Fast Neutrino Flavor Conversions in 1D Core-Collapse Supernova Simulations

CTAP Workshop, November 10, 2022

In honor of Georg Raffelt

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Max-Planck-Institut für Physik
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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

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

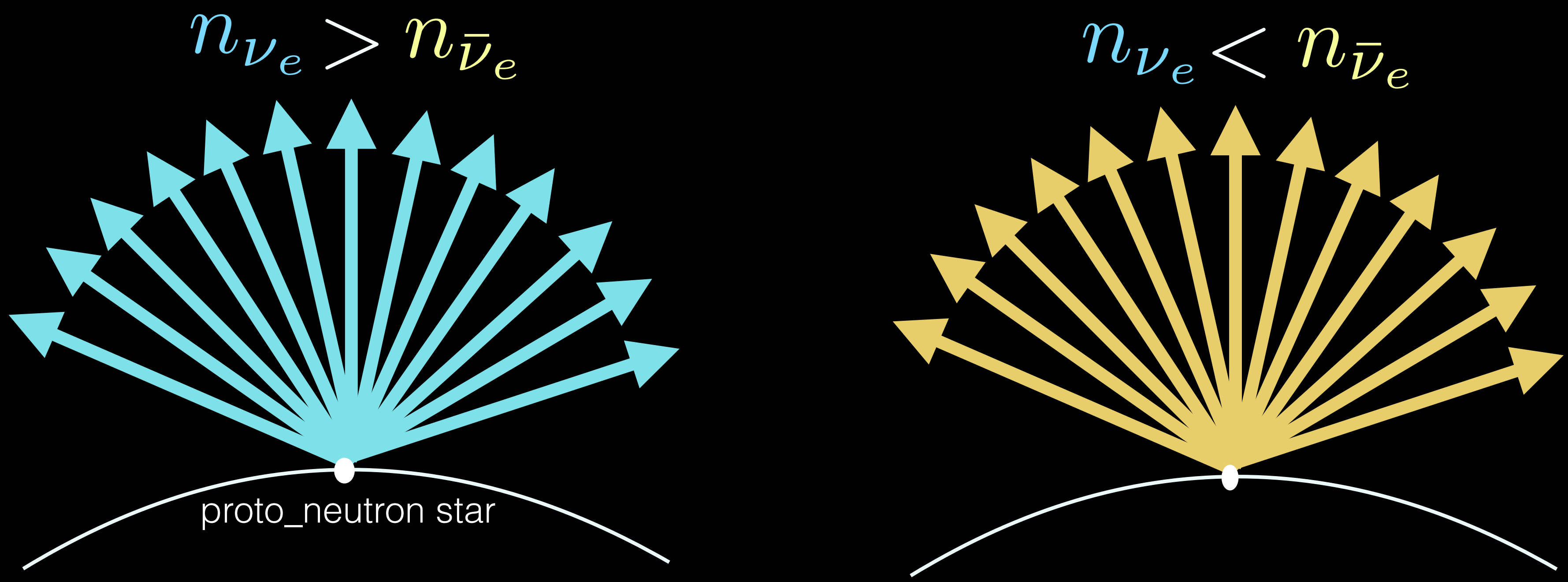
$$H = \frac{1}{2}\begin{bmatrix} -\omega\cos 2\theta + \sqrt{2}G_{\mathrm{F}}n_e & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta - \sqrt{2}G_{\mathrm{F}}n_e \end{bmatrix} + H_{\nu\nu}$$

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

- It is important to understand neutrino flavor evolution

Fast Flavor Conversions

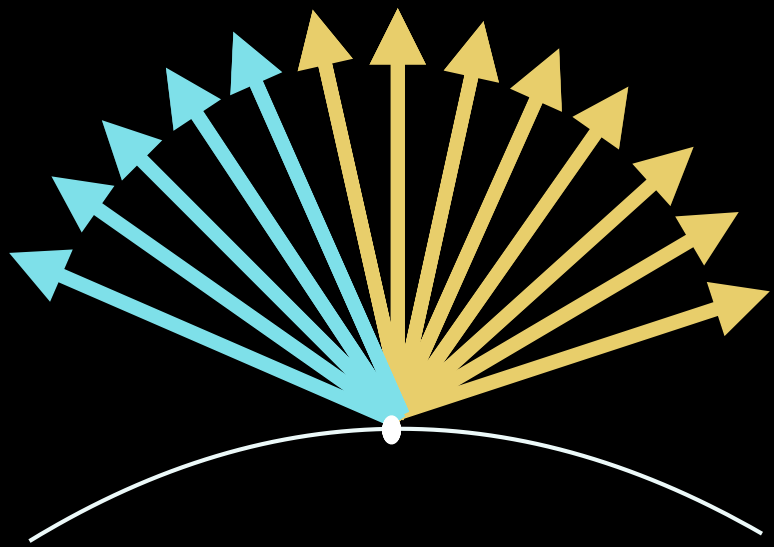
- In our traditional understanding, we assumed that neutrinos are emitted isotropically from the surface of the neutrino source
- $f_{\nu_e}(\theta) - f_{\bar{\nu}_e}(\theta)$ is either always positive or negative



- 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

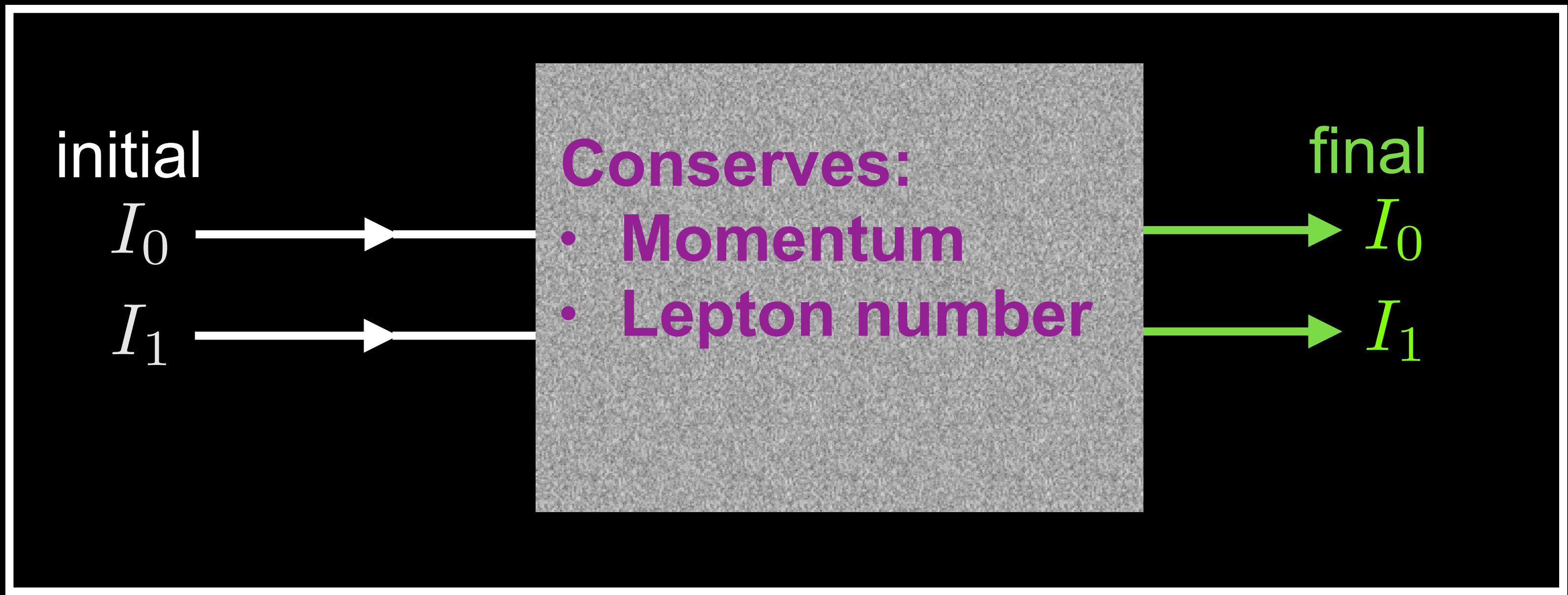
- Neutrino oscillations can now occur at densities that had been long thought to be the realm of collisional and scattering processes

Including FFC in CCSNe

- FFC can not be implemented self-consistently

- We assume FFC lead to a sort of flavor equilibrium

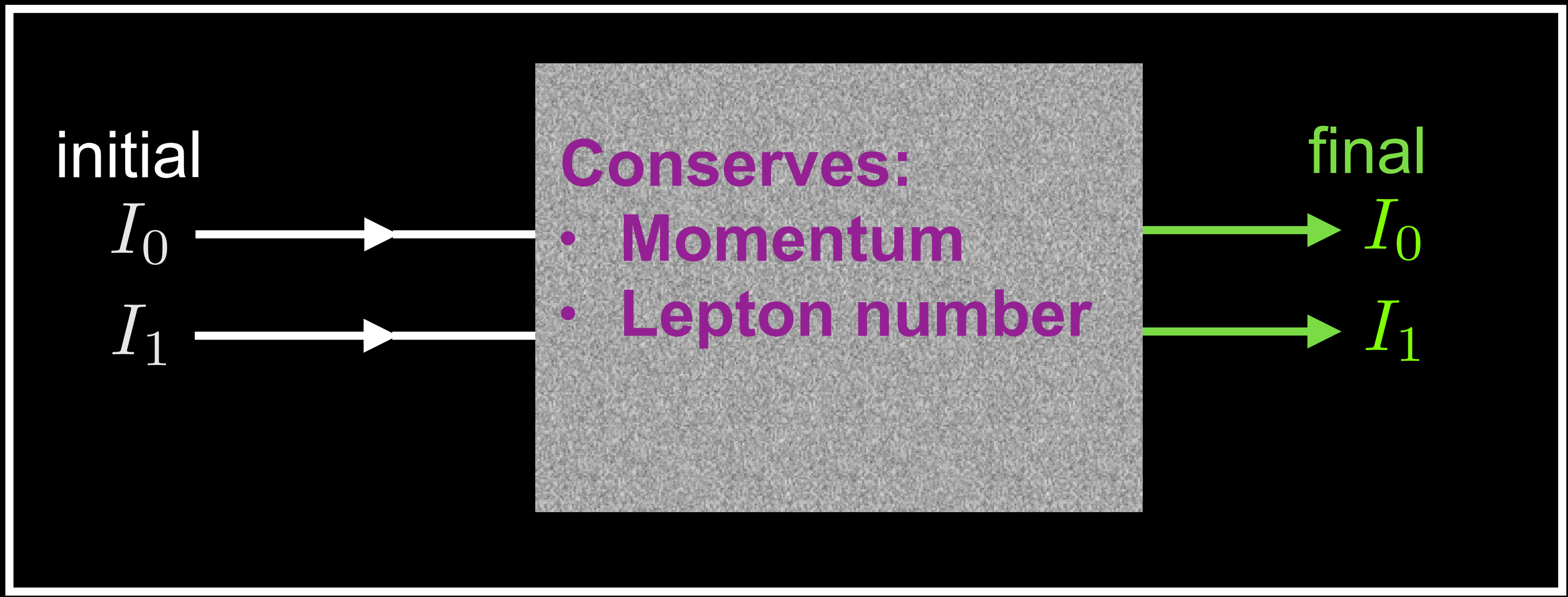
FFC



Including FFC in 1D CCSNe

- We perform SN simulations including FFC for a 1D 20M⊙ model, in a parametric way
- We set a density threshold ($\rho_c = 10^9 - 10^{14}$ g cm^{-3}) below which FFC can occur

