# Dynamics of Neutrinos in Neutron Star Mergers

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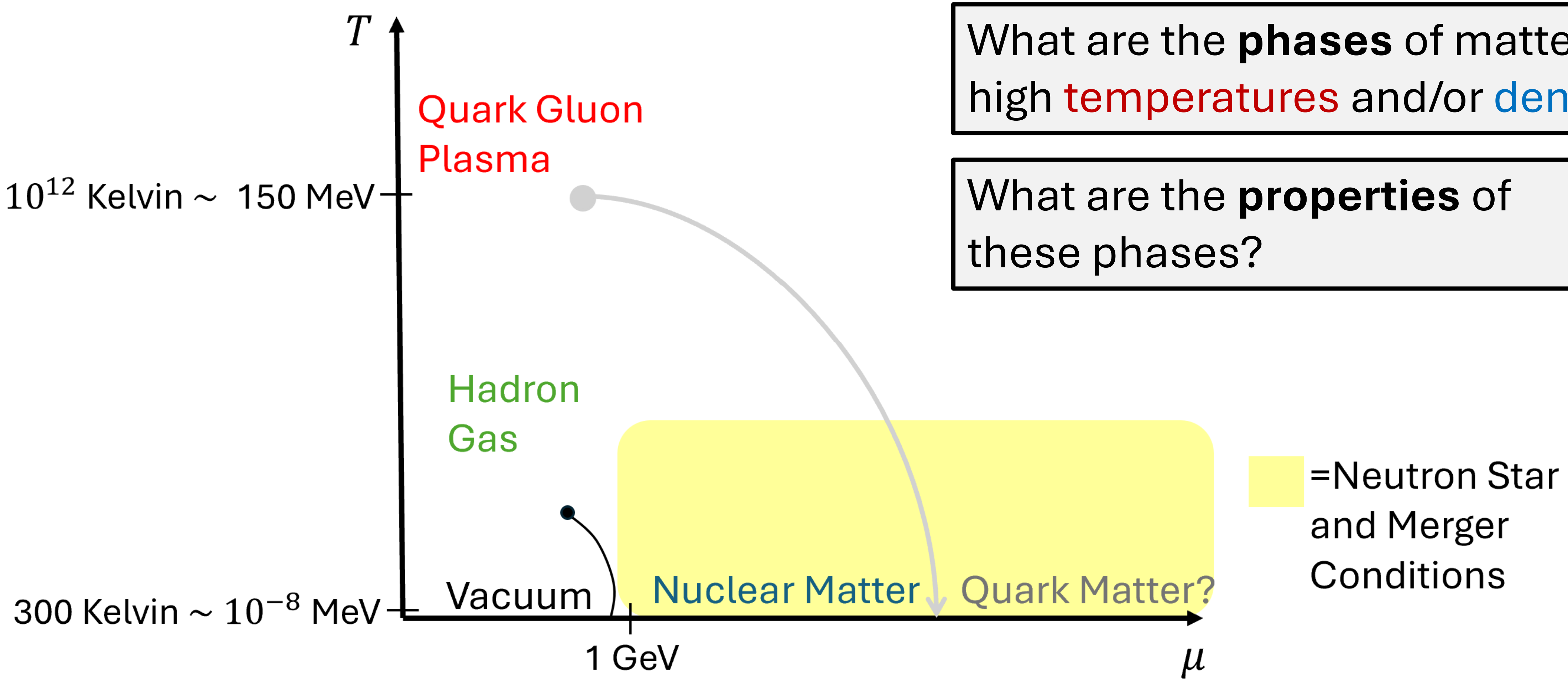
# Outline

Modeling neutrinos correctly in mergers is **important**!
→How do **differences** in the neutrino population affect static and dynamic properties of dense matter?

Present **first results** on a comparison between neutrino population assumptions in neutron star merger simulations

# Phases of Quarks and Gluons




What are the **phases** of matter at high temperatures and/or densities?

What are the **properties** of these phases?

# Method of Attack

- Methods to exactly solve QCD do **not** work at neutron star densities!
- Perturbative methods **only work** at ~ 7 times neutron star densities ($\sim 40\ n_0$)

Microscopic Model → Static and Dynamic Properties → Simulation → Observables

# Microscopic Model Example

**Microscopic Model** → Static and Dynamic Properties → Simulation → Observables

## QMC-RMF 1,2,3,4

Four relativistic mean-field theories informed by chiral effective field theory and astrophysics

- Tabulated at a range of temperatures, densities, and proton fractions
- Provides an equation of state
- Provides particle dispersion relations

**compose.obspm.fr/eos/297**

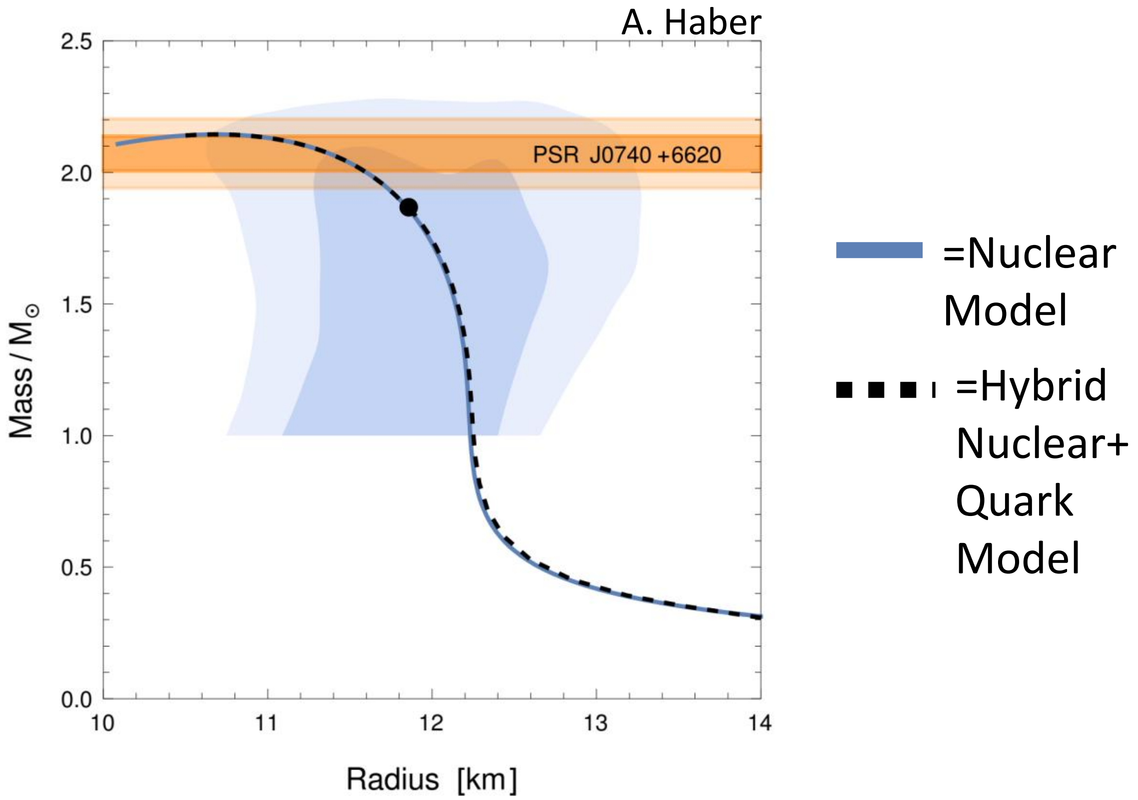
Alford, **Brodie**, Haber, Tews: 2205.10283

# Static Properties of Neutron Star Matter

Microscopic Model → **Static** and Dynamic **Properties** → Simulation → Observables

- Example: The equation of state $P(\rho)$
- Impacts many observables, e.g., stellar mass and radius!

