3D Simulations of the Neutrino Fast Flavor Instability

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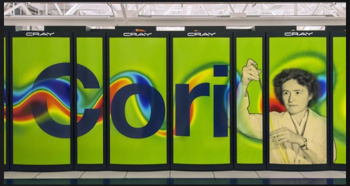
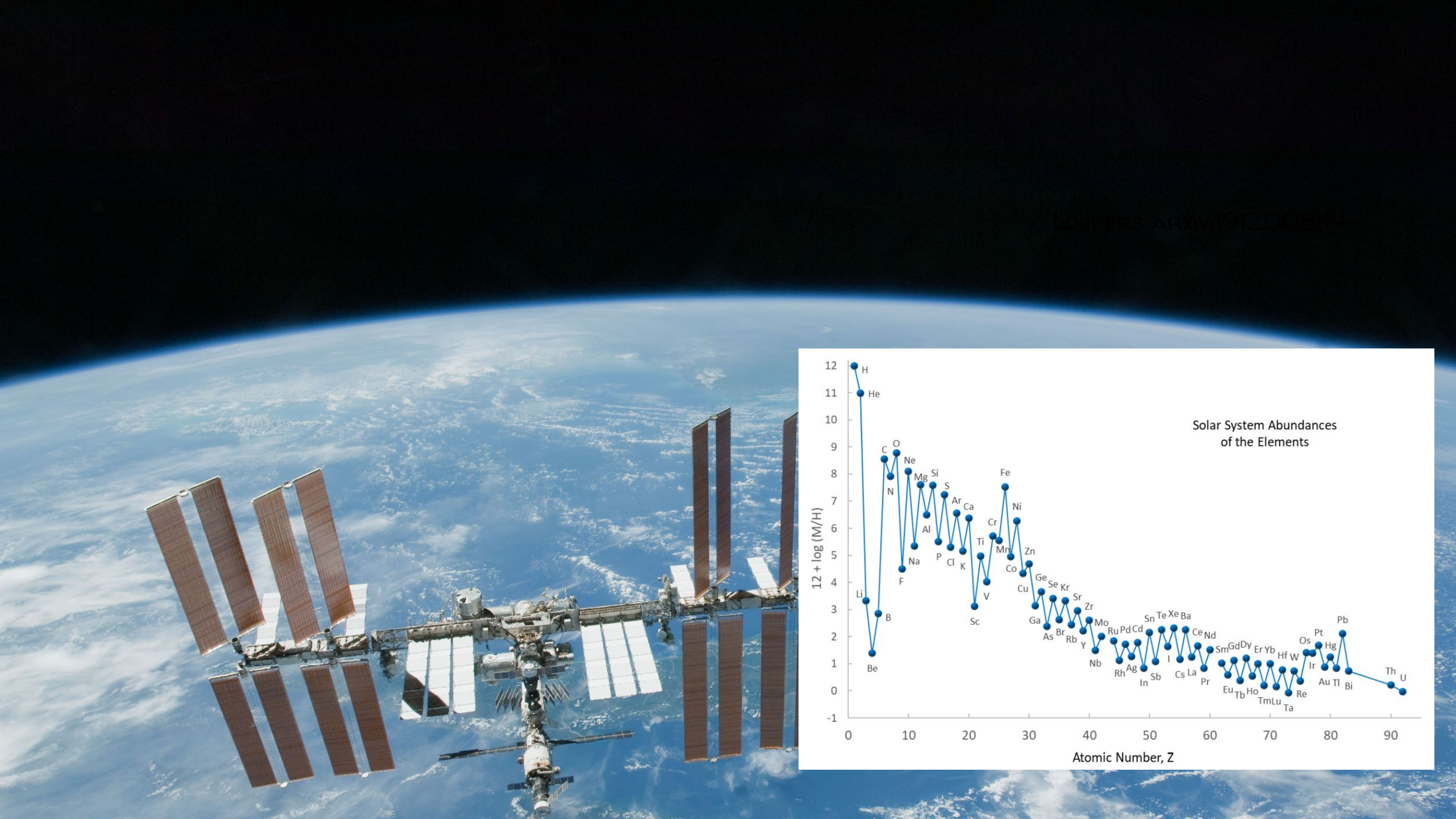
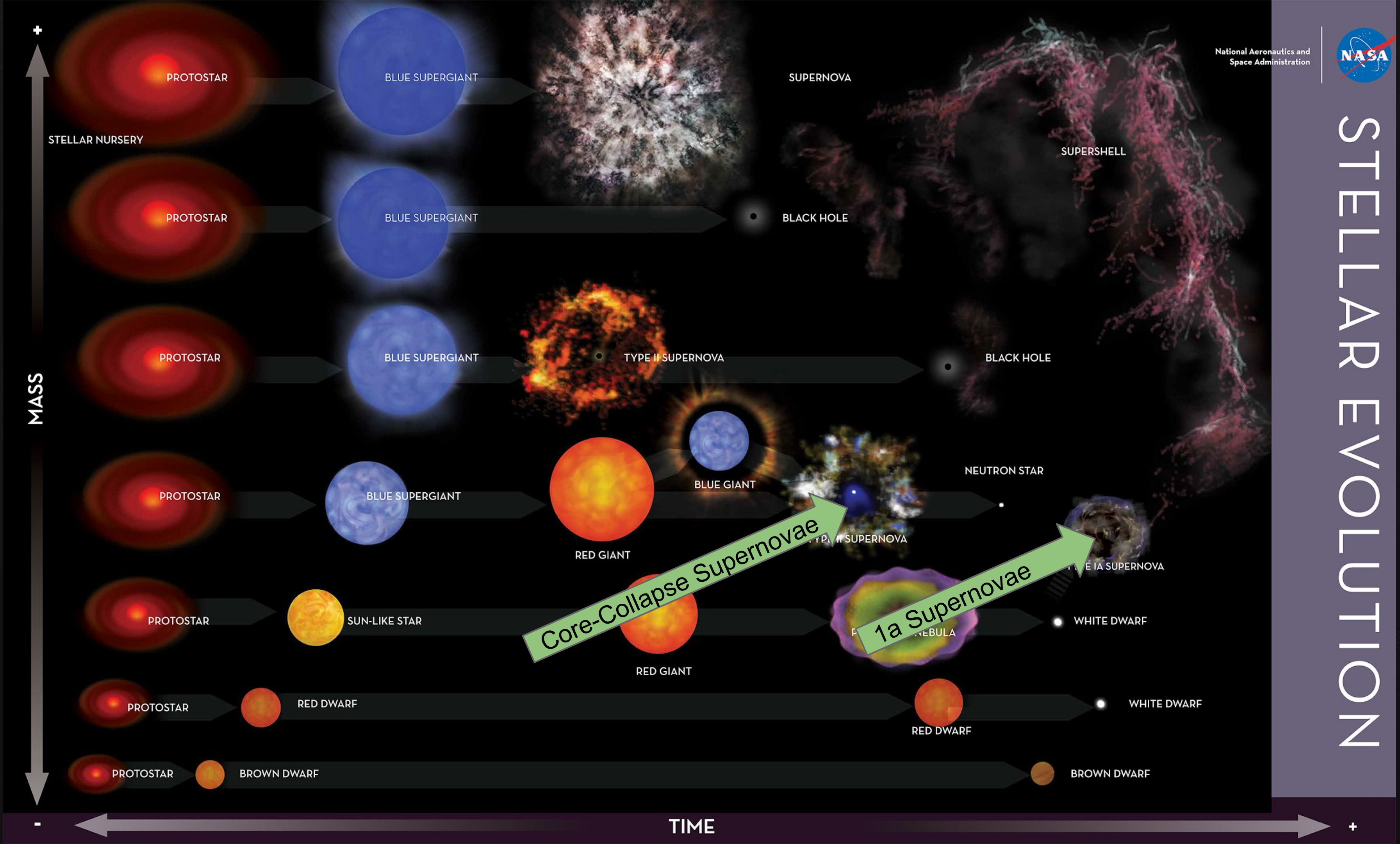
NSF

HEISING-SIMONS FOUNDATION

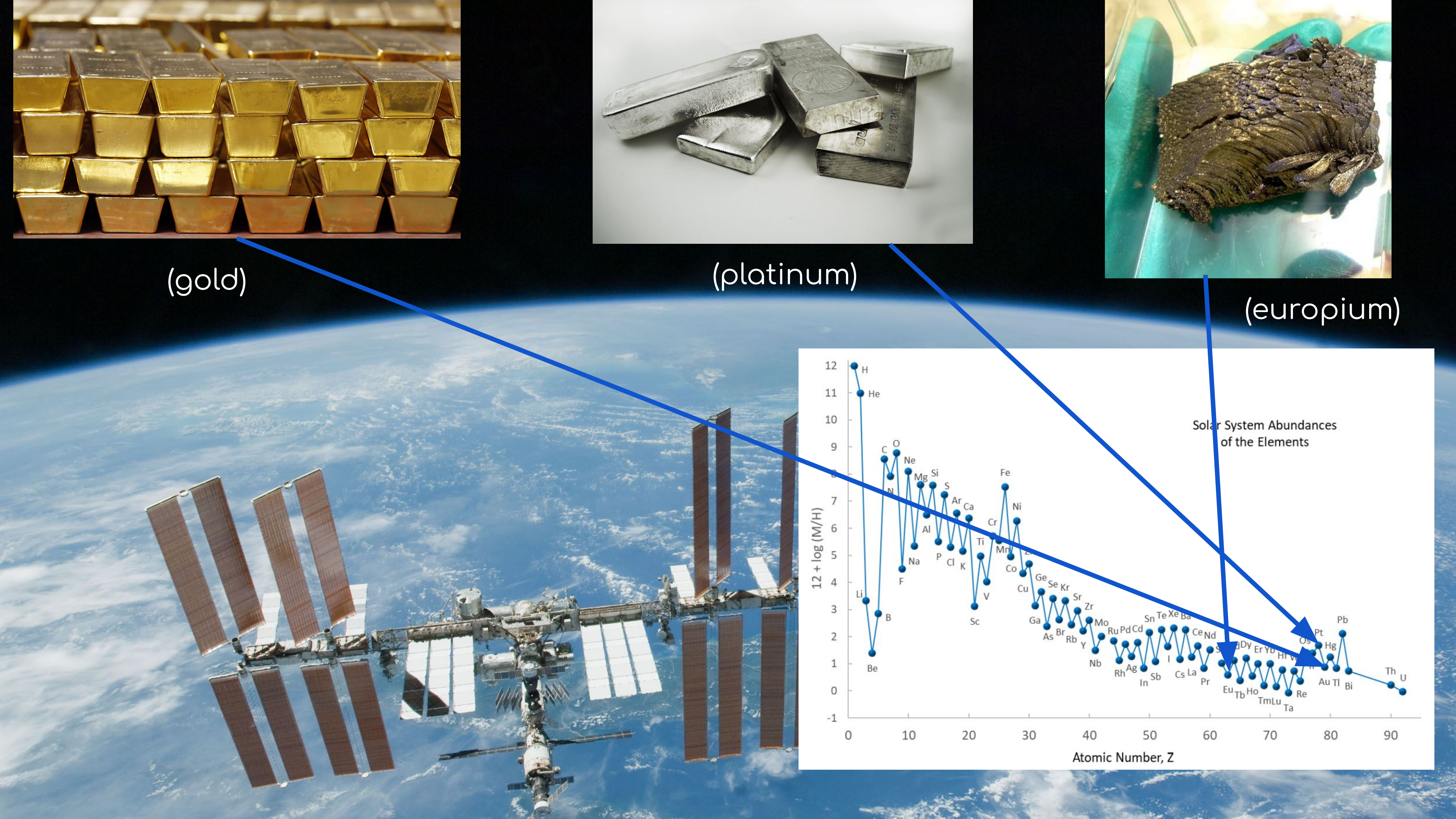




Lodders arXiv:1912.00844
Solar System Abundances
of the Elements
12 + log (M/H)
Atomic Number, Z