FFC



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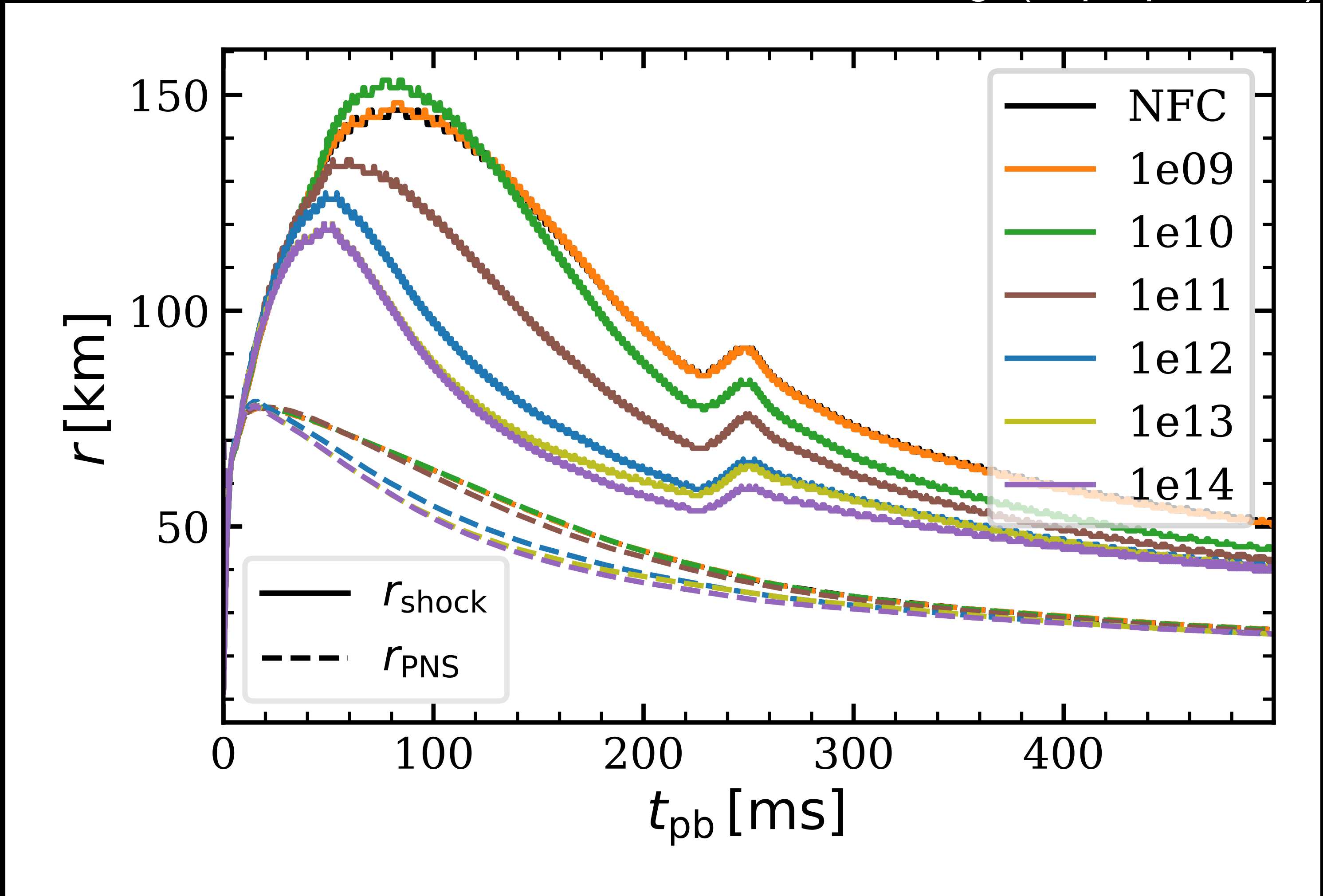
Ehring+(In preparation)



Including FFC in 1D CCSNe

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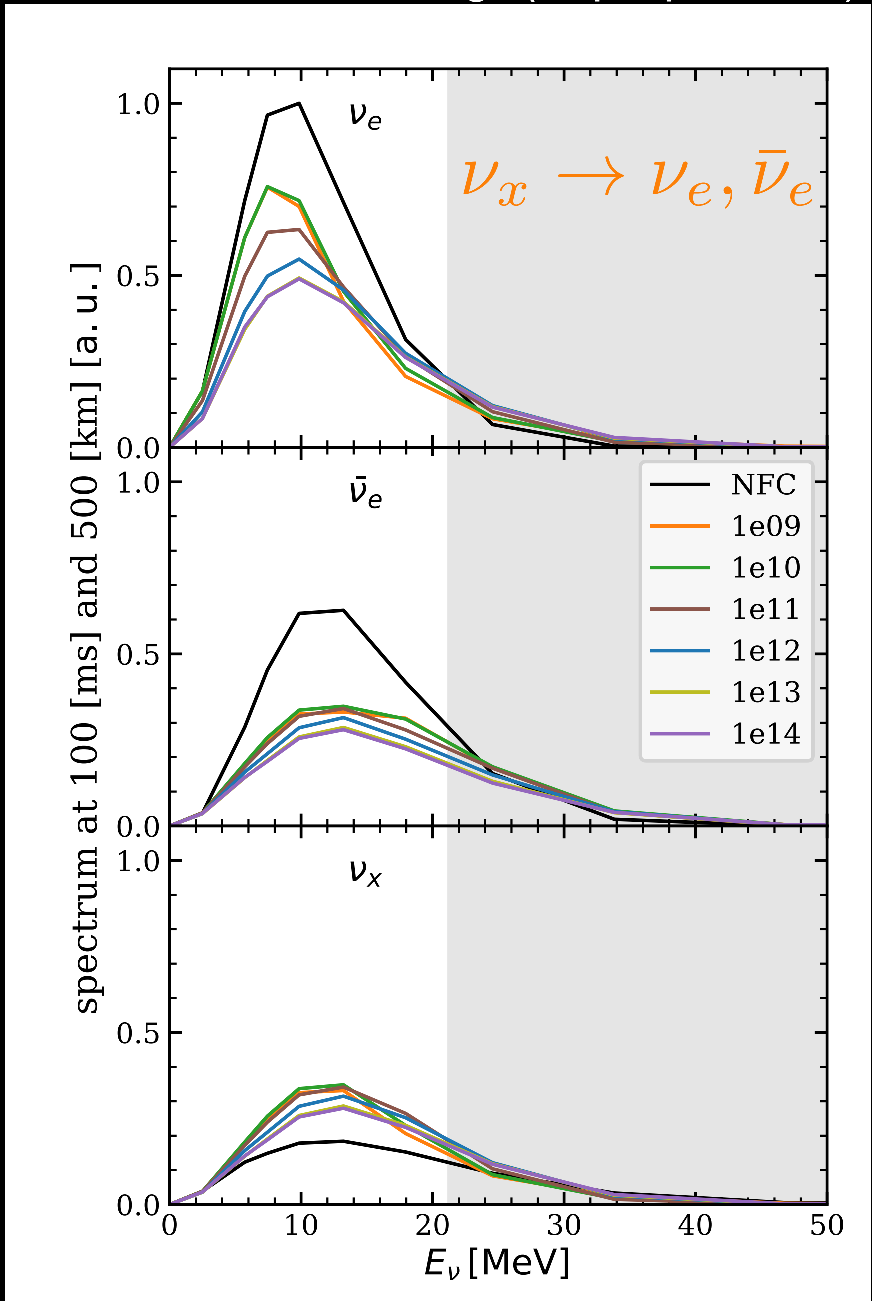
- Two competing effects here
  - $\nu_x \rightarrow \nu_e, \bar{\nu}_e$ at the tail increases heating



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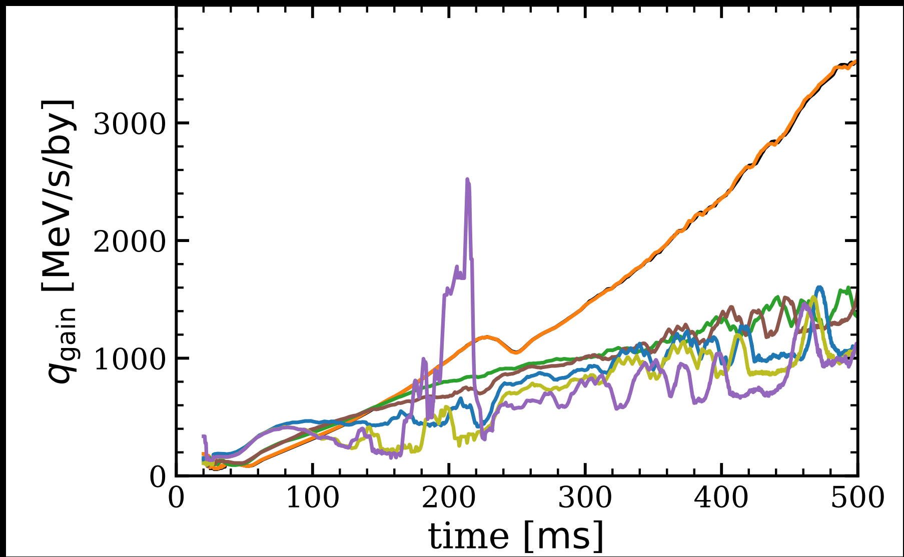