Not informative enough about underlying degrees of freedom

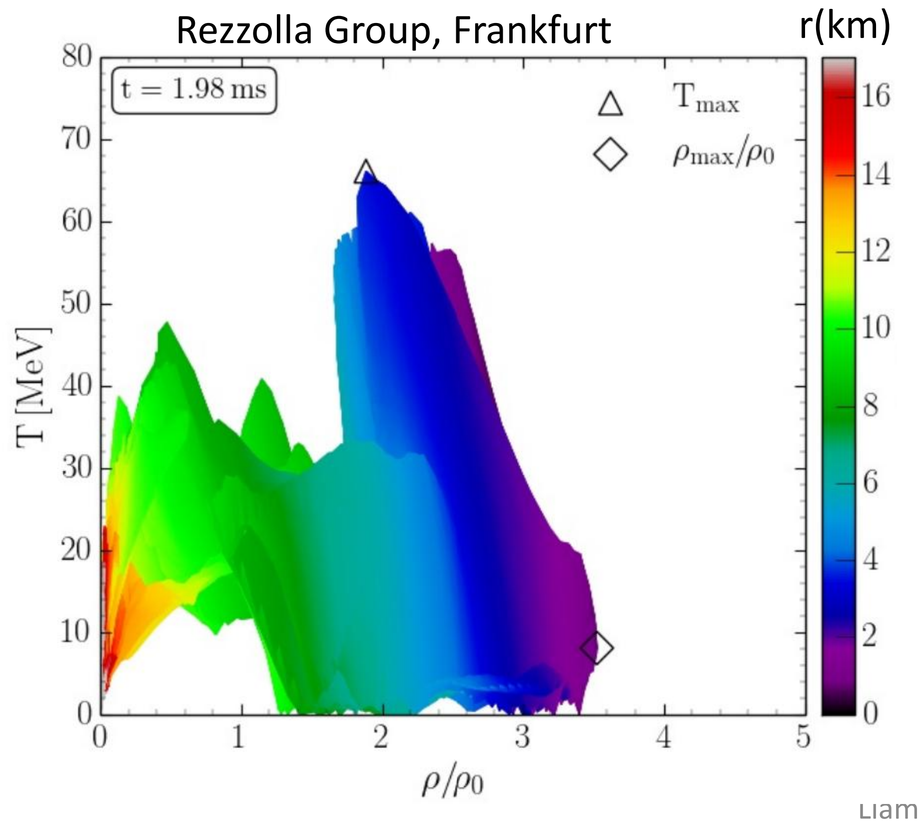


# Dynamic Properties of Neutron Star Matter

Microscopic Model → Static and **Dynamic Properties** → Simulation → Observables

Dynamics are more **sensitive** to the degrees of freedom! Which ones to consider?

Rezzolla Group, Frankfurt




Temperature Gradients → Thermal Conductivity

Density Gradients → Bulk Viscosity

**Gradients** in space (and time)
→ Need **relevant** equilibration processes in simulations!

# Importance of Neutrinos

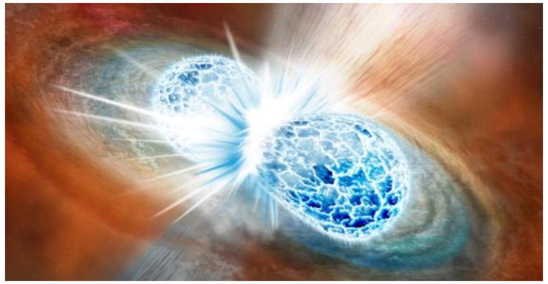
- **Longest** mean free path compared to neutrons, protons, electrons

- Assumptions about the neutrino population impact:

1. Equilibrium proton fraction → **Equation of state**
2. Proton fraction equilibration → **Gravitational-wave signal**

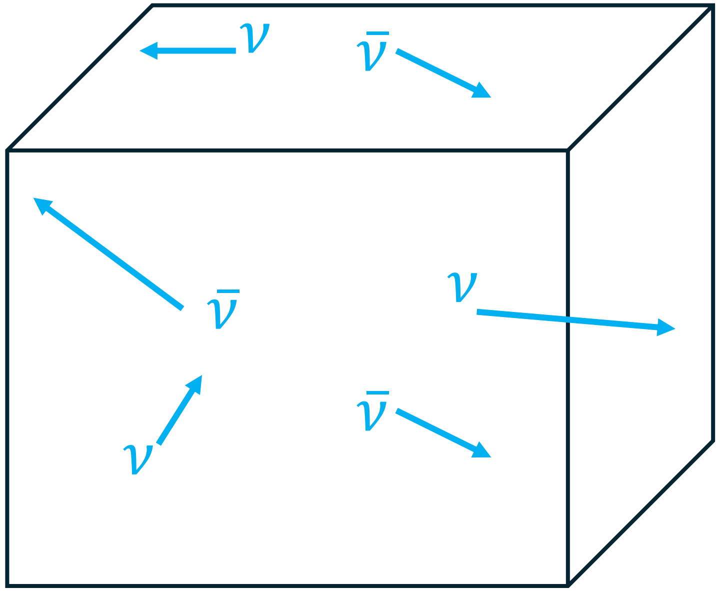
Important to get neutrino physics right!

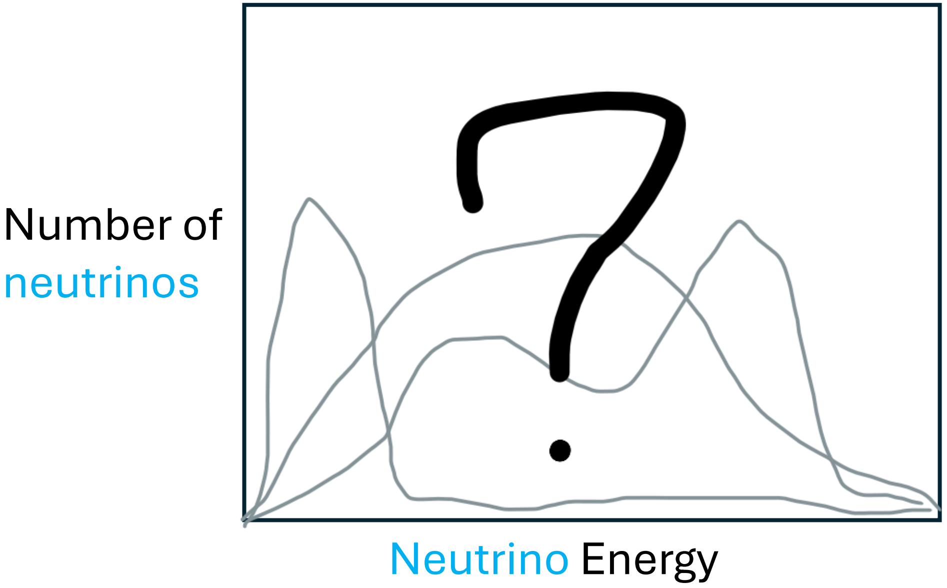
# What is the neutrino population?



