How Neutrino Oscillations Change Explodability of Massive Stars?

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VILLUM FONDEN

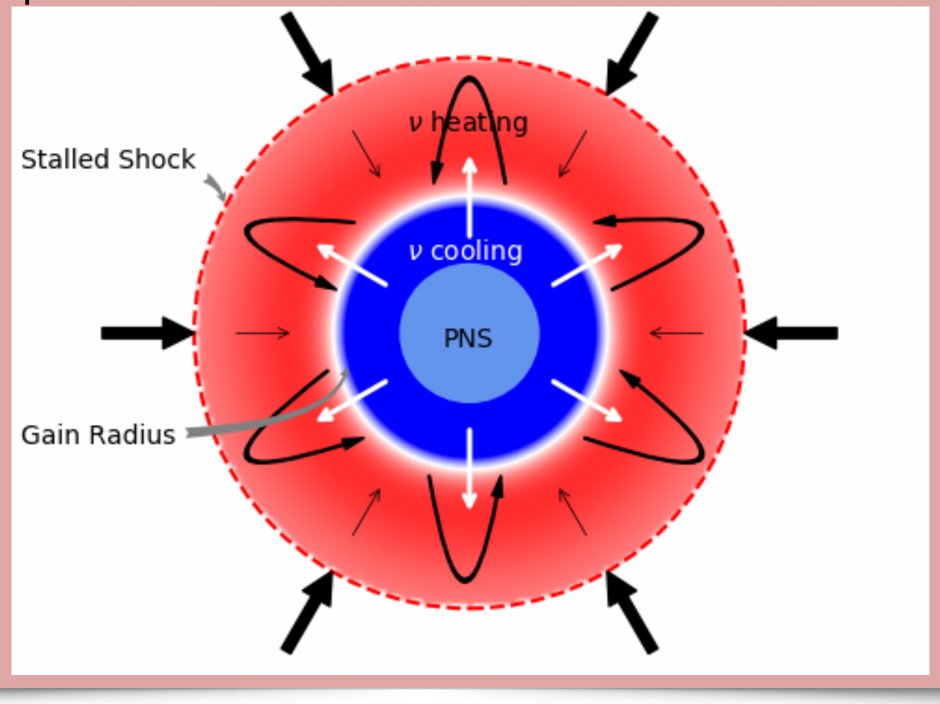
Core-collapse Supernova Theory

Introduction

Understanding what is the explosion mechanism and predicting which massive stars explode have been two main questions in core-collapse supernova (CCSN) theory for decades. Answering these questions is key in understanding nucleosynthesis, neutron star and black hole formation and distributions.

DELAYED NEUTRINO MECHANISM

The delayed neutrino mechanism is a leading explanation for how core-collapse supernovae explode. Neutrinos streaming from the proto-neutron star heat the material just behind the stalled shock, reviving it into an explosion. The CCSN mechanism is very complex and includes magneto-hydrodynamics, general relativity, neutrino transport, and nuclear physics. Capturing these processes requires 3D simulations, which are computationally very expensive—each run can take ~10 million CPU hours.



Can we predict which massive stars explode and which collapse to black holes?

STRATEGY

-Develop better analytic understanding of explosion mechanism.

- Derive analytic condition for successful explosions.
- Develop predictive analytic theory that enables predictions of which stars explode based on the progenitor profile without expensive simulations.

-Perform systematic study of what important physics affects the explosion condition.

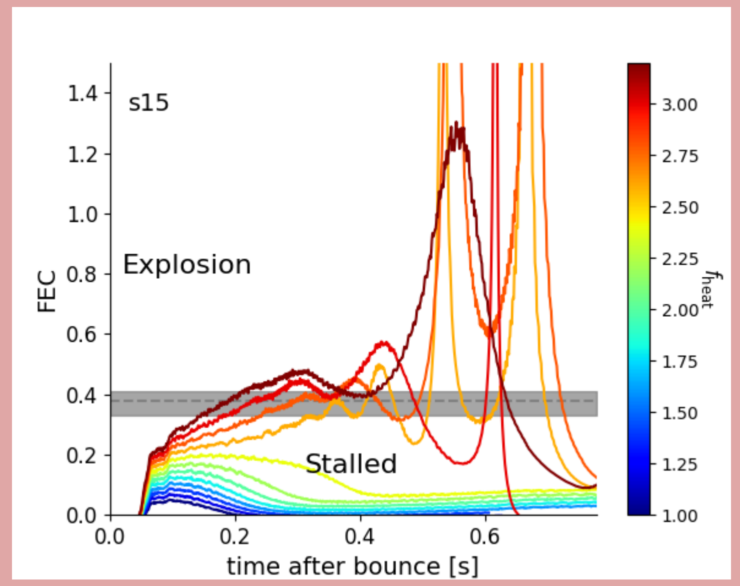
Analytic Force Explosion Condition

1D SPHERICAL EXPLOSIONS

Based on the fundamental hydrodynamic equations and **(im)balance** between neutrino heating, accretion ram pressure, and gravity:

$$\frac{Q_g}{G\,|\dot{M}|\,M_{\rm NS}/R_{\rm NS}} - a\frac{\kappa}{\sqrt{GM_{\rm NS}R_{\rm NS}}/|\dot{M}|} > b$$

Gogilashvili et al. (2021)