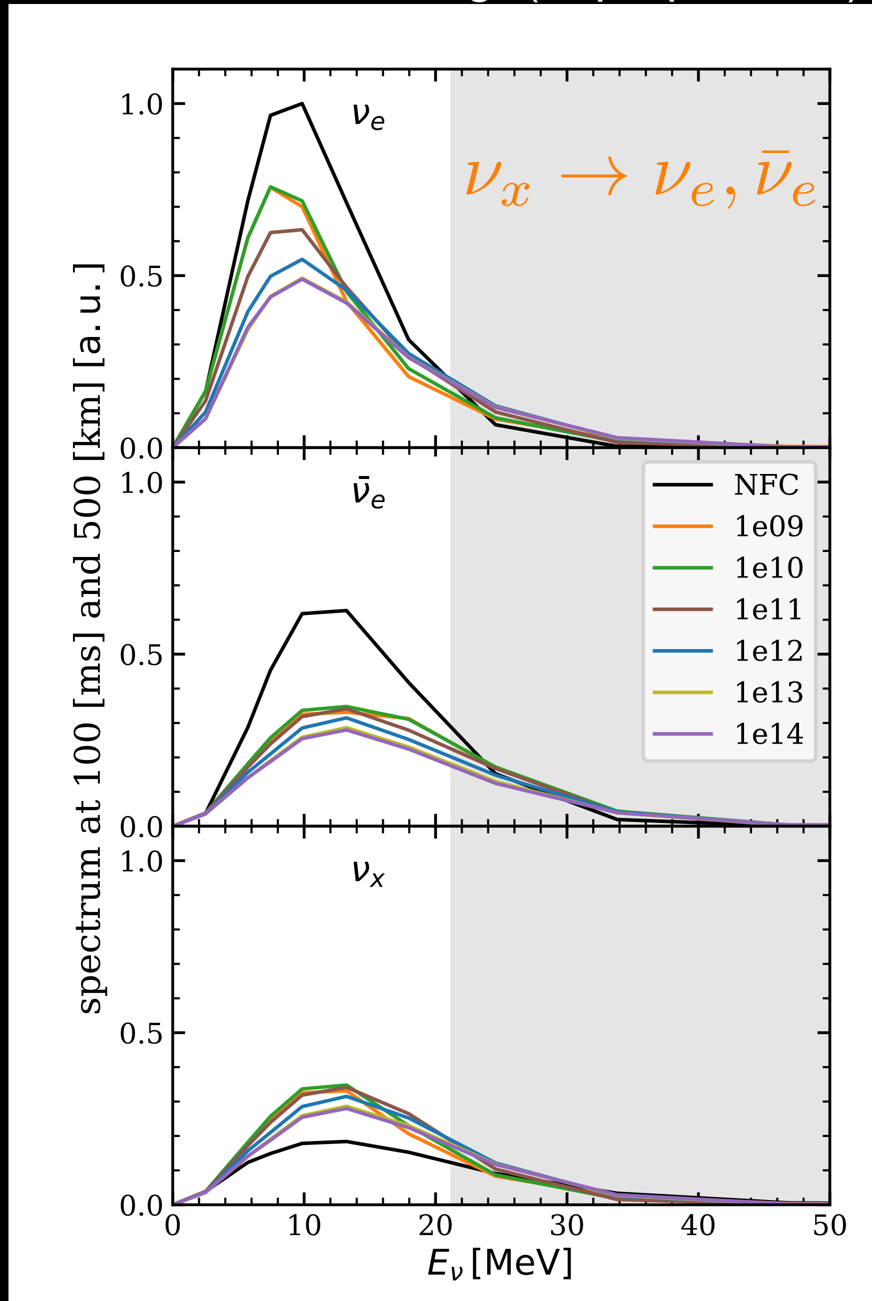

Including FFC in 1D CCSNe

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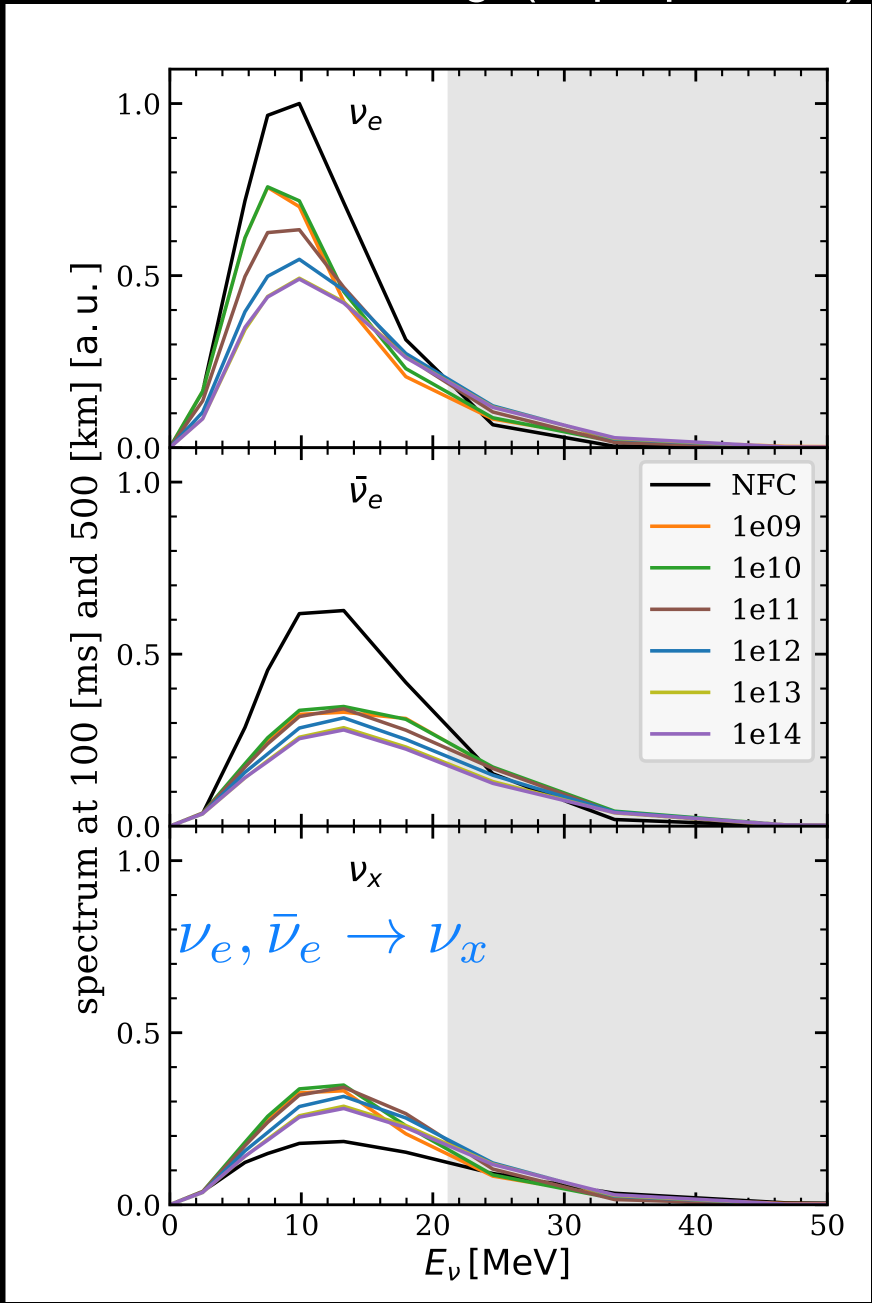
- Two competing effects here
  - $\nu_x \rightarrow \nu_e, \bar{\nu}_e$ at the tail increases heating
  - $\nu_e, \bar{\nu}_e \rightarrow \nu_x$ at the peak increases total neutrino luminosity



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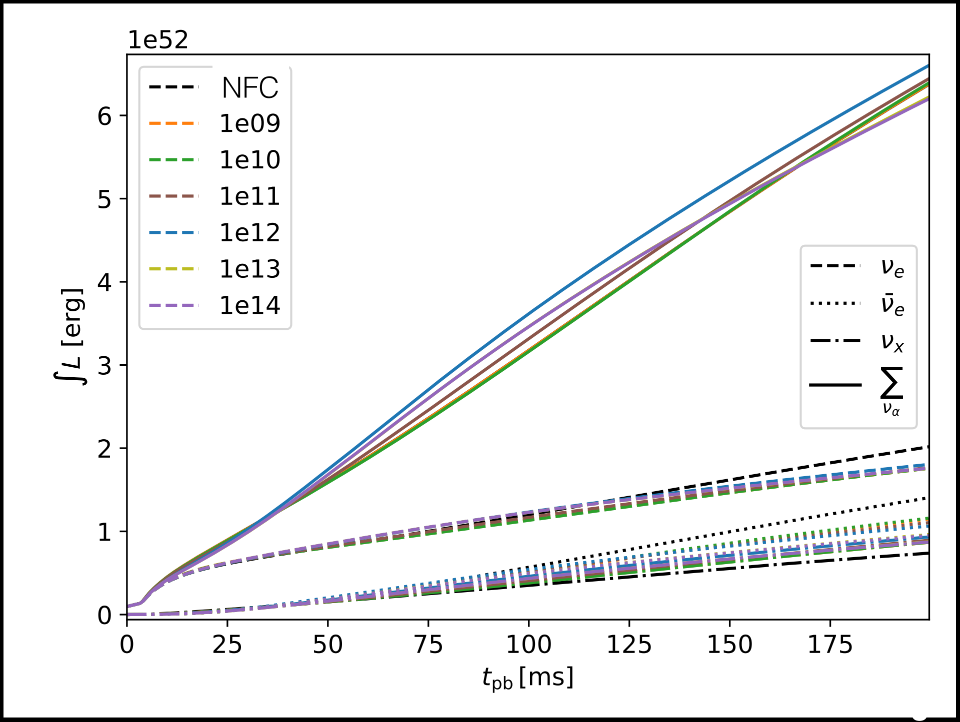