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


(gold)
(platinum)
(europium)
Solar System Abundances of the Elements
12 + log (M/H)
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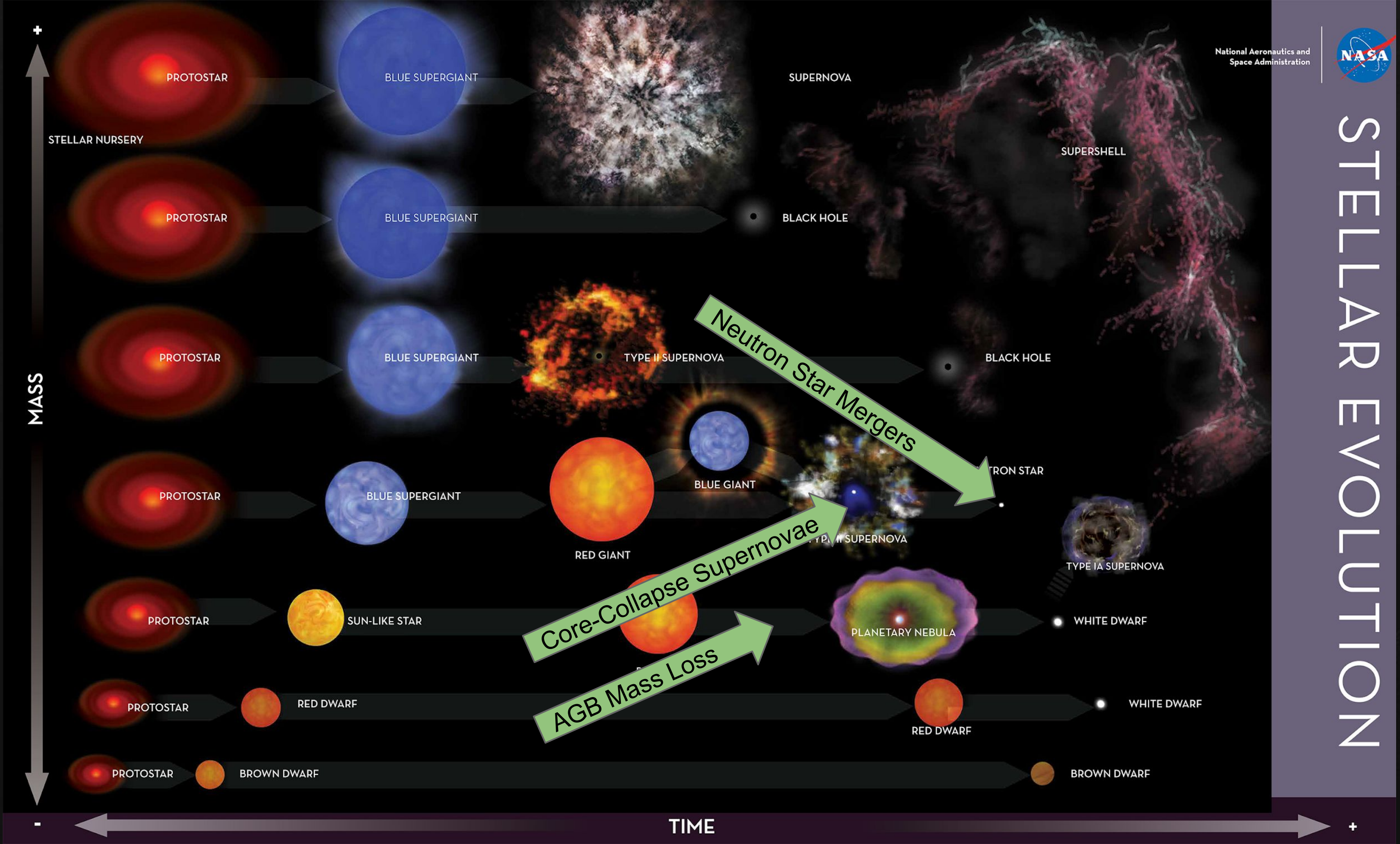

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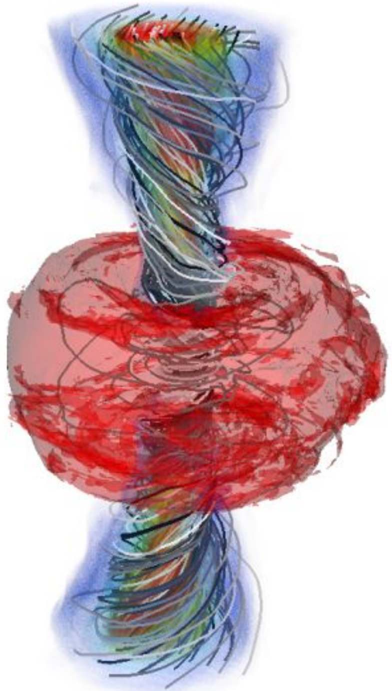
BLUE GIANT
SUPERNOVA
TRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
Neutron Star Mergers
Core-Collapse Supernovae
AGB Mass Loss

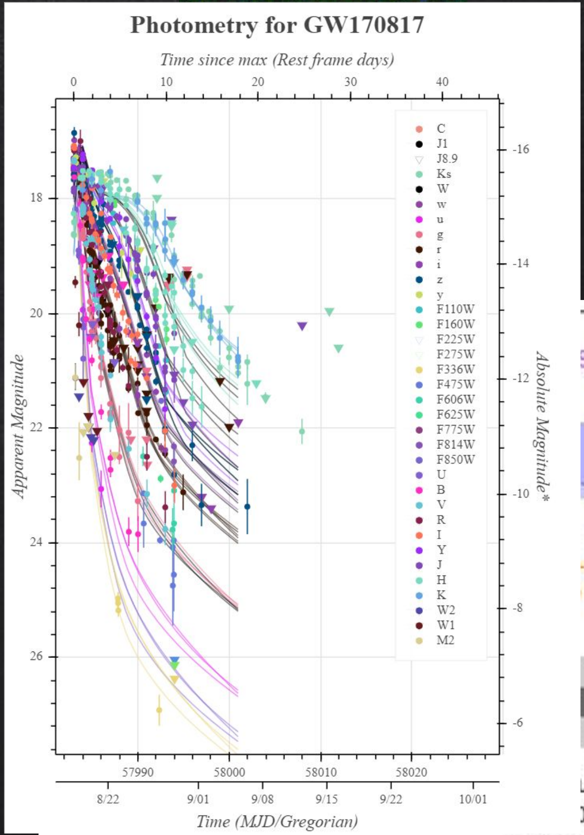
What’s the big deal with neutron star mergers?

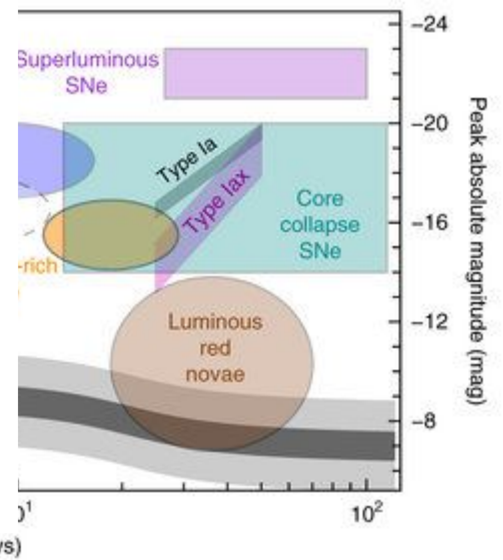


Moesta et al. (2020)

What’s the big deal with neutron star mergers?

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

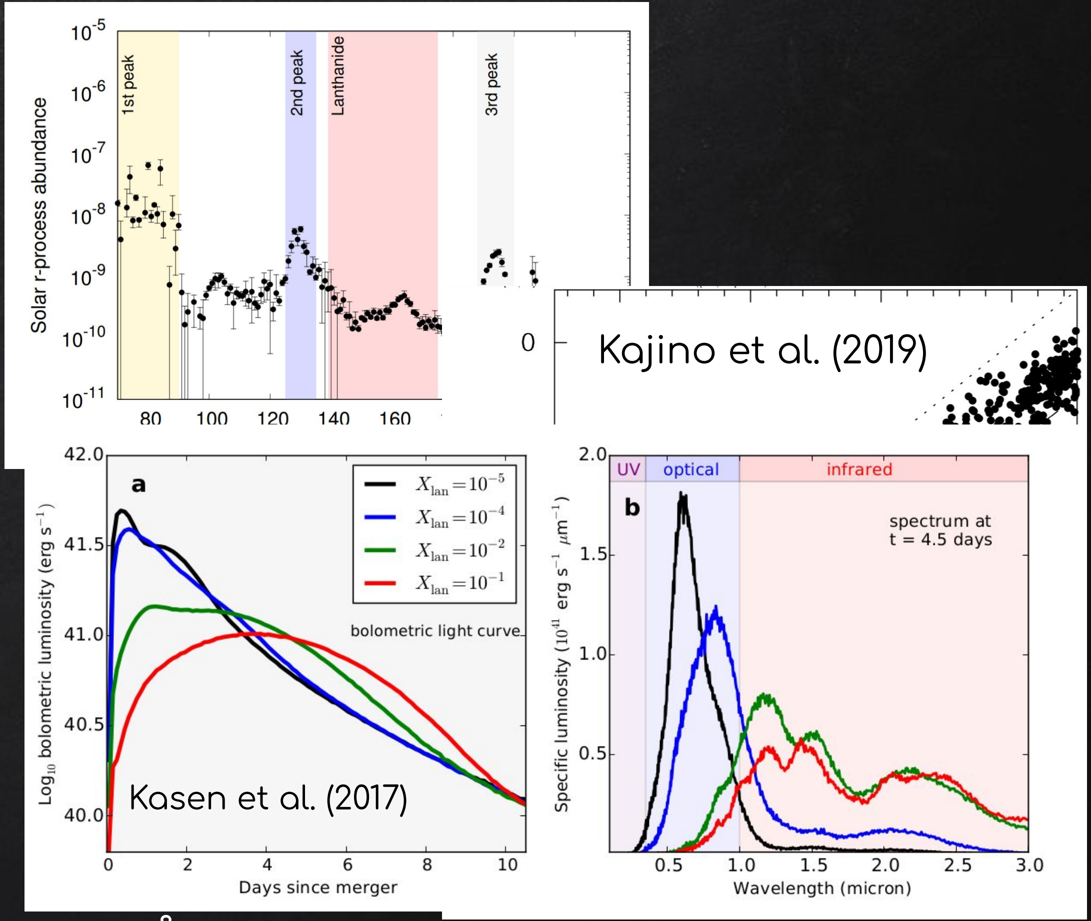




Open Kilonova Catalog

What’s the big deal with neutron star mergers?

1. **Transients** - Can we explain everything we see?
2. **Heavy elements** - Where did all this stuff come from?



What's the big deal with neutron star mergers?

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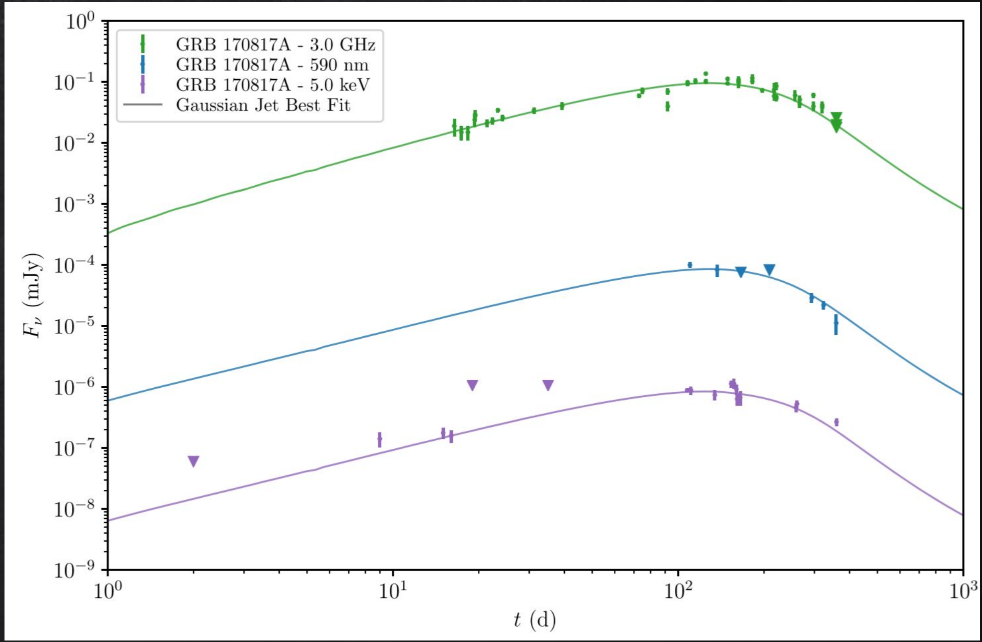
3. **Short GRBs** - How can nature create such an energetic burst in so little time?



