Neutrino Quantum Kinetics in Neutron Star Mergers

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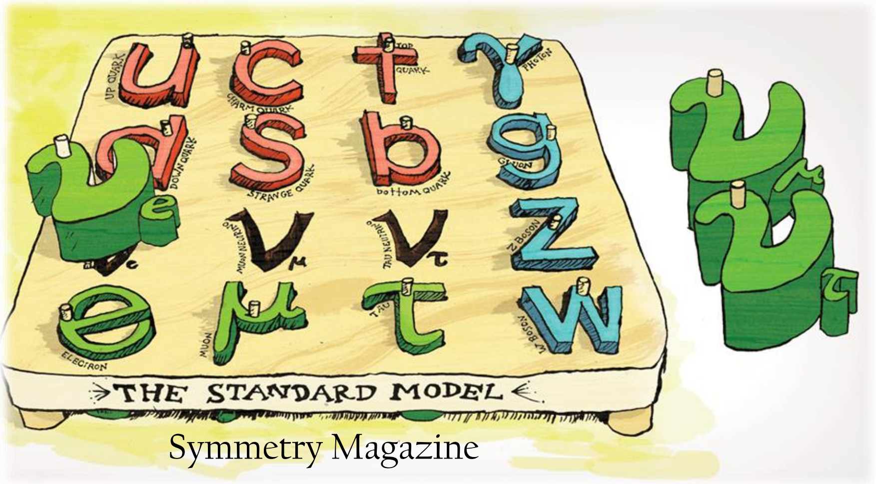
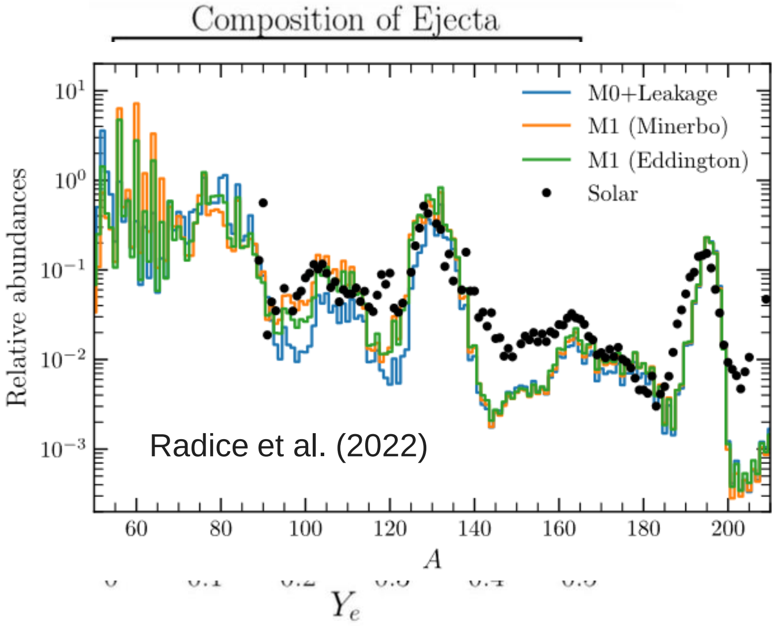
GSI
10/18/2022

Electron Neutrinos are Special

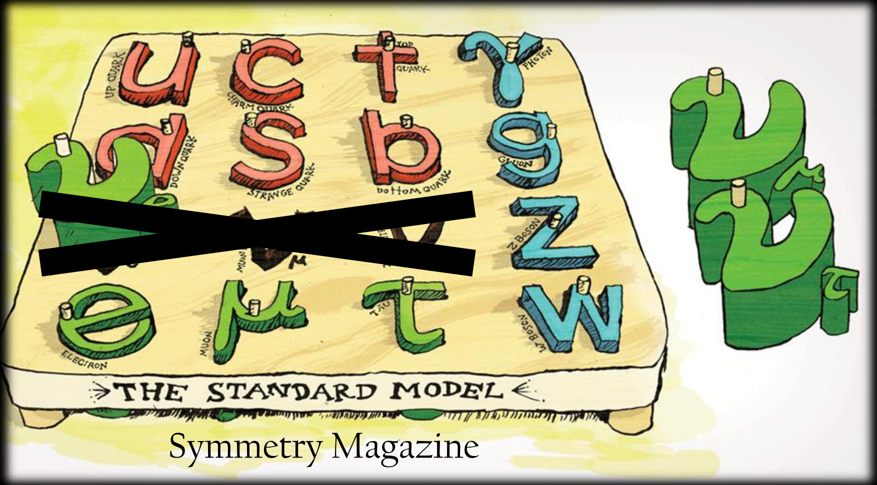


Symmetry Magazine



Need accurate neutrino transport to extract physics from observed neutrinos, gravitational waves, and light.

Electron Neutrinos are Special



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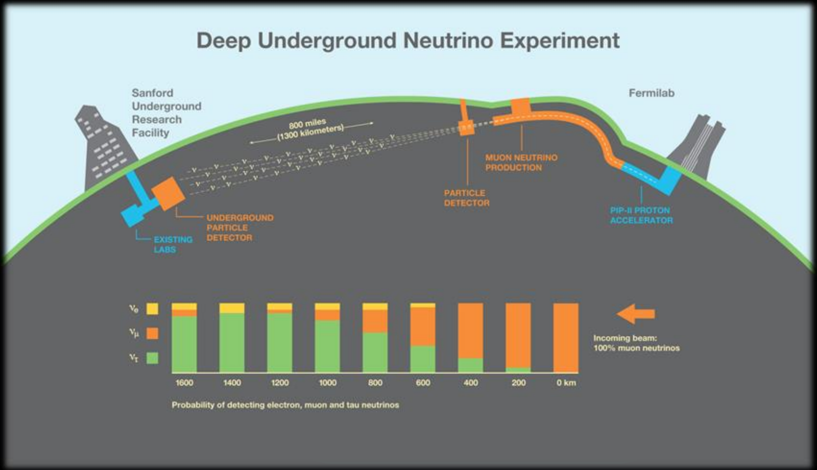
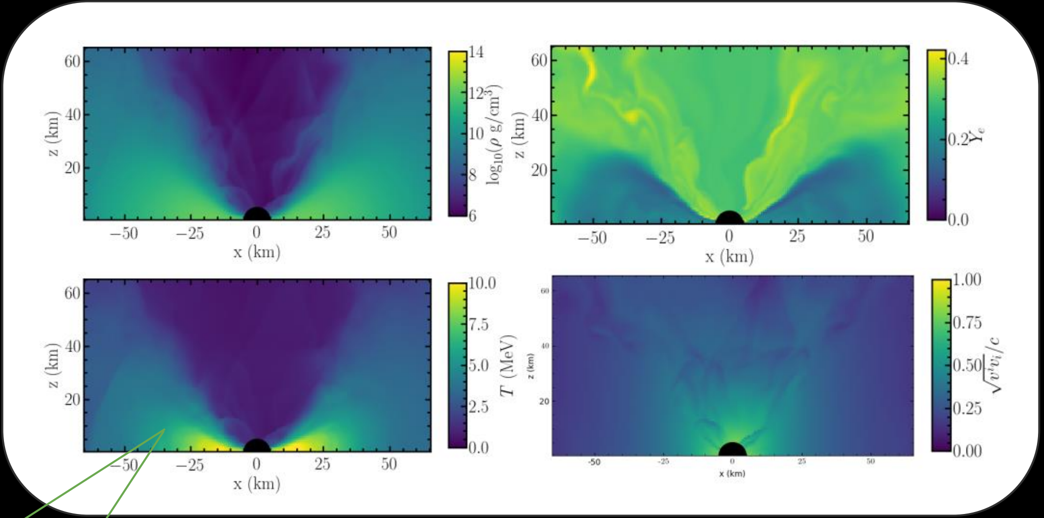
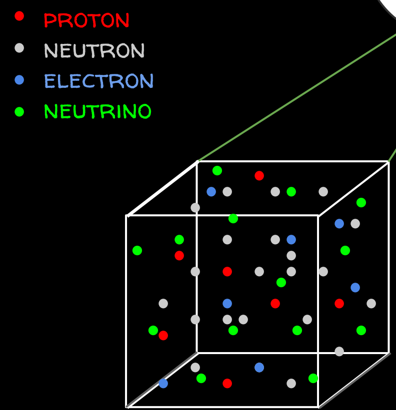


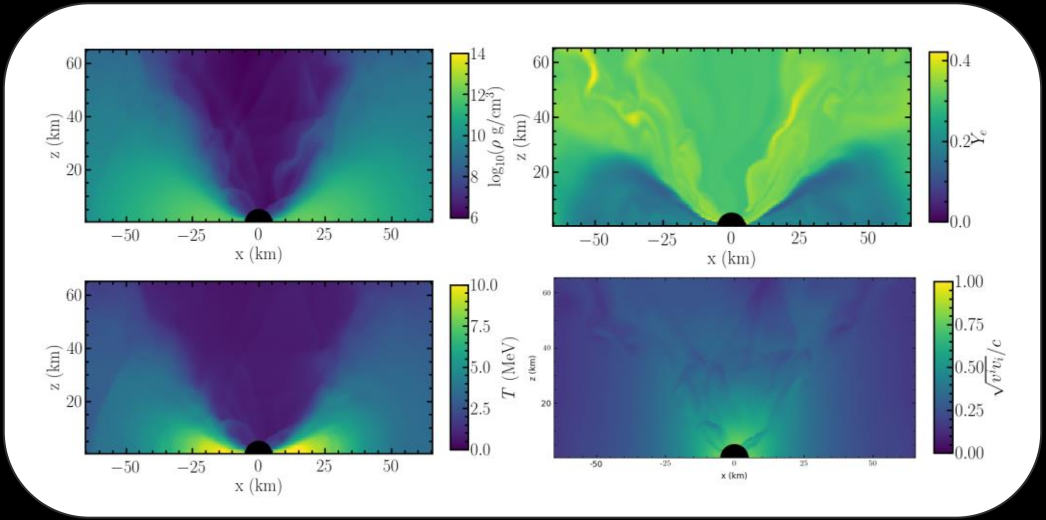
Quantum Neutrino Plasma



(Data from Radice+ 2018)