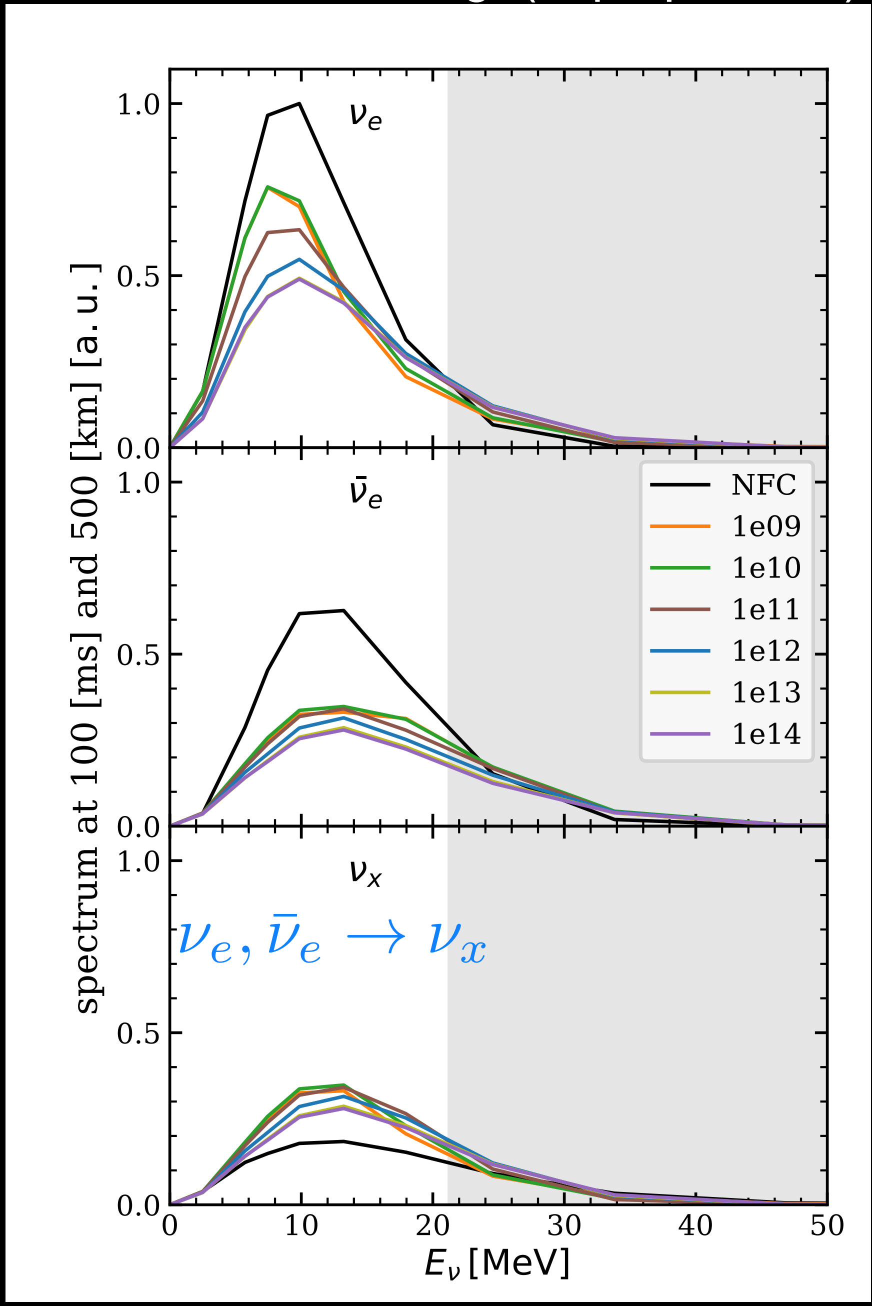

Neutron Star Mergers

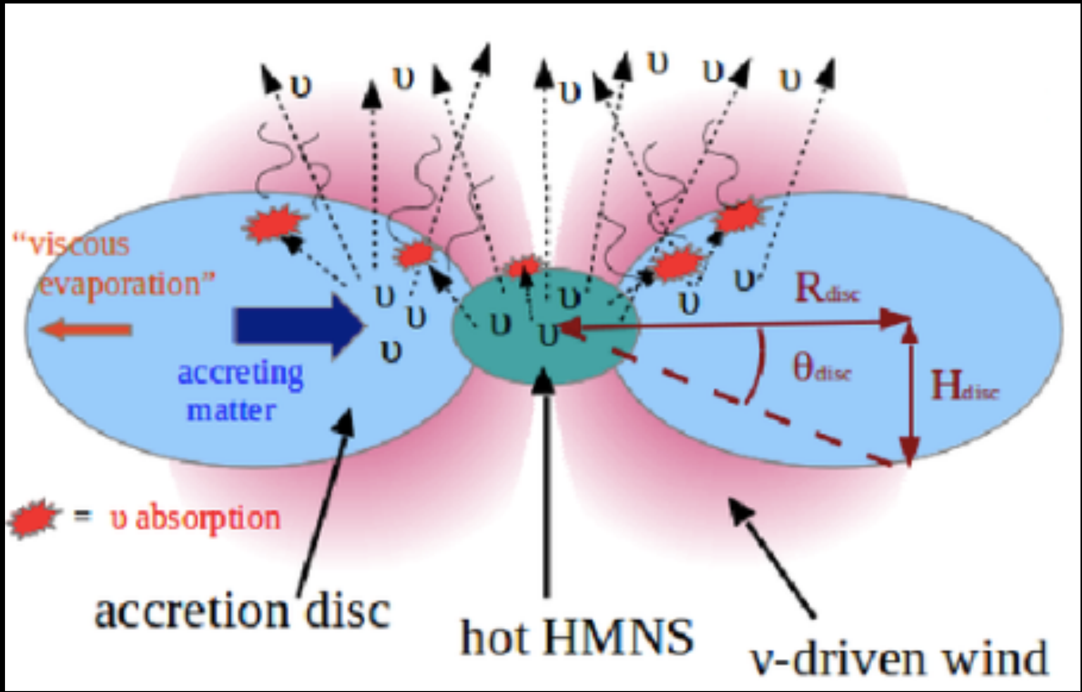

Figure from Perego et. al., arxiv: 1405.6730

- Hot hyper massive NS and the accretion disk emit a huge number of neutrinos

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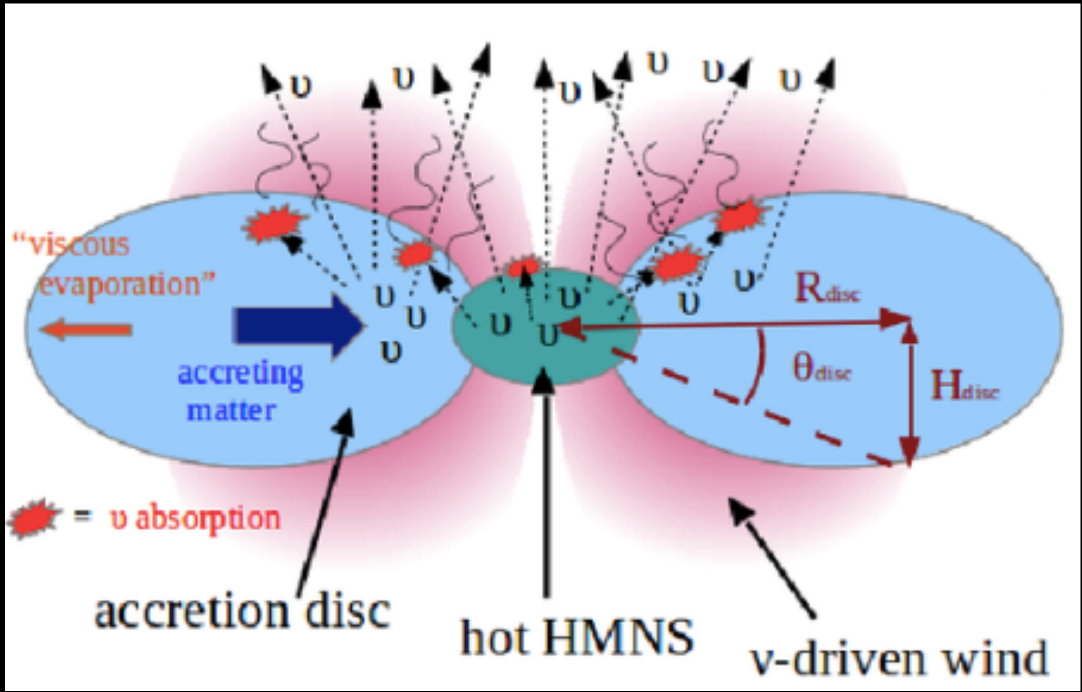

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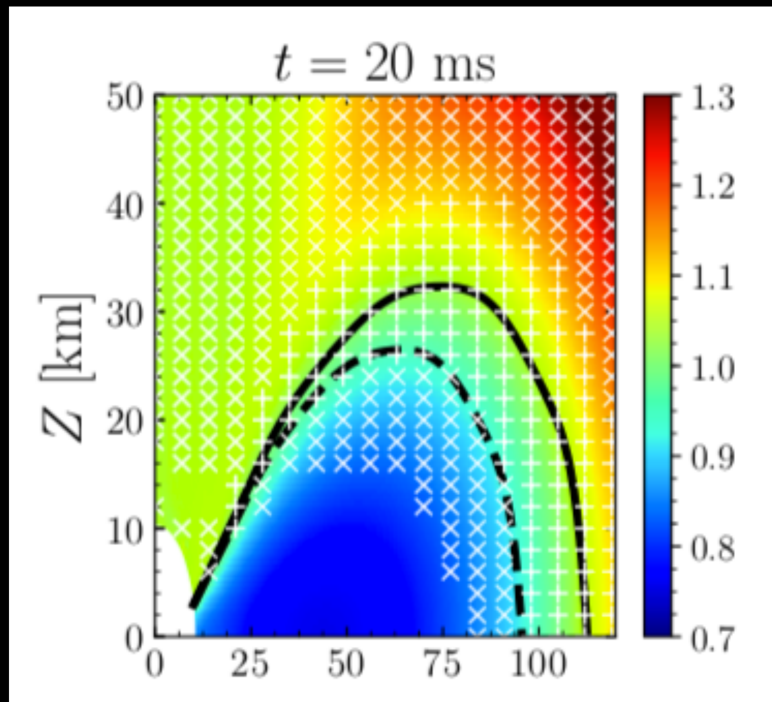
- Hot hyper massive NS and the accretion disk emit a huge number of neutrinos

Just+2022 (also Li+2021, Fernandez+2022, Grohs+2022,)

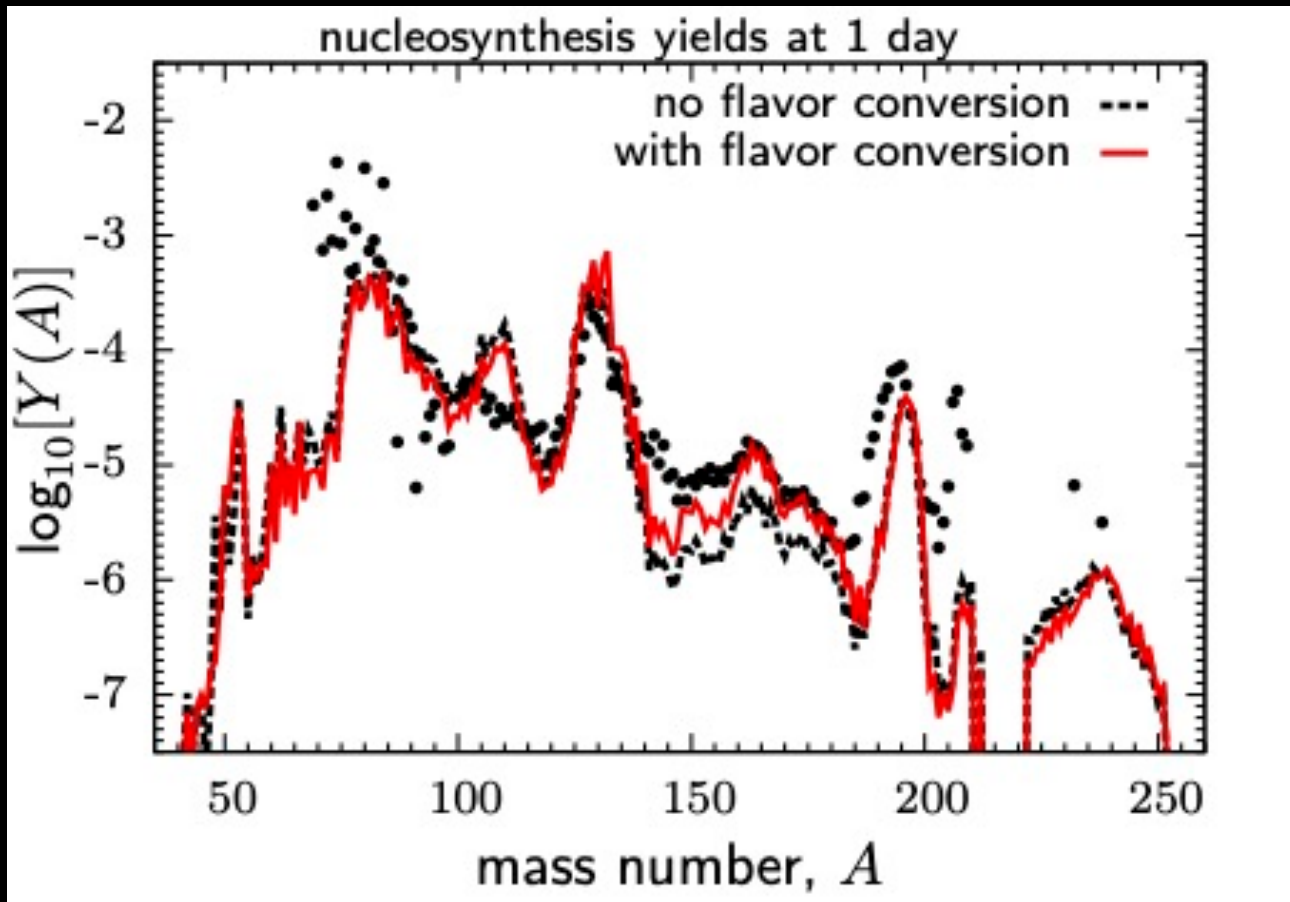


- Fast modes can occur in a wide region even inside the disk

- Any self-consistent neutrino transport should implement fast conversions.

Neutron Star Mergers

- We perform simulations with self-consistent neutrino transport
- The presence of fast conversions inside the torus opens up a new cooling channel
- The impact of the fast modes remains small on the Y_e due to a sort of self-regulating mechanism



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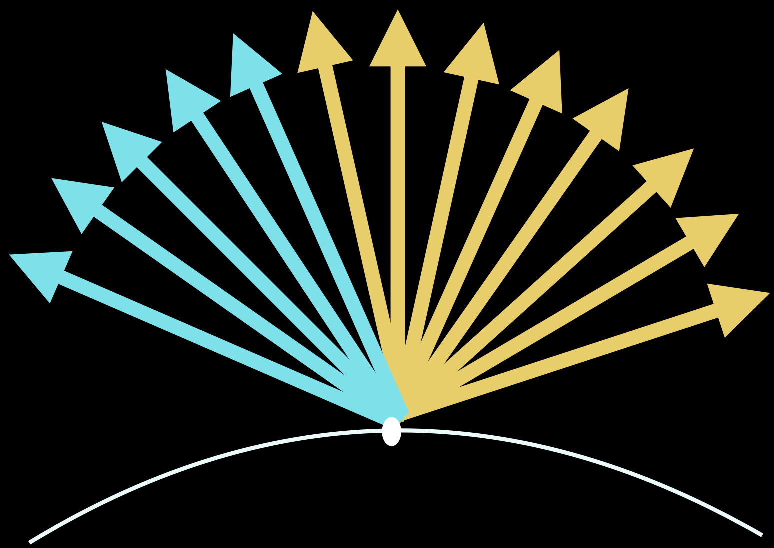


Fast Flavor Conversions

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

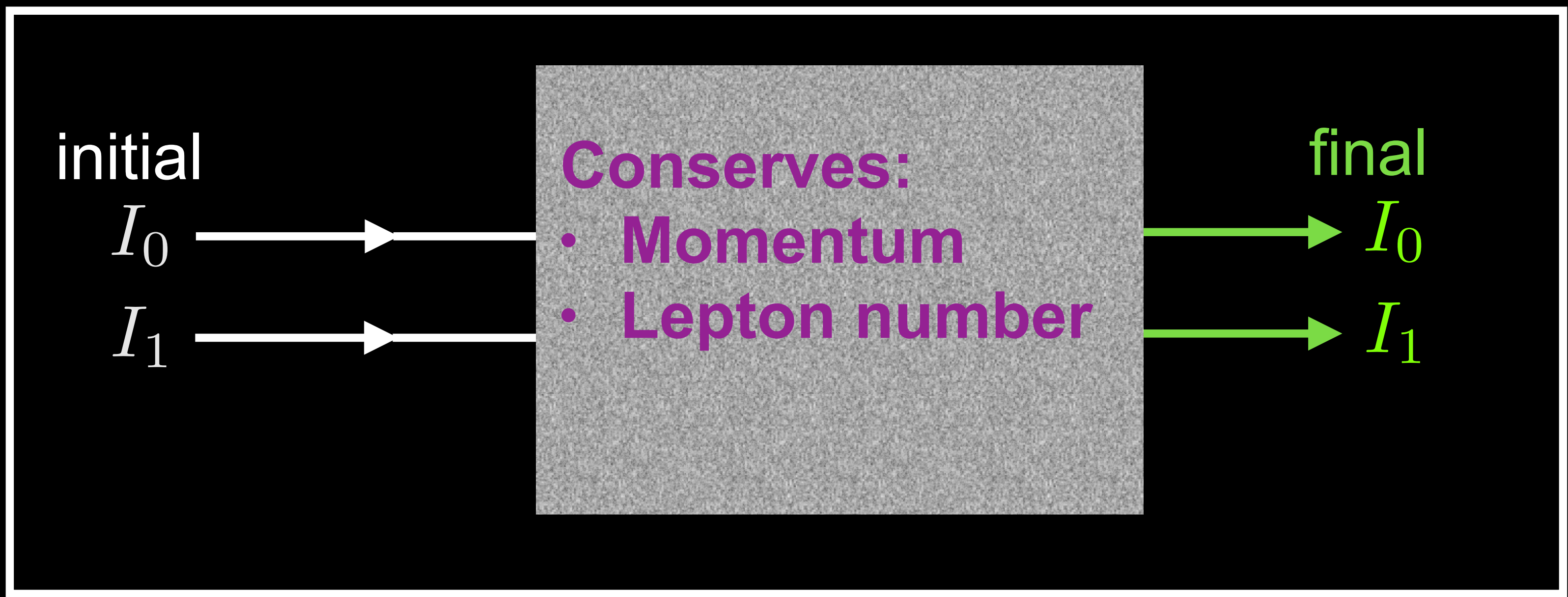
$$I_n = \int \mathrm{d}\cos\theta_\nu \;\; \cos^n\theta_\nu \;\; f_\nu(\cos\theta_\nu)$$

- We can still make progress!

