Solving the Mysteries of Supernovae

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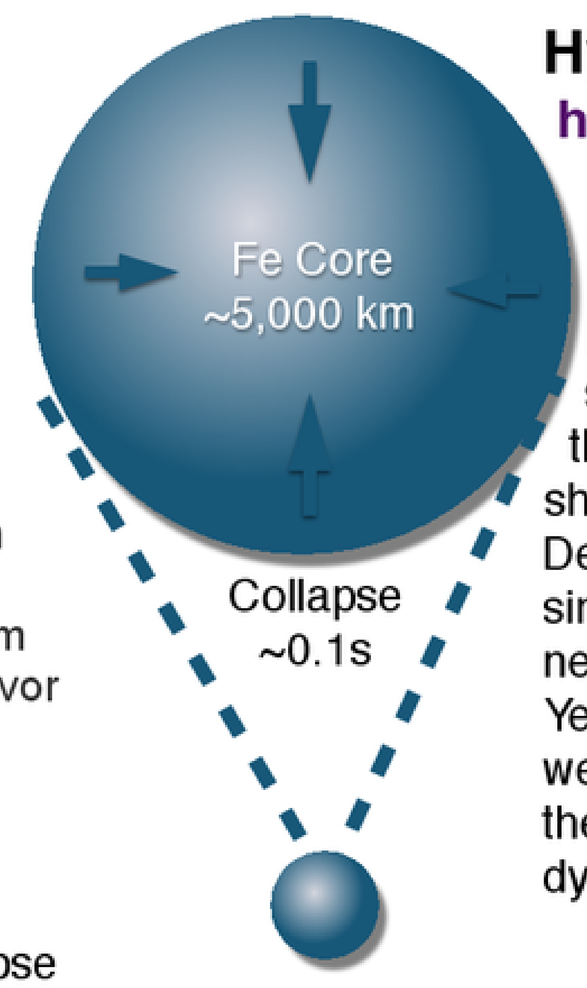
Abstract

A major challenge for theoretical astrophysics is to explain how massive stars end their lives. The death of massive stars, supernovae, are some of the most energetic explosions in the Universe; they herald the birth of neutron stars and black holes, are prodigious emitters of neutrinos and gravitational waves, influence galactic hydrodynamics, trigger further star formation, and are a major site for nucleosynthesis. Though these explosions play an important and multifaceted role in many cosmic phenomena, the details of the explosion mechanism have remained elusive for many decades. I endeavor to deepen our understanding of the mechanism of explosion.

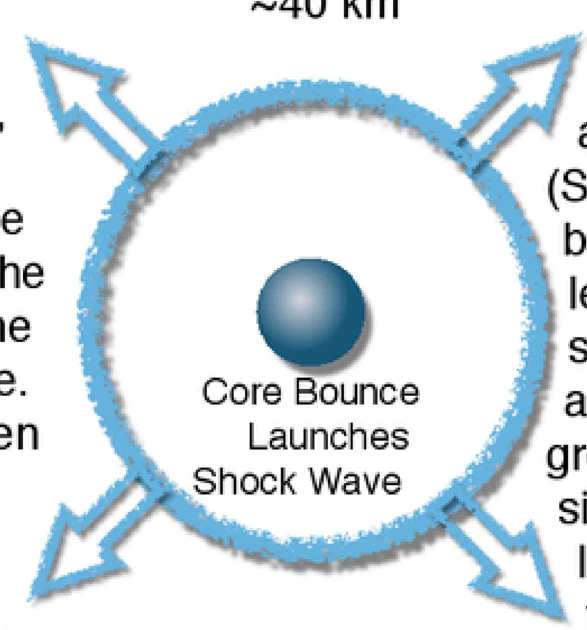


The Problem

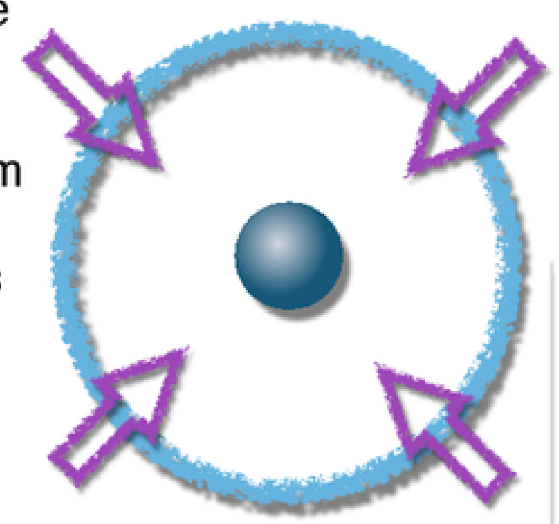
In general, the explosion is initiated by the collapse of the massive star's core. The center of the star fuses lighter elements into heavier elements until the core is composed entirely of Fe group elements. Once the Fe core builds up about 1.4 solar masses, it becomes gravitationally unstable and collapses. Once the core density reaches nuclear densities, the core becomes a neutron star (NS). The density in the NS is so great and the nucleons are so close that the dominant pressure is due to the strong nuclear force. This stiff pressure stops the collapse, and the sudden bounce launches a strong shock wave that propagates outward against the falling star. If the shock wave successfully reaches the surface, it would cause the star to explode. Initially, it does not reach the surface.