Ryan et al. (2020)

What's the big deal with neutron star mergers?

1. Transients - Can we explain everything we see?
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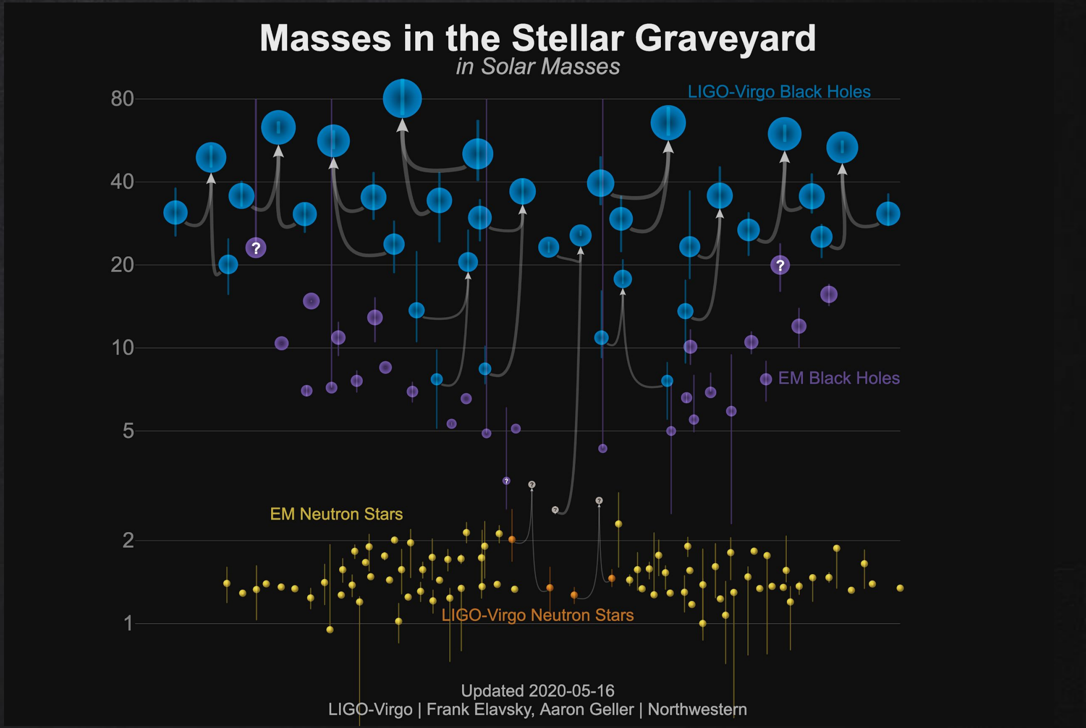
4. Black Holes - how do they form?



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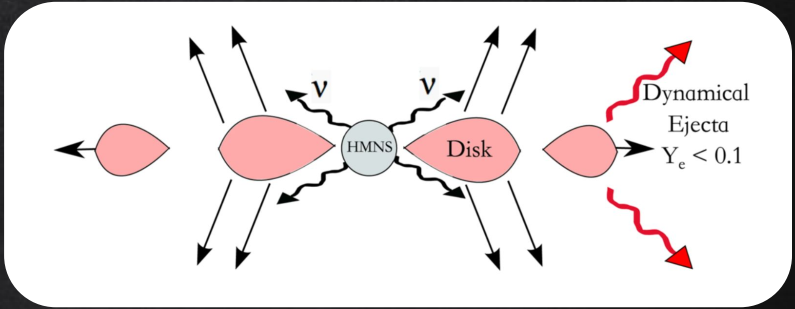
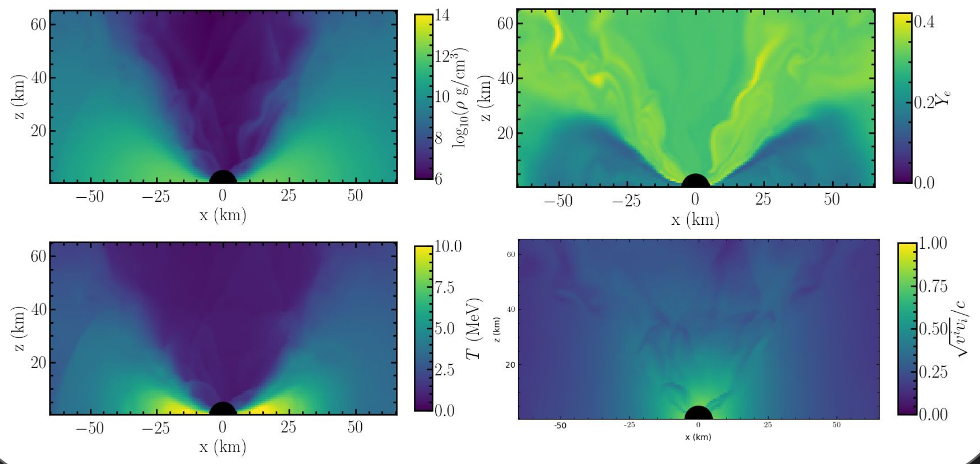


Metzger & Fernandez (2014)

Neutrinos can:

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

Do we really understand?



(Data from Radice+ 2018)

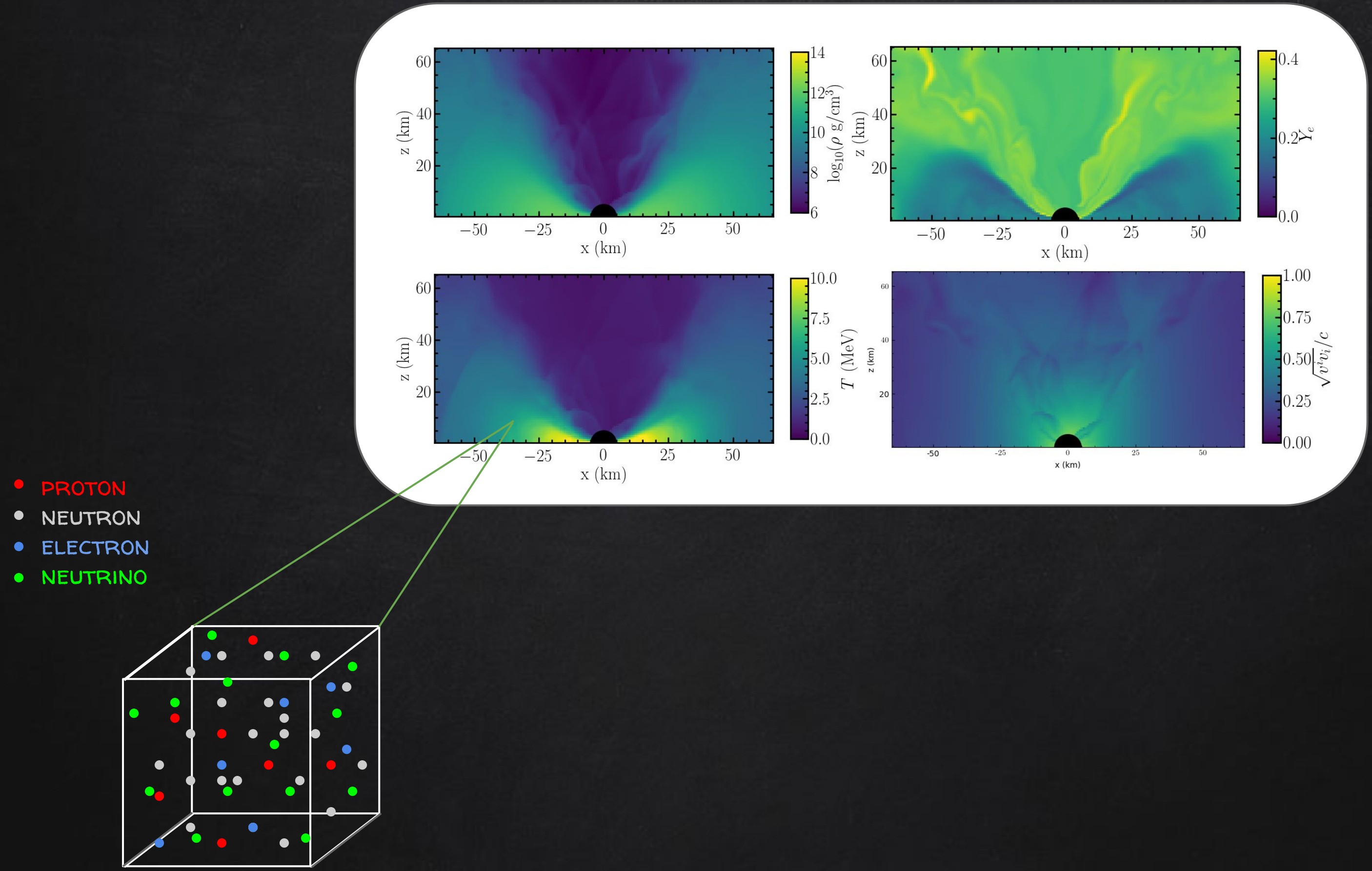
Open Questions

- 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?

So let's model it!

- GR magnetohydrodynamics
- Nuclear equation of state
- Radiation transport

Do we really understand?



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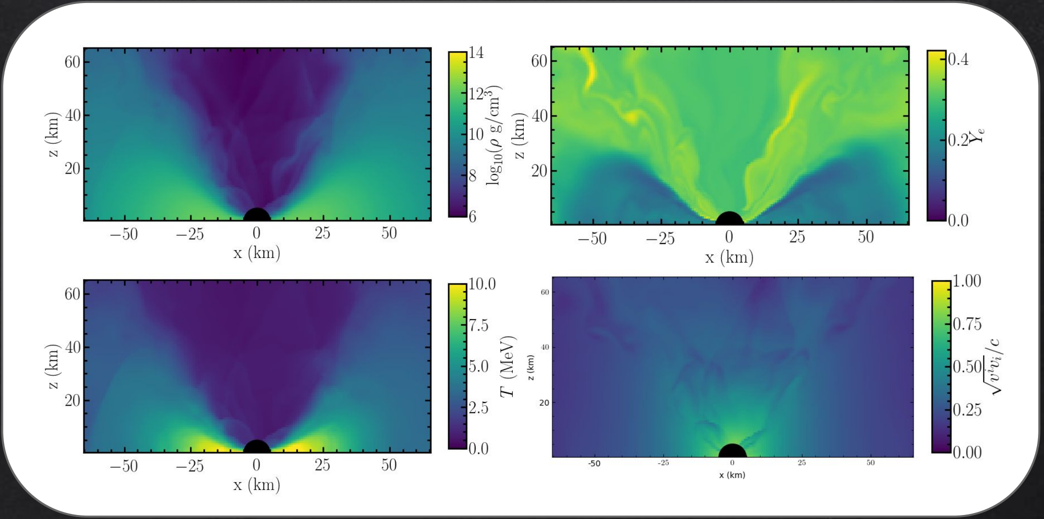

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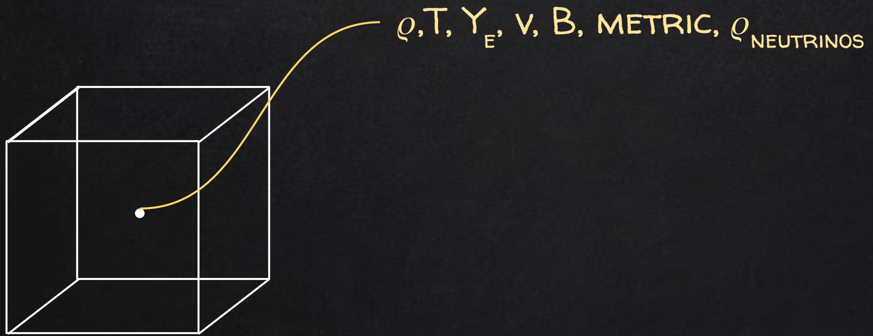