Dasgupta+2018; Abbar2020; Johns+2021; Richers2022;

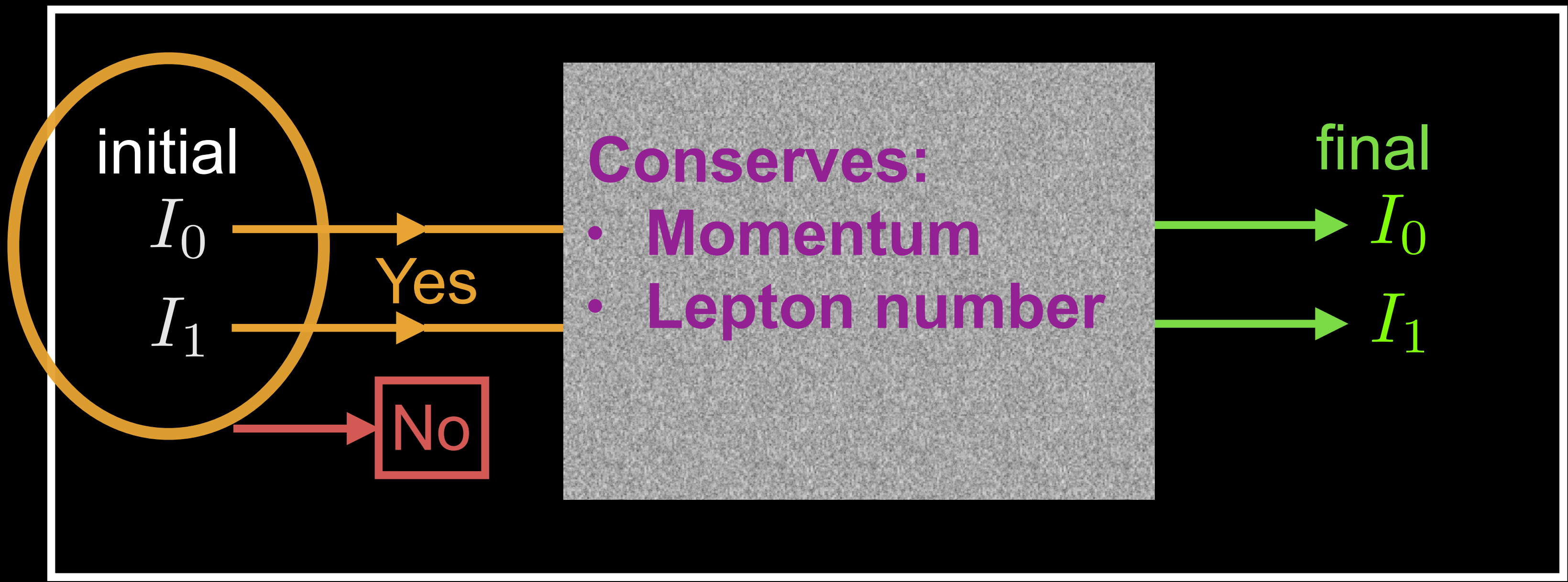
- But these methods are normally inefficient and very slow

- FFC can not be detected on the fly



Application of Machine Learning

- A classification problem!



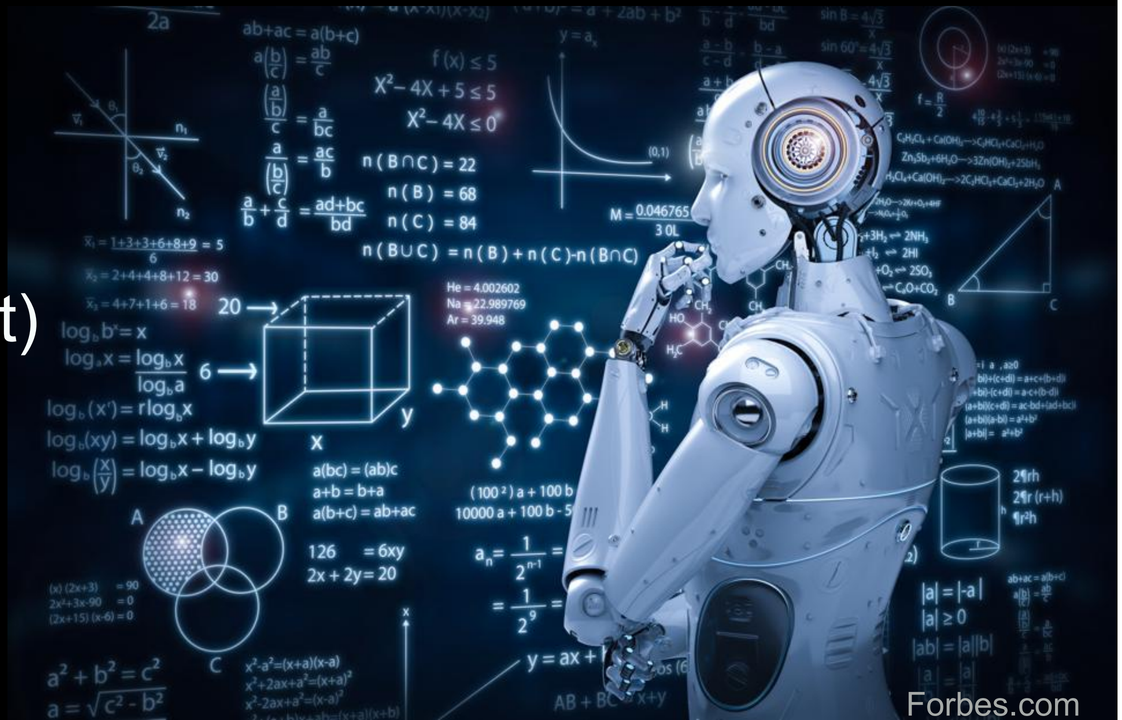
Application of Machine Learning

- Machine learning can help us

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

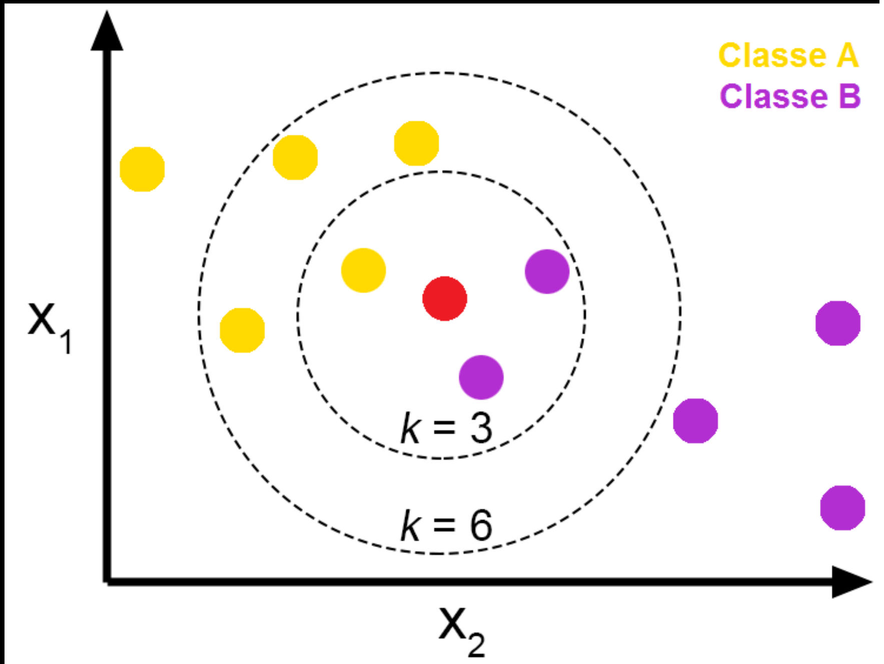
- A number of ML algorithms out there. I here introduce:

    - KNN
    - Decision Tree
    - Naive Bayes
    - SVM
    - Logistic Regression



KNN

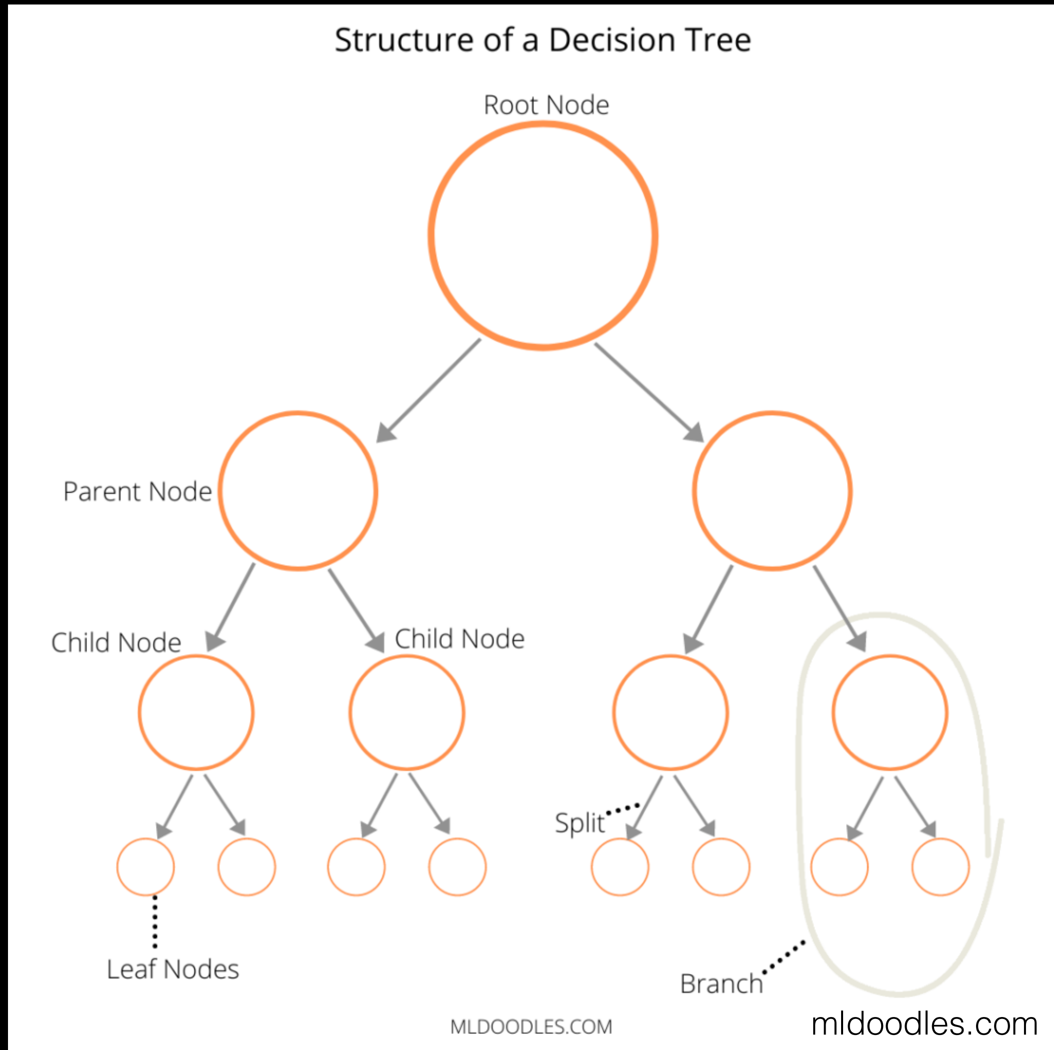
- KNN is one of the simplest forms of machine learning algorithms mostly used for classification. It **classifies the data point on how its neighbor is classified**.