Robin Dienel/Carnegie Institution for Science

Consider a single fluid cell in a merger simulation



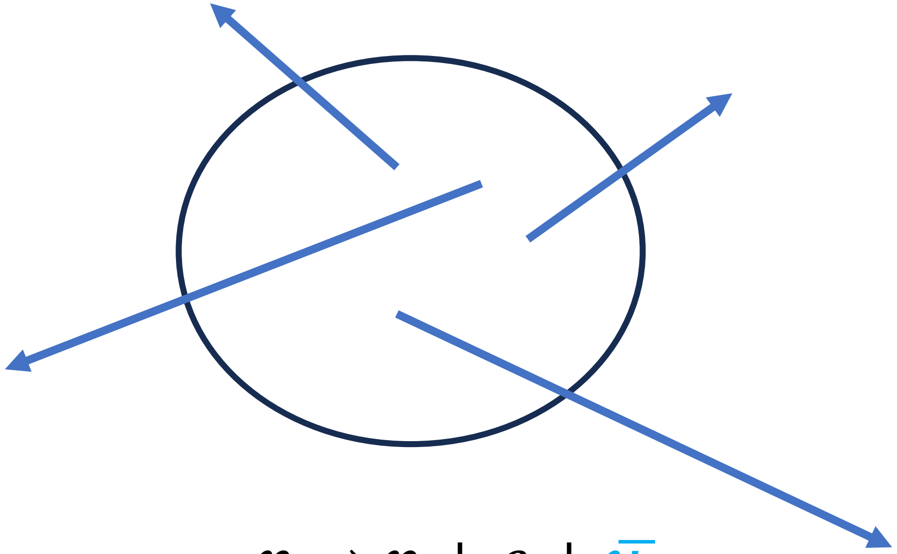

How do **differences** in the neutrino population affect the static and dynamic properties of matter in a merger?

# Neutrinos: Free, Trapped, or …?

Tractable Limits Commonly Used

## Free

Leave the Merger

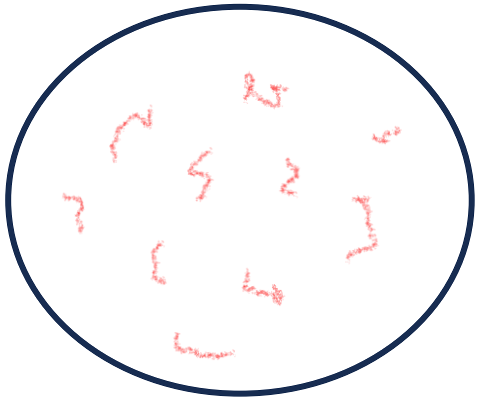


$$n \rightarrow p + e + \overline{\nu_e}$$

$$p + e \rightarrow n + \nu_e$$

## Trapped

Thermal Equilibration → Form Fermi-Dirac



$$n \leftrightarrow p + e + \overline{\nu_e}$$

$$p + e \leftrightarrow n + \nu_e$$

# Other Weak Interaction Processes

Absorption: $\nu + n \rightarrow p + e^-$

Scattering: $\nu + n \rightarrow \nu + n$

Pair annihilation: $\nu + \bar{\nu} \rightarrow e^+ + e^-$

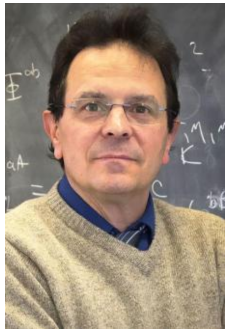
Can consider reactions including muons, pions, quarks,…

Neutrino opacities in two-flavor color-superconducting quark matter

(with **Marco Hofmann** (Darmstadt) & others, 2509.04240)

$$\nu_l + d_b \rightarrow l^- + u_b$$

$$\nu_l + s_b \rightarrow l^- + u_b$$



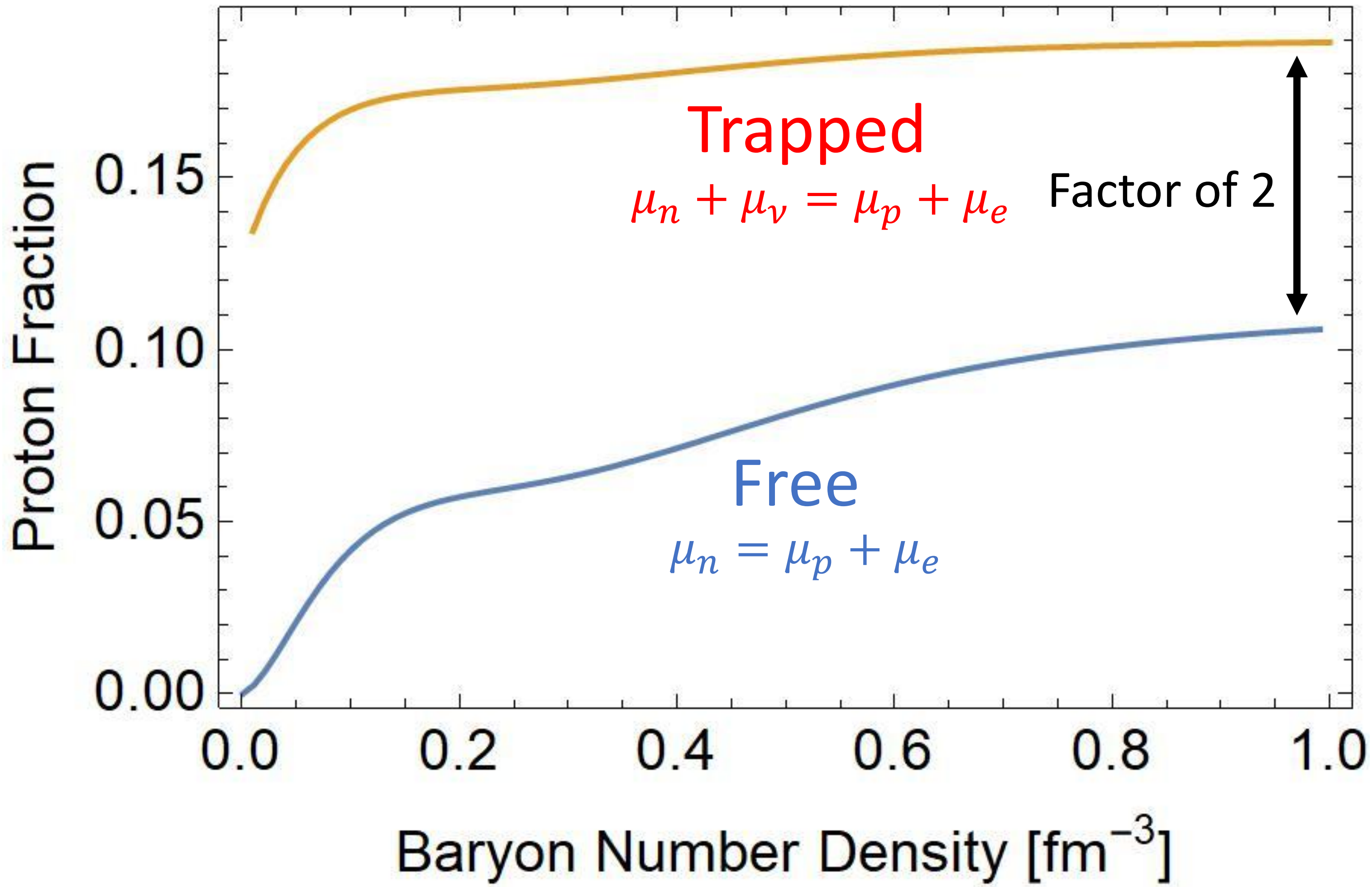
Enhanced (10x) neutrino emission compared to standard direct Urca!