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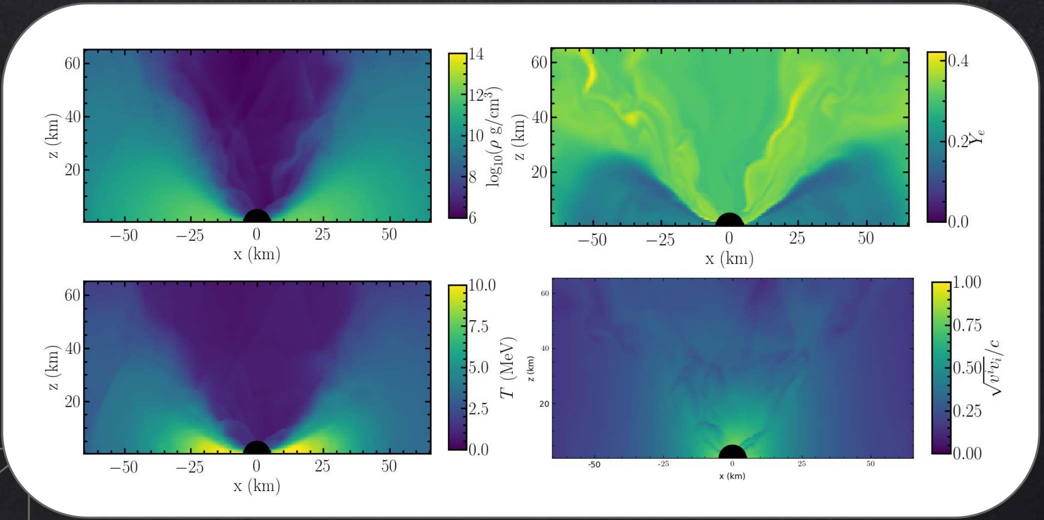

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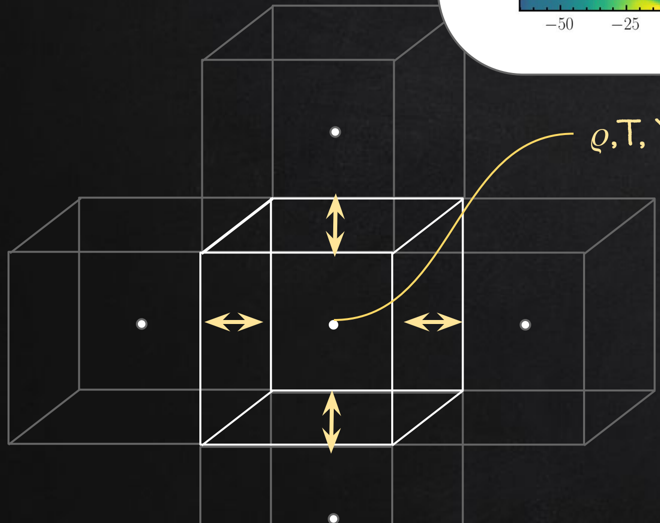
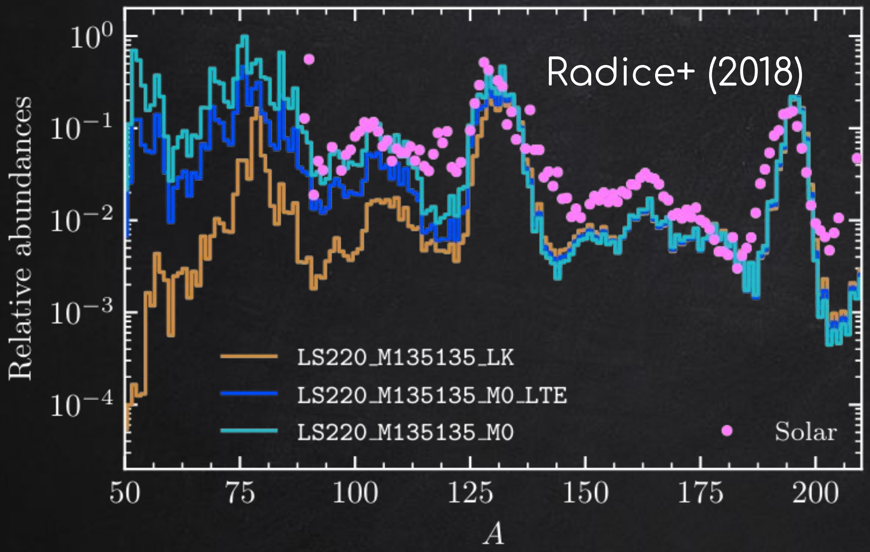
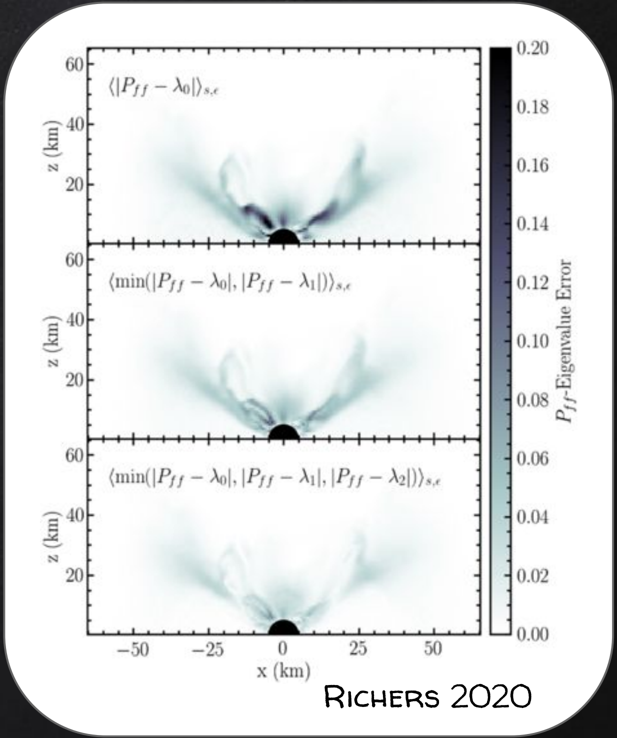


ρ, T, Y_E, V, B, METRIC, $\rho_{NEUTRINOS}$

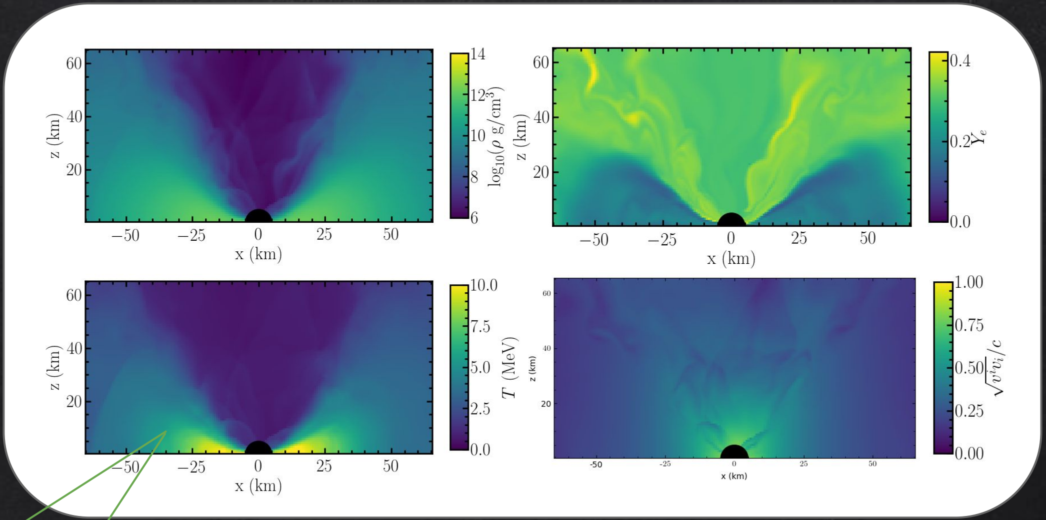
Parameter studies require many simulations



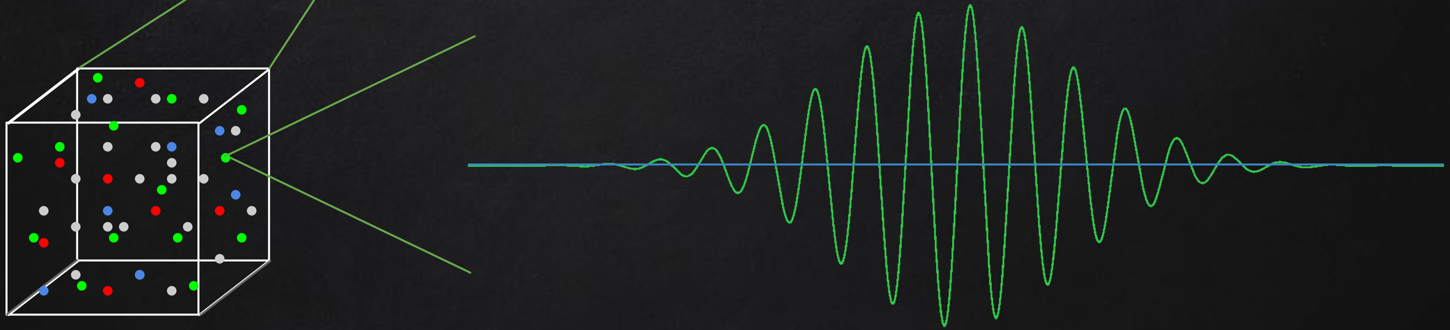


But approximations induce errors.

Do we really understand?



(Data from Radice+ 2018)



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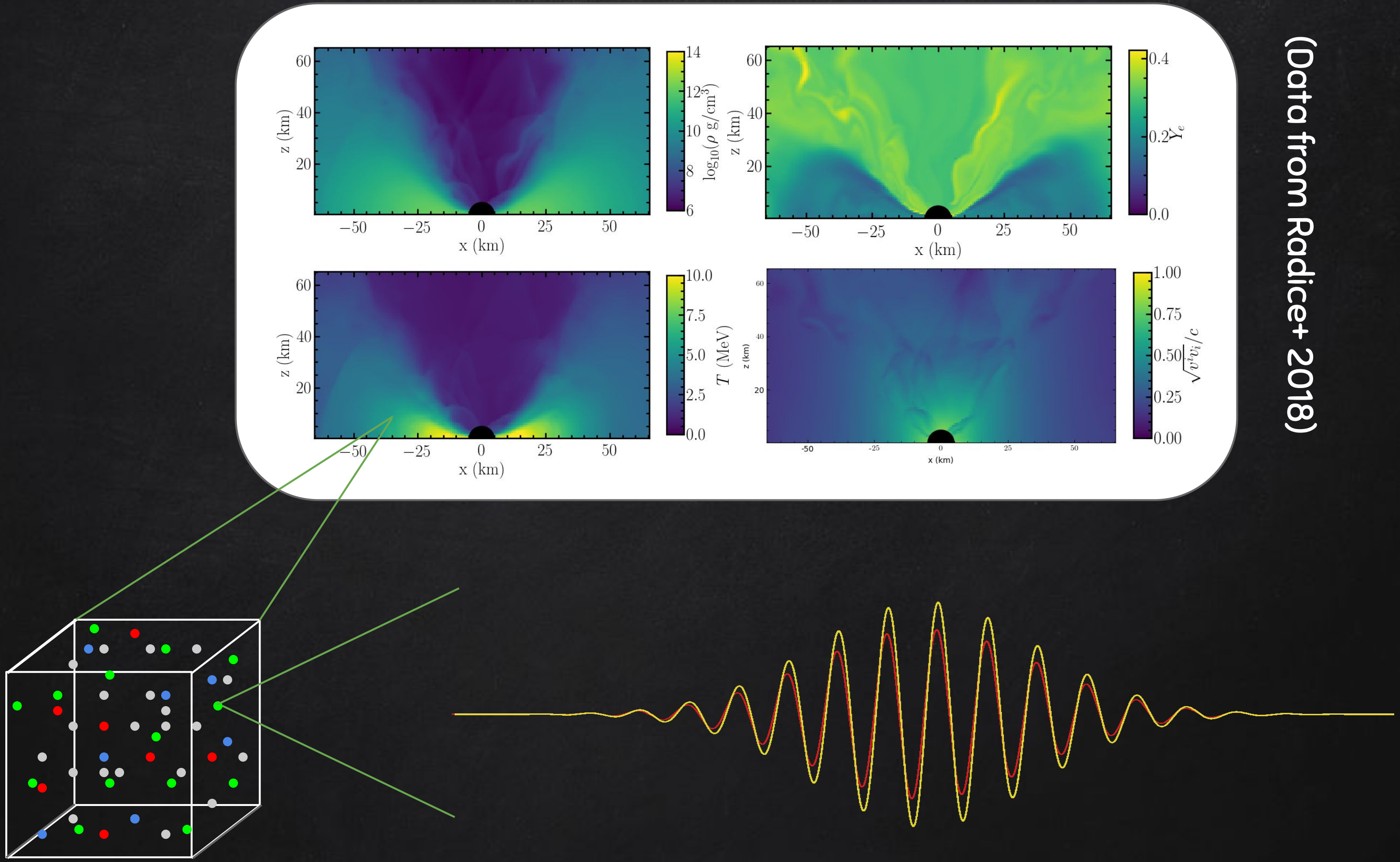