townrdsdatascience.com

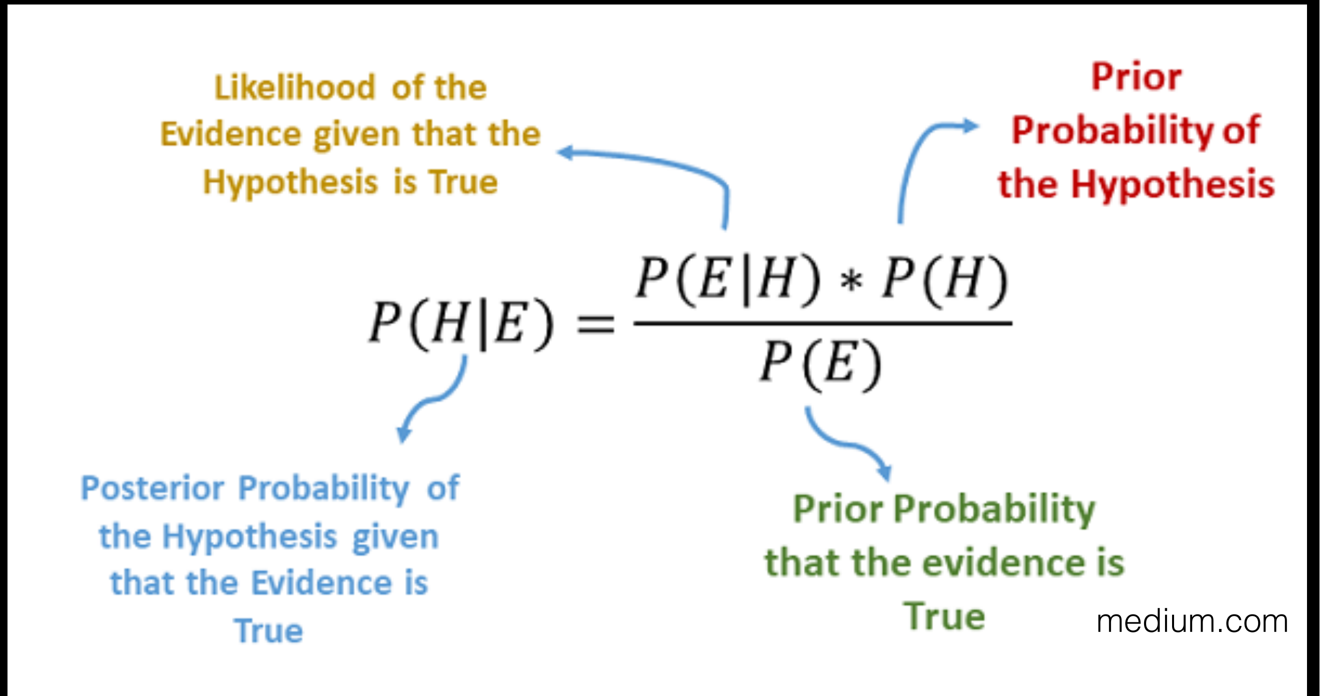
Decision Tree

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



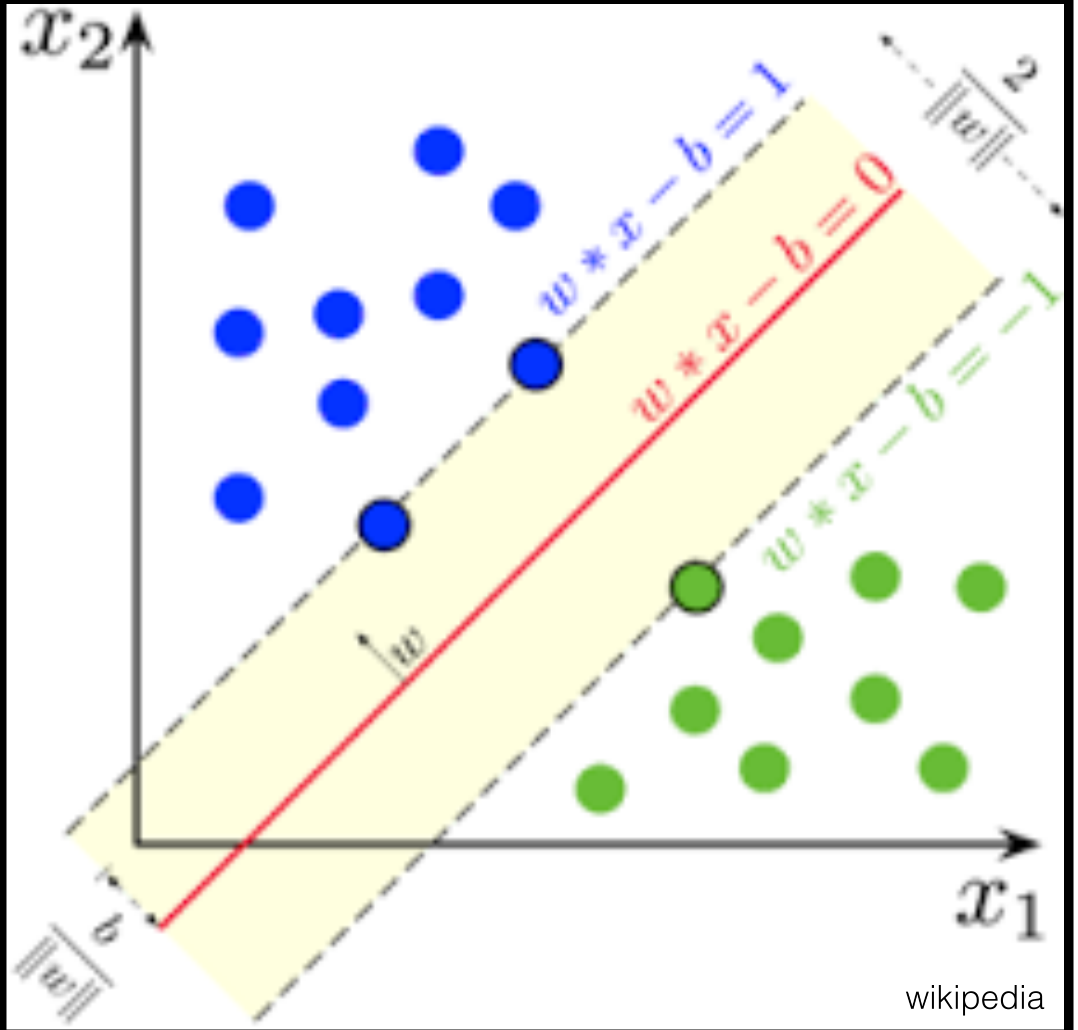
Naive Bayes

- Naive Bayes classifier is a probabilistic machine learning model which is based on the Bayes theorem



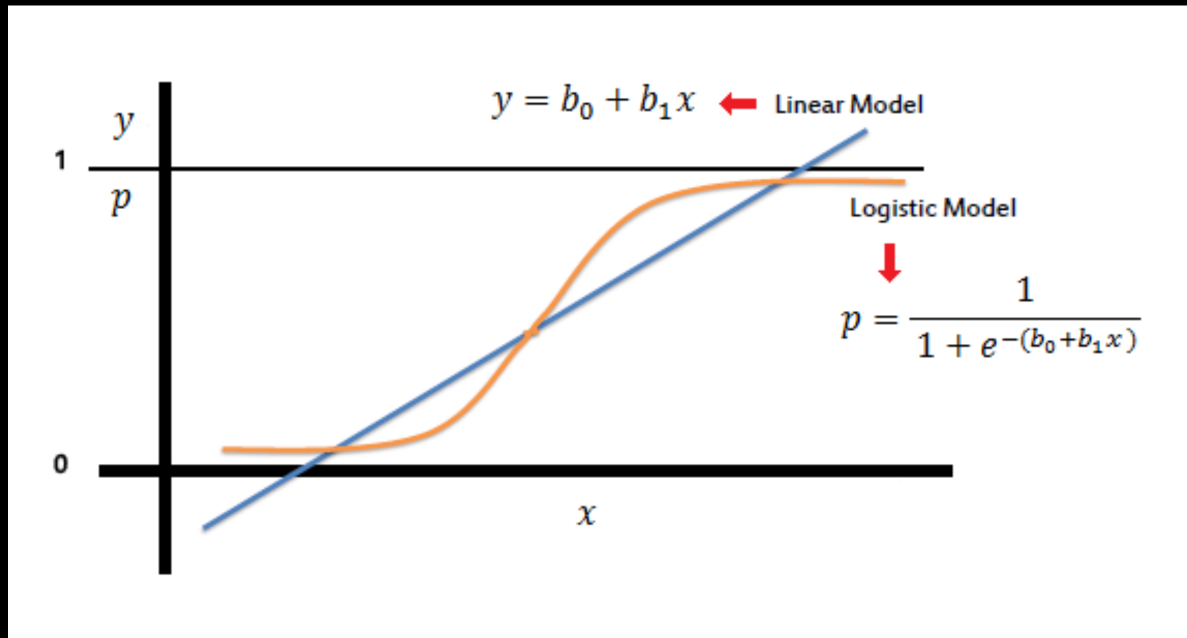
SVM

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



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

Application of Machine Learning

- For training, we use analytical maximum-entropy distribution

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

Application of Machine Learning

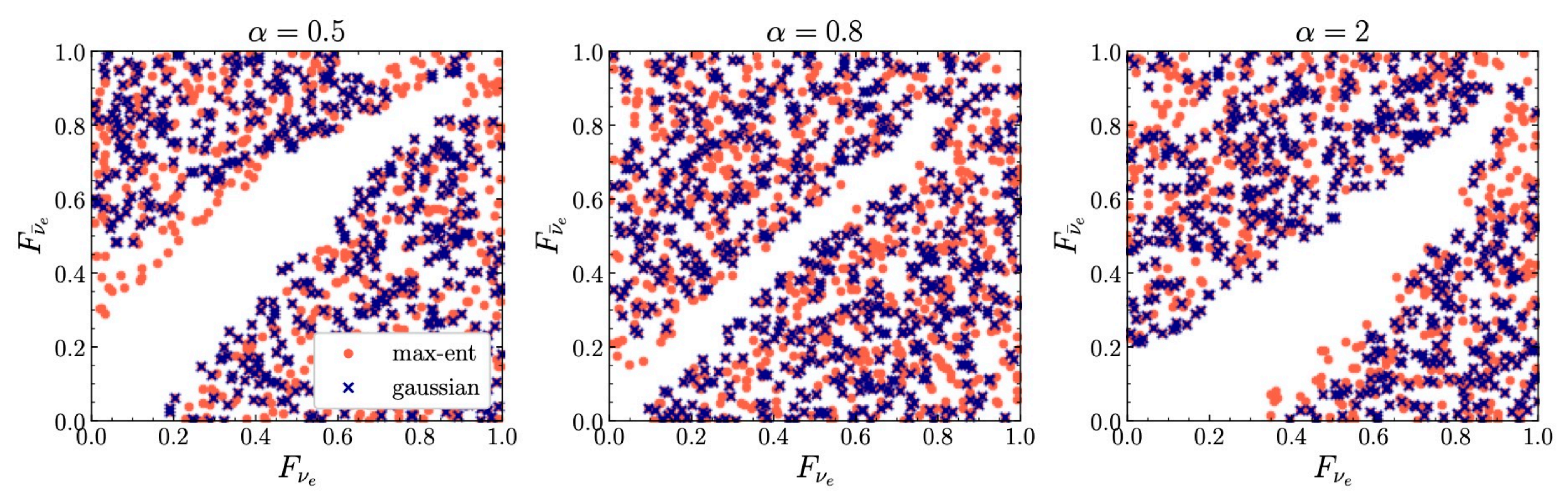
- For training, we use analytical maximum-entropy distribution