Quantum Neutrino Plasma



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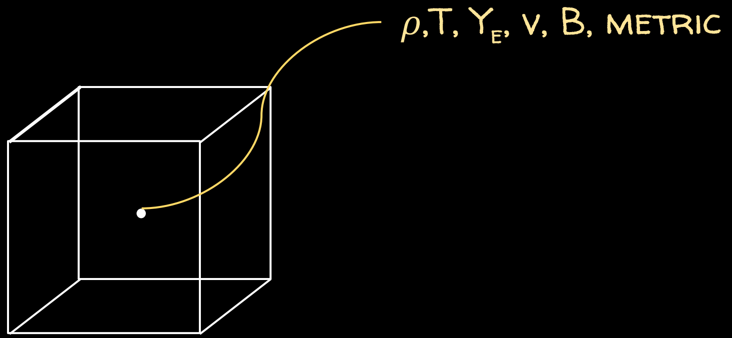
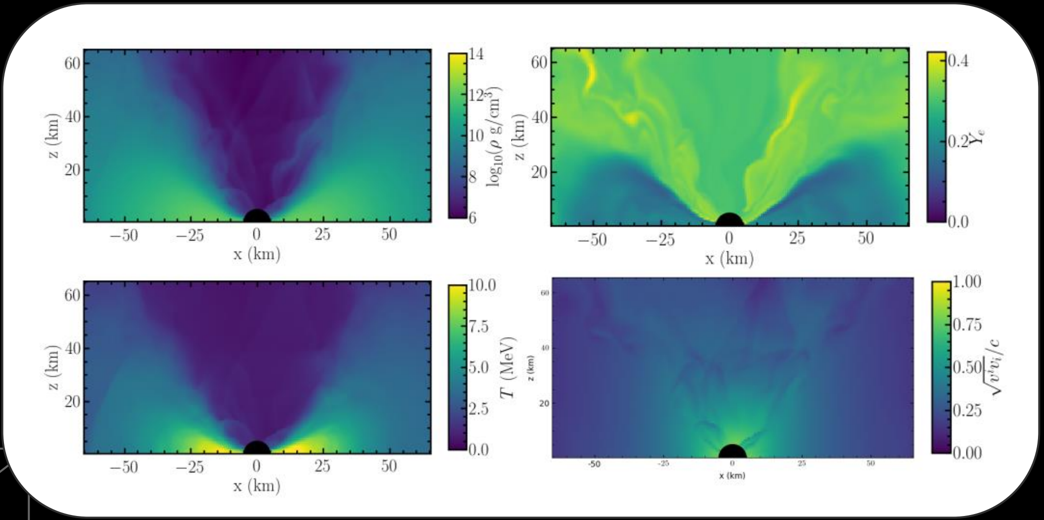


Quantum Neutrino Plasma



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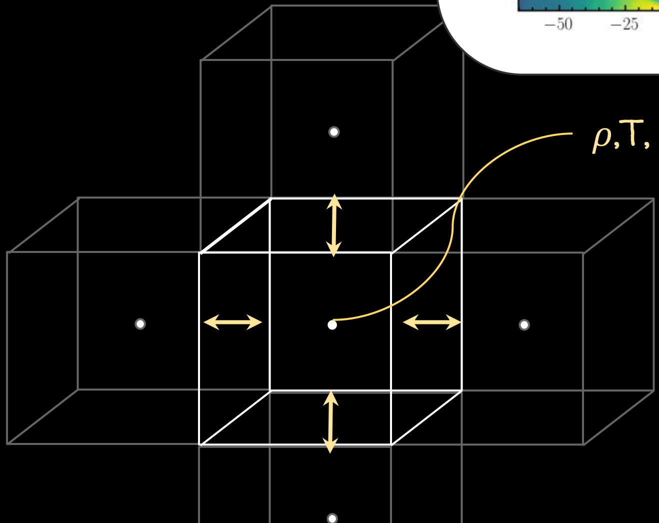


ρ, T, Y_E, V, B, METRIC

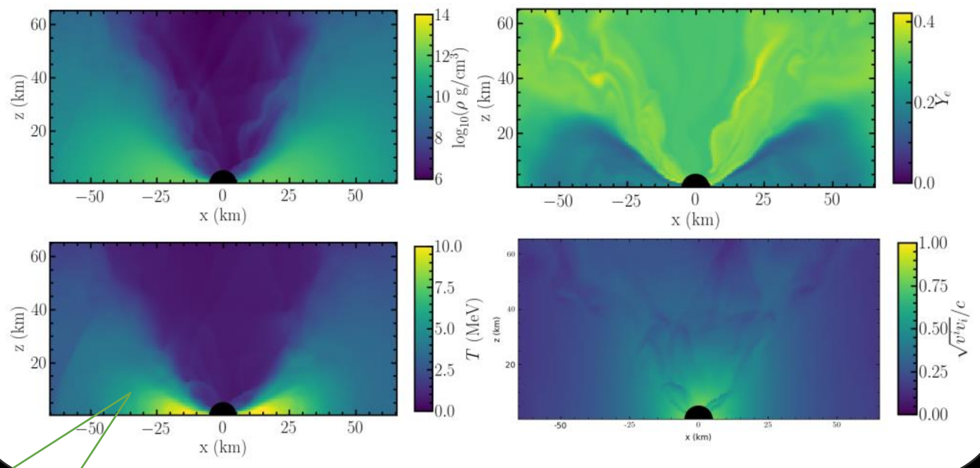
$$D_t\rho = -\rho\vec{\nabla}\cdot\vec{u}$$

$$D_t\vec{u} = -\frac{\vec{\nabla}P}{\rho}$$

Equation of State

(because in equilibrium)

Quantum Neutrino Plasma



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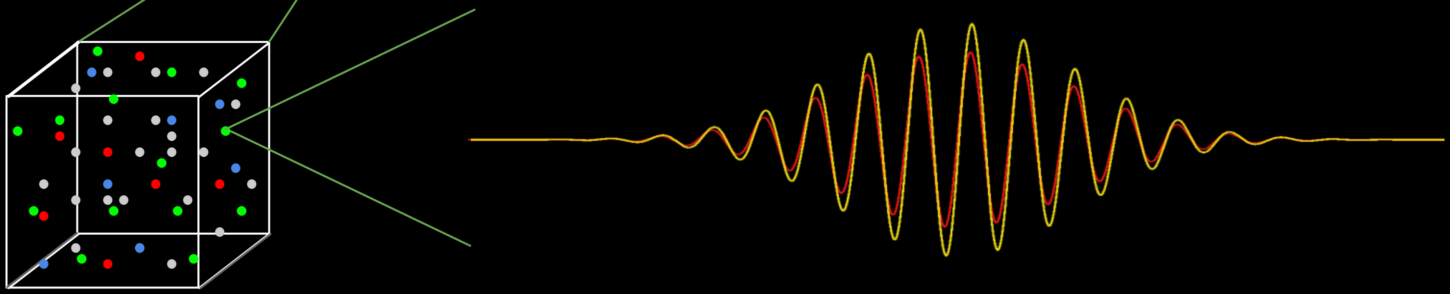
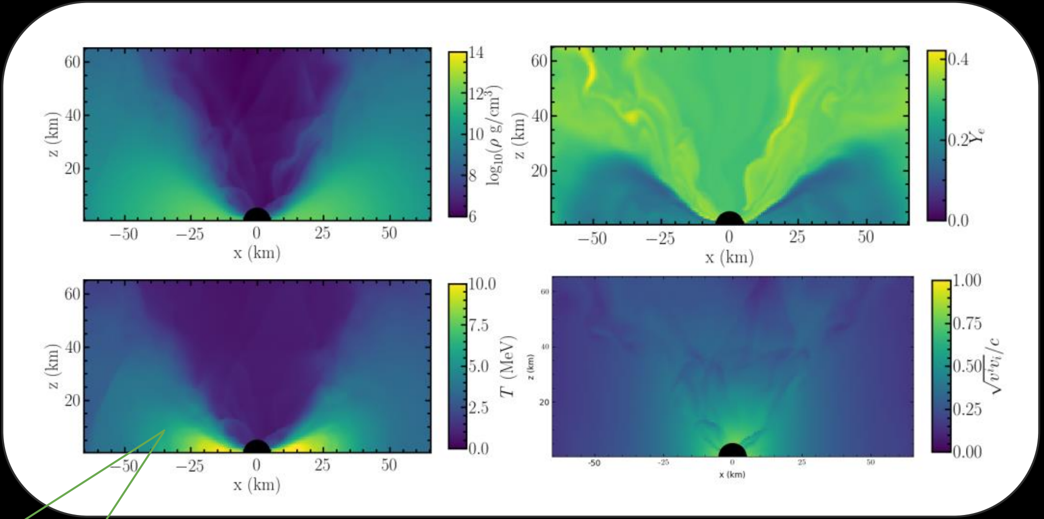


Quantum Neutrino Plasma



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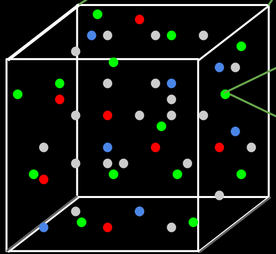
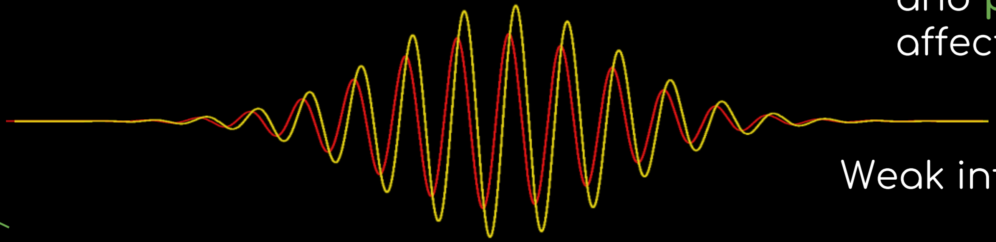
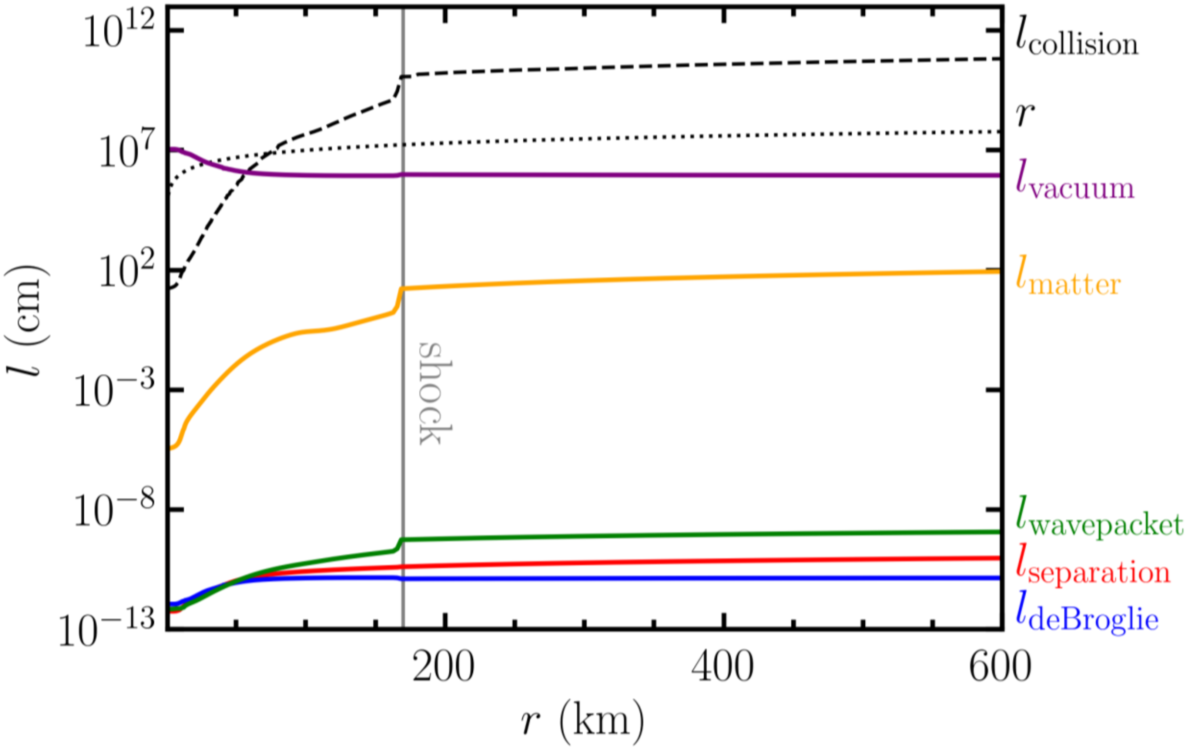