(with **Rob Pisarski** (Brookhaven), 2501.02055, accepted by PRL)

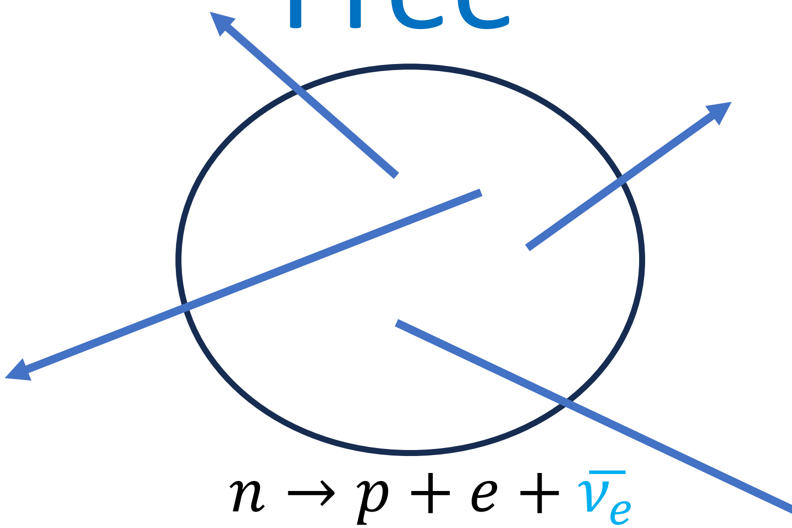
Standard: $n(939) \rightarrow p(939) + e^- + \bar{\nu}_e$

