Three Dimensional Simulations of the Fast Flavor Instability

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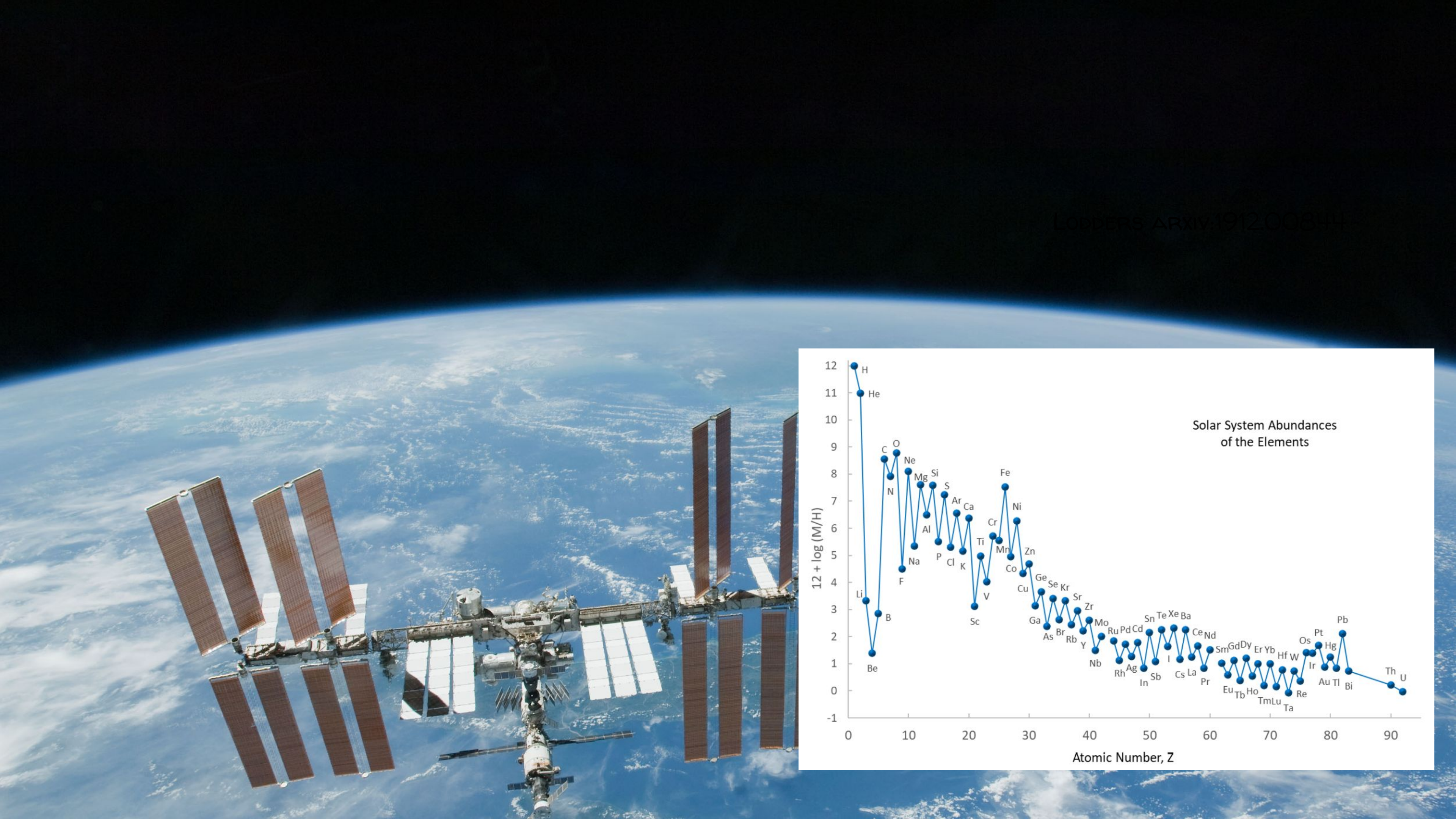
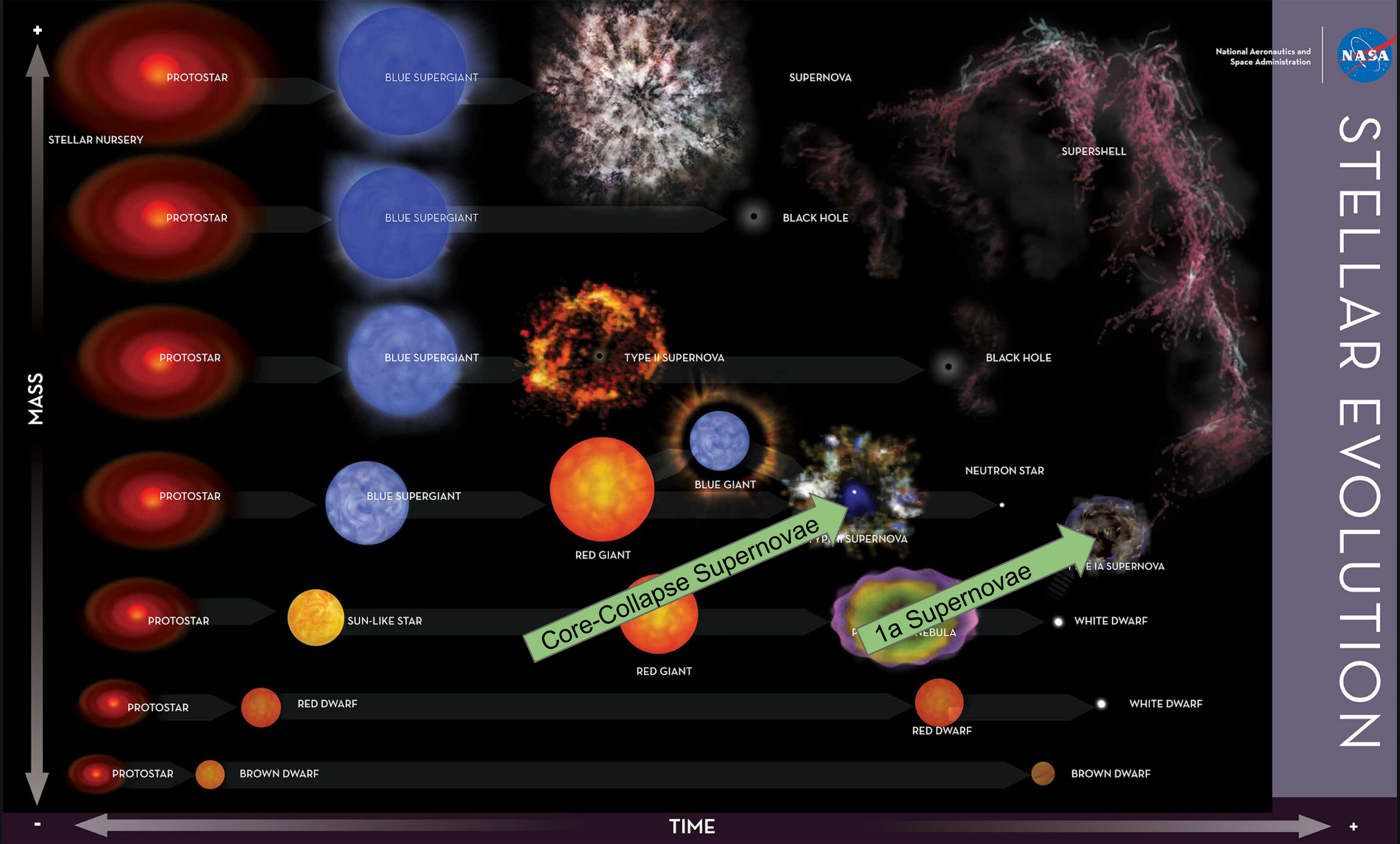
Andrew Myers


Lodders arXiv:1912.00844
Solar System Abundances
of the Elements
12 + log (M/H)
Atomic Number, Z



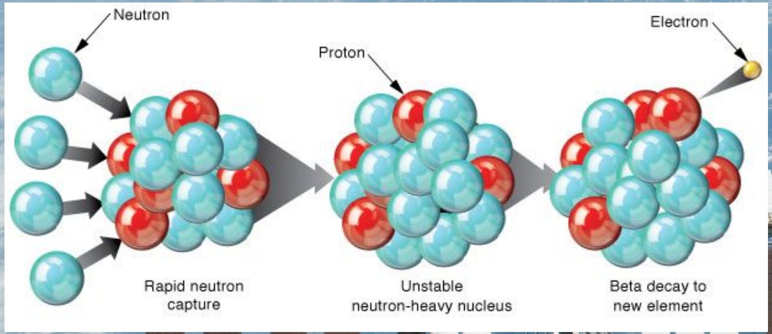
STELLAR EVOLUTION
National Aeronautics and Space Administration
NASA
MASS
TIME
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
SUPERNOVA
NEUTRON STAR
IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
Core-Collapse Supernovae
1a Supernovae

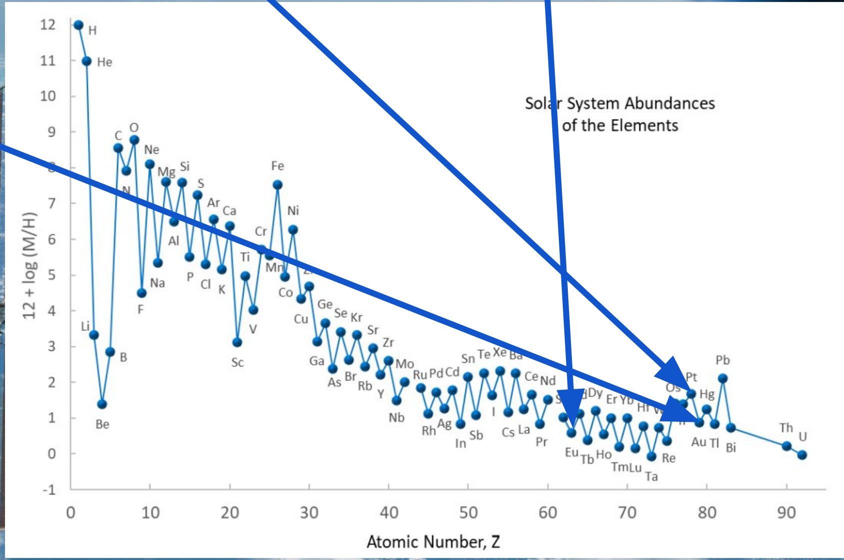
(gold)