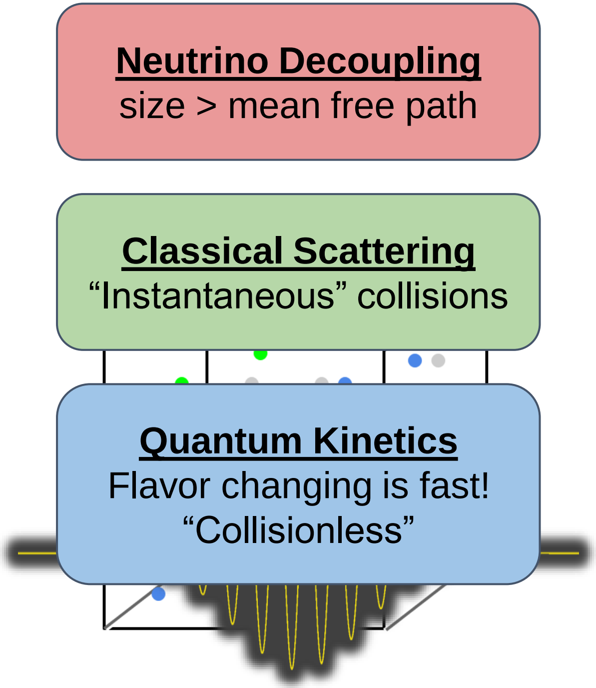


Neutrino mass and potential affect velocity.

Weak interactions → not in equilibrium.

How hard could it be?





$$\boxed{\frac{\partial f_{ab}}{\partial t} + c\boldsymbol{\Omega}\cdot\nabla f_{ab}} = \boxed{\mathcal{C}_{ab}} - \boxed{\frac{i}{\hbar}[\mathcal{H}, f]_{ab}}$$

Transport | Collision | Flavor

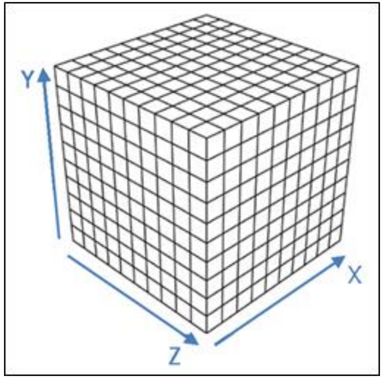
Vlasenko+ (2014)

Volpe (2015)

Blaschke & Cirigliano (2016)

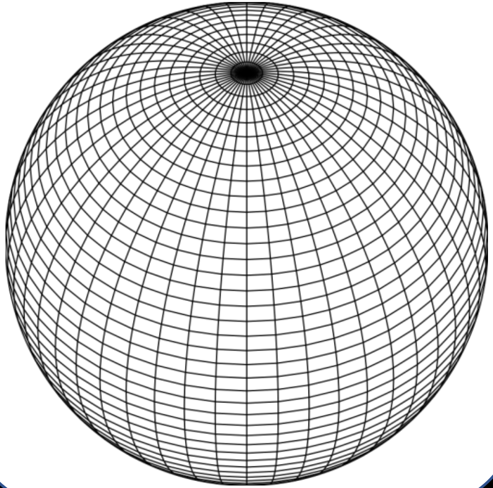
$f_{ab} =$

Position (3D)



x

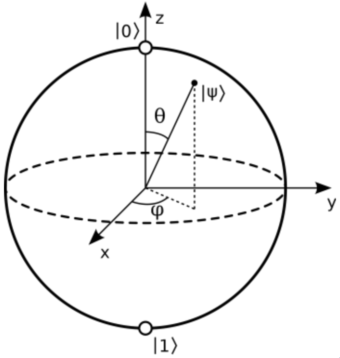
Momentum (3D)



x

Flavor

(3x3 matrix)



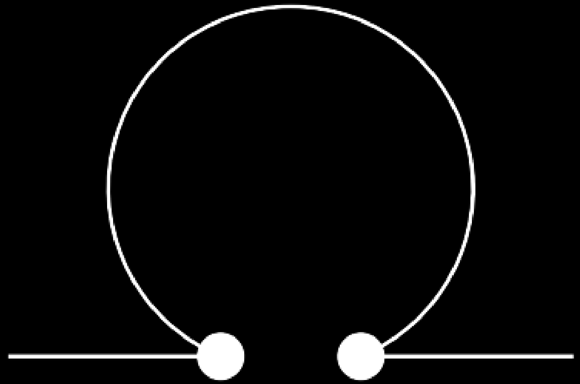
$$\frac{\partial f_{ab}}{\partial t} + c\boldsymbol{\Omega} \cdot \nabla f_{ab} = \mathcal{C}_{ab} - \boxed{\frac{i}{\hbar}[\mathcal{H}, f]_{ab}}$$

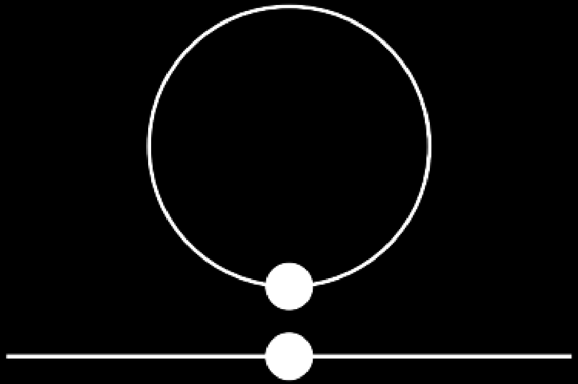
Flavor

Vlasenko+ (2014)

Volpe (2015)

Blaschke & Cirigliano (2016)





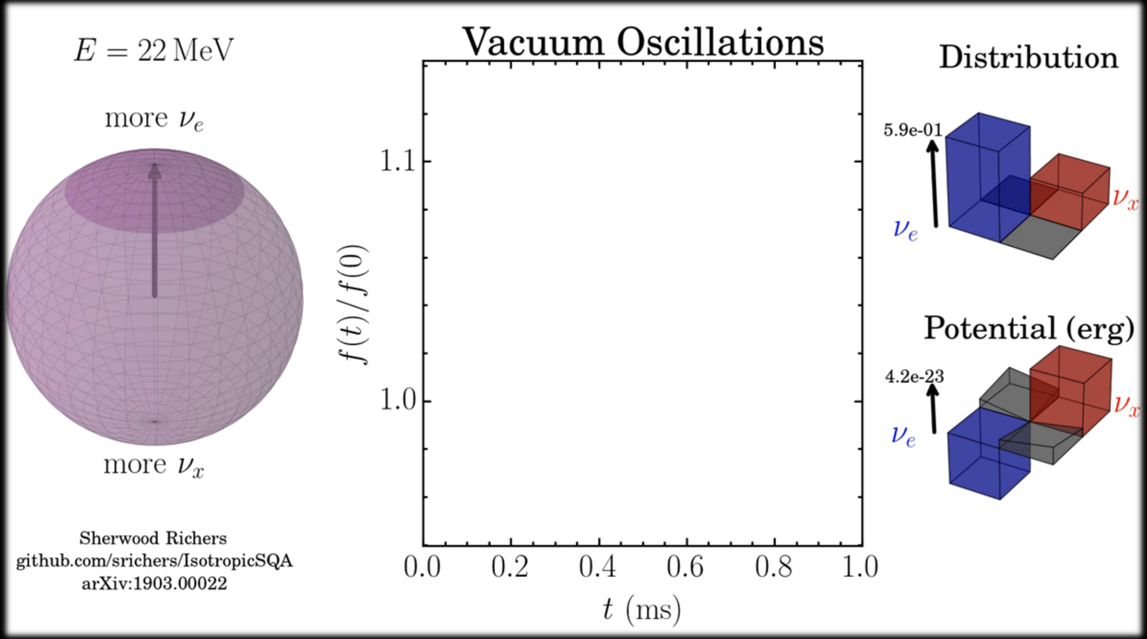
$$\boxed{\frac{\partial f_{ab}}{\partial t}} + \cancel{c\boldsymbol{\Omega}\cdot\nabla f_{ab}} = \cancel{\mathcal{C}_{ab}} - \boxed{\frac{i}{\hbar}[\mathcal{H}, f]_{ab}}$$

Vlasenko+ (2014)

Volpe (2015)

Blaschke & Cirigliano (2016)

Vacuum Oscillations



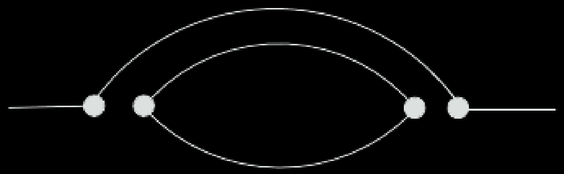
$$\frac{\partial f_{ab}}{\partial t} + c\mathbf{\Omega} \cdot \nabla f_{ab} = \boxed{\mathcal{C}_{ab} - \frac{i}{\hbar}[\mathcal{H}, f]_{ab}}$$

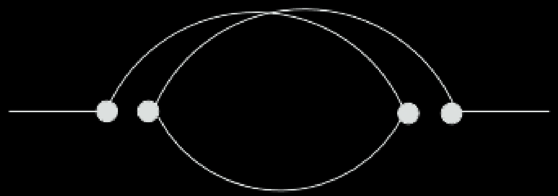
Vlasenko+ (2014)

Volpe (2015)

Blaschke & Cirigliano (2016)

"The Supernova Problem"





Neutrino Transport Reviews
Bruenn (1985)
Burrows, Reddy, Thompson (2007)
Mezzacappa (2022)