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

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

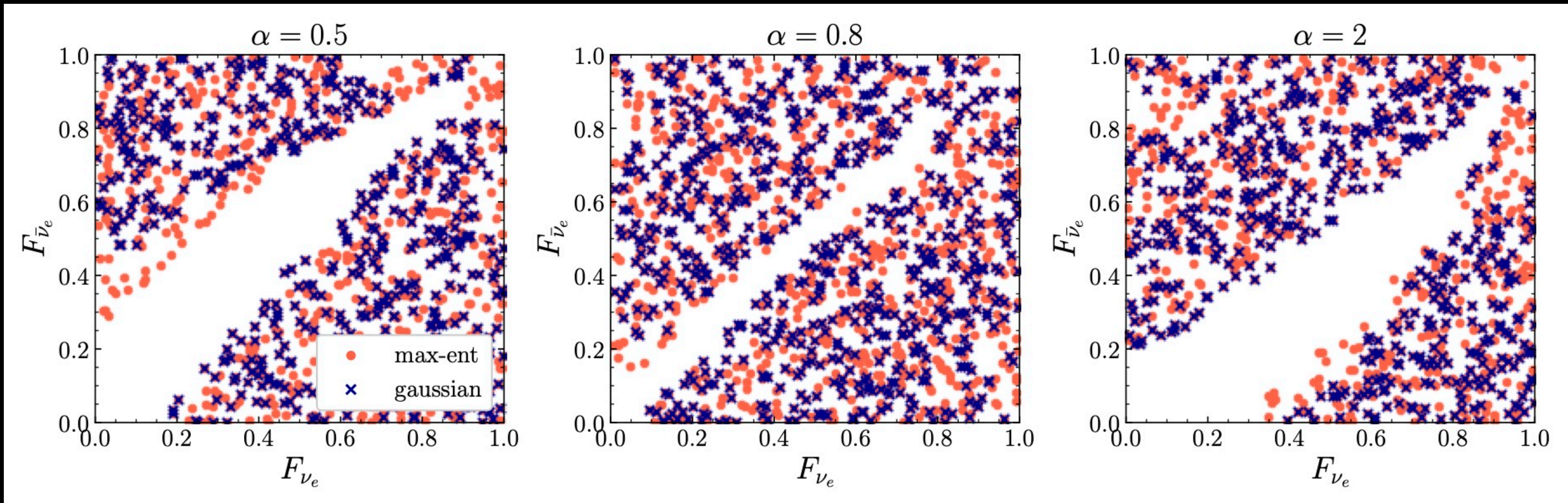
- We have four feature here: I_0 and I_1 for neutrinos and antineutrinos (one is redundant)

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



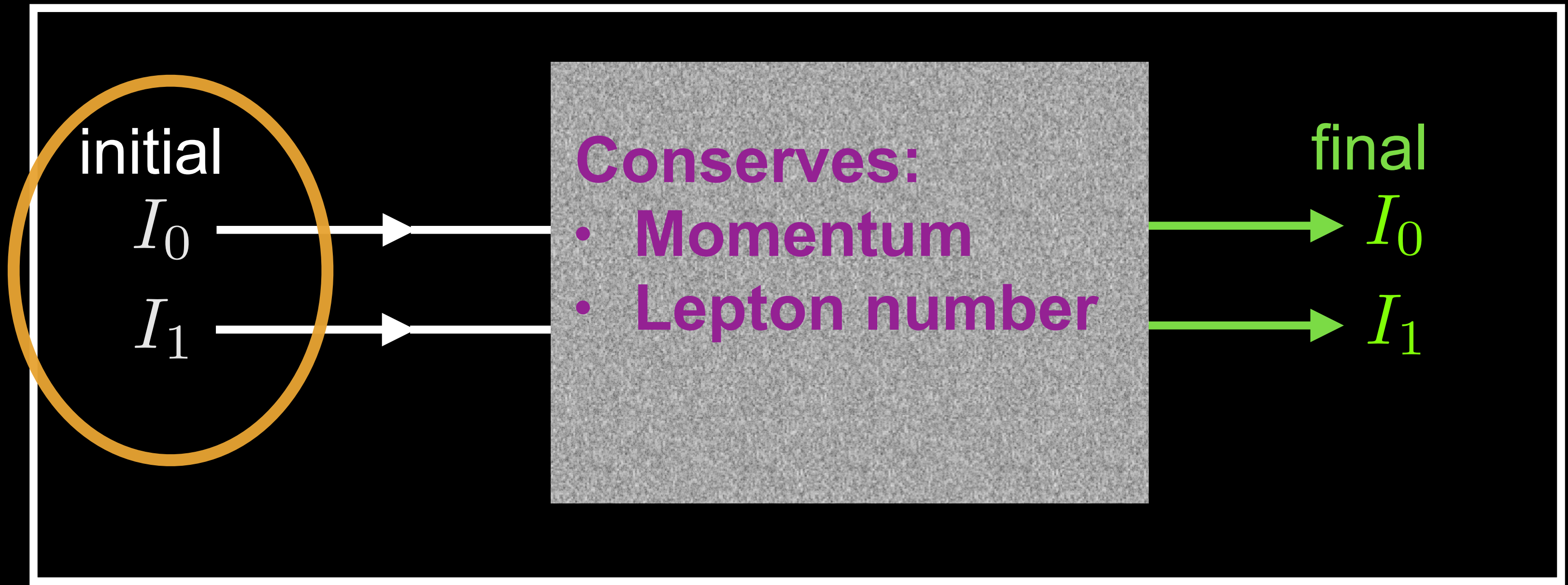
Application of Machine Learning

	accuracy
• KNN	~ 95%
• Decision Tree	~ 92%
• Naive Bayes	~ 90%
• SVM	~ 94%
• Logistic Regression	~ 94%



Application of Machine Learning

- Machine learning methods prove to be very promising regarding the detection of FFI