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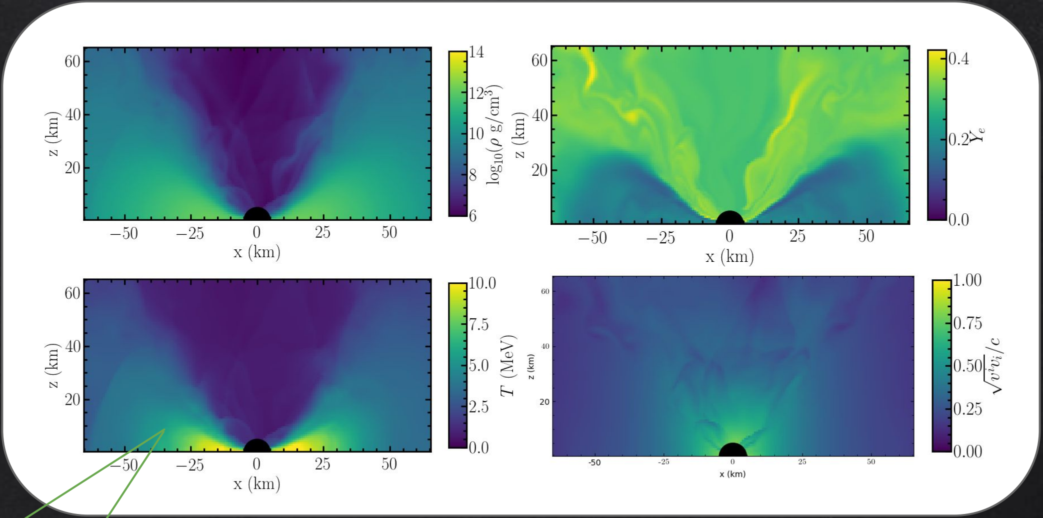

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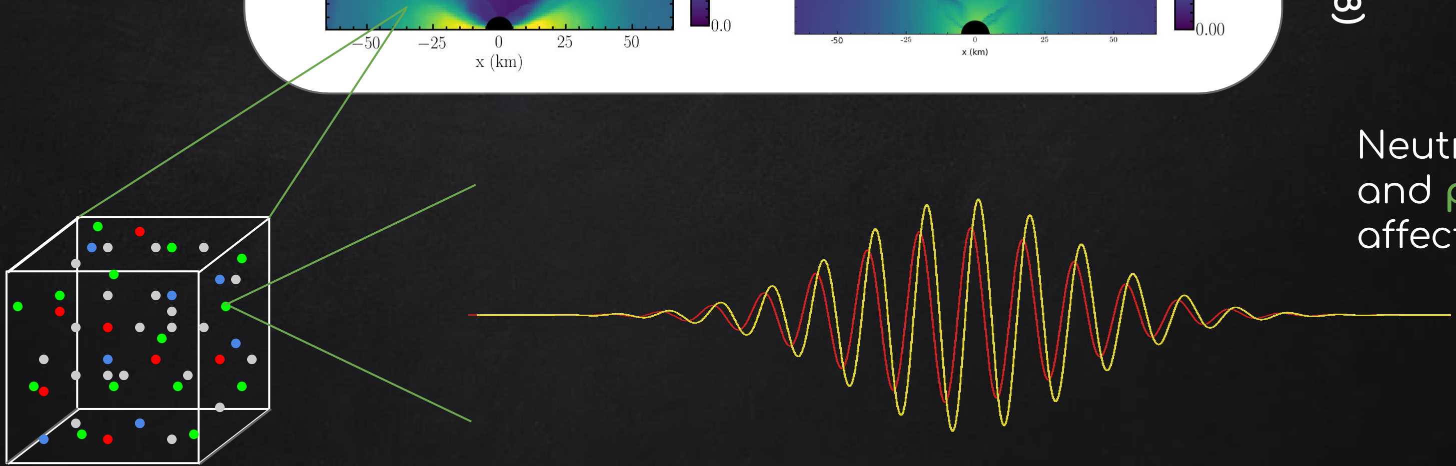
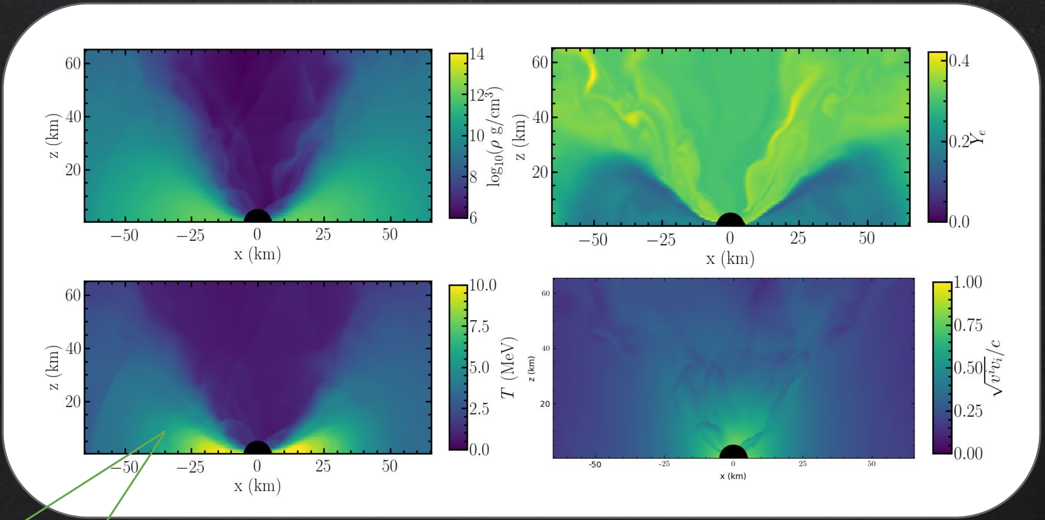


Neutrino mass and potential affect velocity.

Do we really understand?



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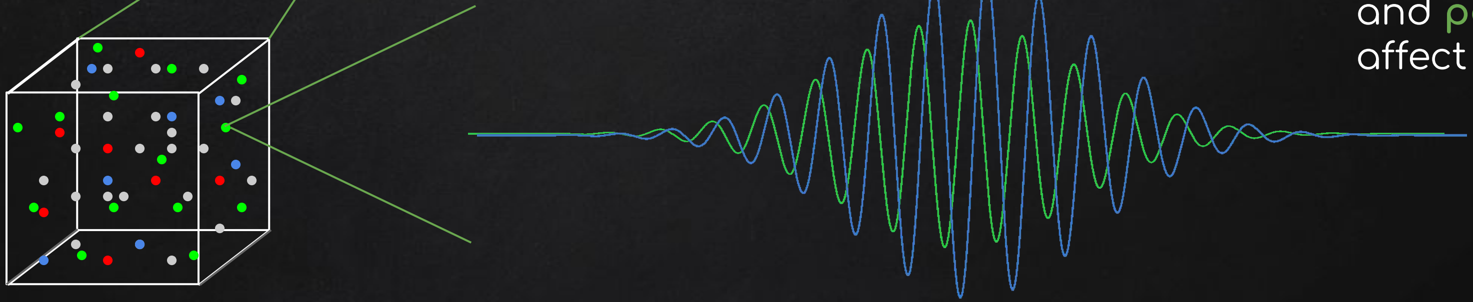
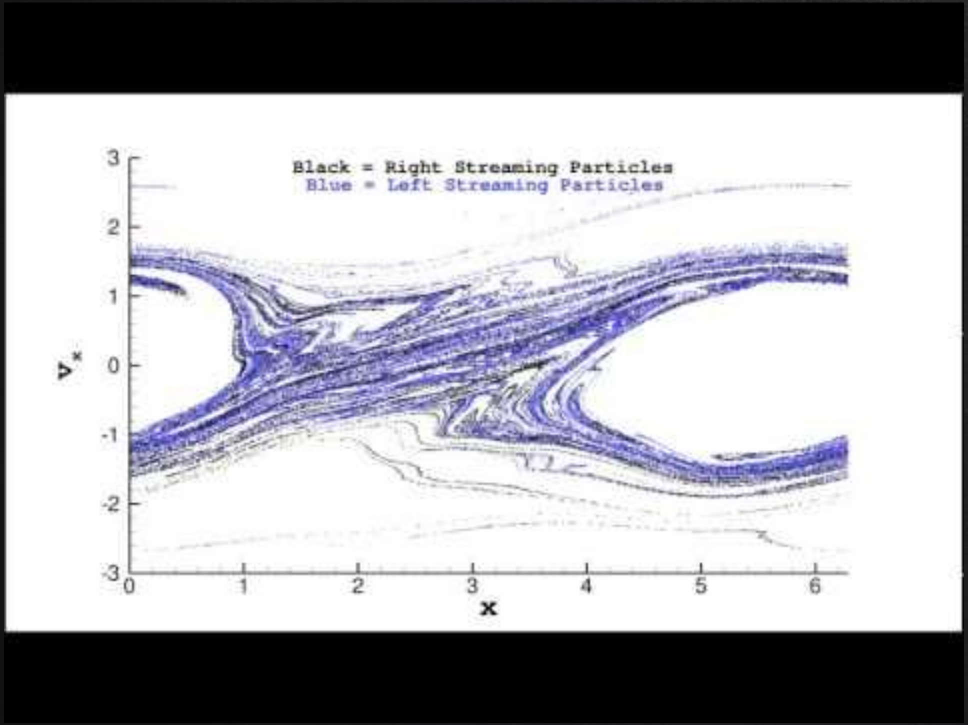


Neutrino mass and potential affect velocity.