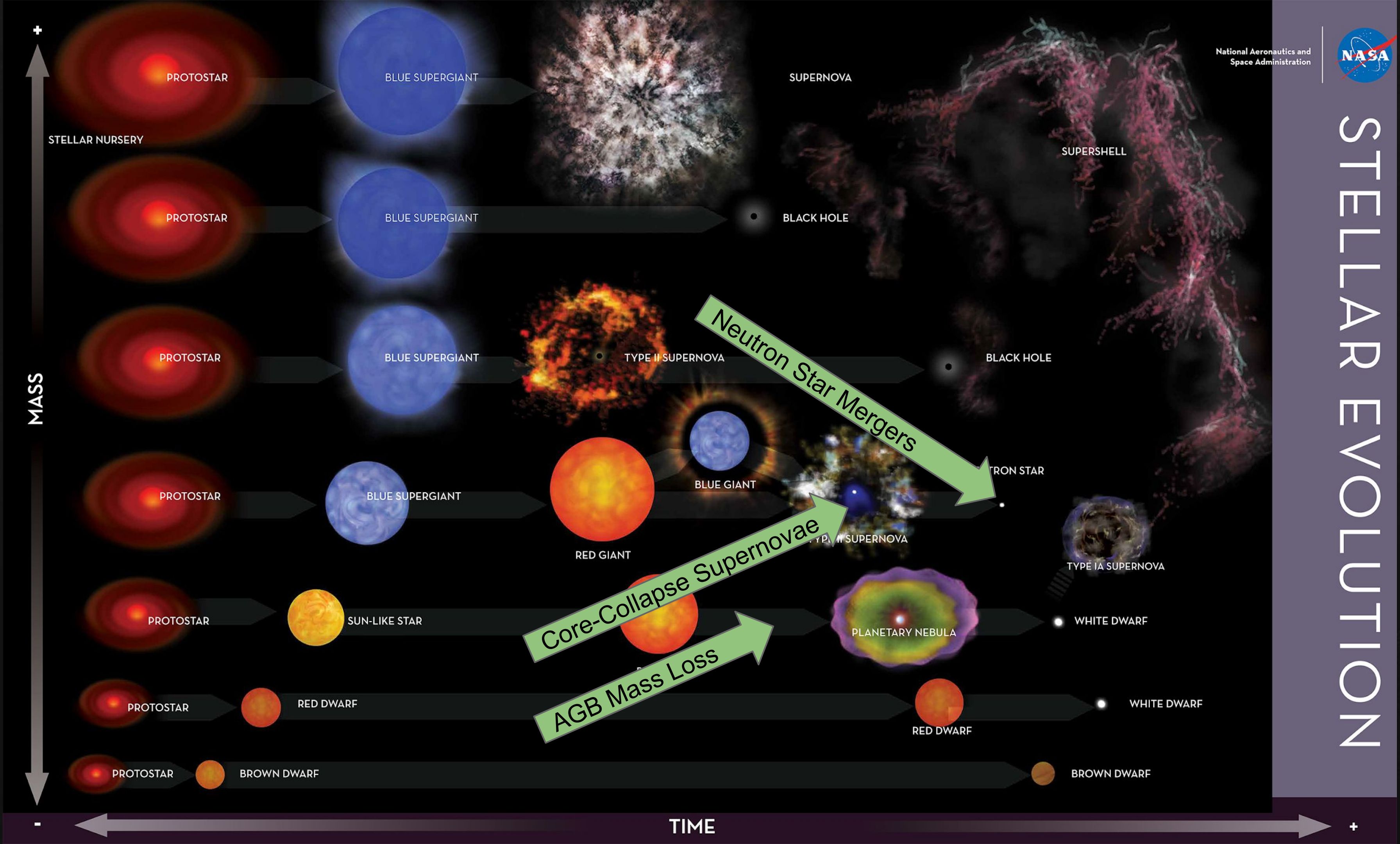
(platinum)

(europium)

Caryn Meissner (2014)







National Aeronautics and Space Administration
STELLAR EVOLUTION
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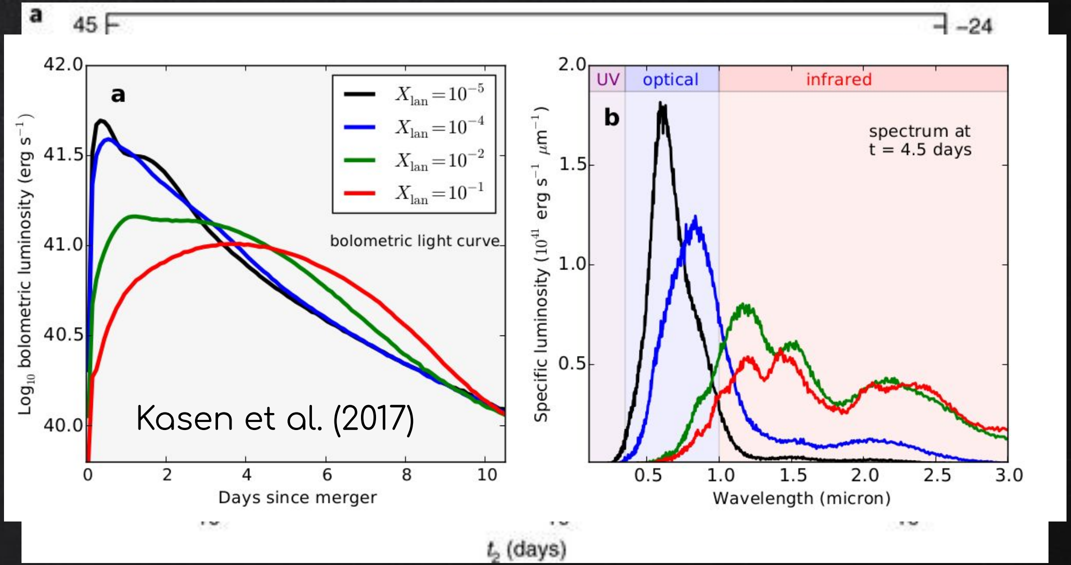
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
Neutron Star Mergers
Core-Collapse Supernovae
AGB Mass Loss

What's the big deal with neutron star mergers?

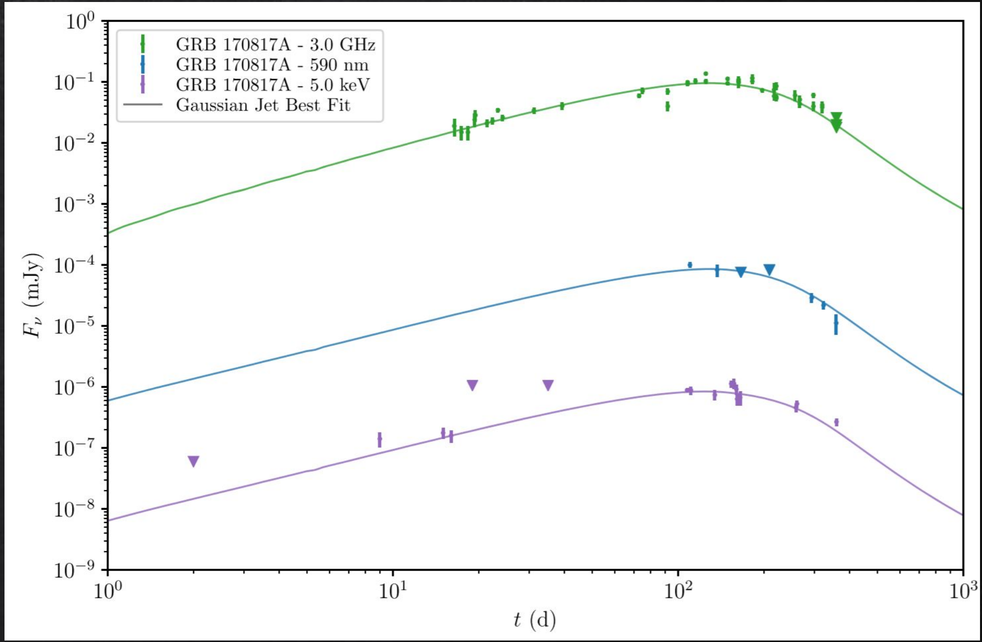
1. **Transients** - Can we explain everything we see?



Kasen et al. (2017)

What's the big deal with neutron star mergers?

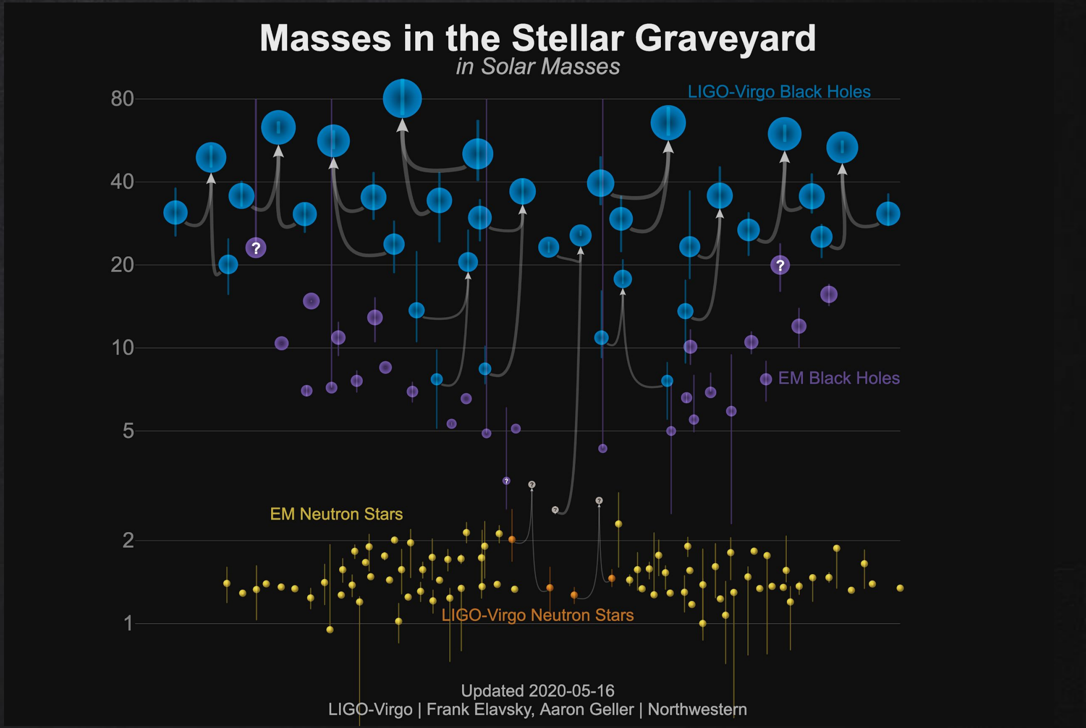
1. **Transients** - Can we explain everything we see?
2. **Short GRBs** - How can nature create such an energetic burst in so little time?



Ryan et al. (2020)

What's the big deal with neutron star mergers?

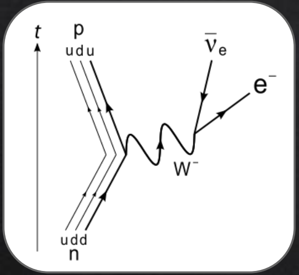
1. Transients - Can we explain everything we see?
2. Short GRBs - How can nature create such an energetic burst in so little time?
3. Black Holes - how do they form?



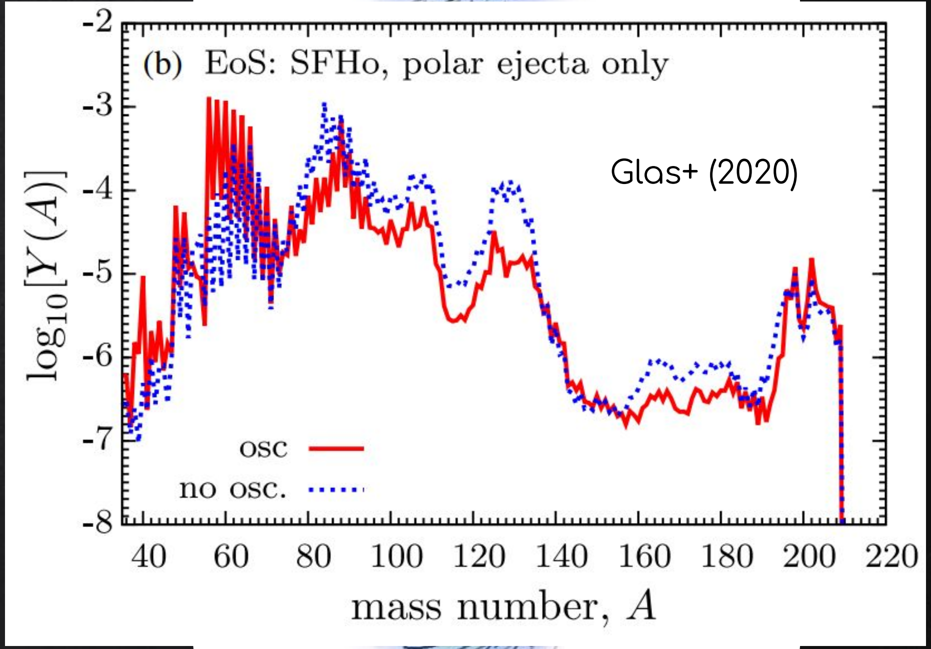
What's the big deal with neutron star mergers?