New: $n(1535) \rightarrow p(939) + e^- + \bar{\nu}_e$

# Impact on the Equation of State



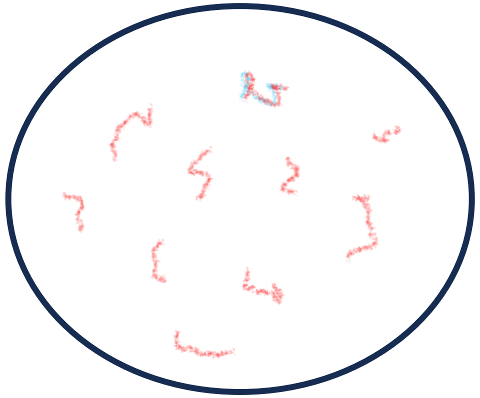

## Free



$$n \rightarrow p + e + \bar{\nu}_e$$

$$p + e \rightarrow n + \nu_e$$

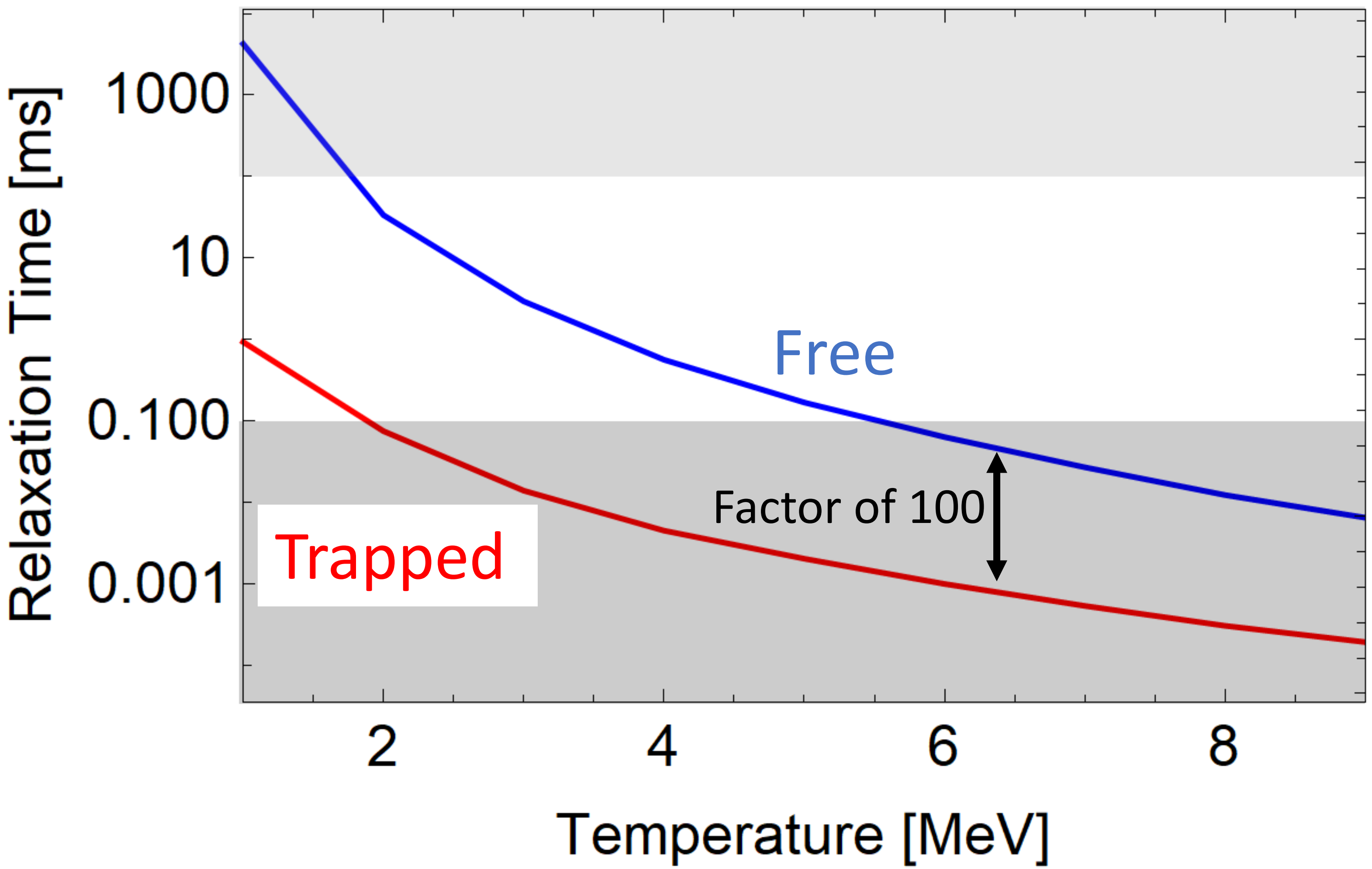
## Trapped

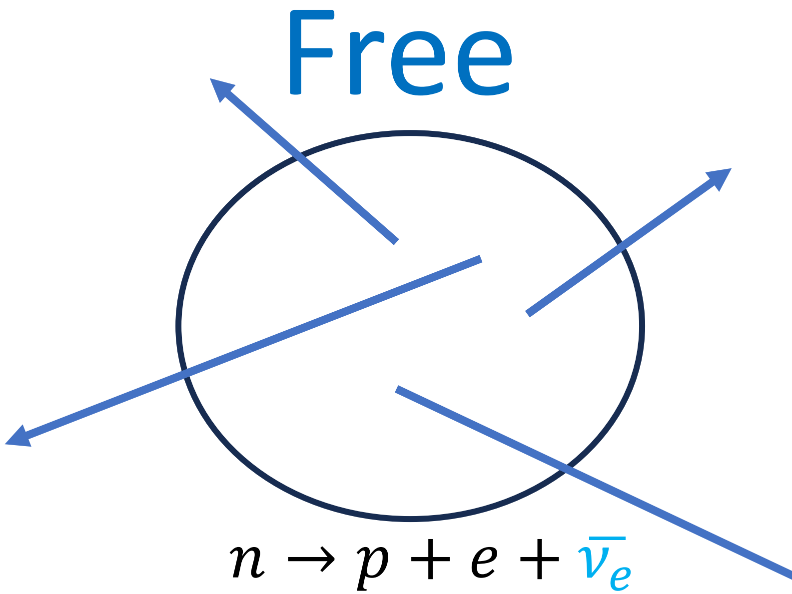


$$n \leftrightarrow p + e + \bar{\nu}_e$$

$$n + \nu_e \leftrightarrow p + e$$

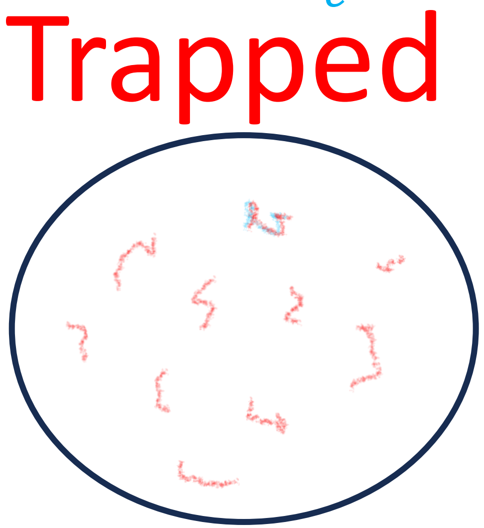
# How quickly does the proton fraction change?




$n \rightarrow p + e + \bar{\nu}_e$

$p + e \rightarrow n + \nu_e$




$n \leftrightarrow p + e + \bar{\nu}_e$

$n + \nu_e \leftrightarrow p + e$

# Bridging the Gap Between Free and Trapped

Microscopic Model → Static and Dynamic Properties → **Simulation** → Observables

Monte Carlo: Solve 7-dimensional Boltzmann equation to get an **energy-dependent** neutrino distribution $f_{\nu}(t, \vec{x}, \vec{p})$. Computationally Expensive.

Another Method:

- Gray Moment: Evolves energy-integrated moments of the neutrino distribution

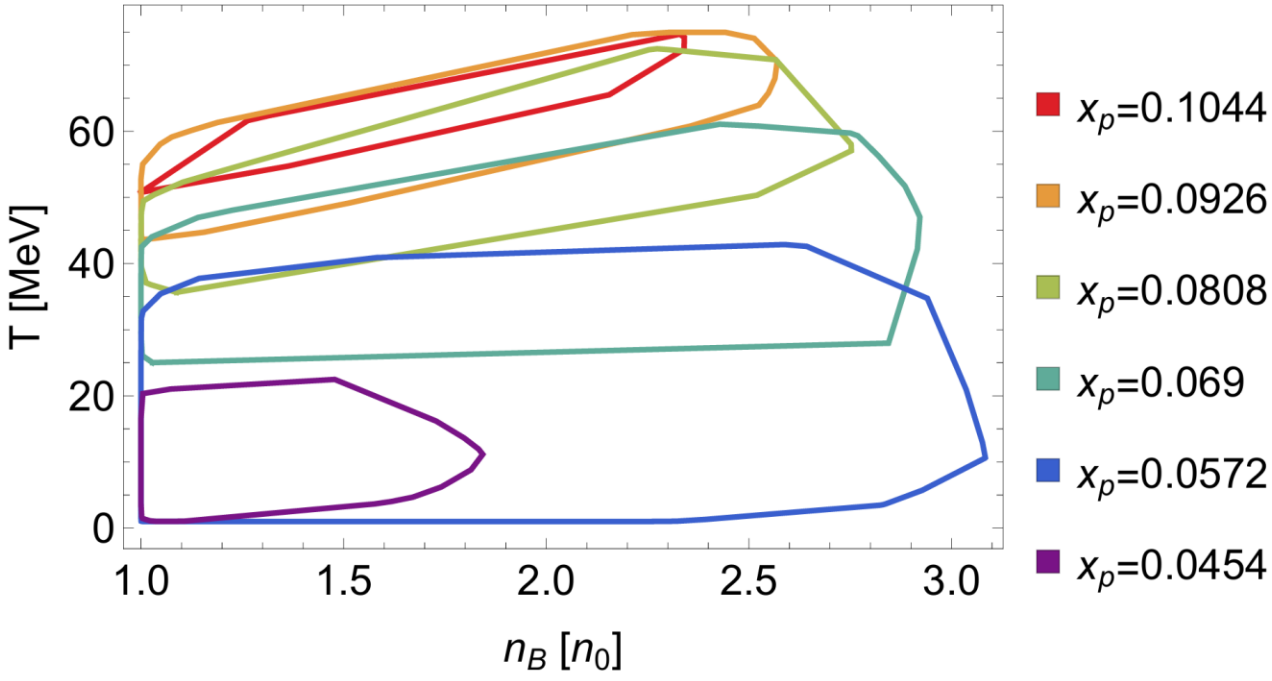
→ Total neutrino energy density, flux, etc. Assume neutrinos are Trapped to get average quantities. Less computationally expensive.

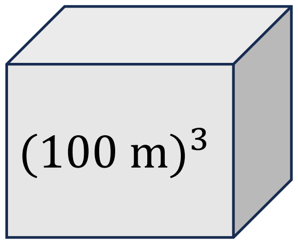
Compare Monte Carlo neutrino distributions to Trapped neutrino population assumption

# Fluid Landscape of Merger

Simulation data from Francois V. Foucart (UNH)

$t = 1$ ms post merger




Fluid Cell Parameters:

Temperature ($T$), Density ($n_B$), Proton Fraction ($x_p$), Lepton Fraction ($x_L$)

$$x_L = x_e + x_\nu - x_{\bar{\nu}}$$

Fluid cells with same $T, n_B, x_p$ can have different $x_L$

# Monte Carlo vs. Trapped Neutrinos

1) Compare when Trapped should be a good approximation ($\lambda_\nu \ll L_{\rm cell}$)
2) Compare when Trapped **may not** be a good approximation

Quantities to Compare:

- Neutrino number density as a function of energy
- Average neutrino energy
- Average neutrino opacity (inverse mean free path)