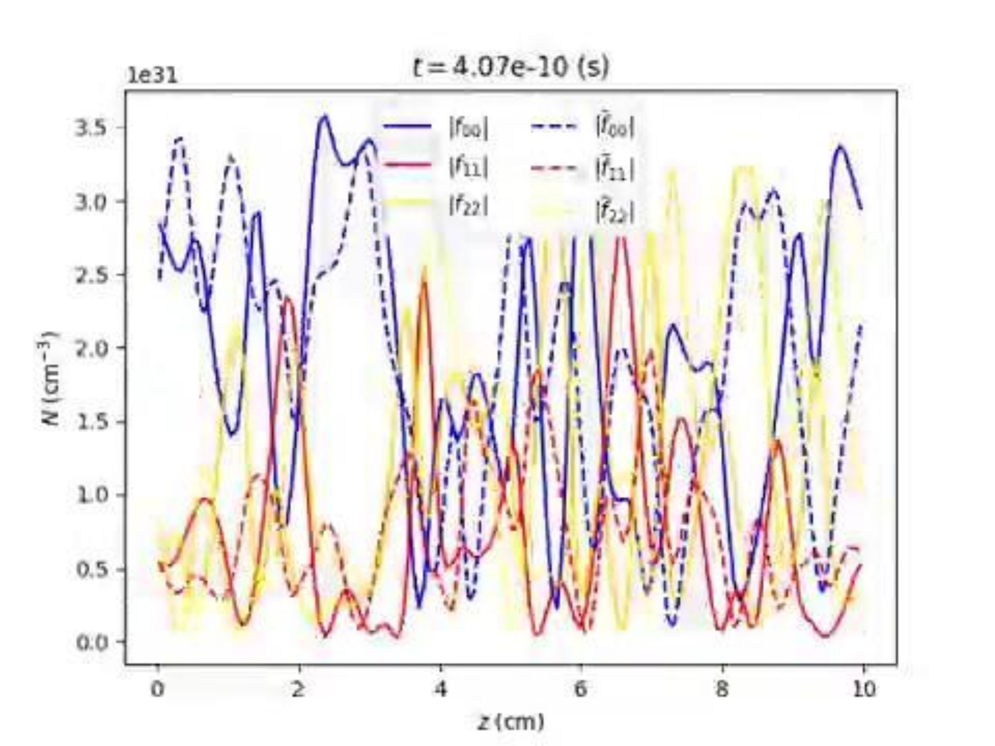
Aside: Plasma Instabilities



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

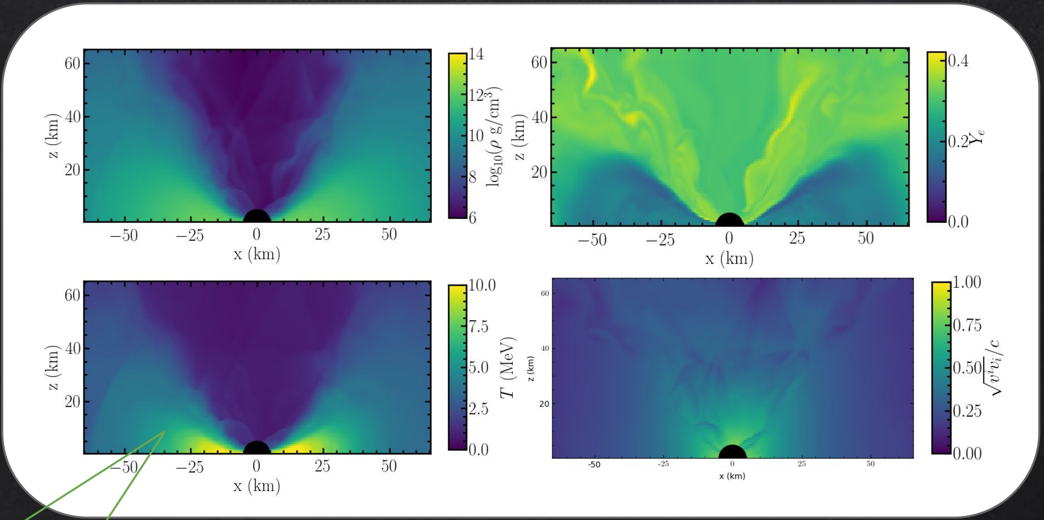
Neutrino Plasma Instabilities



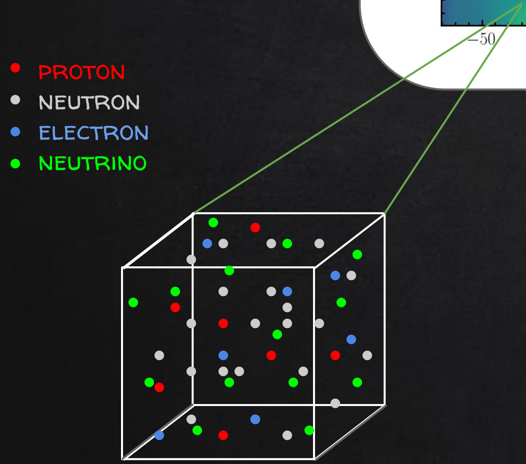
Because neutrinos feel potential from other neutrinos:

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

Do we really understand?

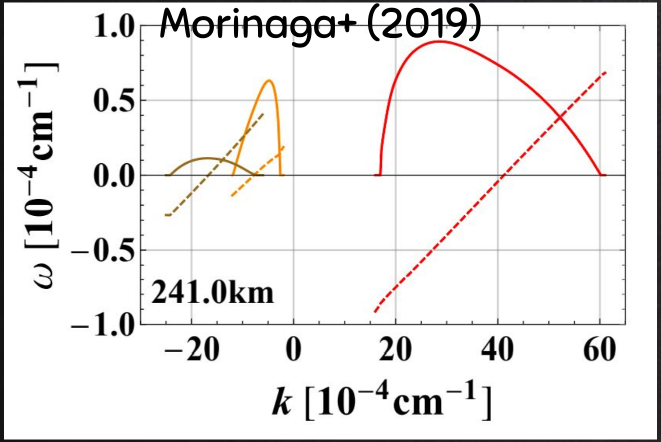


(Data from Radice+ 2018)

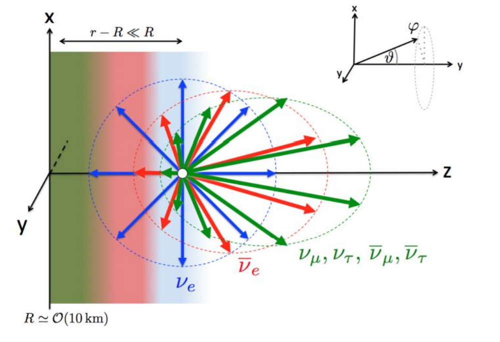


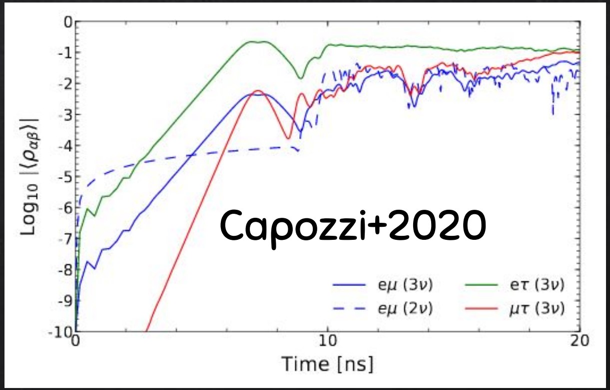
- Neutrino flavor determines nucleosynthesis
- Neutrinos are unstable to fast flavor transformation
- How many of each flavor are present post-instability?

Work So Far

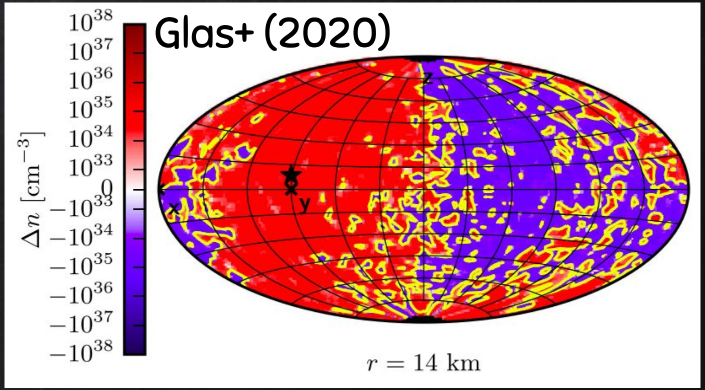


Dispersion Analysis



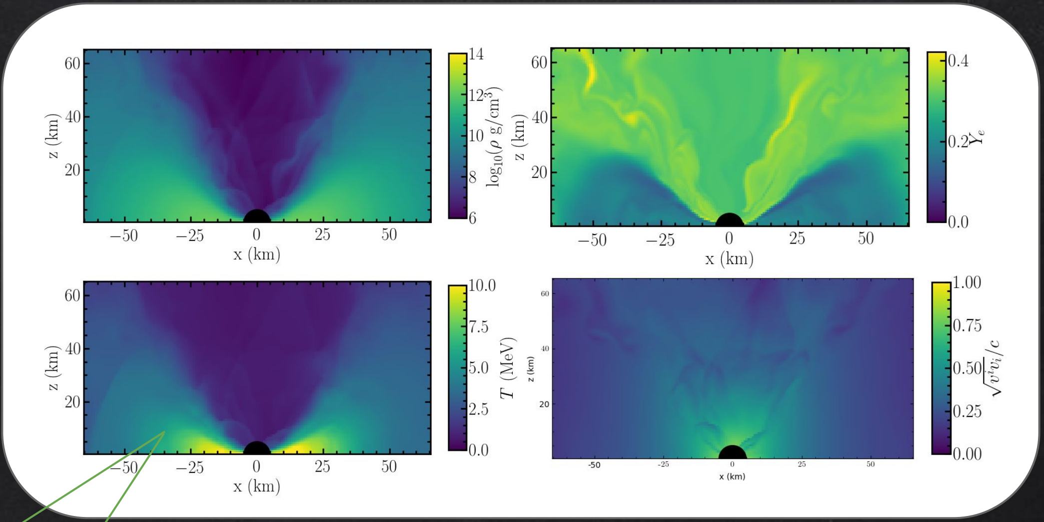


1D Simulation



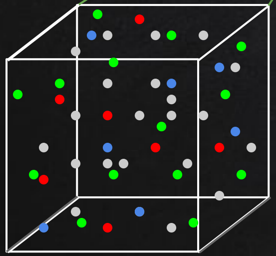
"Hunting for Crossings"

My Goal:



(Data from Radice+ 2018)

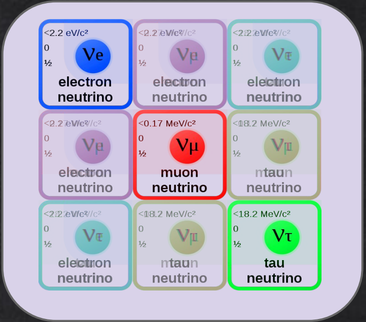
- PROTON
- NEUTRON
- ELECTRON
- NEUTRINO

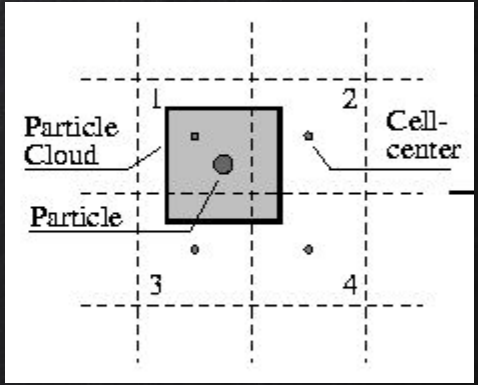


Determine **neutrino flavor abundances** after the **fast flavor instability** saturates

AMReX-based Flavor Simulation

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

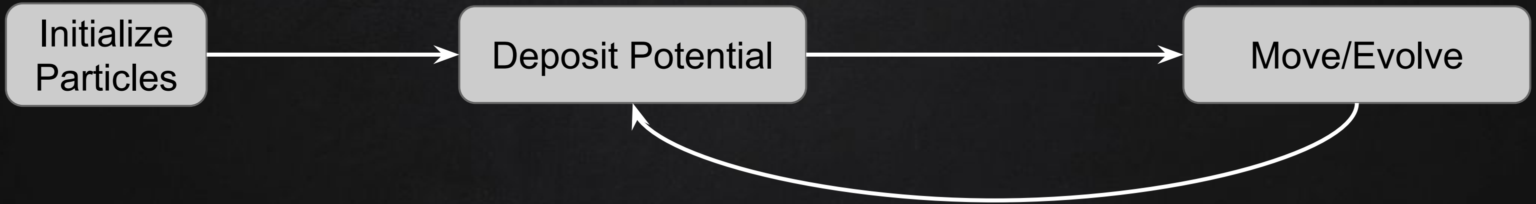




http://ta.twi.tudelft.nl/dv/users/lemmens/MThesis.TTH/chapter4.html

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

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

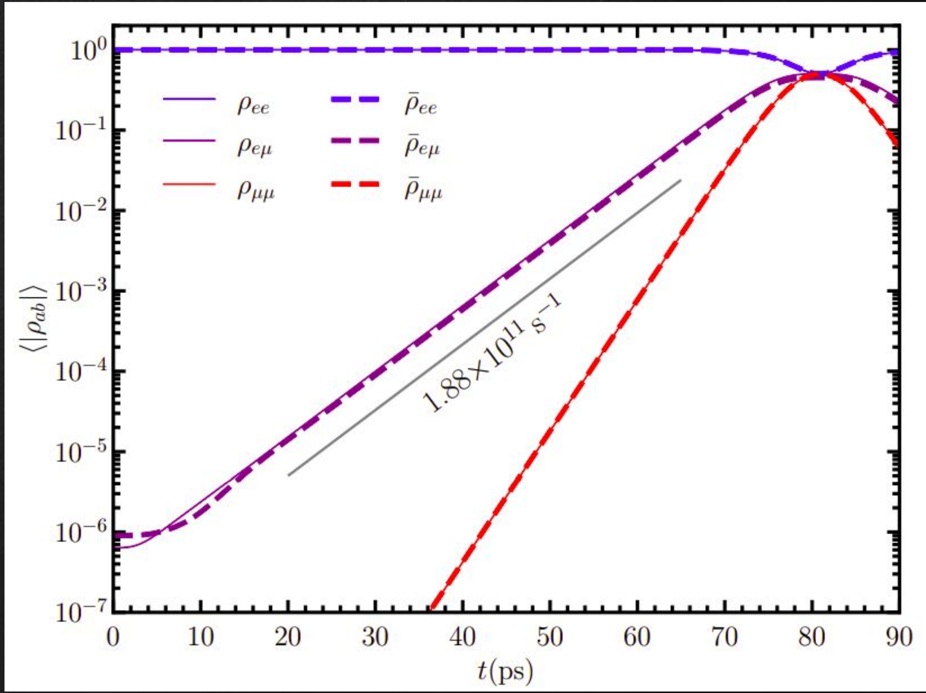


1D Two-Beam Instability
(The problem with an analytic solution)

