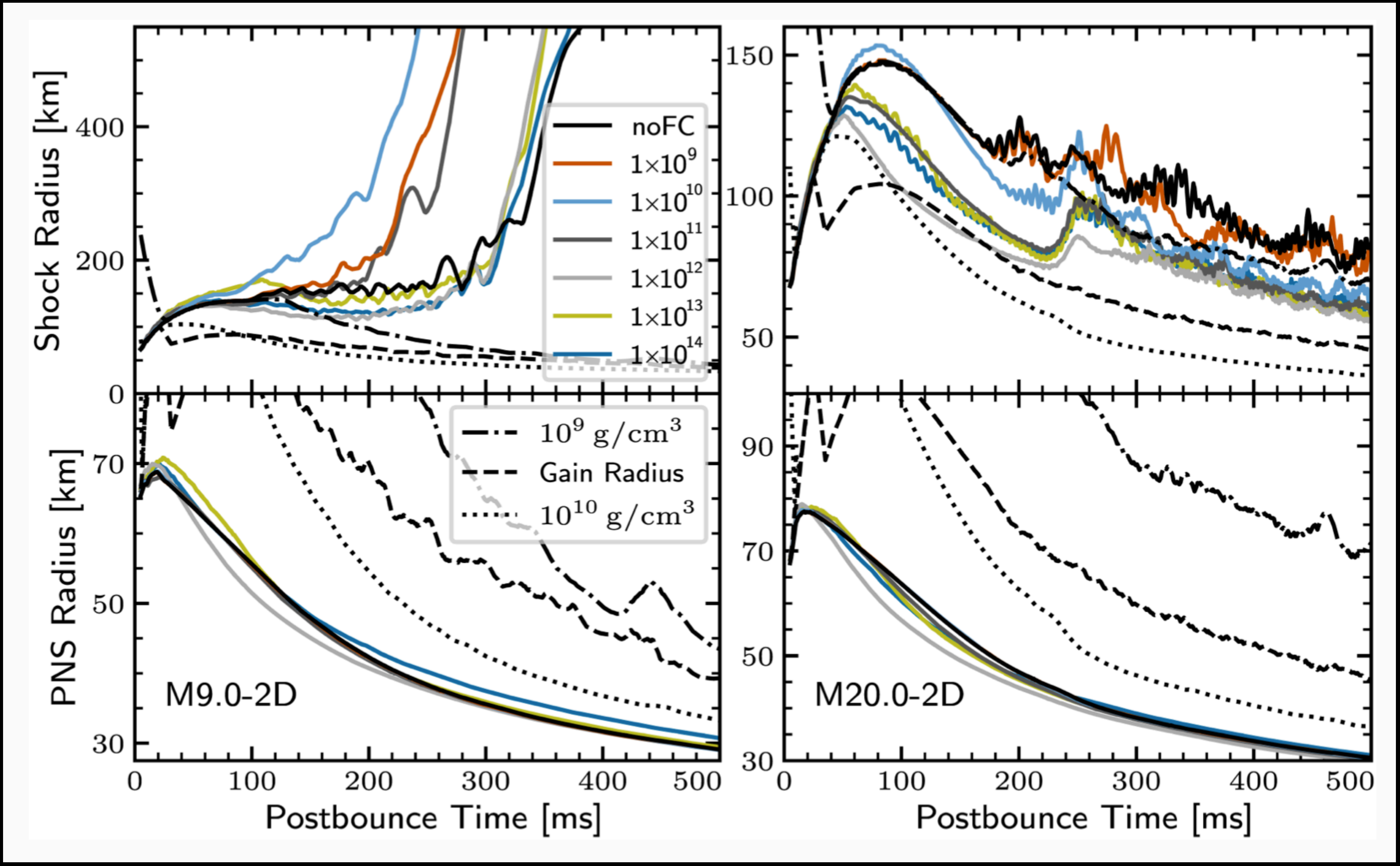

Summary

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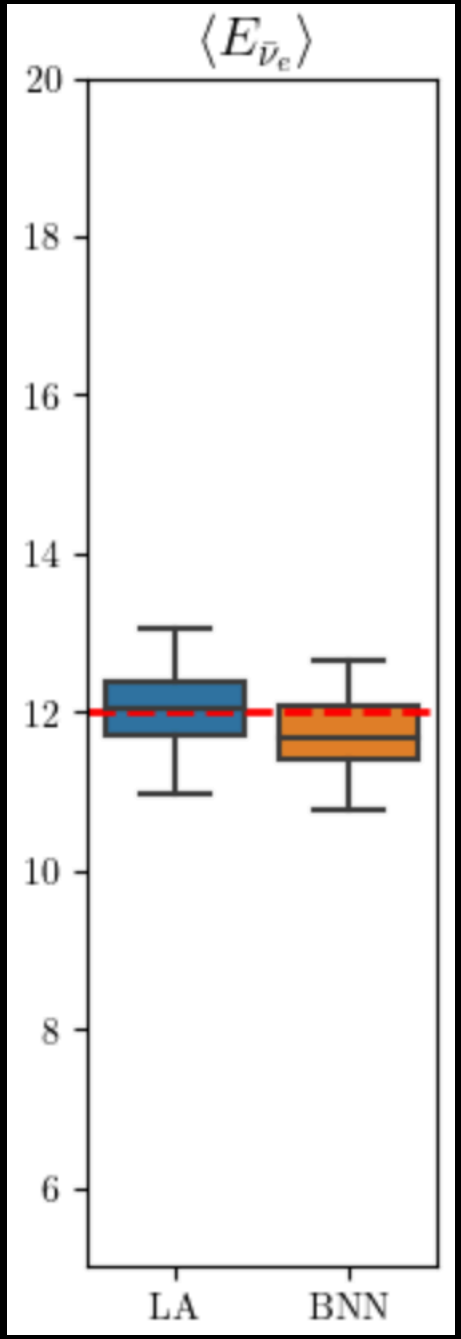
- AI can help with this



Application of Machine Learning

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

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

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

- We have four feature here: I_0 and I_1 for neutrinos and antineutrinos (one is redundant)

$$\alpha = \frac{I_0^{\bar{\nu}_e}}{I_0^{\nu_e}} \qquad F_\nu = \frac{I_1}{I_0}$$