Neutrinos can:

1. Cool the disk/remnant
2. Drive outflows/jets
3. Protonize outflows



But this depends on the neutrino *flavor*



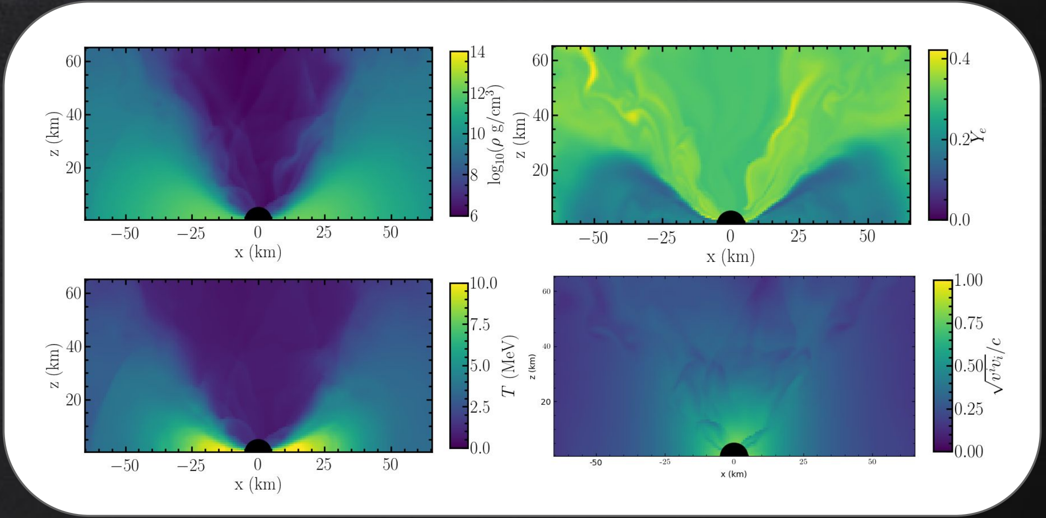
Glas+ (2020)

Moesta et al. (2020)

Does current physics agree with what we see?

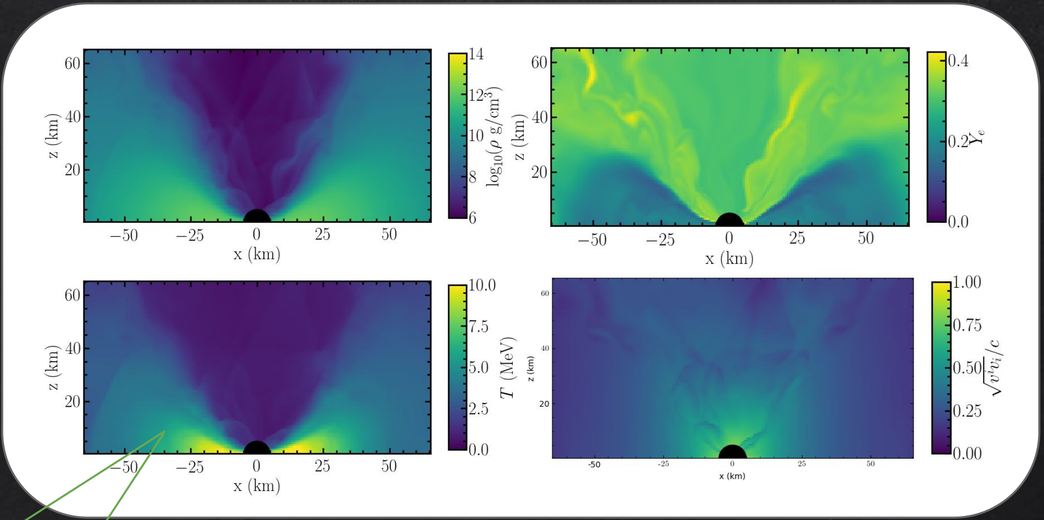
Open Questions

- How is the outflow launched?
- When is a black hole formed?
- Does the ejecta match the solar r-process pattern?
- Are we seeing new physics?

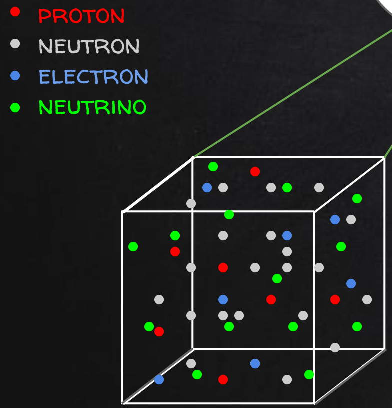


(Data from Radice+ 2018)

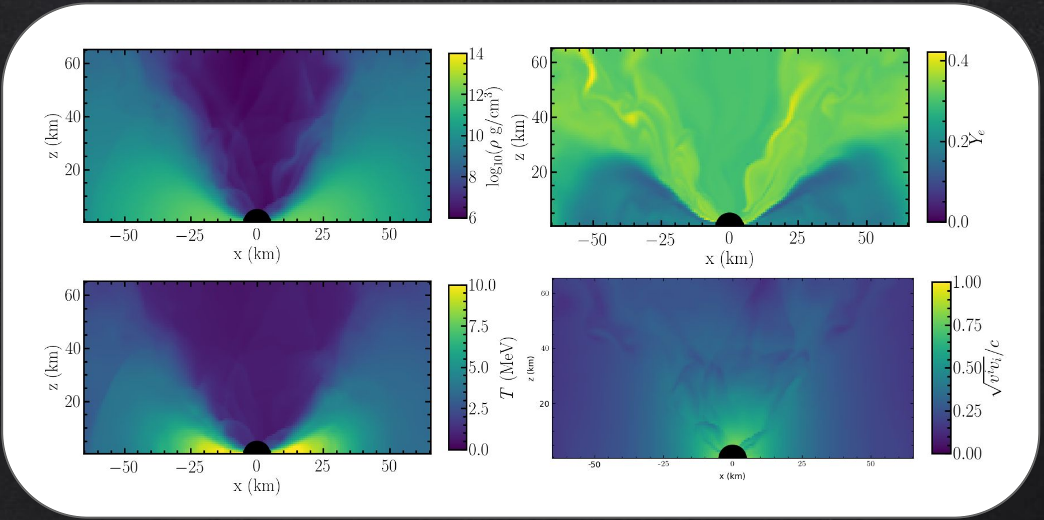
Quantum Neutrino Plasma



(Data from Radice+ 2018)

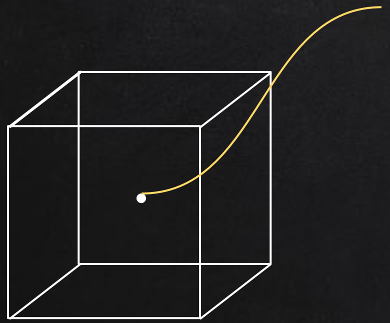


Quantum Neutrino Plasma

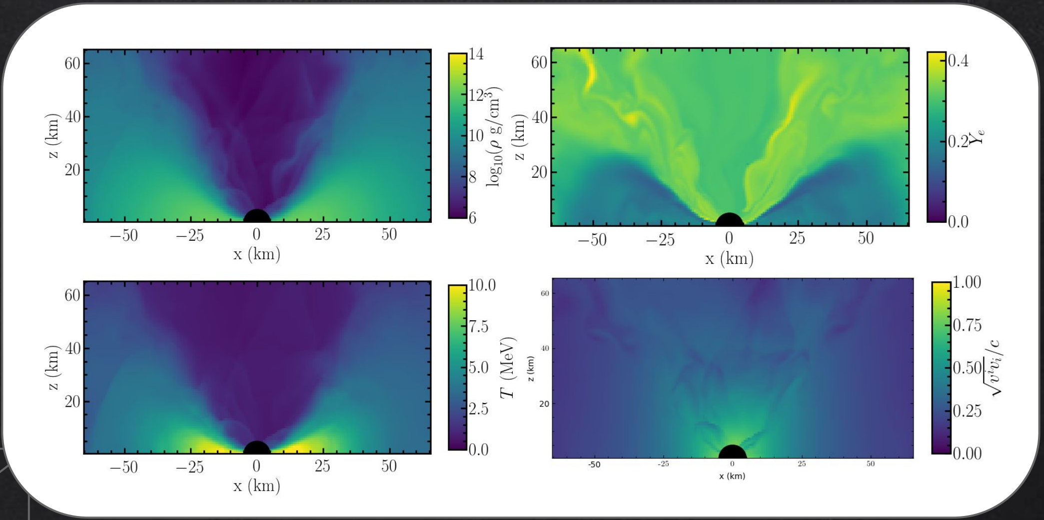


(Data from Radice+ 2018)

ρ, T, Y_E, V, B, METRIC



Quantum Neutrino Plasma



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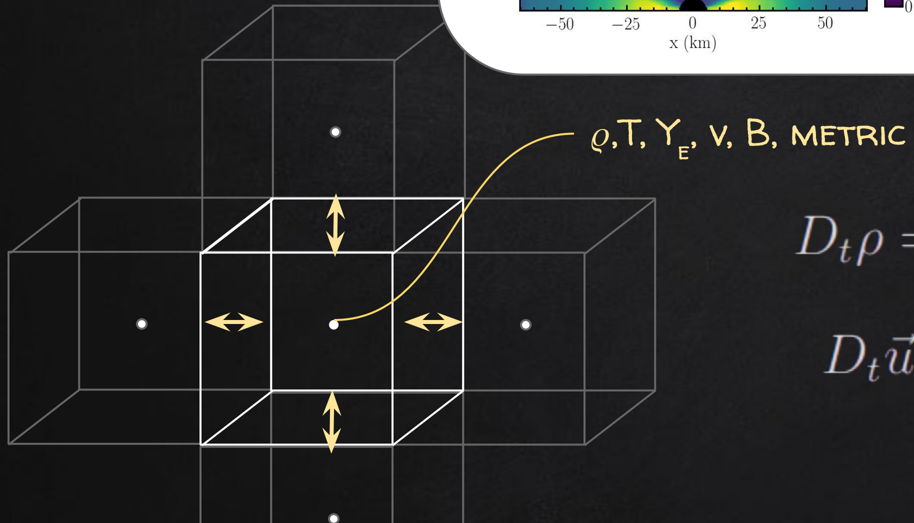


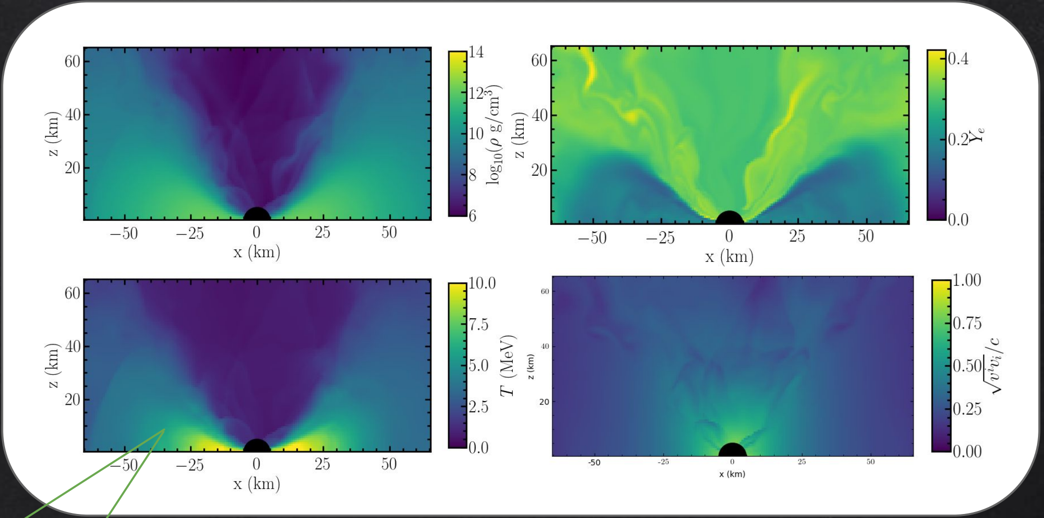
$$D_t \rho = -\rho \vec{\nabla} \cdot \vec{u}$$