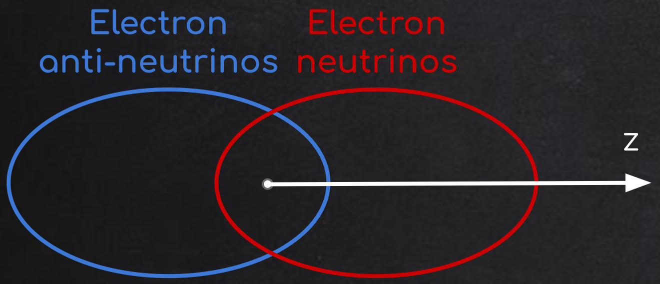
Electron Neutrinos

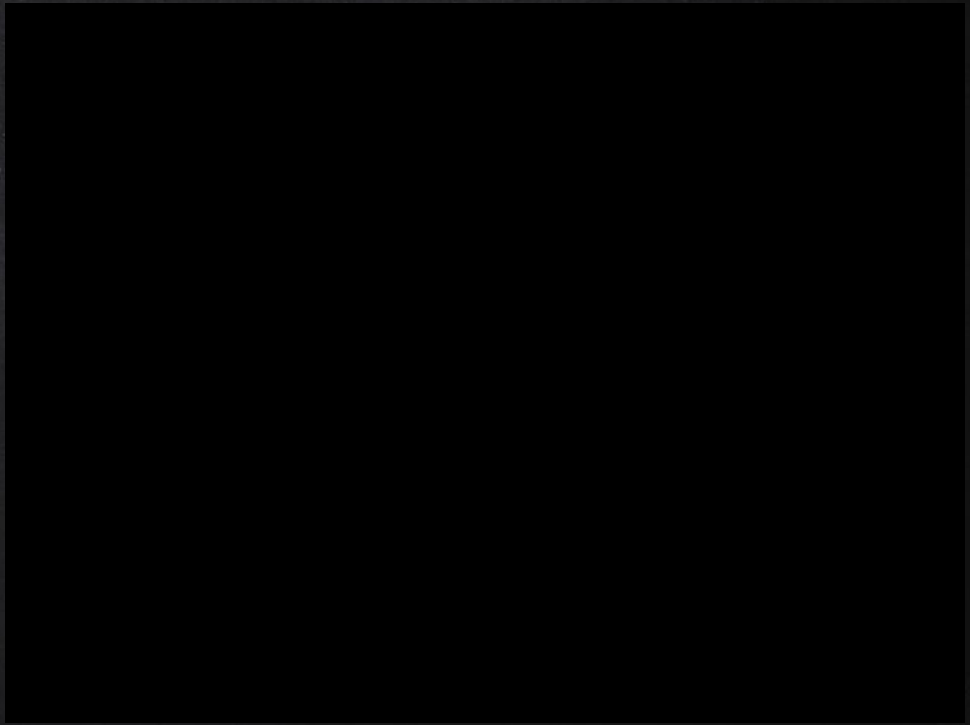
Electron Anti-neutrinos

Consistency check complete!



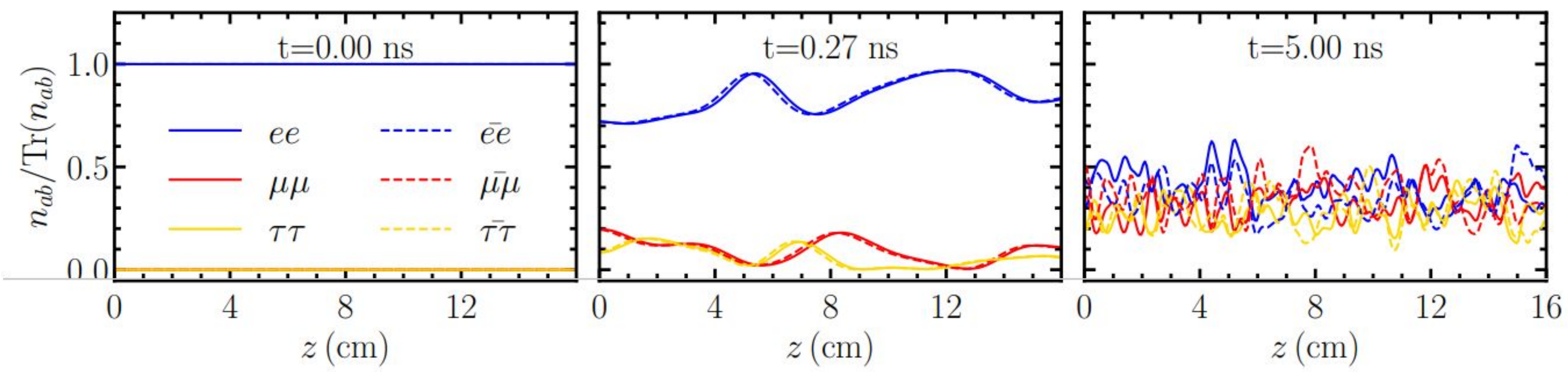
1D "Fiducial" Test





1D "Fiducial" Test

Initial Conditions | "Linear Growth" | Saturation



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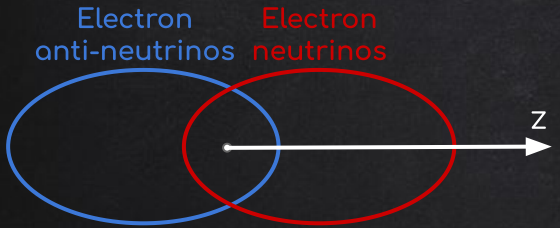
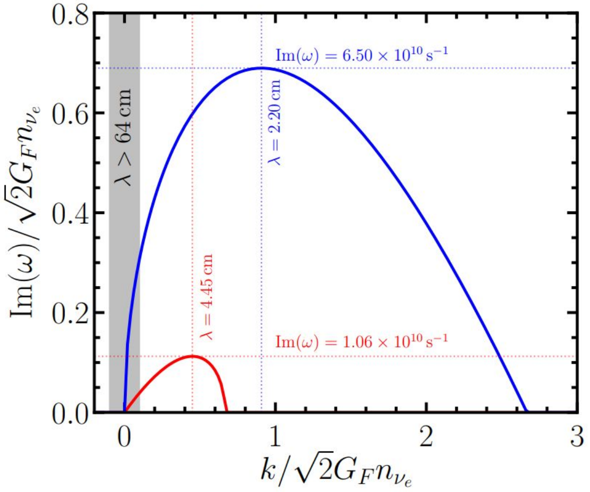
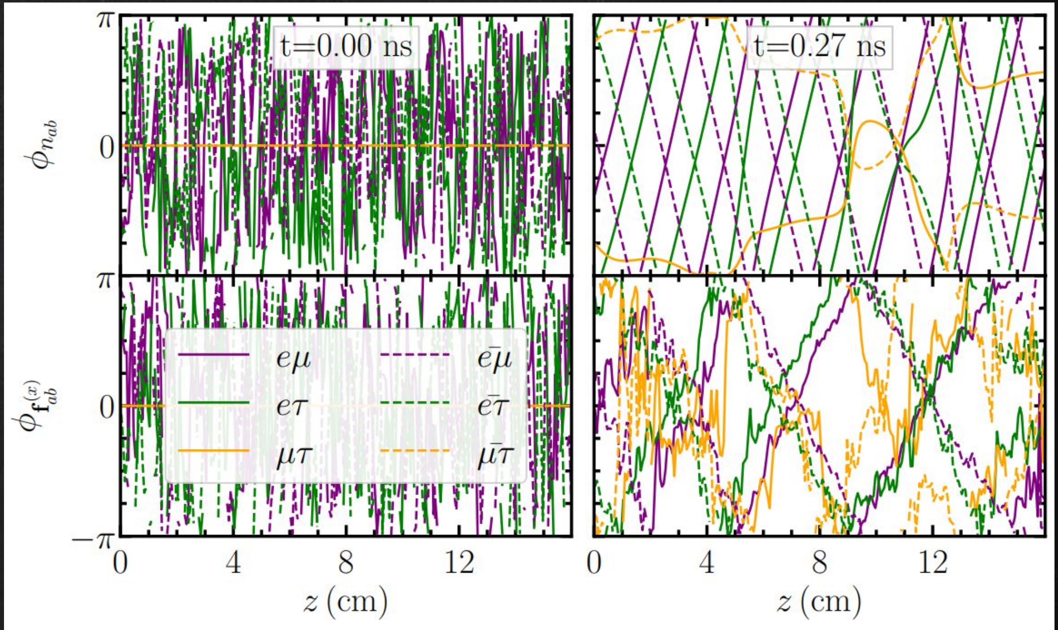
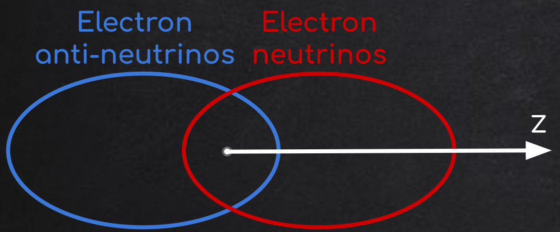


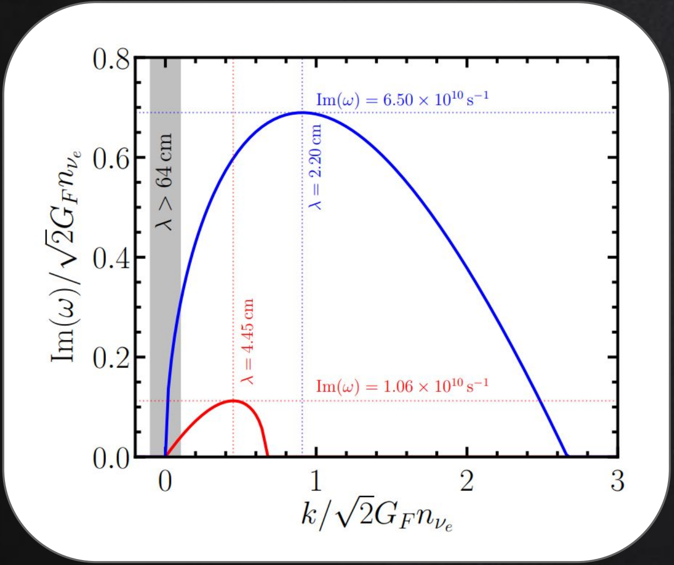


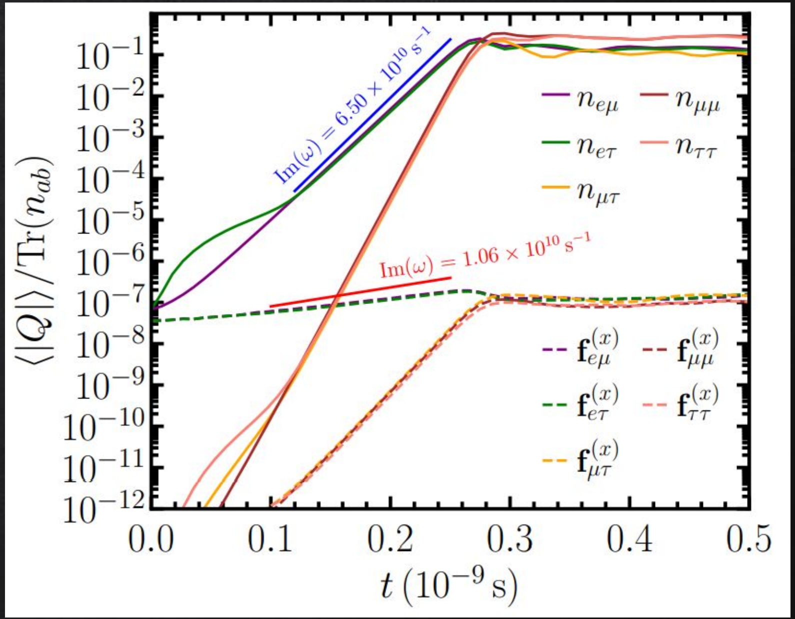


The wavelengths match!