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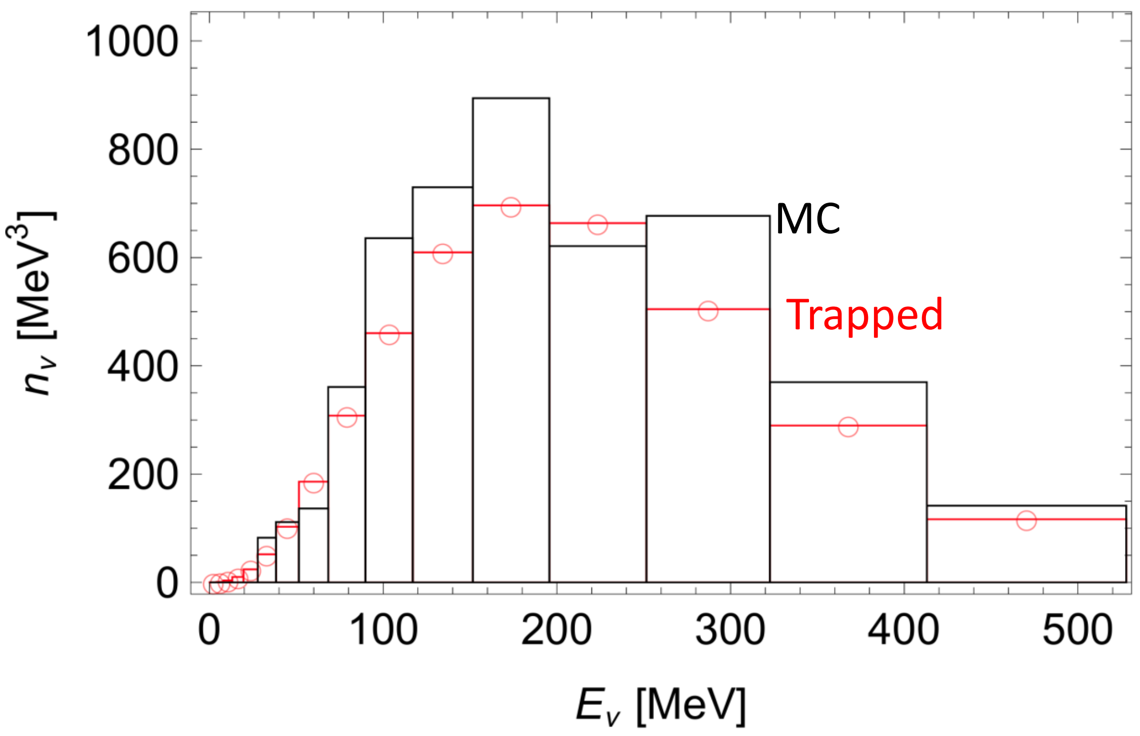
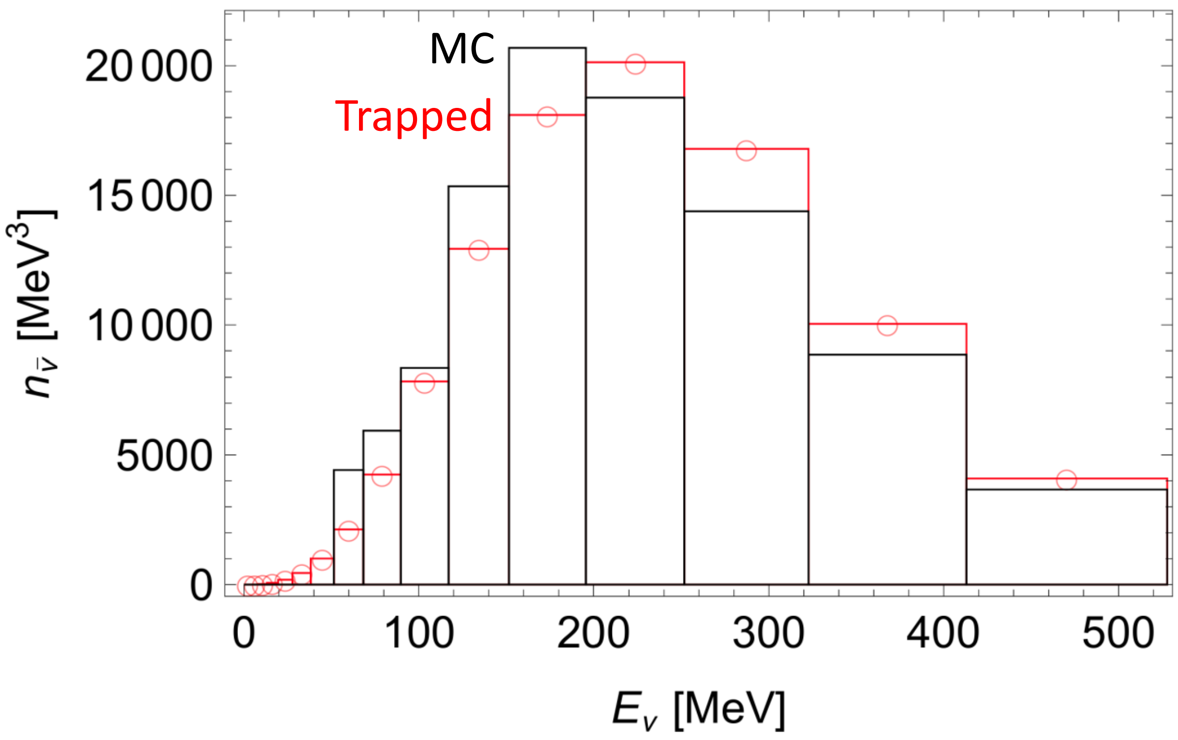
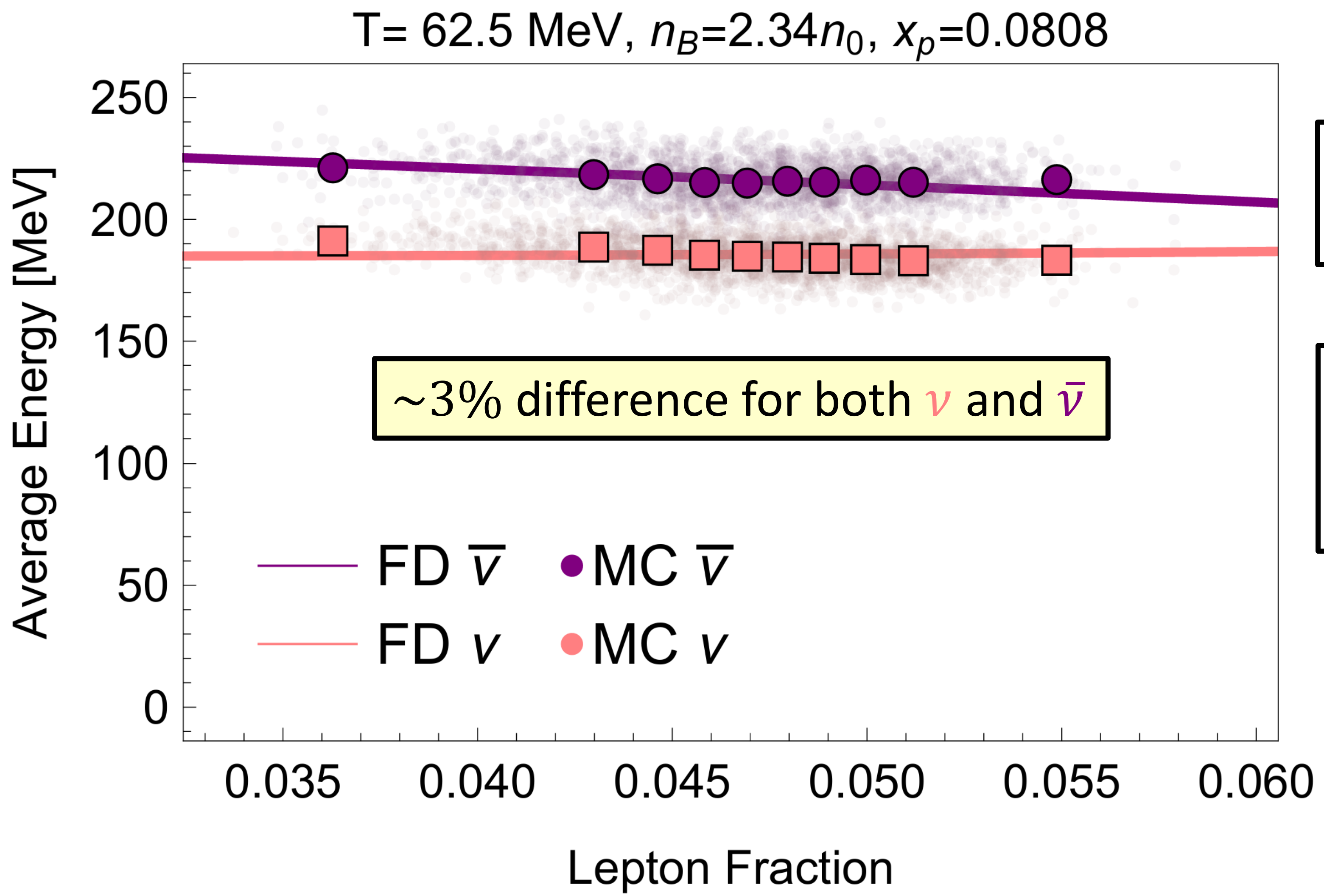
# Monte Carlo vs. Trapped Neutrinos