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

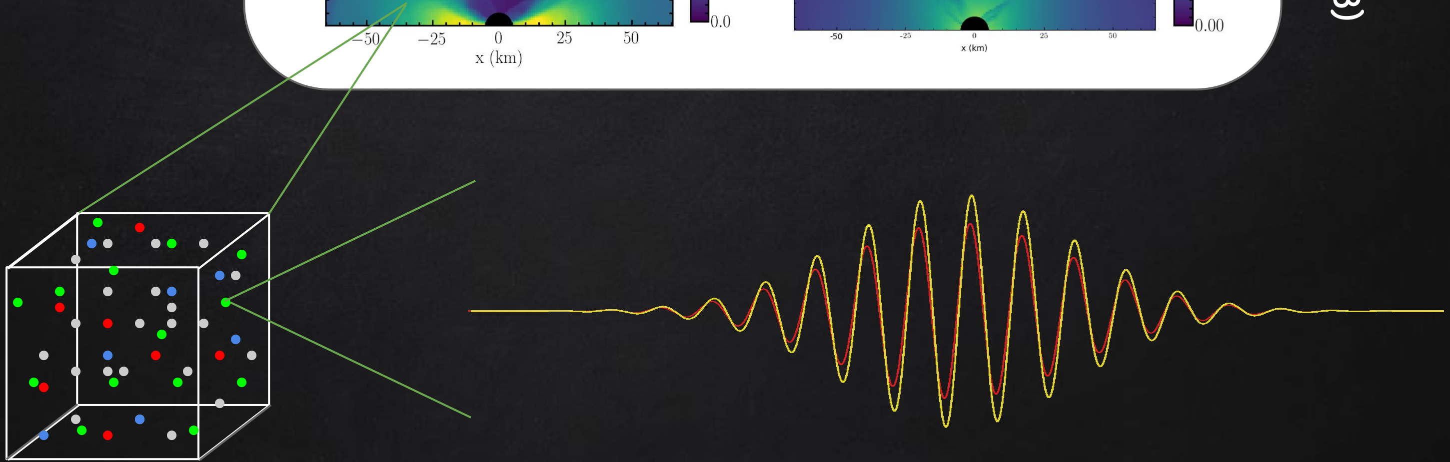
Equation of State

(because in equilibrium)

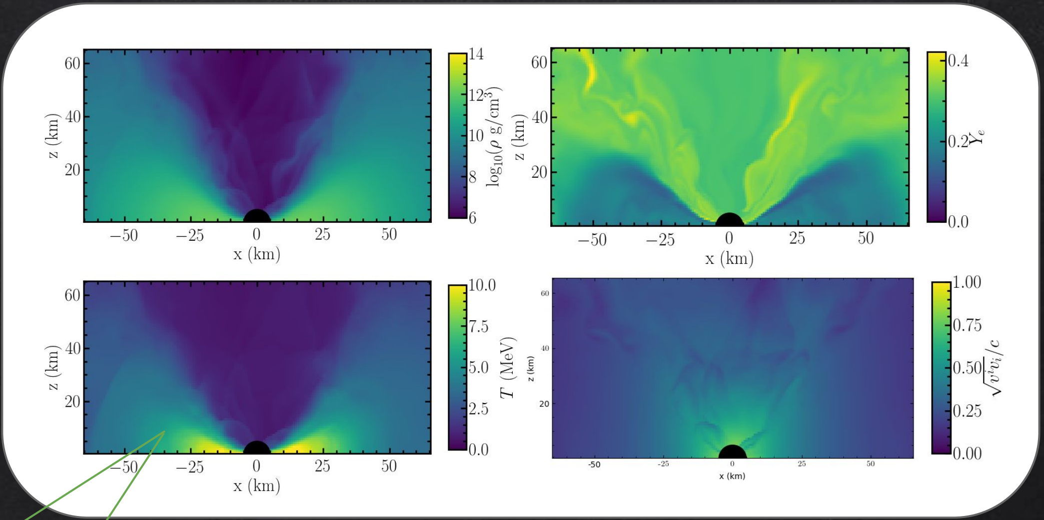
Quantum Neutrino Plasma



(Data from Radice+ 2018)



Quantum Neutrino Plasma



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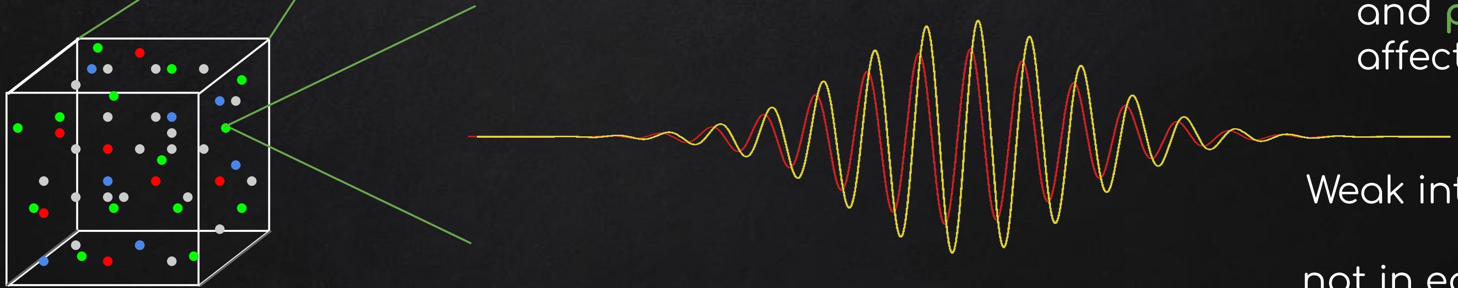


Neutrino mass and potential affect velocity.

Weak interactions
→
not in equilibrium.

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

<u>Transport</u>:

- Carry energy for supernova
- Irradiate merger ejecta
- Suppress large-scale structure
- CMB damping
- (same as hydrodynamics)

<u>Flavor Transformation</u>:

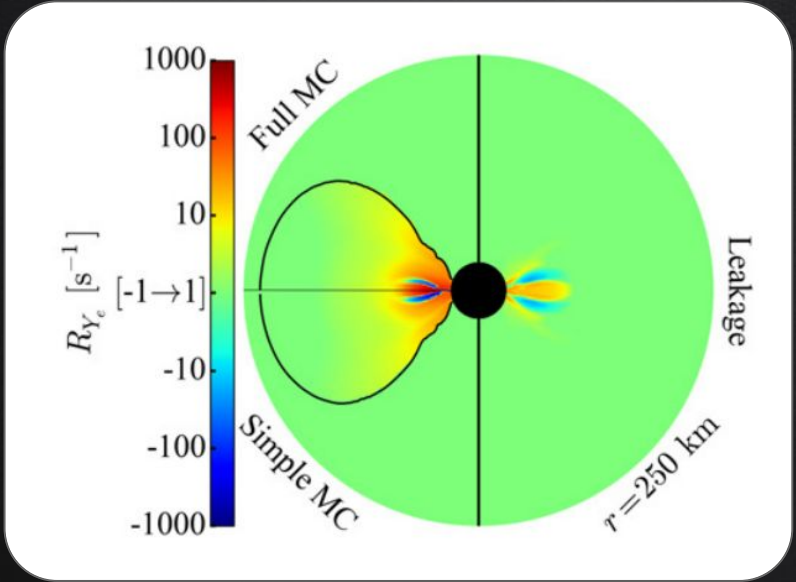
- Solar neutrino problem
- Neutrino mass
- Sterile neutrino / dark matter
- Neutrino flavor instabilities
- Quantum computing

<u>Collisions</u>:

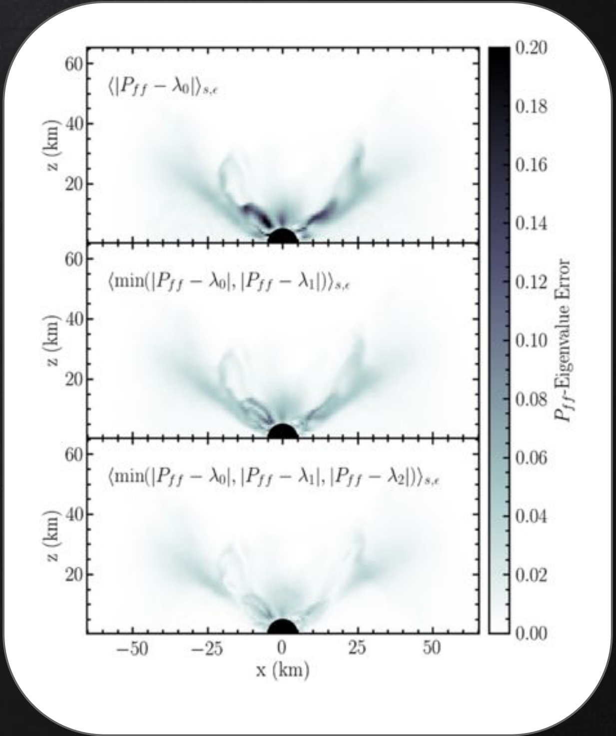
- PNS cooling
- Pre-supernova neutrinos
- n ↔ p conversion
- Nuclear equation of state
- Detector design

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

Richers+ (2015)



Richers (2020)