1D "Fiducial" Test

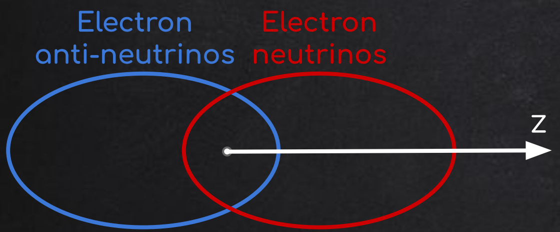




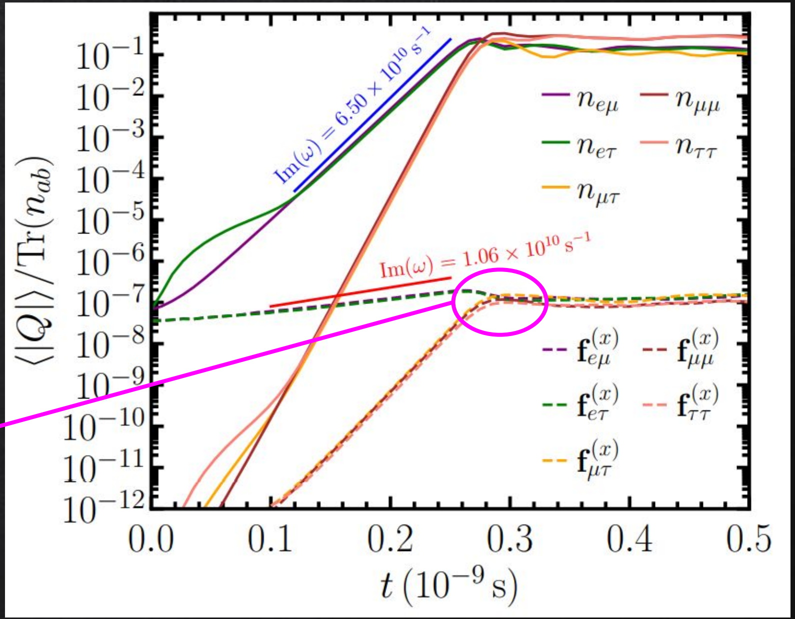


The growth rates match, too!

1D "Fiducial" Test



Saturation of the **isotropic** mode kills the growth of the **anisotropic** mode



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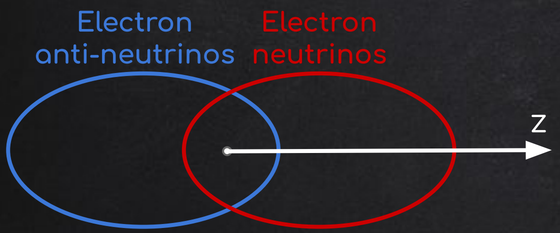

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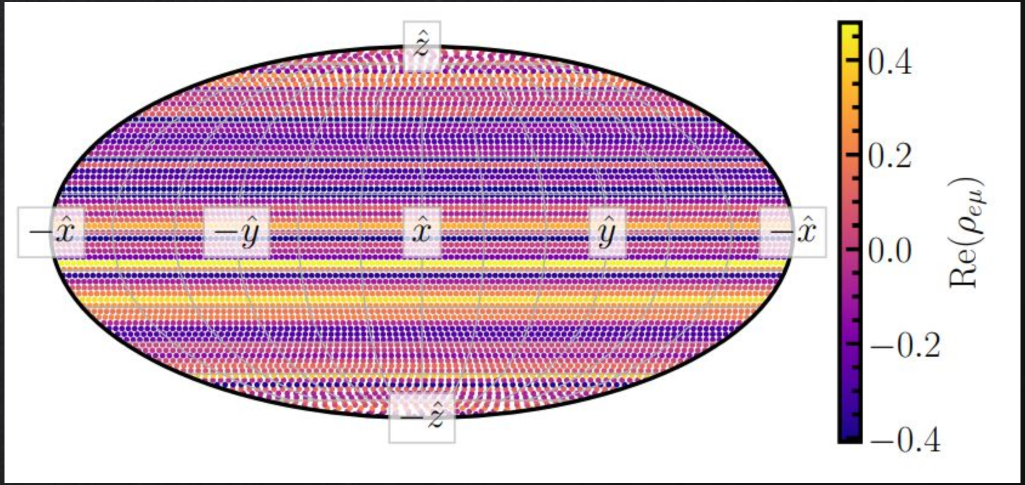
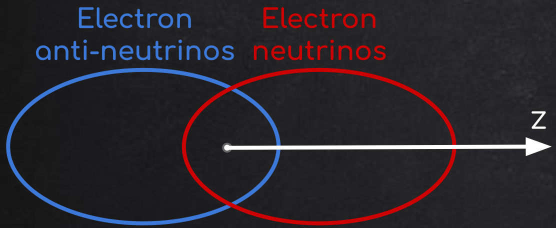


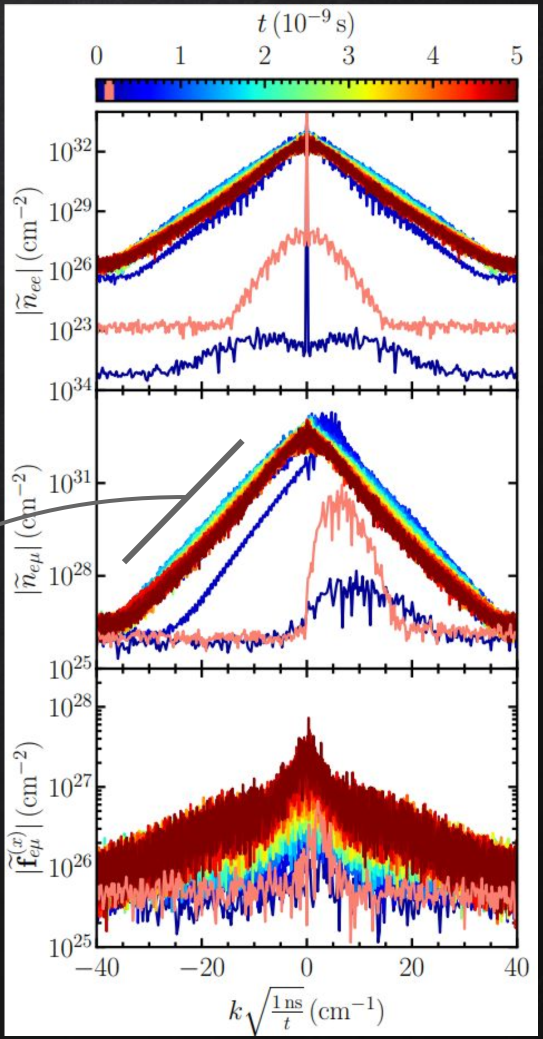
The flavor distribution is **highly symmetric** even after saturation.

1D "Fiducial" Test

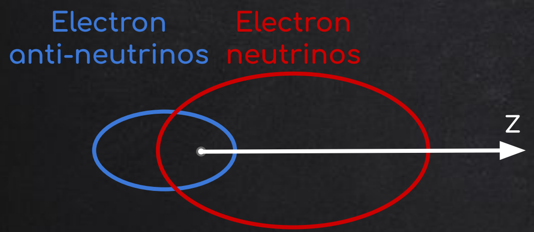


Diffusion in Fourier space is described by

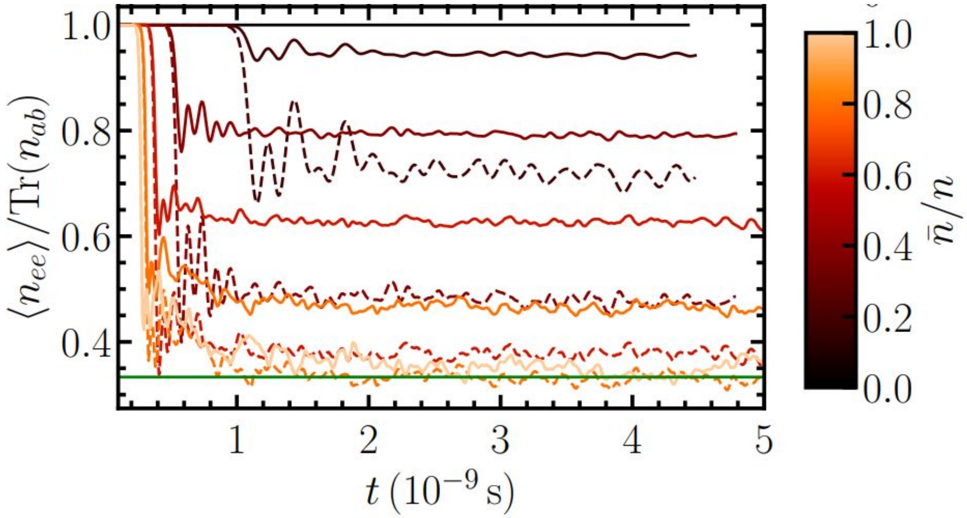
$$|\widetilde{n}_{e\mu}| \sim \exp\left[-|k|\left(\frac{t}{10^{-9}\,\mathrm{s}}\right)^{-1/2}\right]$$



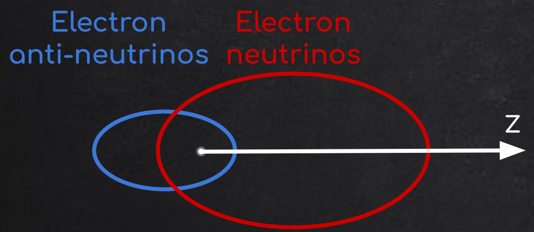
1D Parameter Sweep



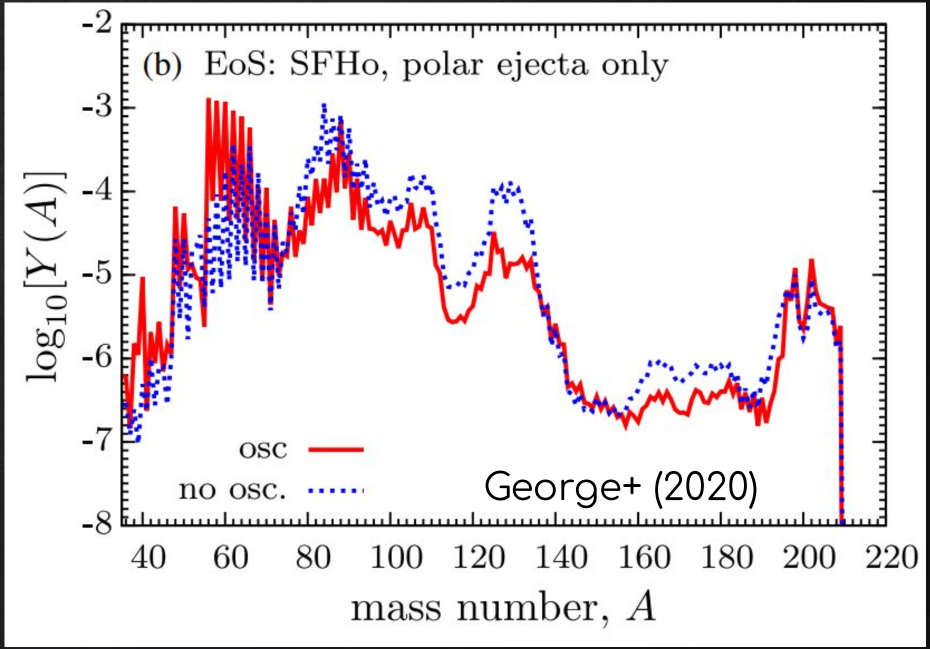
The **growth rate** and **final flavor content** depend on the distribution details.



1D Parameter Sweep



Effects of flavor mixing are likely over-estimated [This was known, but we confirmed.]



George+ (2020)

Conclusions

We need *many* more simulations!

"Fiducial" simulation:

Saturation of the isotropic mode kills the growth of the anisotropic mode

The flavor distribution is highly symmetric even after saturation.

3D is similar to 1D, but decoheres more quickly.

Parameter Sweep:

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

Numerical Methods:

Nucleosynthesis:

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

Effects of flavor mixing are likely over-estimated [This was known, but we confirmed.]