Sample fluid cell: $T = 62.5$ MeV, $n_B = 2.34 n_0$, $x_p = 0.08$, $x_L = 0.0474$



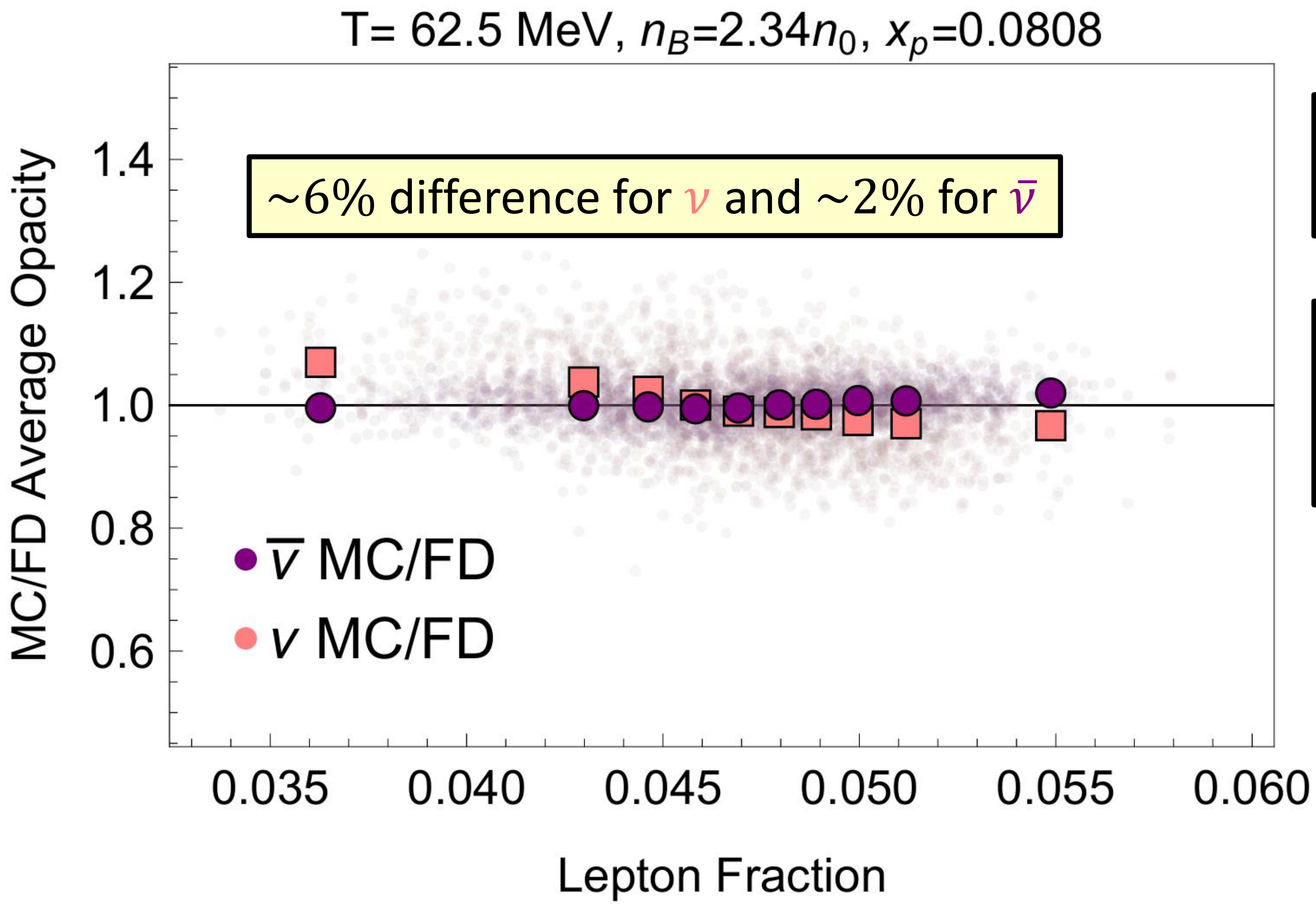
# Result (Trapped=☺): Average Energy




Pale Points: Average energy within single fluid cells

Large Circles/Squares: Average energy within a lepton fraction bin

# Result (Trapped=☺): Average Opacity

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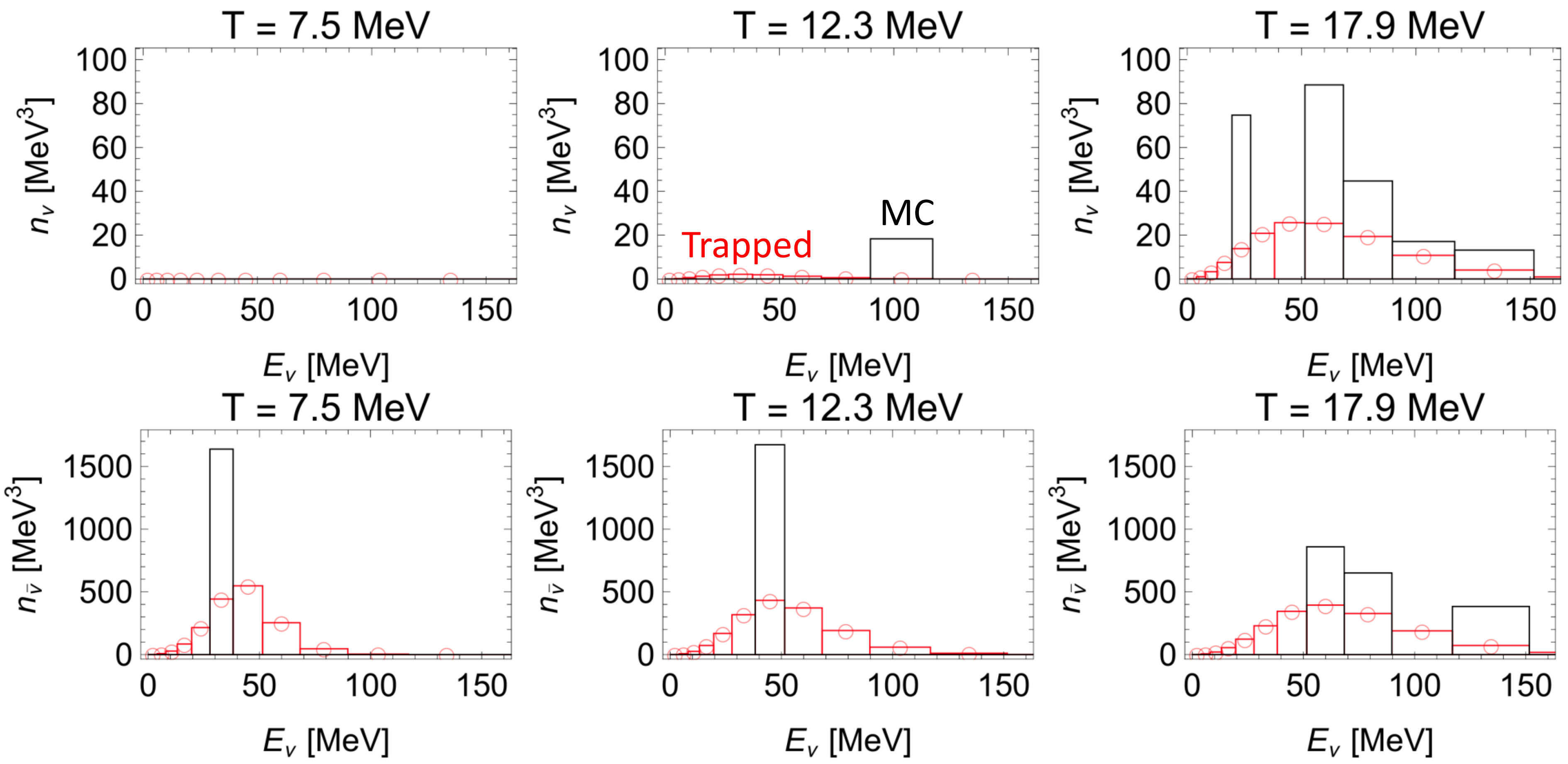
Quantities to Compare:

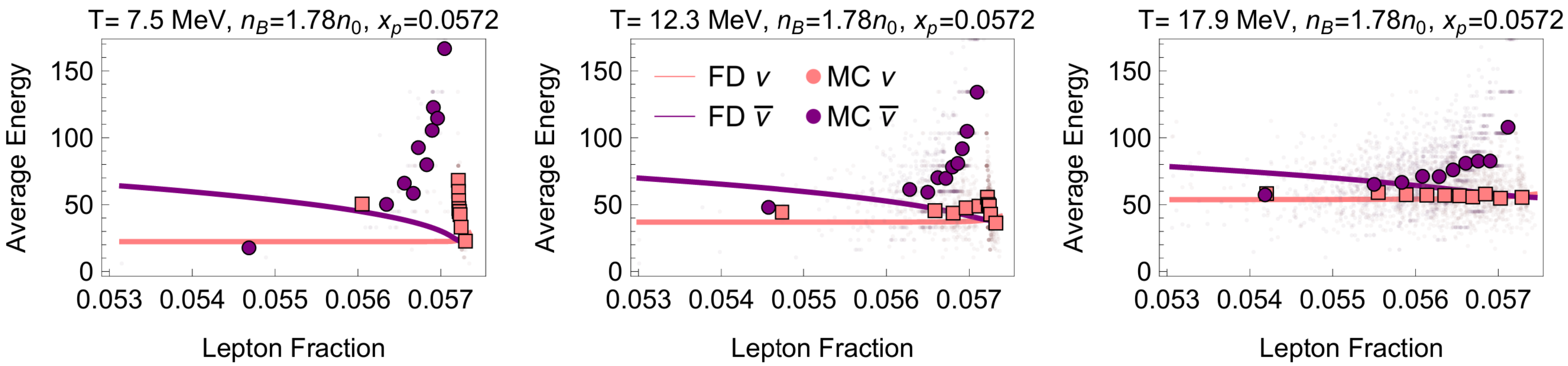
- Neutrino number density as a function of energy
- Average neutrino energy
- Average neutrino opacity (inverse mean free path)

# Result (Trapped=?): Number Density

Sample fluid cells: $n_B = 1.78n_0, x_p = 0.0572, x_L = 0.0565$



# Result (Trapped=?): Average Energy



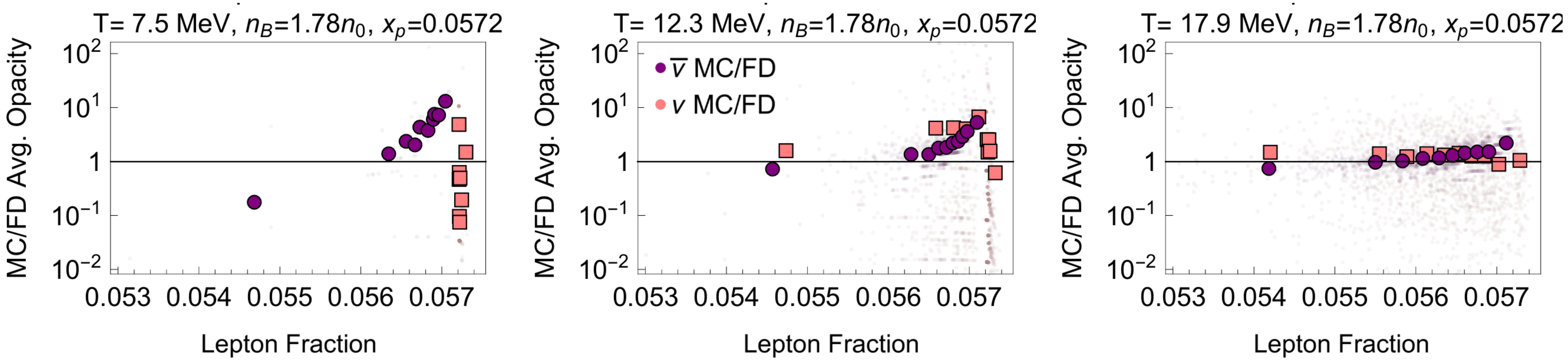

$\nu^{\mathrm{MC}}$ differ with Trapped $\sim 100\%$
$\bar{\nu}^{\mathrm{MC}}$ differ with Trapped $\sim 200\%$

$\nu^{\mathrm{MC}}$ differ with Trapped $\sim 50\%$
$\bar{\nu}^{\mathrm{MC}}$ differ with Trapped $\sim 100\%$

$\nu^{\mathrm{MC}}$ differ with Trapped $\sim 25\%$
$\bar{\nu}^{\mathrm{MC}}$ differ with Trapped $\sim 50\%$

As temperature increases, the difference decreases

# Result (Trapped=?): Average Opacity




$\nu^{\mathrm{MC}}$ differ with Trapped $\sim$20,000%
$\bar{\nu}^{\mathrm{MC}}$ differ with Trapped $\sim$400%

$\nu^{\mathrm{MC}}$ differ with Trapped $\sim$400%
$\bar{\nu}^{\mathrm{MC}}$ differ with Trapped $\sim$150%

$\nu^{\mathrm{MC}}$ differ with Trapped $\sim$100%
$\bar{\nu}^{\mathrm{MC}}$ differ with Trapped $\sim$50%

As temperature increases, the difference decreases

# Conclusions

- Neutrinos strongly impact the static and dynamic properties of dense matter
- Benchmarked Monte Carlo neutrino distributions against Fermi—Dirac
- Early post merger neutrinos don't form Fermi—Dirac until $\mathrm{T} > 20\ \mathrm{MeV}$!

For high temperatures ($\mathrm{T} \sim 60$ MeV):

- $\langle E \rangle$ and $\langle \kappa \rangle$ for neutrinos and antineutrinos from Monte Carlo differs from Trapped at the **few percent** level

For moderate temperatures ($\mathrm{T} \sim 7 - 18$ MeV):

- $\langle E \rangle$ and $\langle \kappa \rangle$ for neutrinos and antineutrinos from Monte Carlo differs with Trapped at the $\mathbf{10 - 200\%}$ level, growing **closer** as temperature increases