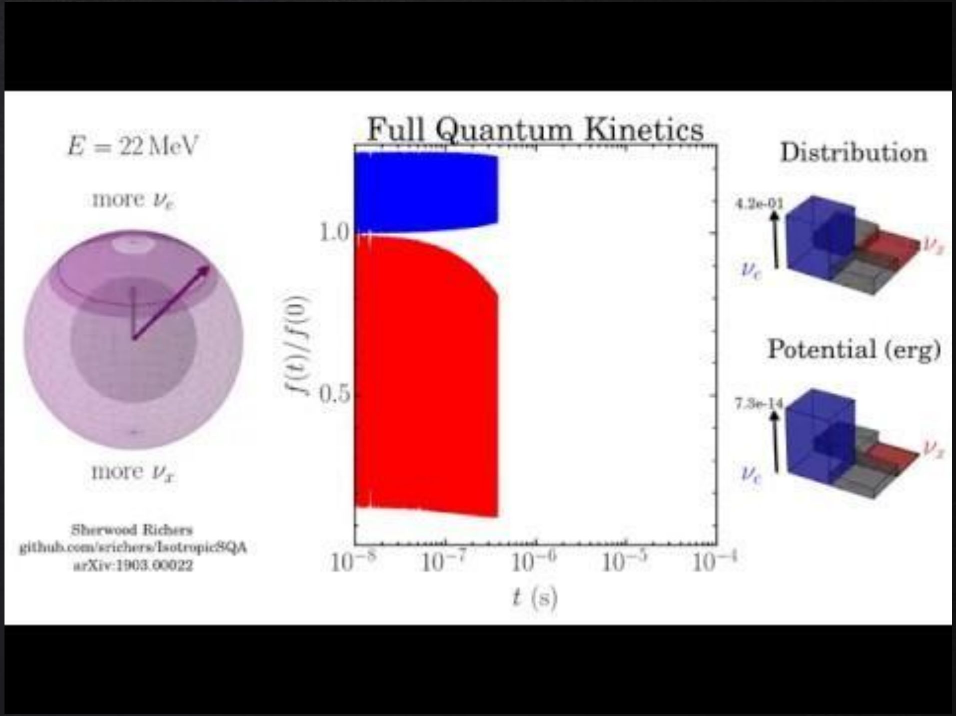


Transport approximations cannot be reconciled

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

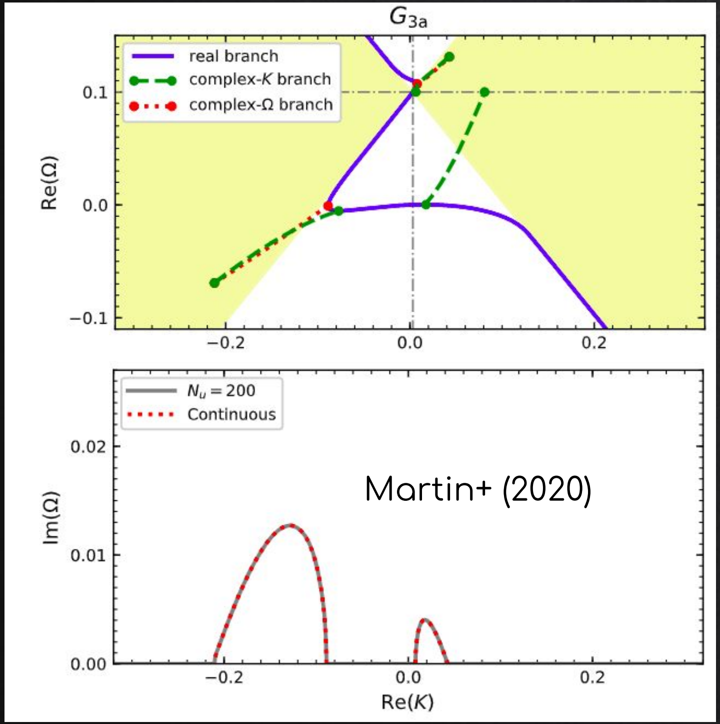
Oscillations can <u>**speed up**</u> or <u>**slow down**</u> decoherence

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



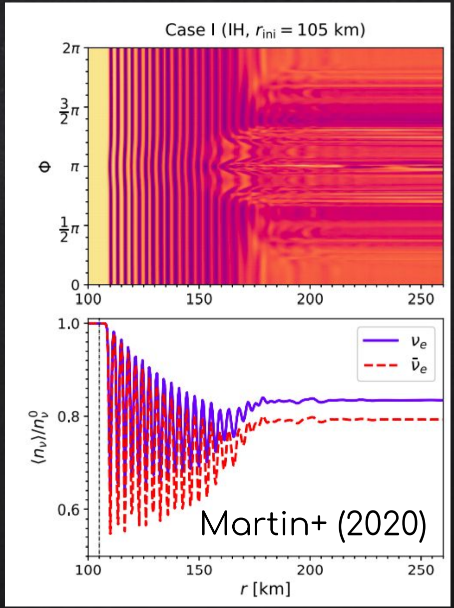
Richers+ (2019)

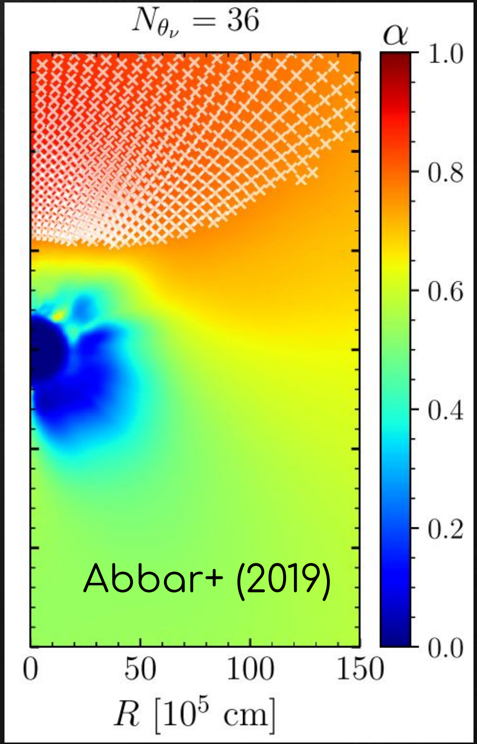
$$\boxed{\frac{\partial f_{ab}}{\partial t} + c\mathbf{\Omega}\cdot\nabla f_{ab}} = \cancel{\mathcal{C}_{ab}} - \boxed{\frac{i}{\hbar}[\mathcal{H}, f]_{ab}}$$



Dispersion Analysis

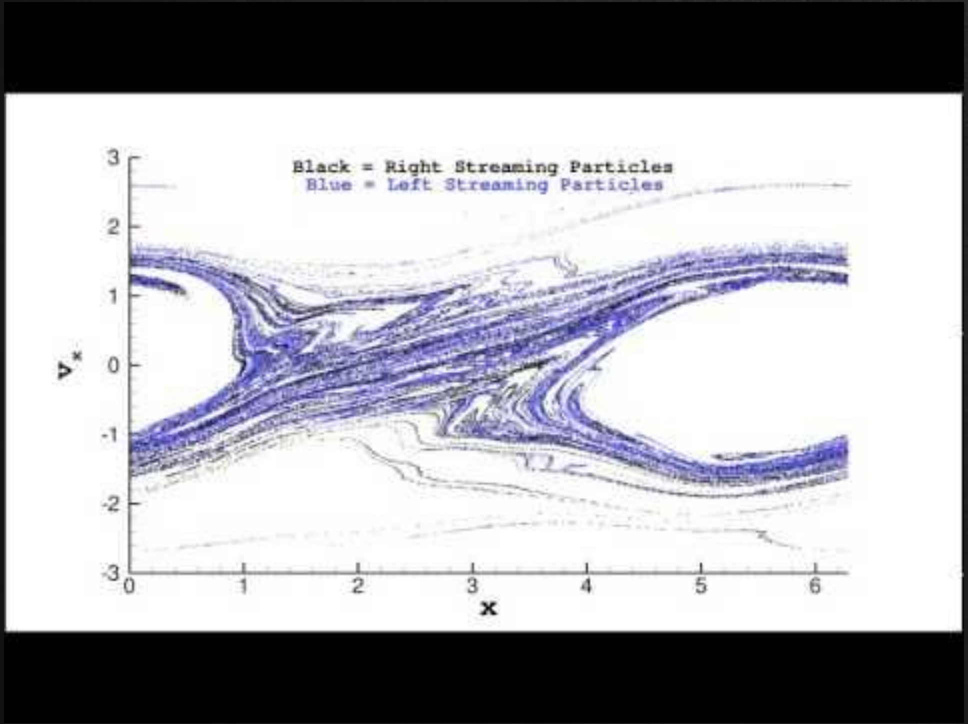
Direct Simulation





“Hunting for Crossings”

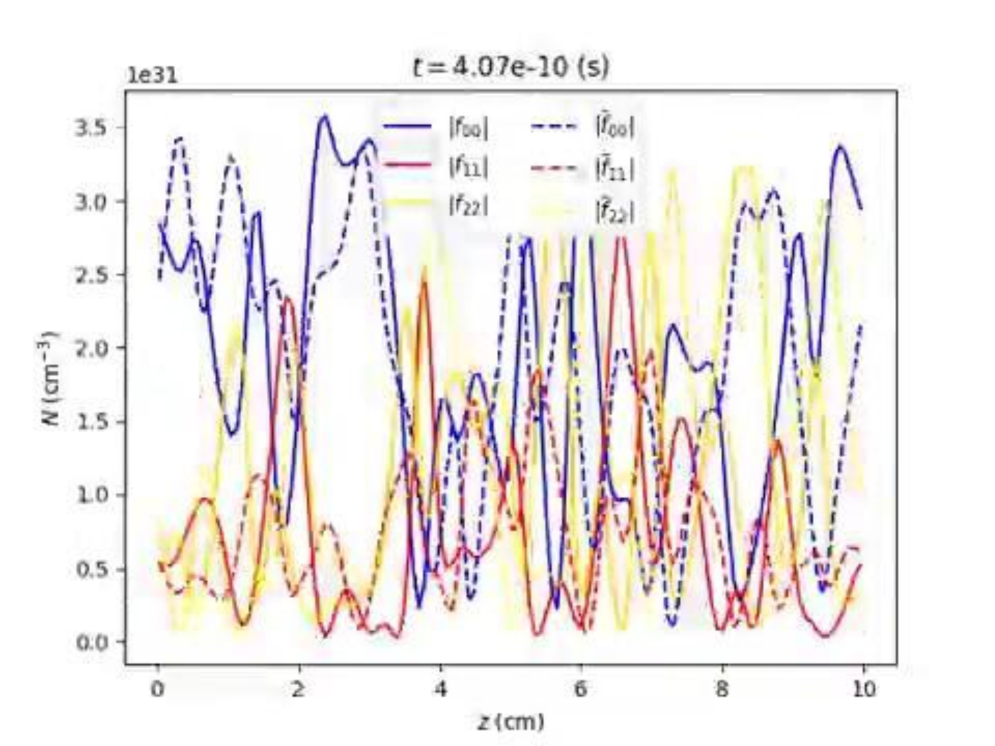
Aside: Plasma Instabilities



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

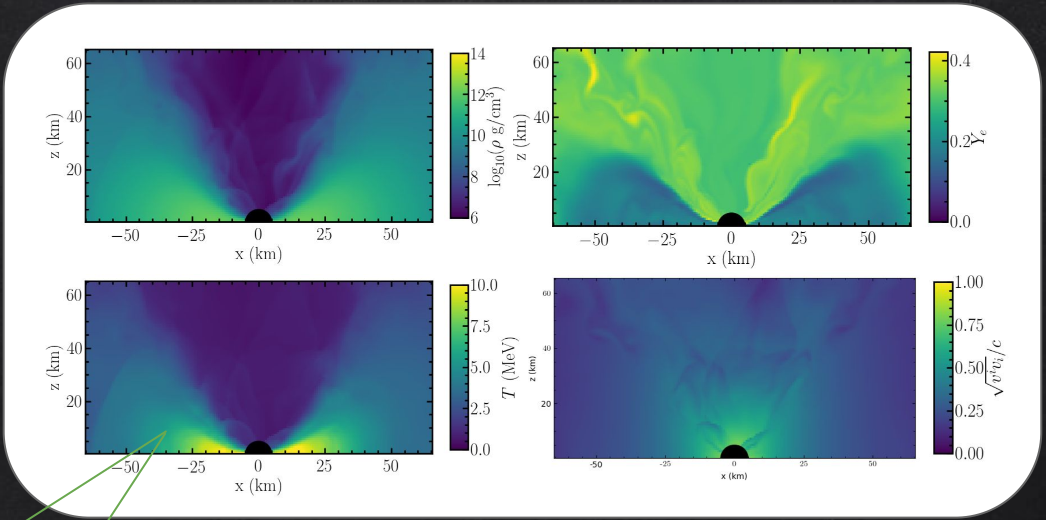
Neutrino Plasma Instabilities



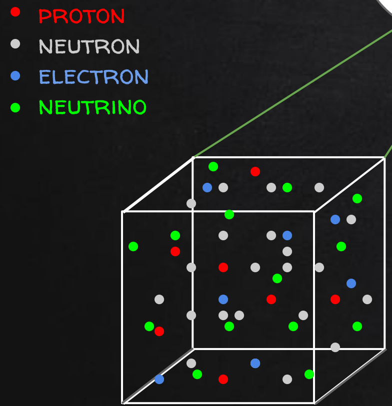
Because neutrinos feel potential from other neutrinos:

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

My Goal:



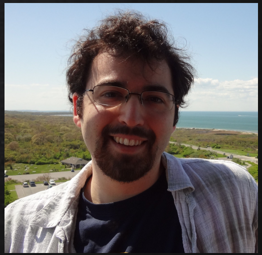
(Data from Radice+ 2018)



Determine neutrino flavor abundances after the fast flavor instability saturates

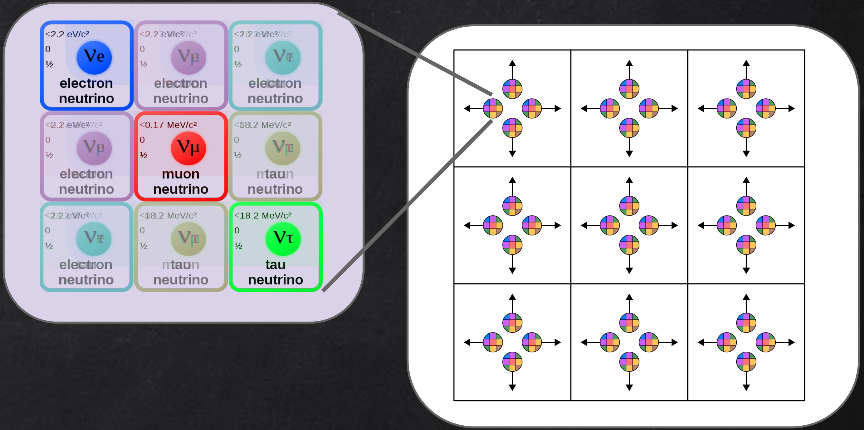
$$\boxed{\frac{\partial f_{ab}}{\partial t} + c\boldsymbol{\Omega}\cdot\nabla f_{ab}} = \cancel{\mathcal{C}_{ab}} - \boxed{\frac{i}{\hbar}[\mathcal{H}, f]_{ab}}$$

AMReX-based Flavor Simulation



Don Willcox
(LBNL)

- ✘ Particle-in-cell method
- ✘ 3-dimensional
- ✘ Arbitrary number of flavors
- ✘ CPU and GPU capable



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

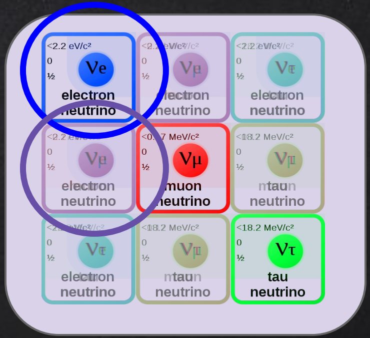
$$\frac{d\mathcal{F}}{d\lambda} + \text{force} + \text{drift} = -p^\mu u_\mu \left(\mathcal{C} - \frac{i}{\hbar c}[\mathcal{H}, \mathcal{F}] \right)$$

Initialize Particles → Deposit Potential → Move/Evolve → Deposit Potential

“Quantum Coherence Phase”

<u>Abundance</u> of electron neutrinos

ϱ_{ee}

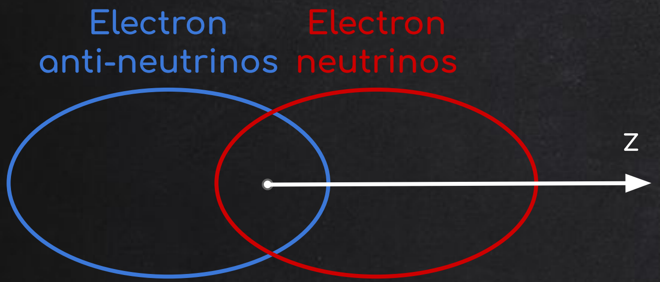


Abundance of mixed-state neutrinos

$\varrho_{e\mu}$ =A $e^{i\phi}$

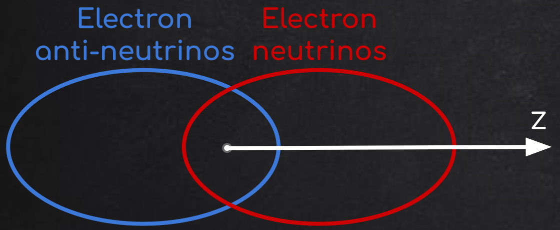
Shows <u>wavefronts</u>.

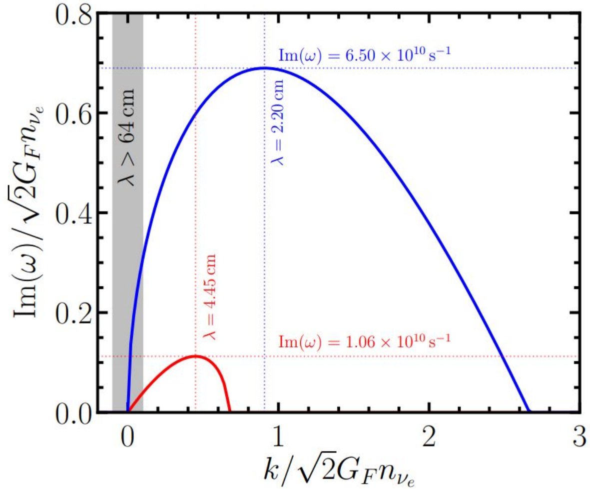
1D “Fiducial” Test

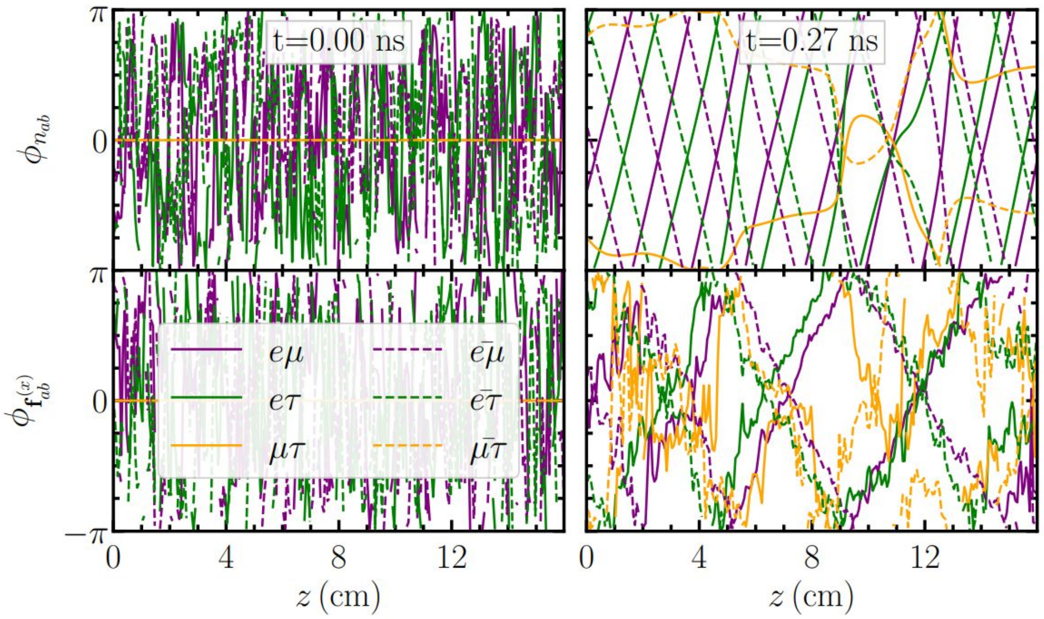


1D "Fiducial" Test

$\varrho_{e\mu}$=A $e^{i\phi}$



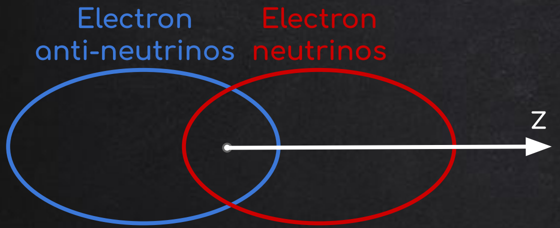


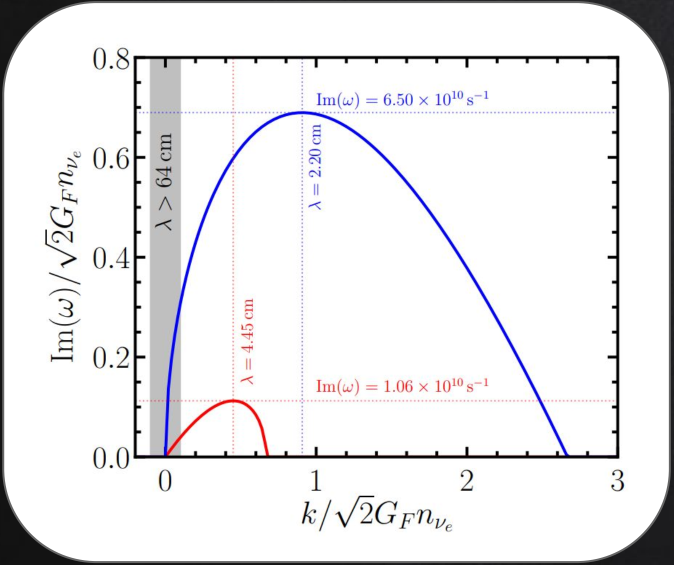


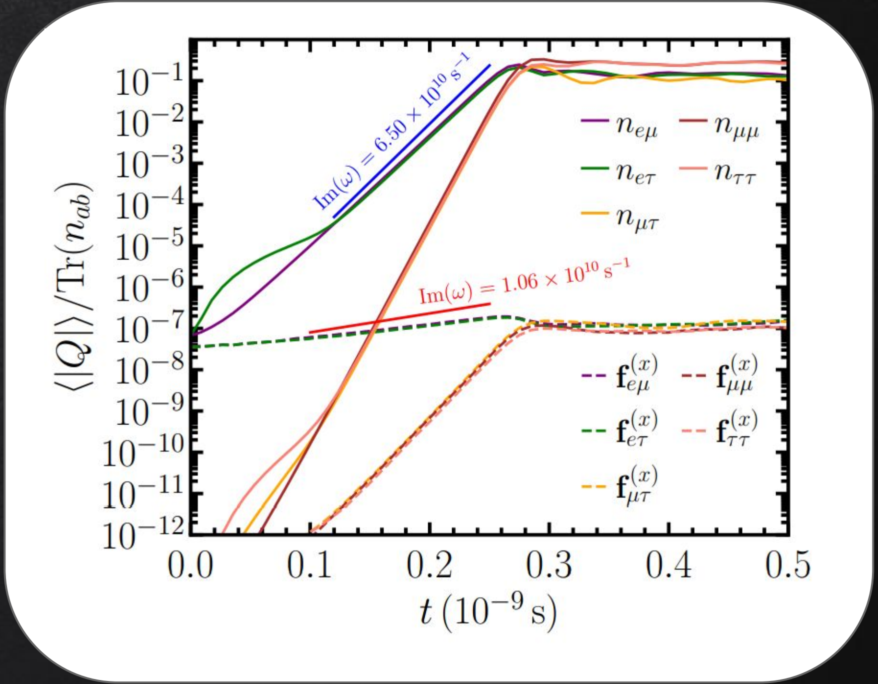
The wavelengths match!