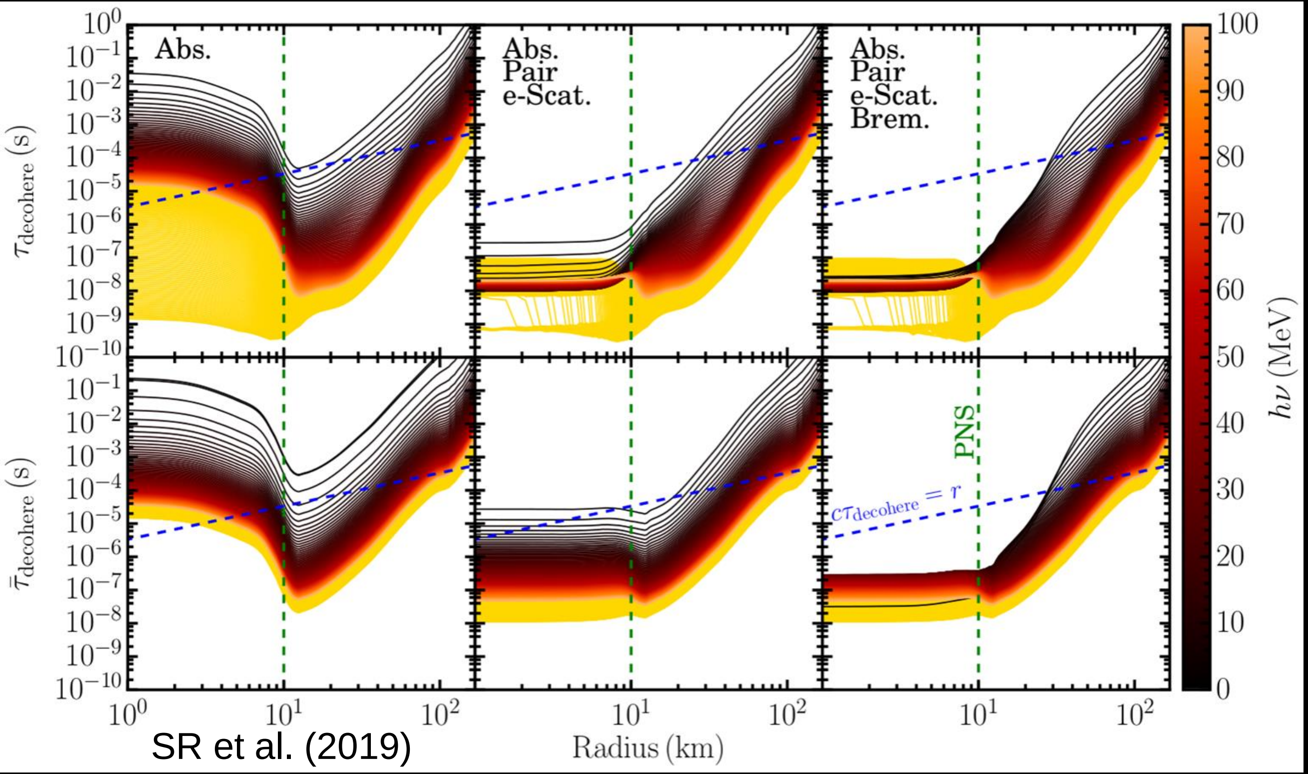
Combining with one-loop effects
Cherry (2012)
Vlasenko (2017)
SR et al. (2019)
Johns (2021)
Martin et al. (2021)
Sasaki et al. (2021)
Nagakura (2022)
Hansen et al. (2022)

$$\frac{\partial f_{ab}}{\partial t} + c\boldsymbol{\Omega}\cdot\nabla f_{ab} = \boxed{\mathcal{C}_{ab} - \frac{i}{\hbar}[\mathcal{H}, f]_{ab}}$$

Vlasenko+ (2014)

Volpe (2015)

Blaschke & Cirigliano (2016)

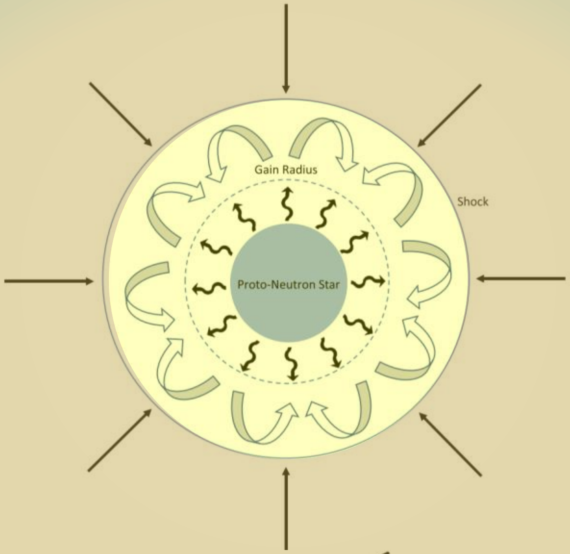


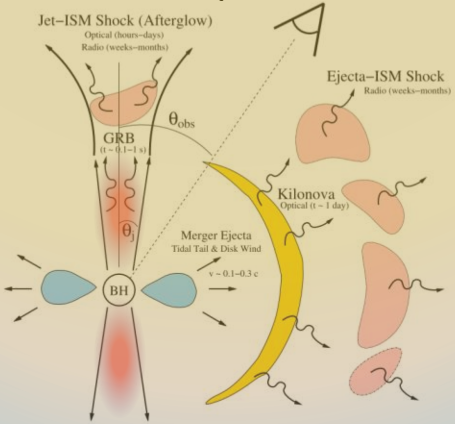
SR et al. (2019)

Many processes are important!

- **Collisional instability (Johns 2021)**
- **Universal behavior (Padilla-Gay 2022)**
- **Suppression or enhancement of flavor transformation (Shalgar, Abbar, Sasaki, ...)**

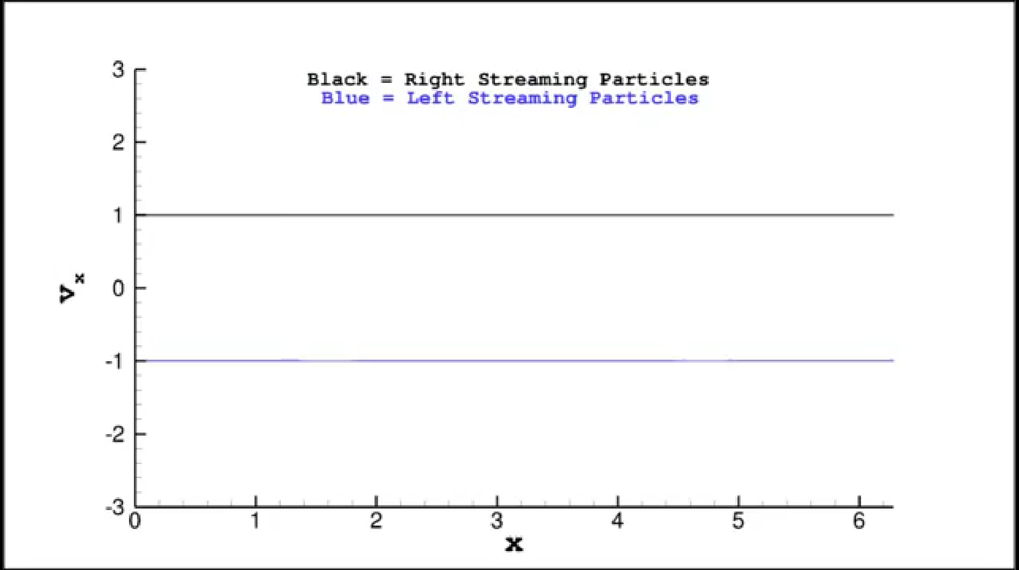
Flavor Transformation





- Vacuum (easy)
- MSW (easy)
- Collective Oscillations
- Matter-Neutrino Resonance
- Halo Effect
- Fast Flavor Instability

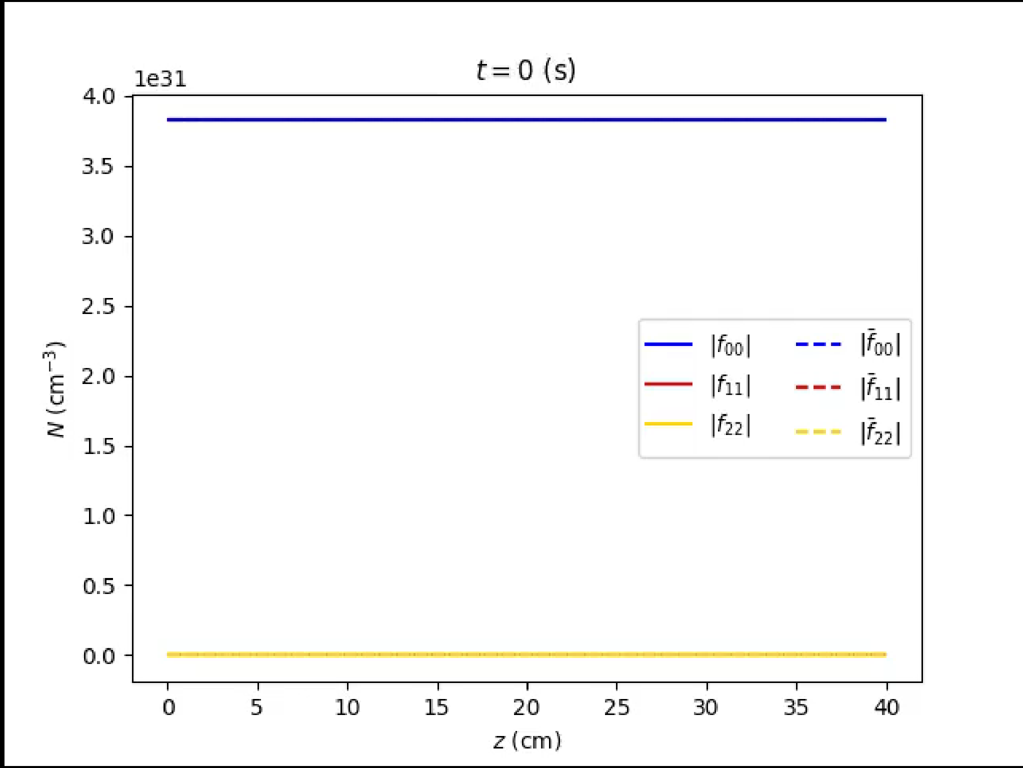
Aside: Plasma Instabilities



Because charged particles feel potential from other charged particles:

1. Perturbation in particle velocities induces electric+magnetic field
2. Electric+magnetic field influences particle velocities
3. Particle perturbations grow exponentially