ASPHERICAL EXPLOSIONS

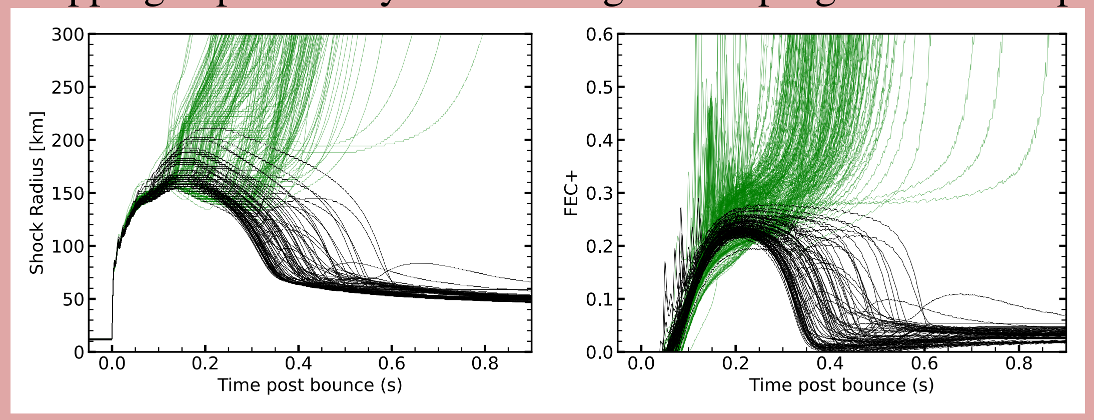
In multi-dimensional settings, convection and turbulence lower the heating requirement compared to 1D.

$$\tilde{Q}_g - a\tilde{\kappa} + \tilde{W}_b + c\tilde{R}^r_r > b$$

Additional terms make explosions in multi-D easier than in 1D, reducing the critical

Testing with ~340 1D+ simulations in GR1D

We tested the Force Explosion Condition using 341 1D+ simulations in GR1D. Each simulation included realistic microphysics and neutrino transport. The results show that the force explosion condition reliably predicts the transition between exploding and failing models, making it a powerful tool for mapping explodability across a large set of progenitors. transport.



Boccioli et al. (2024)

Flavor Conversions

Flavor conversions redistribute flavor spectra and **reduce** the electron-type neutrino number densities and hence luminosities (*Ehring et al. (2023)*); below we show the simple equipartition prescription and its consequence for the force explosion condition.

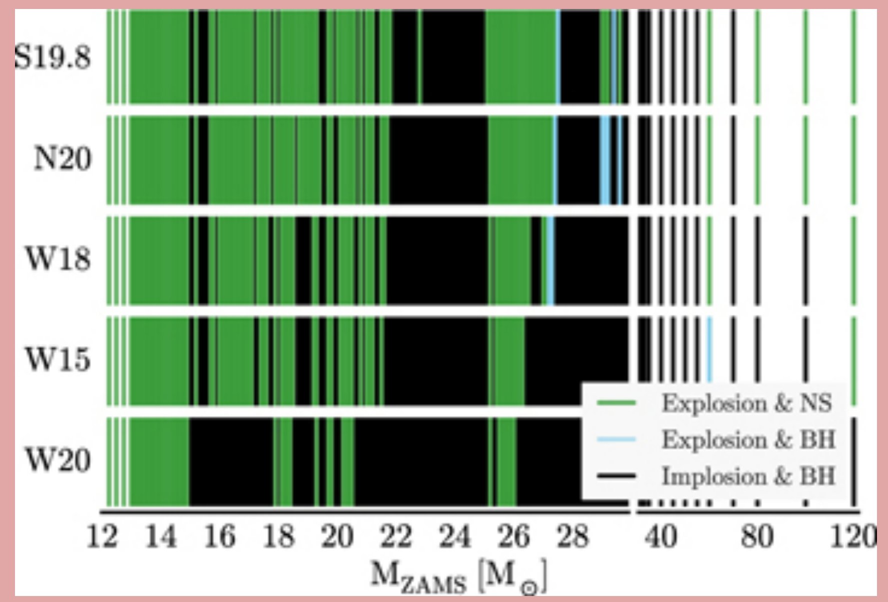
$$n^{\rm new}_{\nu_e} = \frac{1}{3}(n^{\rm old}_{\nu_e} + 2n^{\rm old}_{\nu_x})$$
$$n^{\rm new}_{\bar{\nu}_e} = \frac{1}{3}(n^{\rm old}_{\bar{\nu}_e} + 2n^{\rm old}_{\bar{\nu}_x})$$

This changes Q_g by altering neutrino luminosities and opacities, and it can change $G\,|\dot{M}|\,M_{\rm NS}/R_{\rm NS}$ by modifying the proto-neutron-star structure (mass, radius, or accretion rate). Because both terms can be affected, flavor conversion may either enhance explosion for some progenitors or cause it to fail for others.

For example, flavor conversions can modify neutrino luminosities and opacities and hence change Q_g. Then, for marginally exploding progenitors, reduced electron-type luminosity after flavor conversion may push them below the explosion threshold, causing failure.

Conclusions

- Flavor conversion can significantly impact the conditions for explosion in CCSNe.
- The force explosion condition framework connects these changes to explodability in a predictive, quantitative way.
- This physics may alter the distribution of explosions and failures across progenitor space.



Sukhbold et al. (2016)

Based on Gogilashvili and Murphy (2021), Gogilashvili et al. (2022), Gogilashvili et al. (2023) and Gogilashvili et al. (2025 in prep).

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