1D “Fiducial” Test

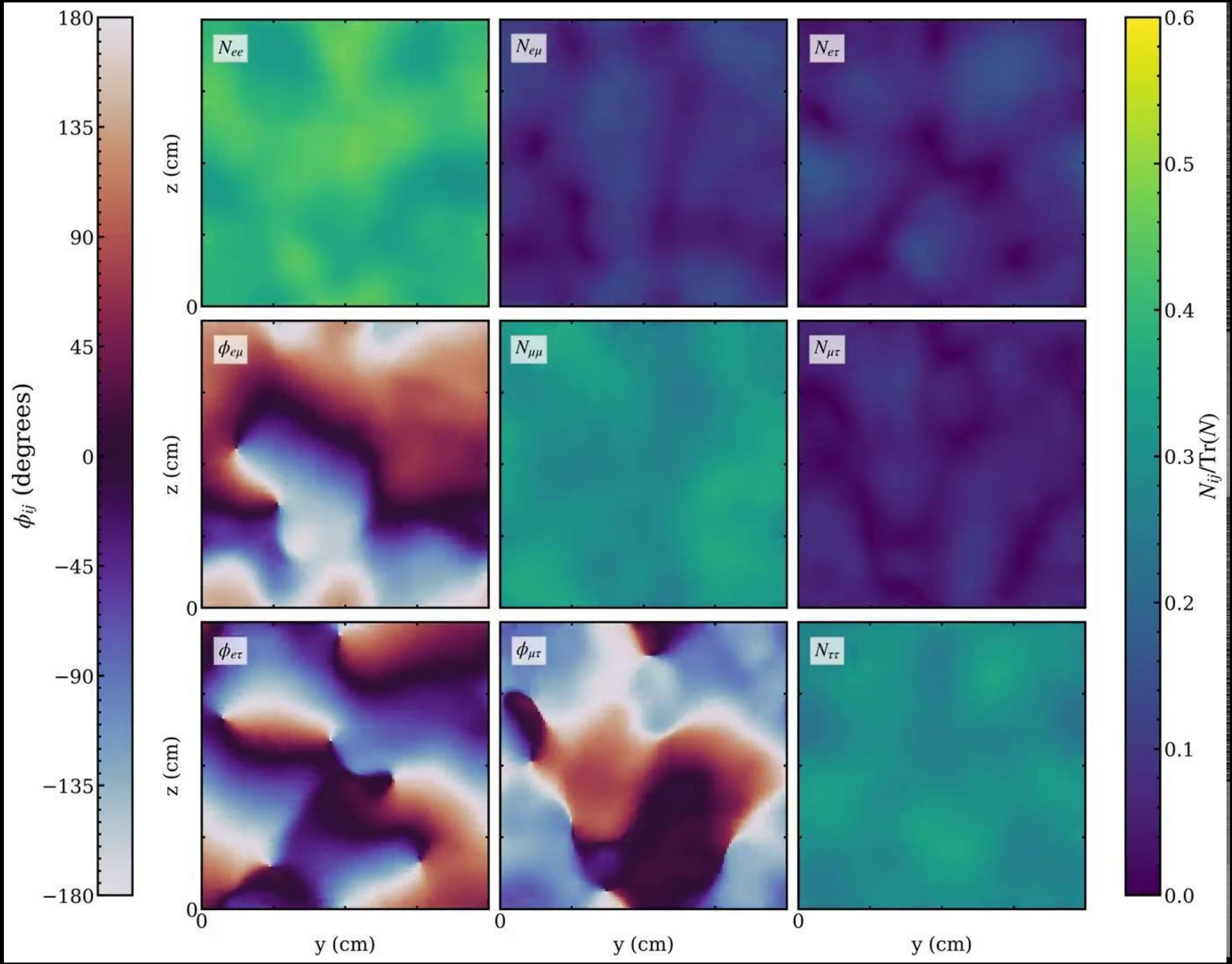
$\varrho_{e\mu} = A\, e^{i\phi}$



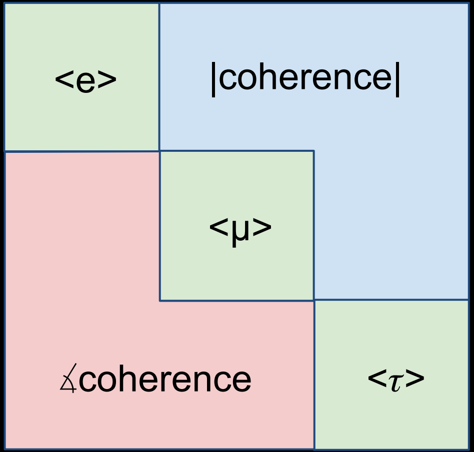


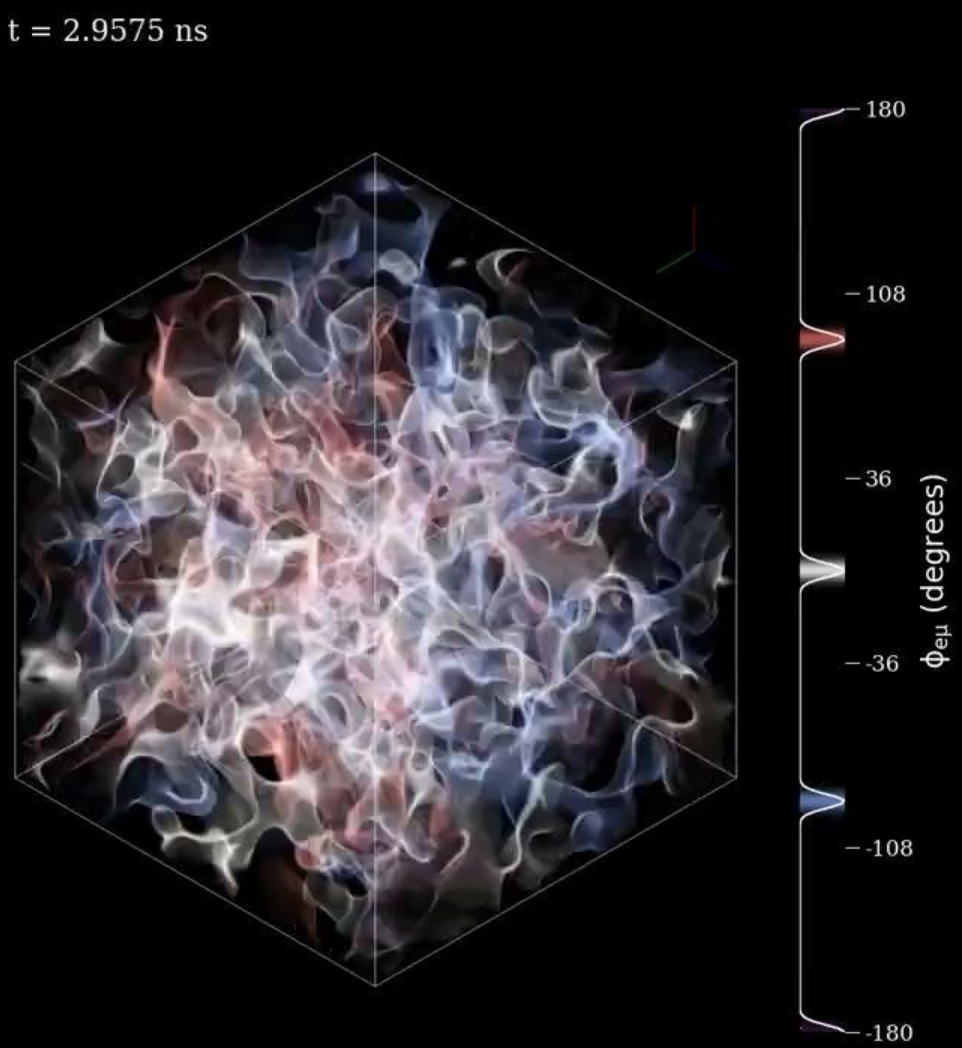


The growth rates match, too!