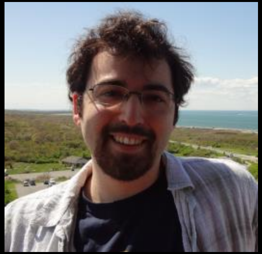
Neutrino Plasma Instabilities



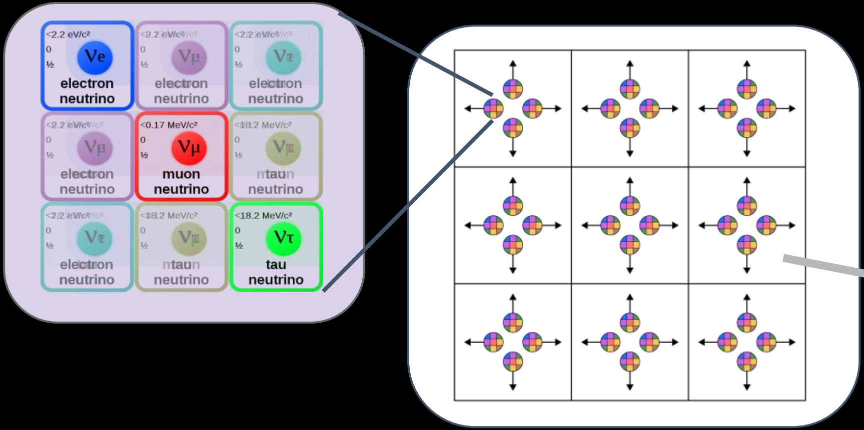
Because neutrinos feel potential from other neutrinos:

1. Perturbation in particle flavor induces flavor background
2. Flavor background influences particle flavor
3. Particle perturbations grow exponentially

AMReX-based Flavor Simulation



Don Willcox
(LBNL)



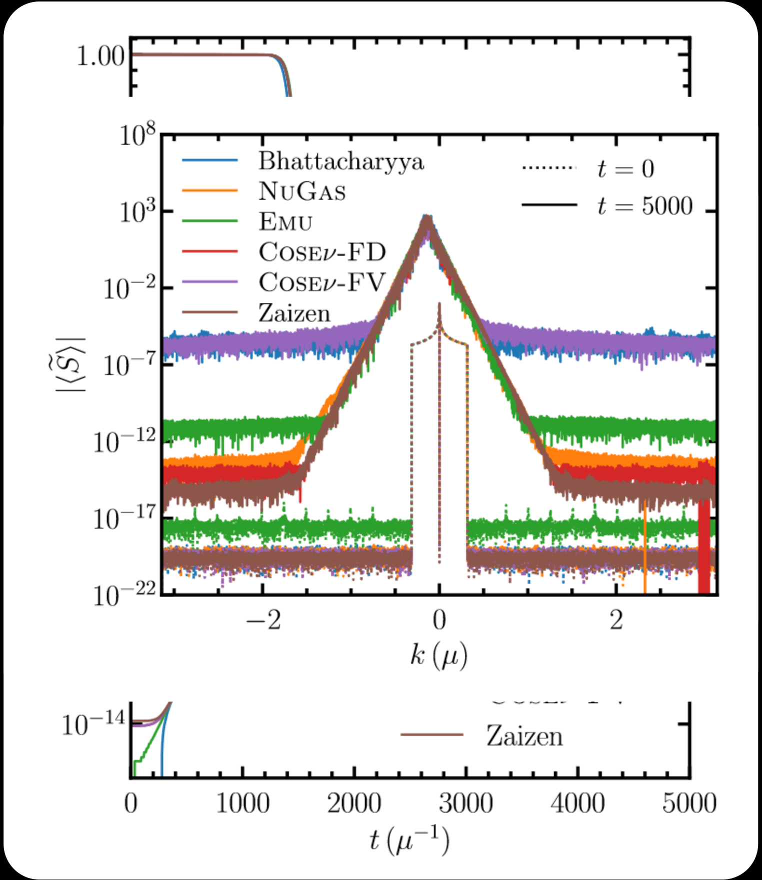
1500 particles per cell

$$H_{\text{neutrino}} = \sqrt{2}G_F\hbar^3 \int d^3\nu'(1-\cos\theta)(f'-\bar{f}')$$

$$\frac{d\mathcal{F}}{d\lambda} + \text{force} + \text{drift} = -p^\mu u_\mu \left(\mathcal{C} - \frac{i}{\hbar c}[\mathcal{H},\mathcal{F}]\right)$$

Initialize Particles → Deposit Potential → Move/Evolve

General Features of the FFI



SR+ (2022), following many other works

1. Exponential growth of perturbations
   Sawyer (2005), Dasgupta, Sen, Mirizzi, Morinaga, Padilla-Gay, Abbar, Xiong, Wu, Bhattacharyya, Zaizen, George, Duan, Sigl, Capozzi, Shalgar, Raffelt, Chakraborty, Kato … [many contributions]

2. Complete mixing within "ELN Crossing", incomplete elsewhere to preserve lepton #
   Bhattacharyya & Dasgupta (2021)

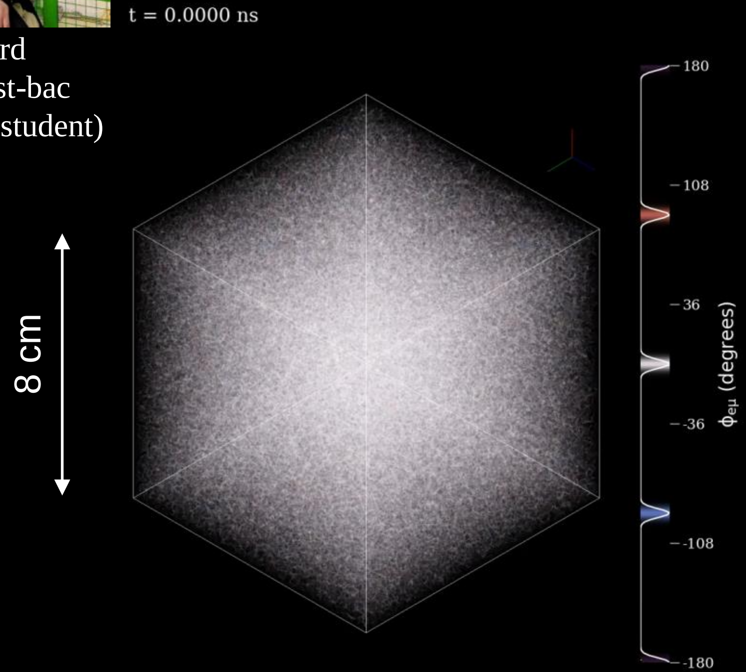
3. Modes spreading to exponential distribution.
   SR et al. (2021)

4. Coherent post-saturation flavor wave
   Duan et al. (2021)

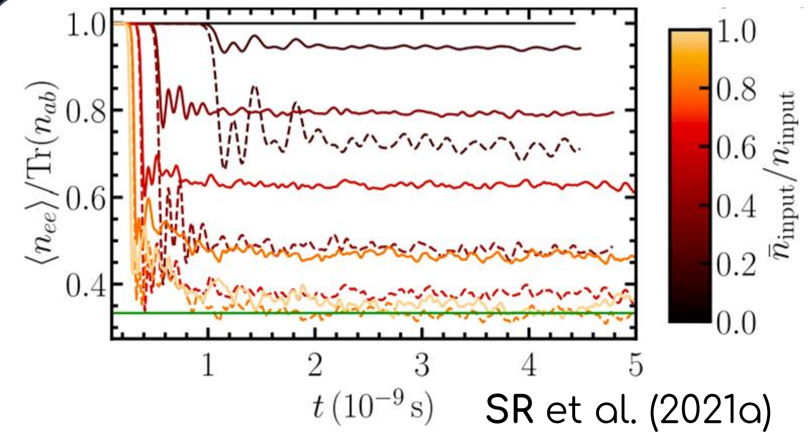
5. Non-trivial interplay with collisions
   Padilla-Gay, Shalgar, Johns, Xiong, Sasaki, Sigl, Tamborra, Hansen, Martin

Only 30 orders of magnitude to go

Nicole Ford
(Berkeley post-bac
→ McGill grad student)



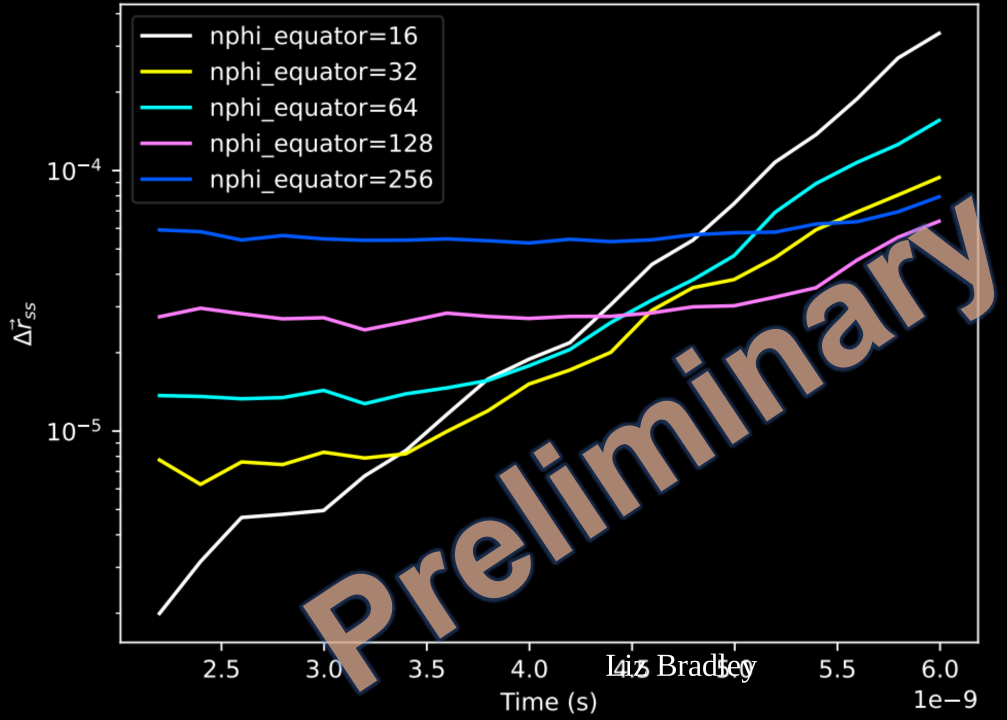
SR et al. (2021b)



SR et al. (2021a)

Amount of flavor transformation depends on the angular distribution.

Is it actually chaotic?