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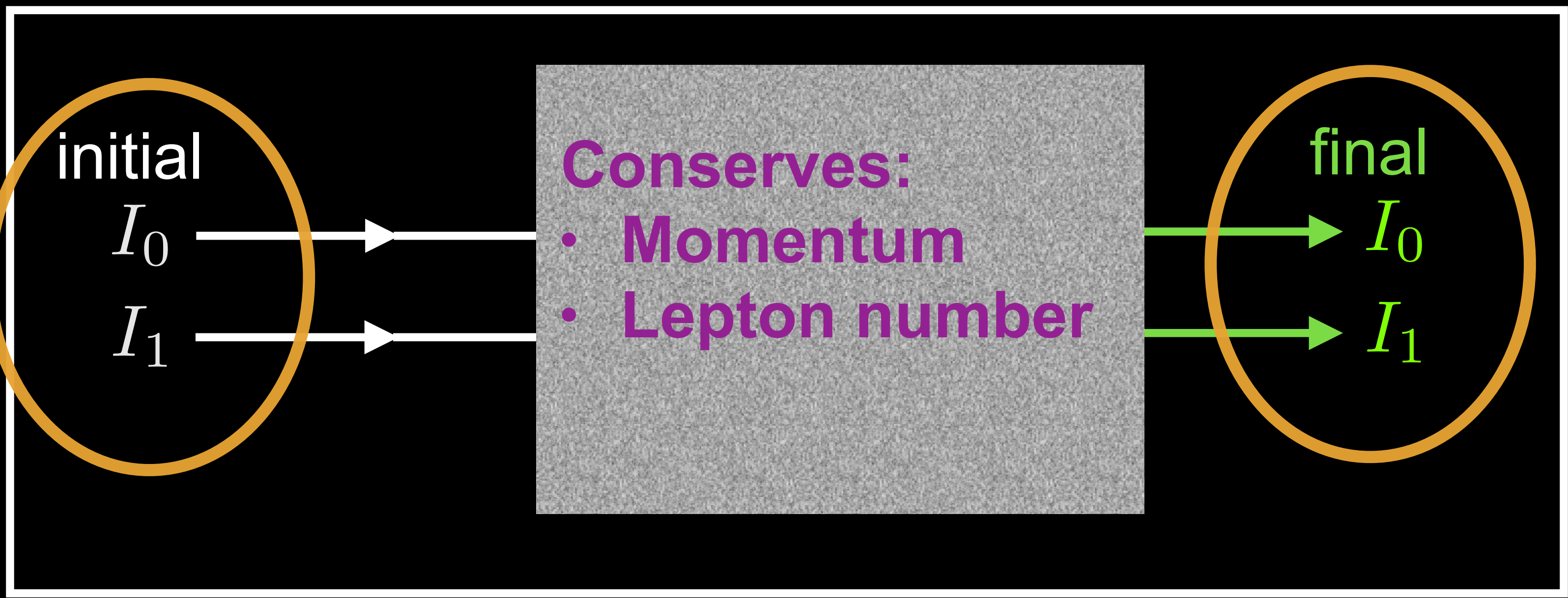
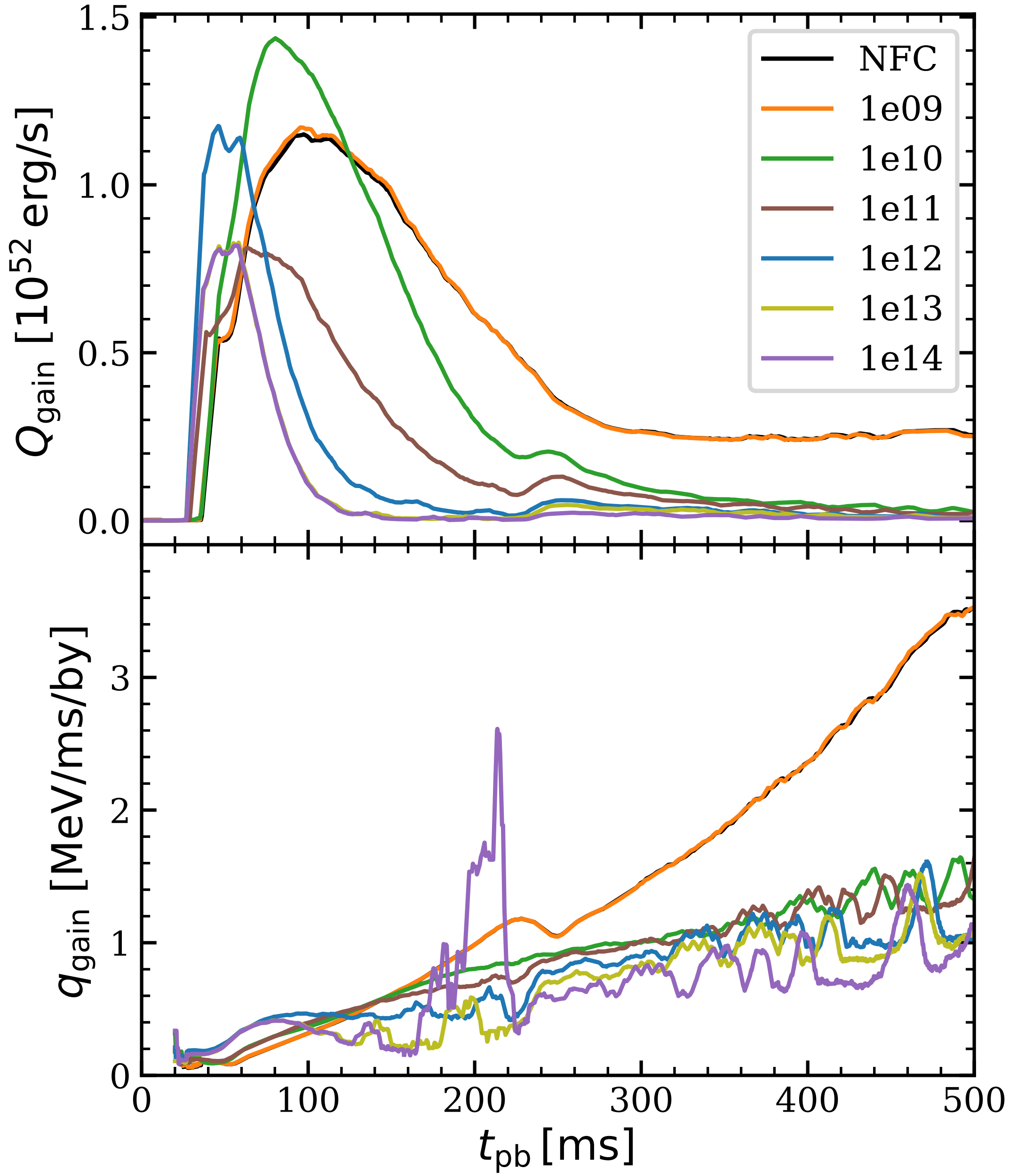
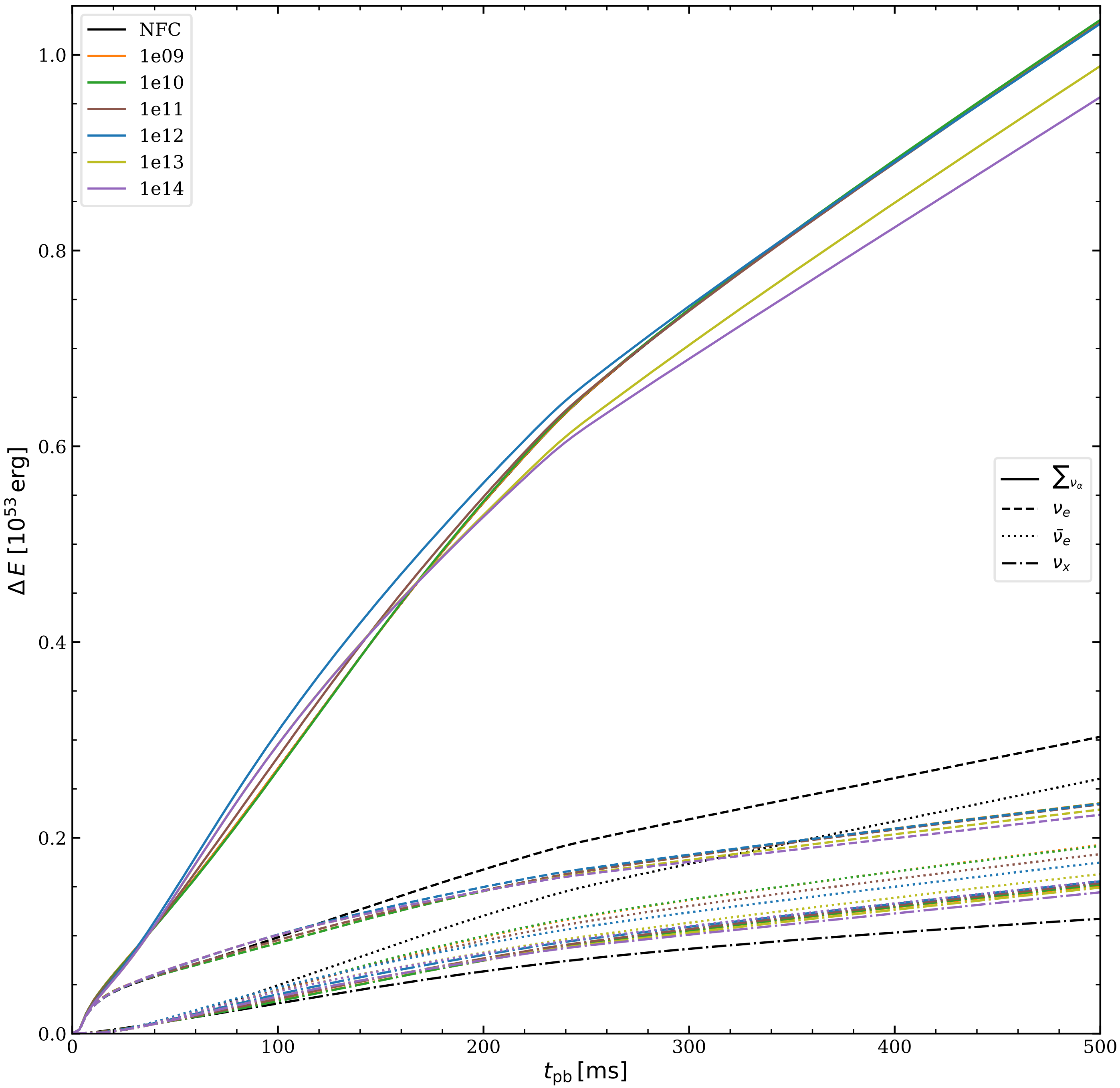
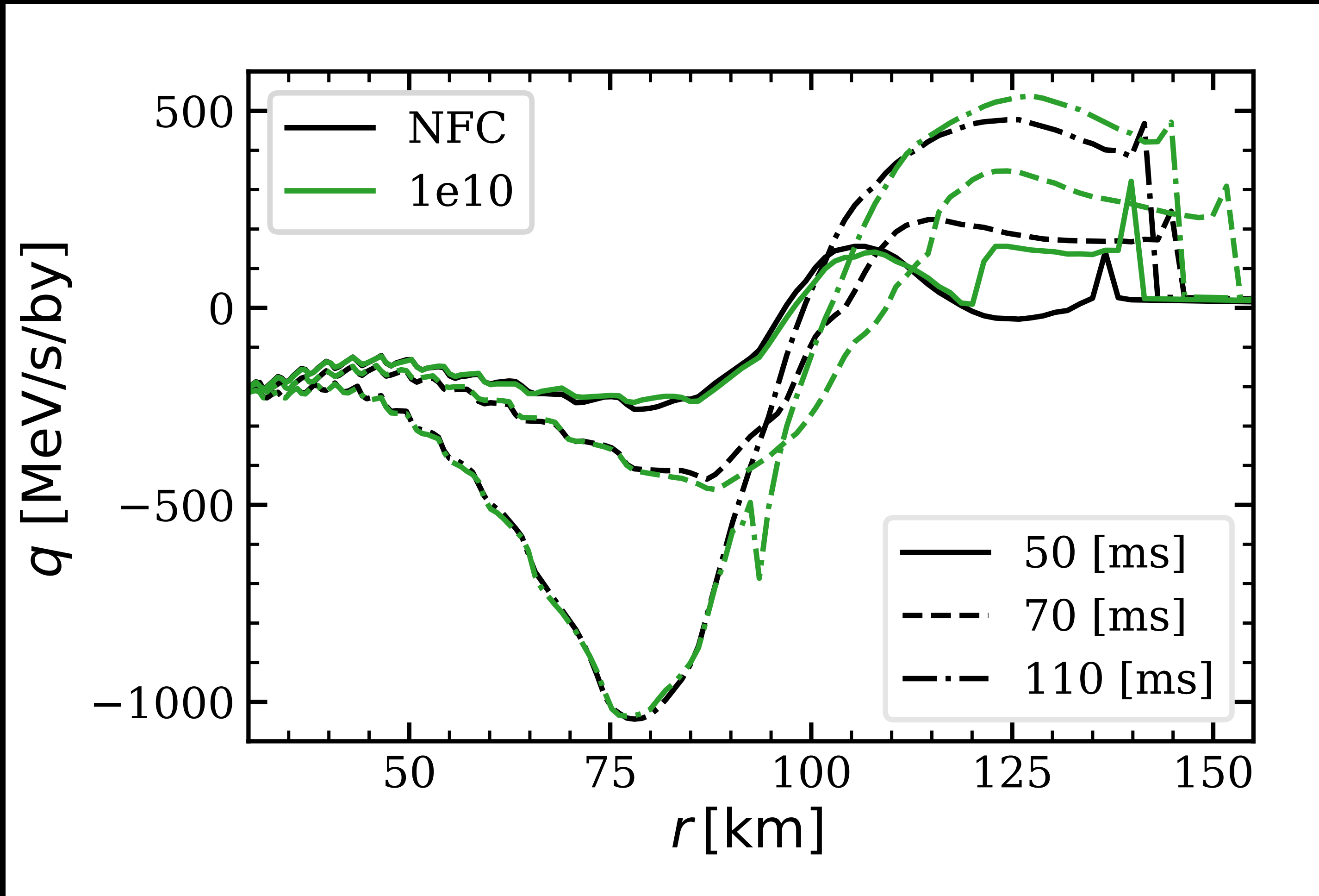




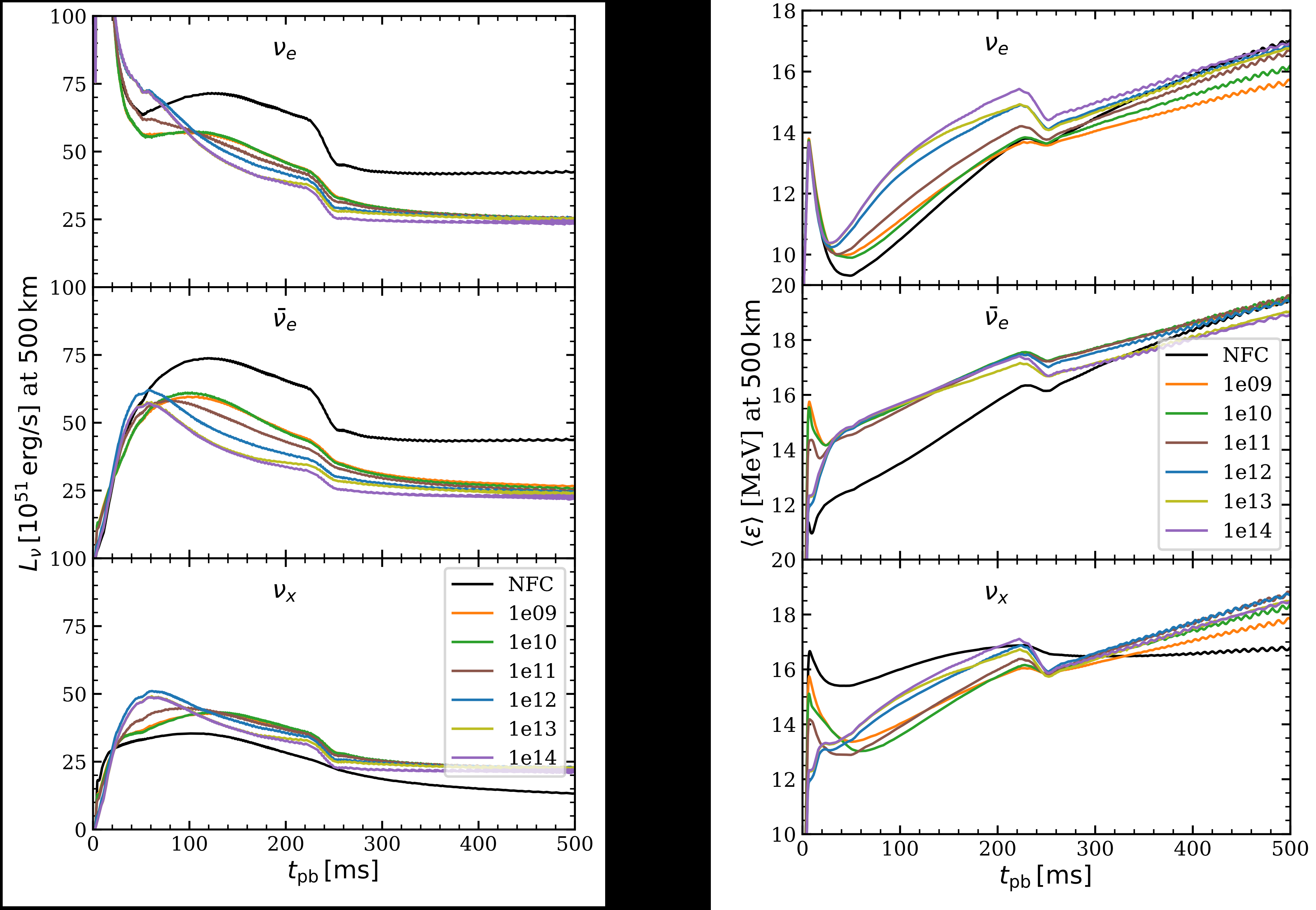
NFC
1e09
1e10
1e11
1e12
1e13
1e14
$Q_{\rm gain}$ [10^{52} erg/s]
0.0
0.5
1.0
1.5
$q_{\rm gain}$ [MeV/ms/by]
0
1
2
3
0
100
200
300
400
500
$t_{\rm pb}$ [ms]



NFC
1e09
1e10
1e11
1e12
1e13
1e14
$\sum_{\nu_\alpha}$
ν_e
$\bar{\nu}_e$
ν_x
$\Delta E\ [10^{53}\ \mathrm{erg}]$
$t_{\mathrm{pb}}\ [\mathrm{ms}]$
0.0
0.2
0.4
0.6
0.8
1.0
0
100
200
300
400
500



NFC
1e10
50 [ms]
70 [ms]
110 [ms]
500
0
−500
−1000
50
75
100
125
150
q [MeV/s/by]
r [km]



ν_e
$\bar{\nu}_e$
ν_x
$L_\nu\,[10^{51}\,\mathrm{erg/s}]$ at 500 km
$\langle\varepsilon\rangle$ [MeV] at 500 km
t_{pb} [ms]
NFC
1e09
1e10
1e11
1e12
1e13
1e14