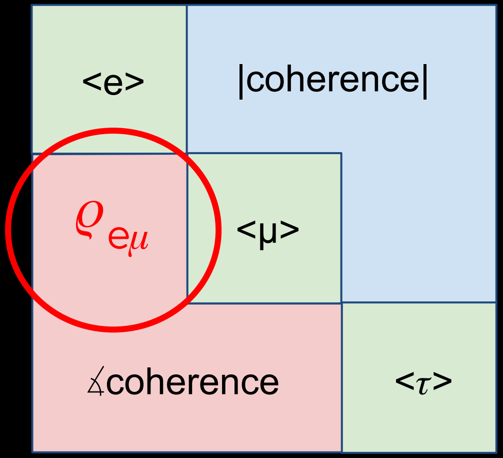


Strongly multi-dimensional in **growth** and **saturation** phases

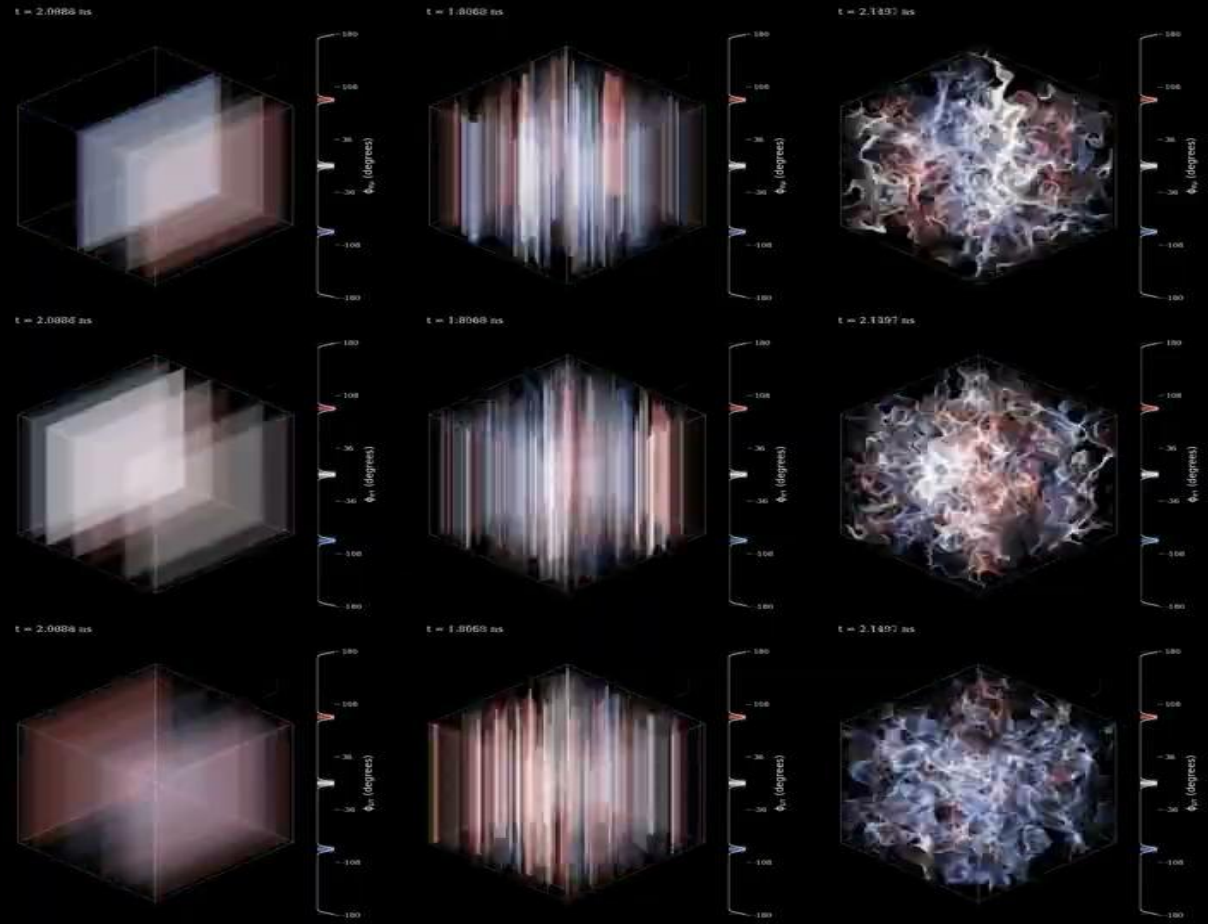




Strongly multi-dimensional in **growth** and **saturation** phases



1D 2D 3D



$\varrho_{e\mu}$

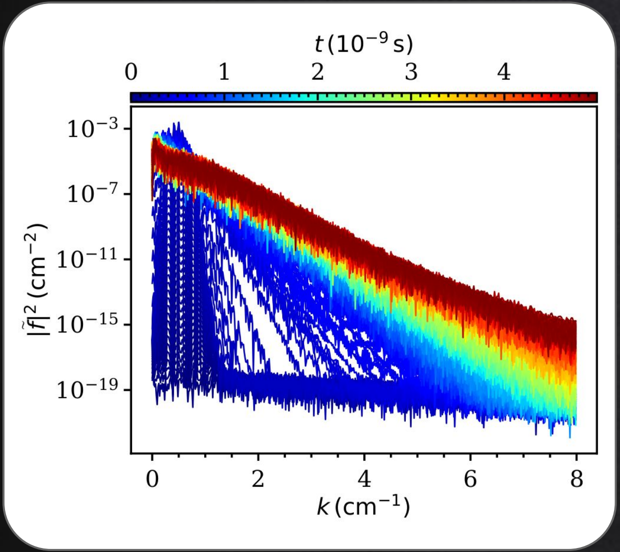
$\varrho_{e\tau}$

$\varrho_{\mu\tau}$

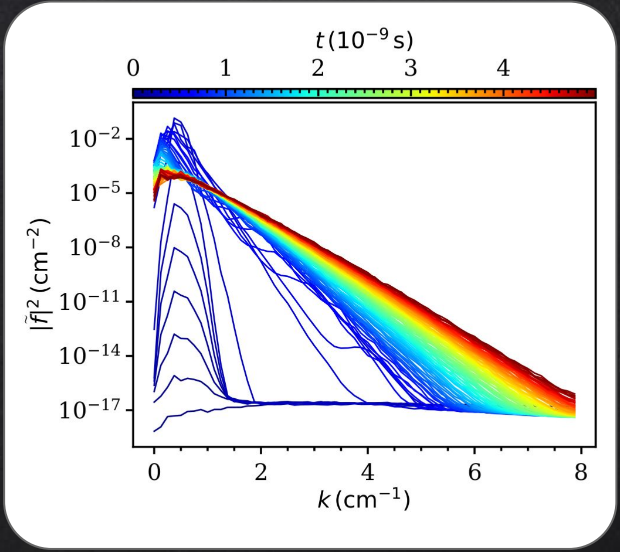
Nature is 3D

Is there a Kolmogorov spectrum?

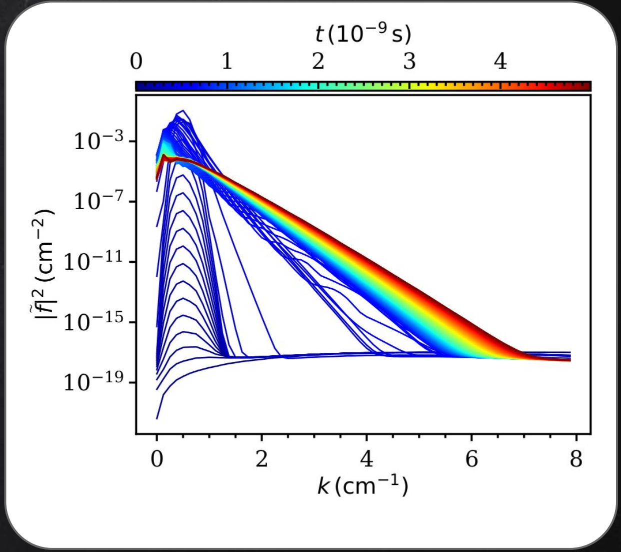
1D



2D



3D

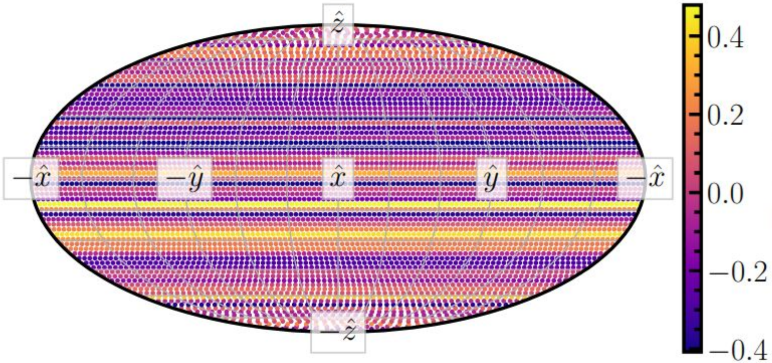


No, it is exponential.

3D converges at lower angular resolution

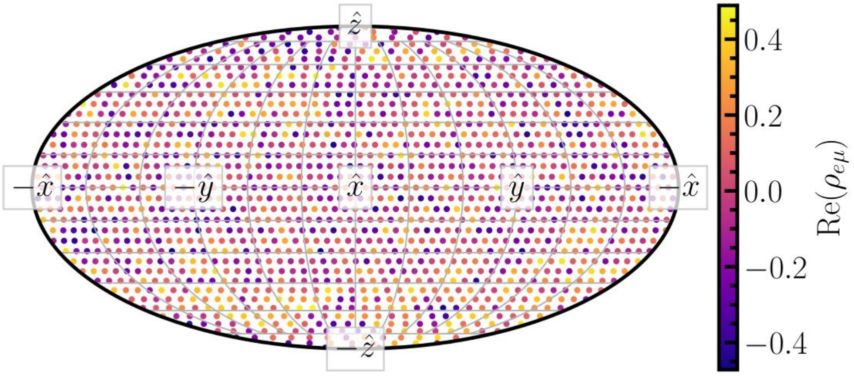
Angular Structure

1D



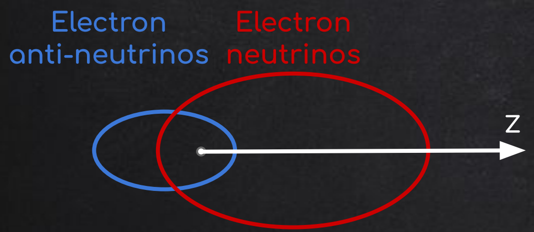
The flavor distribution is **highly symmetric** even after saturation.

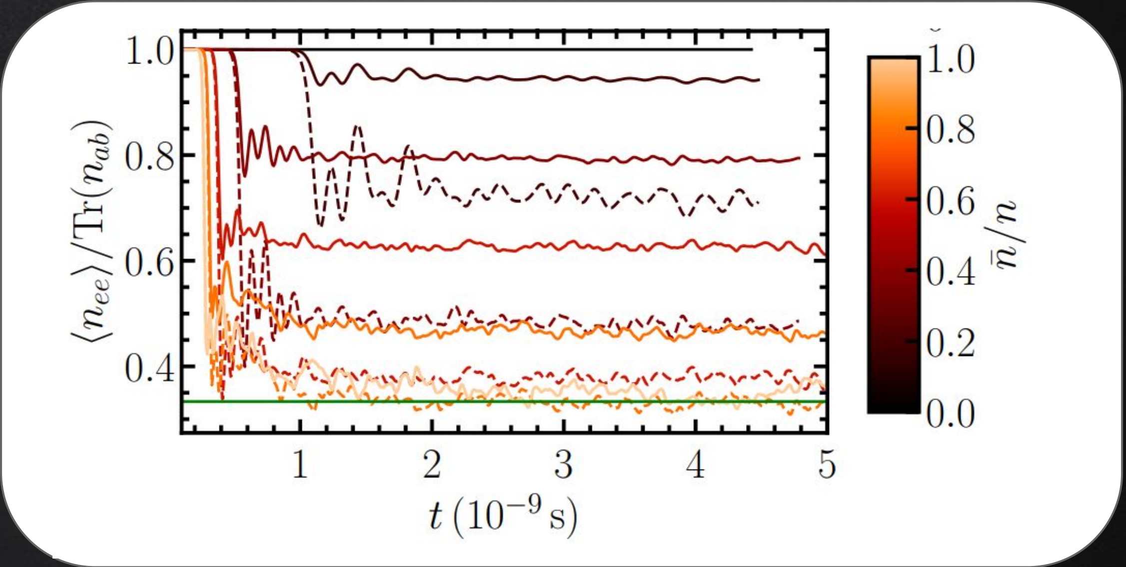
3D



The flavor distribution **quickly randomizes**.

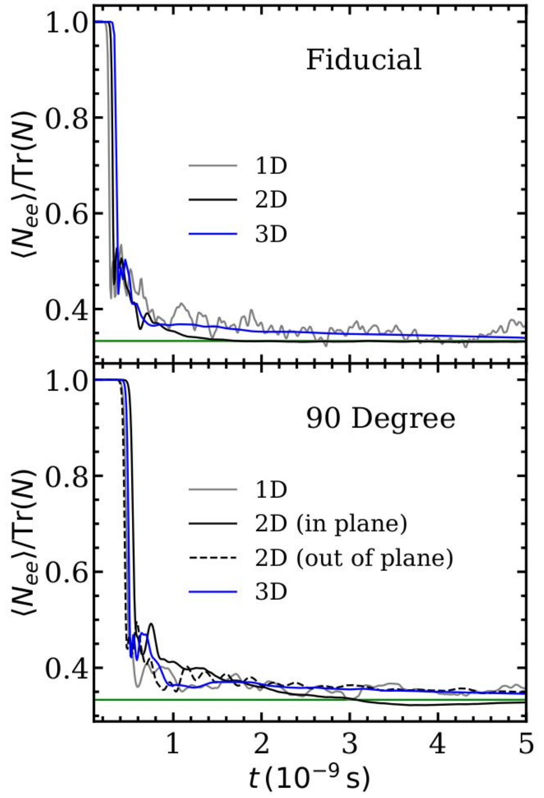
Parameter Sweep

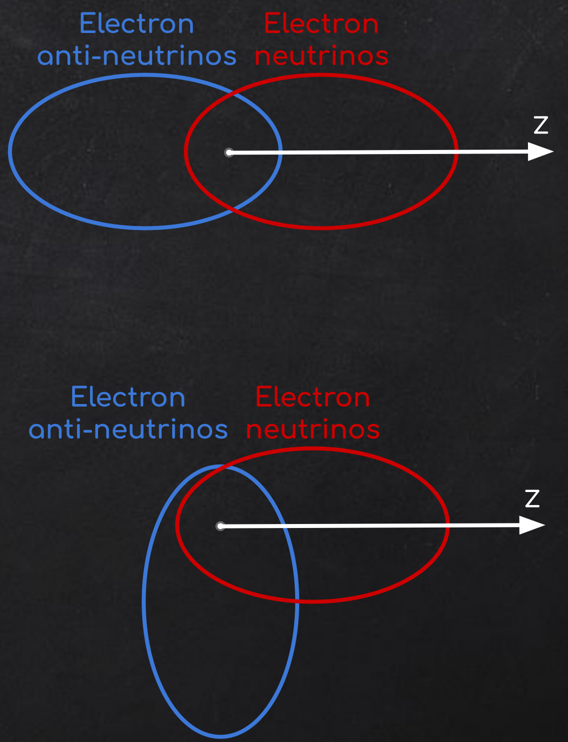




The **growth rate** and **final flavor content** depend on the distribution details.

Do we really need fancy 3D simulations?





1D and 3D *may* produce the same neutrino abundances.

Conclusions

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

The **growth rate** and **final flavor content** depend on the distribution details.

3D may produce same flavor abundance as 1D.

Parameter studies will allow **effective treatment of flavor transformation** in neutron star merger simulations.