Liz Bradley

t

uciary

ectory

Erick Urquilla Orellana
(Licenciatura student @ U. El Salvador)
Applying this fall

How to move past a few centimeters?

reduced coupling — Nagakura 2022

effective models — Li & Sigel 2021
Just et al. 2022
Bhattacharyya et al. 2022
Fernandez, SR et al. 2022

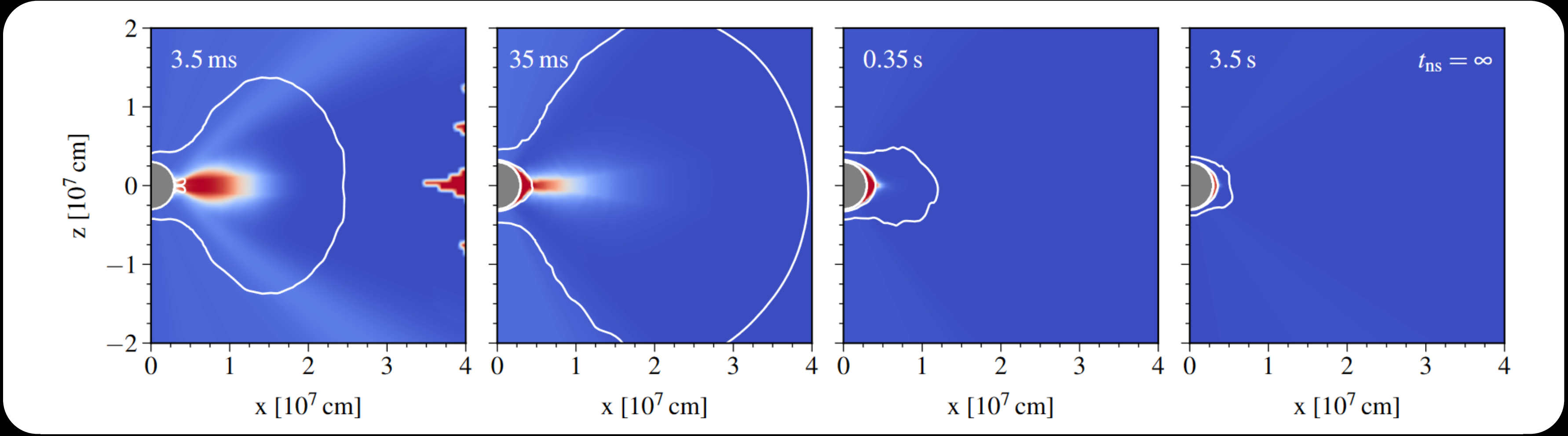
Talk by Abbar?

exact toy models — Padilla-Gay et al. 2021

easier equations — Strack & Burrows 2005
SR et al. 2019
Johns et al. 2020
Myers et al. (inc. SR) 2022
SR 2022
Grohs, SR, et al. 2022

Expect FFI to have a moderate impact on outflows

Run many 2D merger simulations, varying:
- NS lifetime
- Flavor transformation prescription



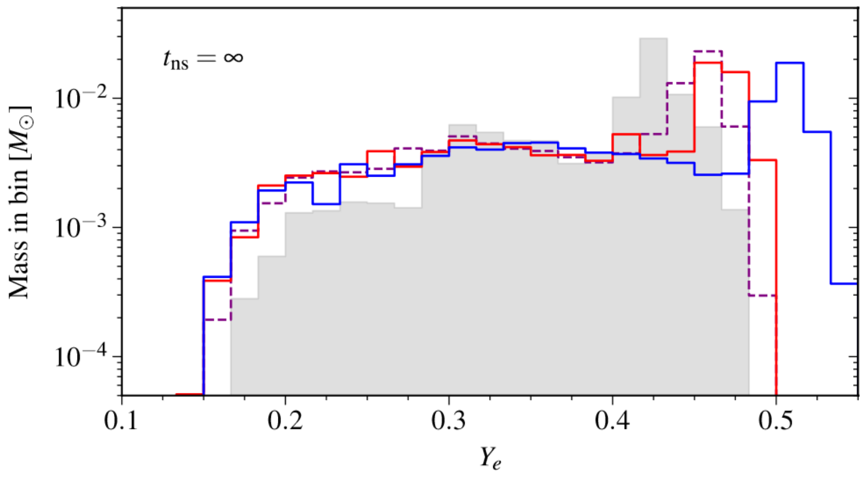
Fernandez, SR, et al. (2022)

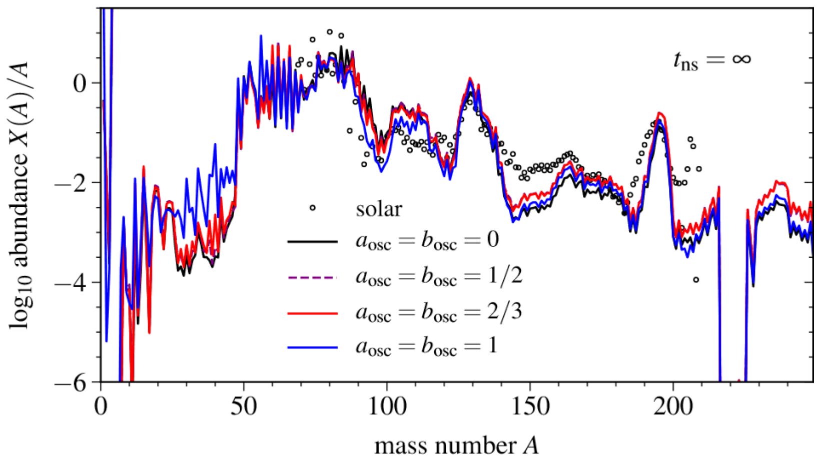
Expect FFI to have a moderate impact on outflows

+ 17.7 s. evolution time
+ 28 simulations

Extract only disk-driven ejecta
(neglects dynamical and prompt ejecta)

- parameterized mixing scheme
- viscous hydro
- 2D





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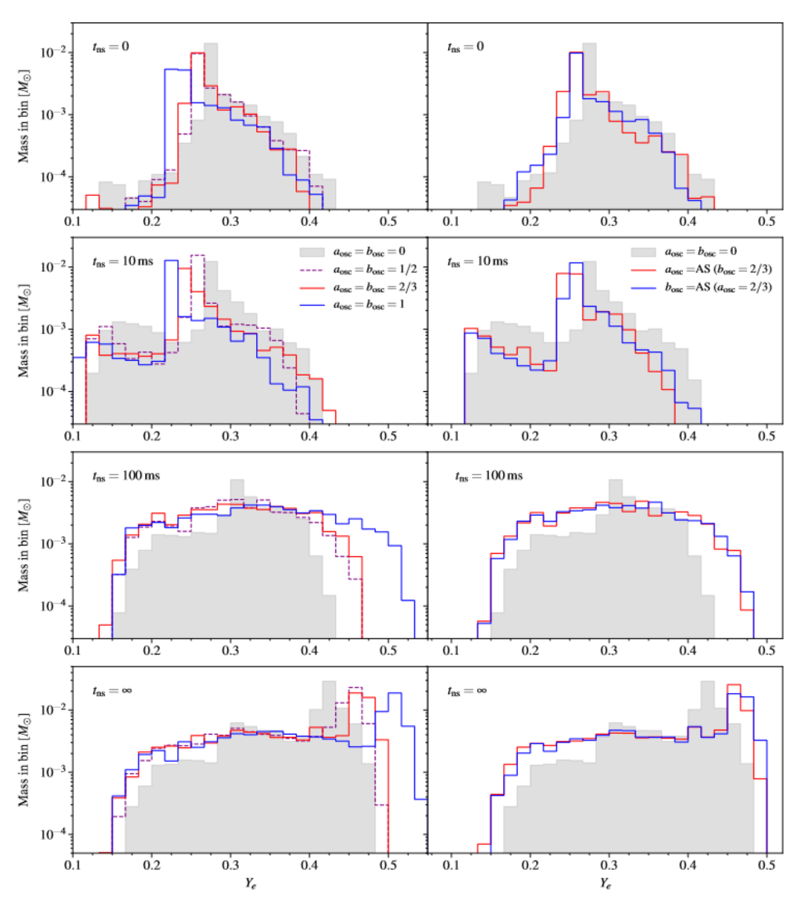

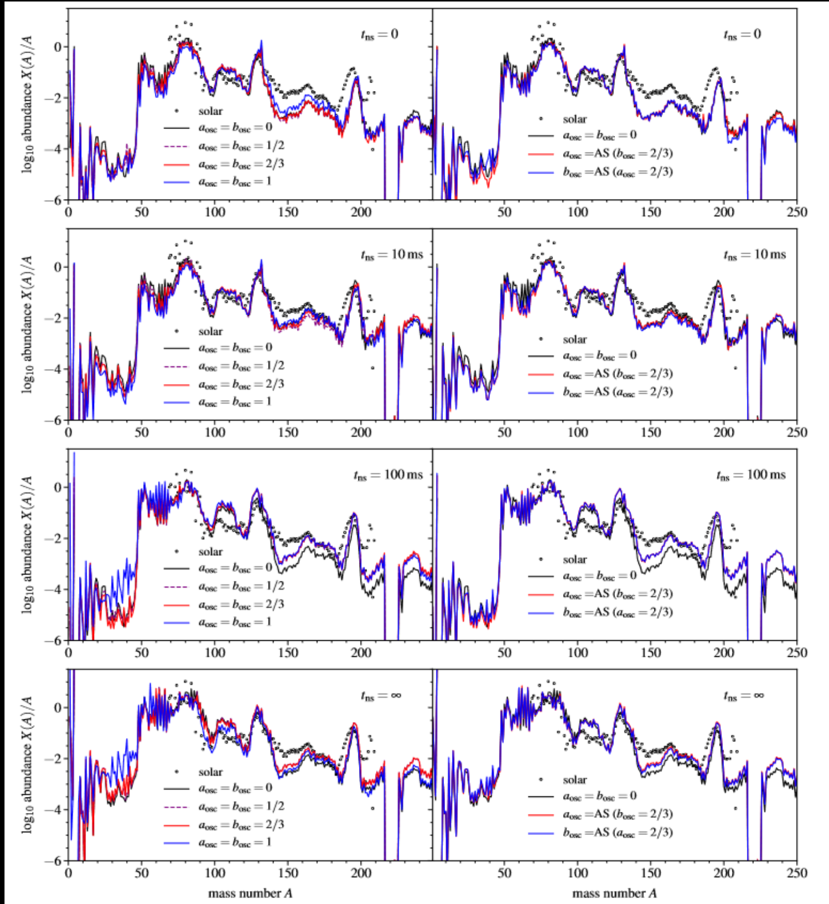

Fernandez, SR, et al. (2022)

How to move past a few centimeters?

reduced coupling — Nagakura 2022

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Abbar talk?

exact toy models — Padilla-Gay et al. 2021

easier equations — Strack & Burrows 2005
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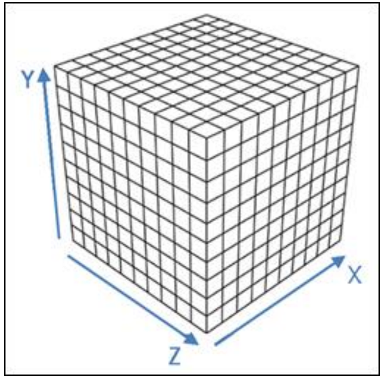
Johns et al. 2020
Myers et al. (inc. SR) 2022
SR 2022
Grohs, SR, et al. 2022

$$\boxed{\frac{\partial f_{ab}}{\partial t} + c\Omega\, \partial_\alpha T^{\alpha\beta}_{ab}} = \boxed{\mathcal{C}_{ab}} - \boxed{\frac{i}{\hbar}\left[\mathcal{H}_{\alpha,ab}, T^{\alpha\beta}_{ab}\right]}$$

Transport Collision Flavor

$f_{ab} =$

Position (3D)

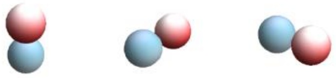


x

Momentum (3D)

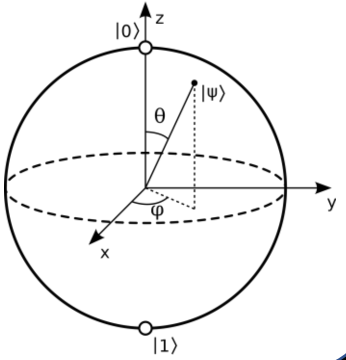
Momentum (1D)

(E) 

(F^i) 

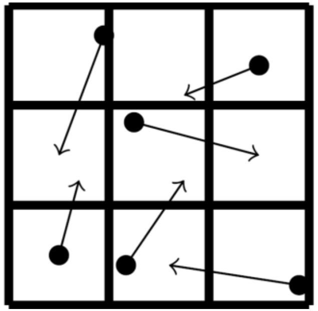
x

Flavor
(3x3 matrix)



Kinetics → Hydrodynamics

$f =$



$\underline{p, n, \gamma, \ldots}$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u + P) = 0$$

$P =$(Equation of State)

$\underline{\nu}$

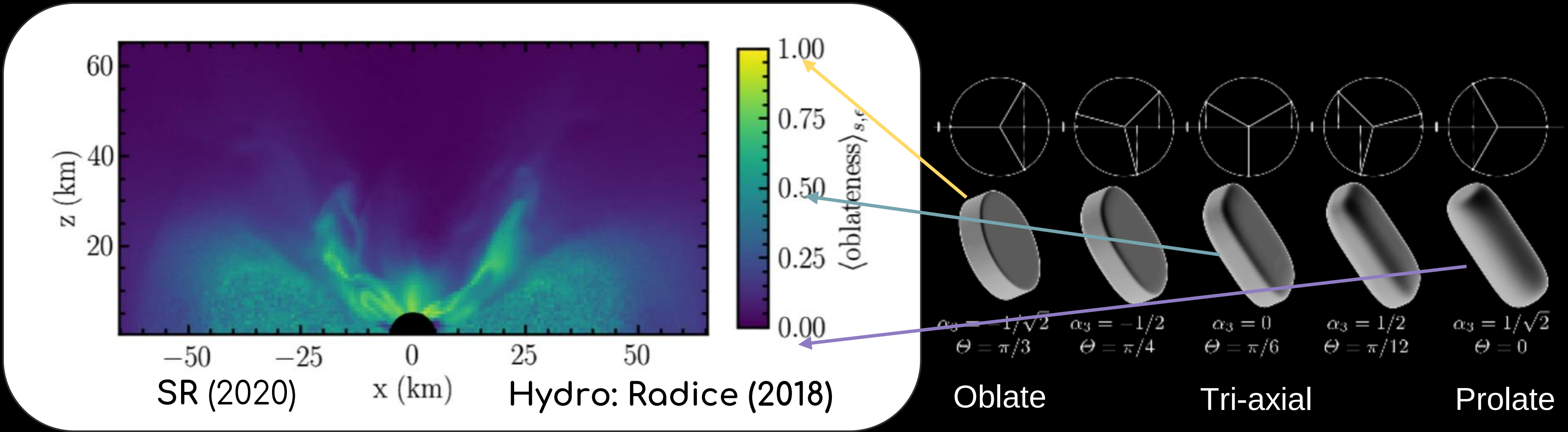
$$\frac{\partial E}{\partial t} + \nabla \cdot F = C_E(E, F)$$

$$\frac{\partial F}{\partial t} + \nabla \cdot P = C_F(E, F)$$

$P =$(Closure)

Moments Are Not Correct

But they sure are handy



Conclusion: The closure is non-trivial.

Use: many & longer simulations

We can predict where instability occurs reasonably well

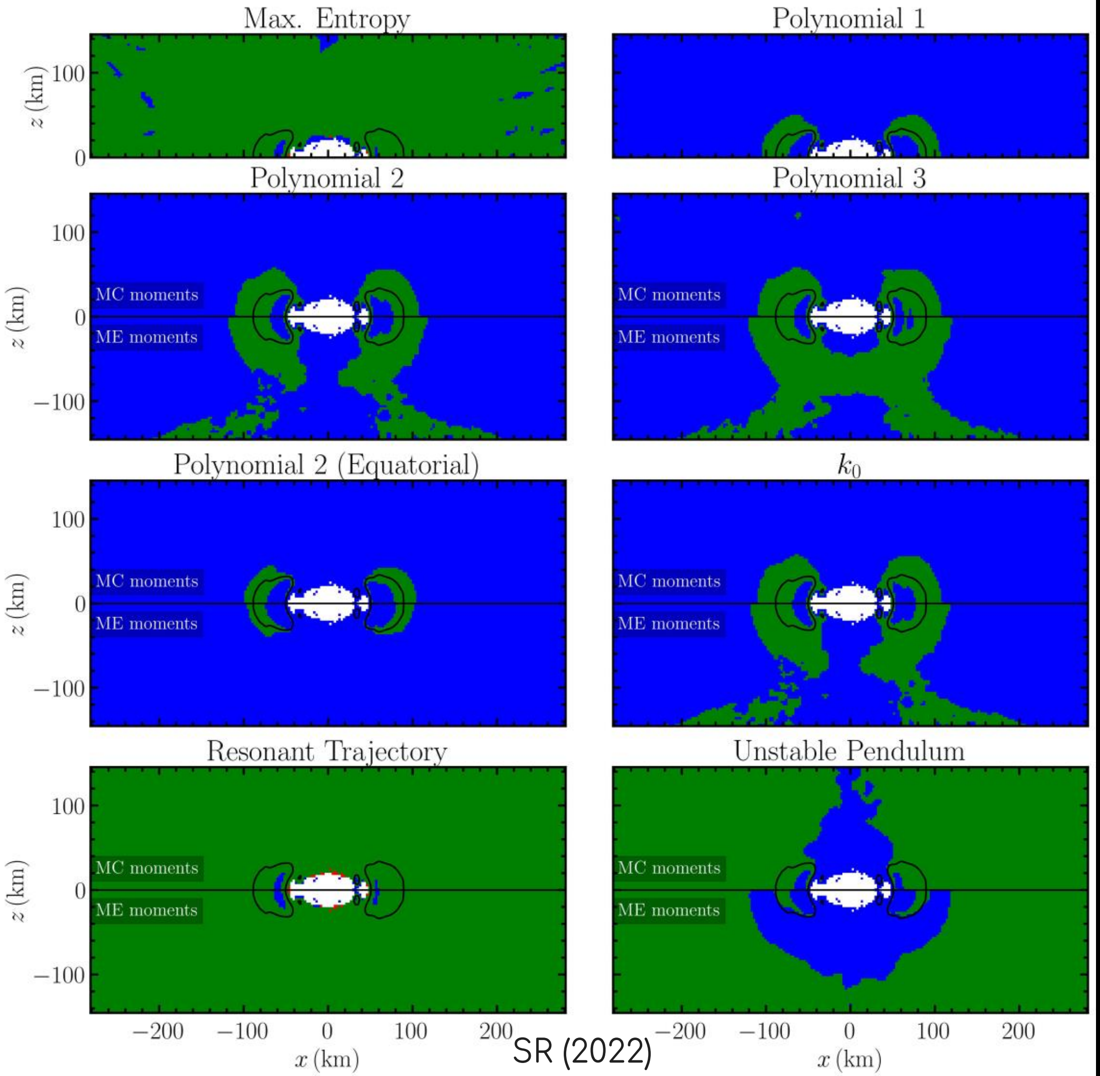
Dasgupta et al. (2018)

Abbar (2020)

Johns (2021)

Johns & Nagakura (2021)

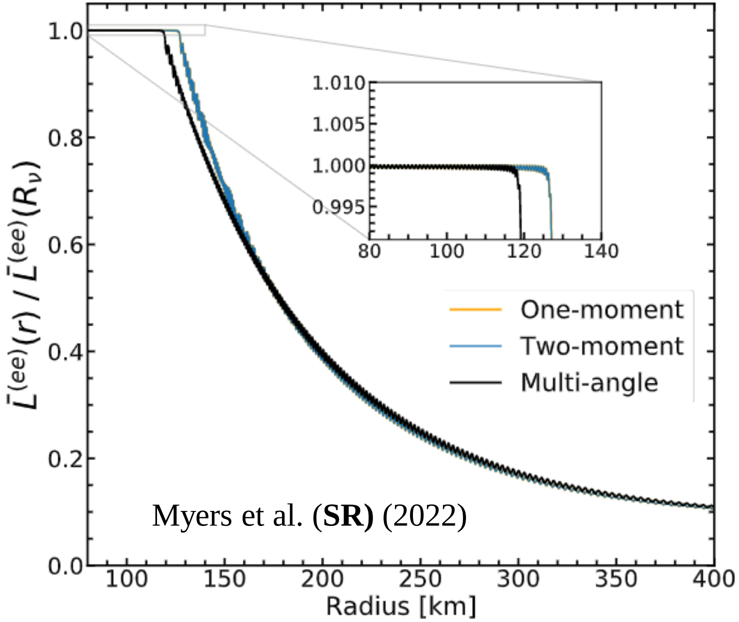
SR (2022)



SR (2022)

Moment-Based Quantum Kinetics

Supernova Collective Oscillations
Geometric Closure

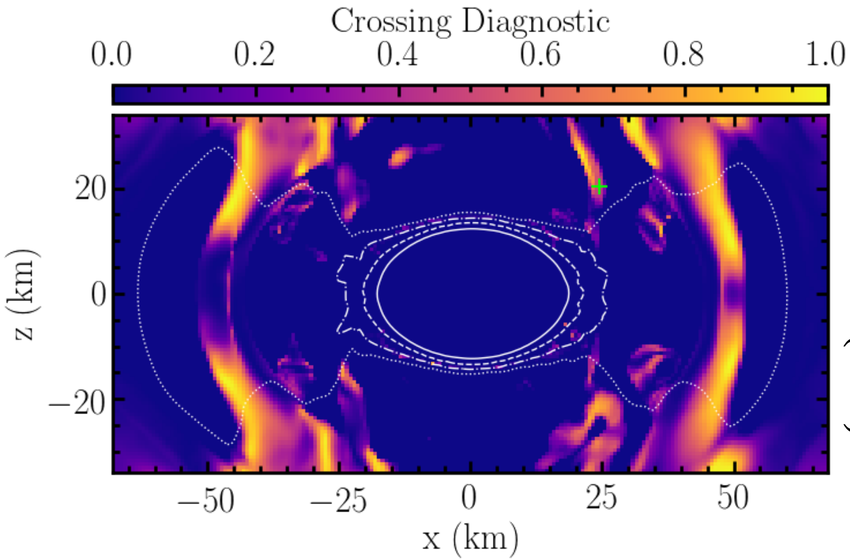


“lightbulb” inner boundary

Moment scheme matches exact scheme surprisingly well

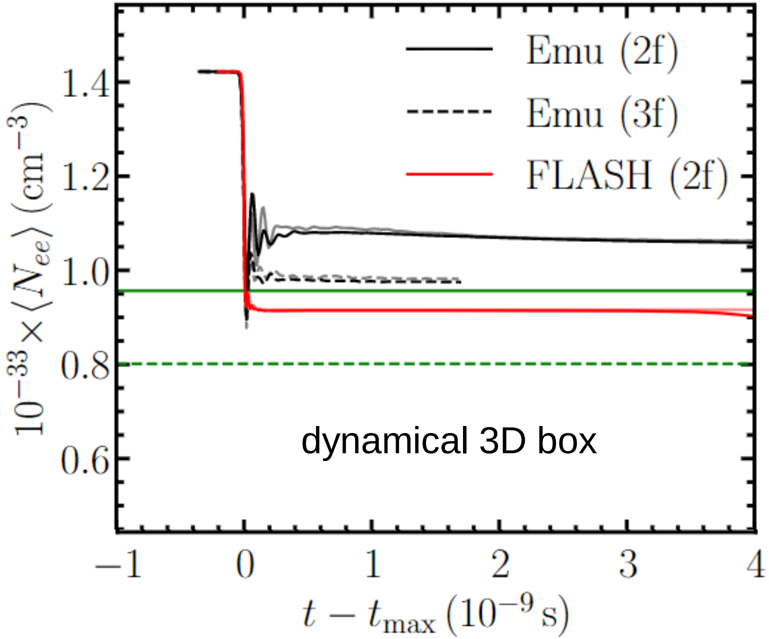
Moment-Based Quantum Kinetics

Grohs, **SR**, et al. (2022)



Rad Hydro:
Foucart et al. (2020)

Merger Fast Flavor Transformation
Modified Max Entropy Closure



Moments can <u>qualitatively</u> predict and simulate instability

Conclusions

$$\boxed{\frac{\partial f_{ab}}{\partial t} + c\boldsymbol{\Omega} \cdot \nabla f_{ab}} = \boxed{\mathcal{C}_{ab}} - \boxed{\frac{i}{\hbar}[\mathcal{H}, f]_{ab}}$$

Flavor transformation has a moderate effect on merger ejecta

Converging understanding of how the FFI transforms flavor
→ sub-grid models are possible

Moment equations can reproduce the FFI (subject to the closure)

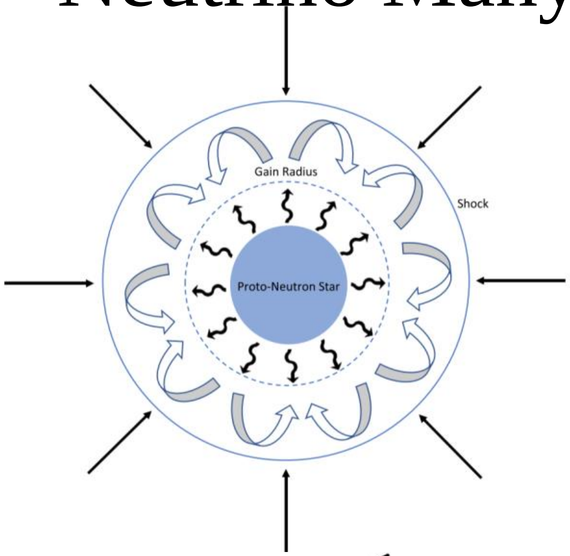
Converging on known, dominant physics

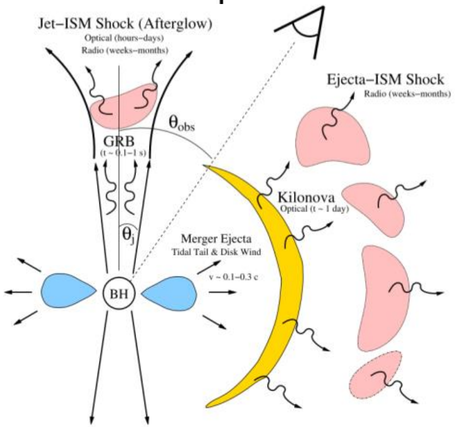
BUT

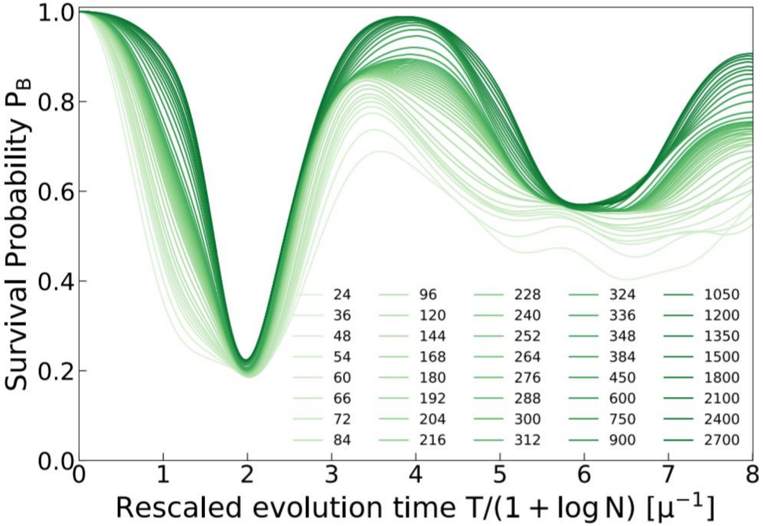
The FFI is only a small part of the story

Postdoc Position Open

Neutrino Many-Body Quantum Kinetics is Difficult



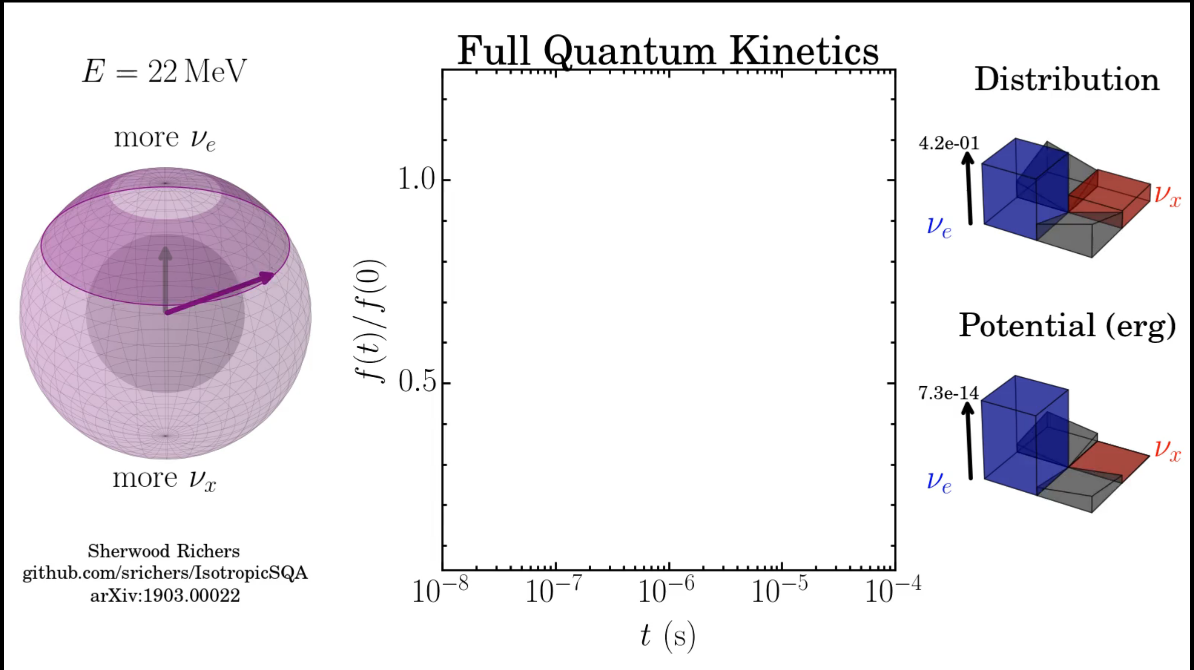




Roggero et al. (2022)

$$\boxed{\frac{\partial f_{ab}}{\partial t}} + \cancel{c\boldsymbol{\Omega}\cdot\nabla f_{ab}} = \boxed{\mathcal{C}_{ab}} - \boxed{\frac{i}{\hbar}[\mathcal{H}, f]_{ab}}$$

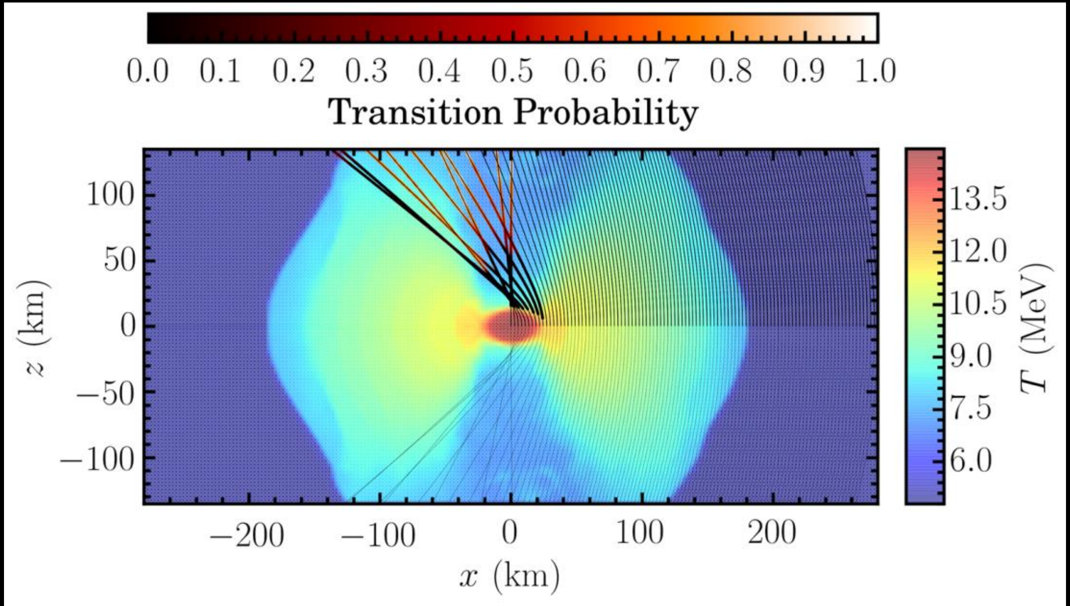
<u>Oscillations</u> and <u>collisions</u> are not generally separable



Richers+ (2019)

$$\cancel{\frac{\partial f_{ab}}{\partial t}} + \boxed{c\mathbf{\Omega} \cdot \nabla f_{ab}} = \boxed{\mathcal{C}_{ab}} - \boxed{\frac{i}{\hbar}[\mathcal{H}, f]_{ab}}$$

Flavor transformation & collisions in the same place.



SR et al. (in prog.)