Instead, the shock wave momentarily stalls at about 200 km and forms a stalled accretion shock. While the shock wave is moving outward, the rest of the star is collapsing downward. If the shock wave can overcome this accretion, it will move outward and unbind the rest of the star in an explosion. Otherwise, the NS will continue to accrete and form a black hole.

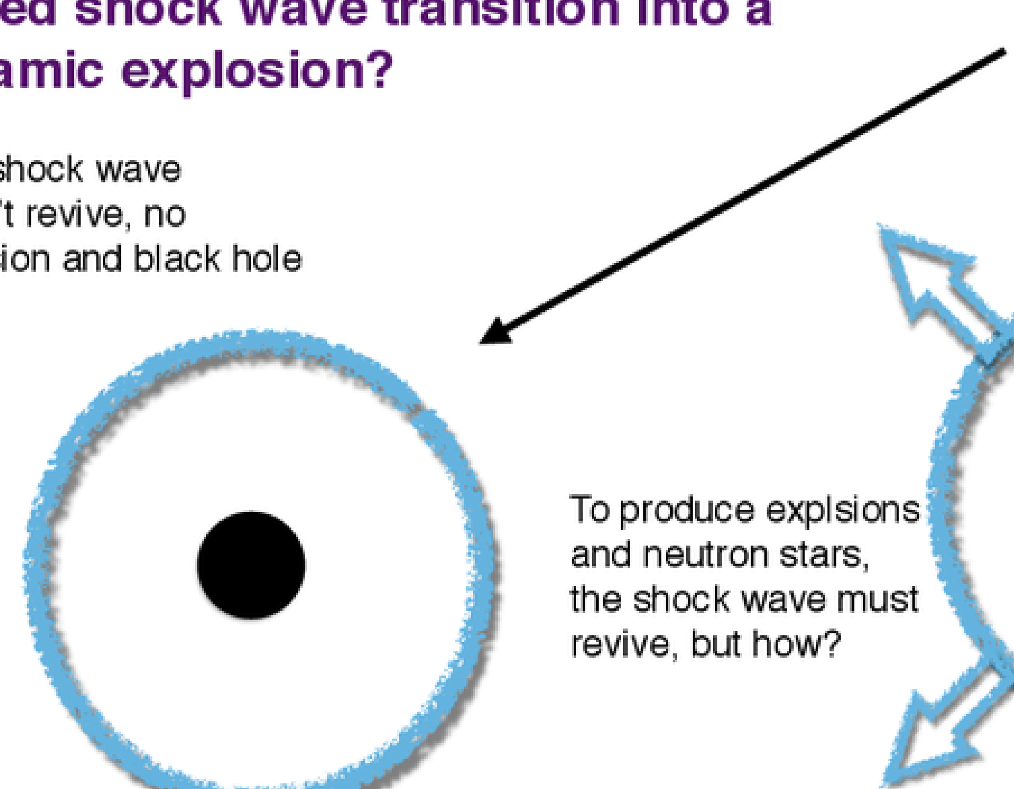
Observations tell us that stars explode and NSs form; these explosions must succeed some of the time. So, the important question in core-collapse supernova theory becomes: **How does the stalled shock wave transition into a dynamic explosion?**



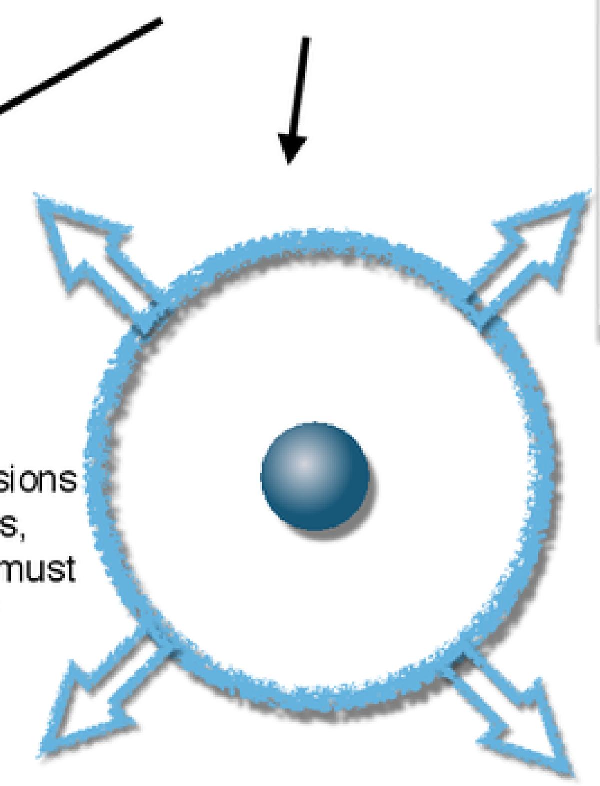
The outward moving shock wave stalls into an accretion shock as the rest of the star continues to collapse.



If the shock wave doesn't revive, no explosion and black hole forms



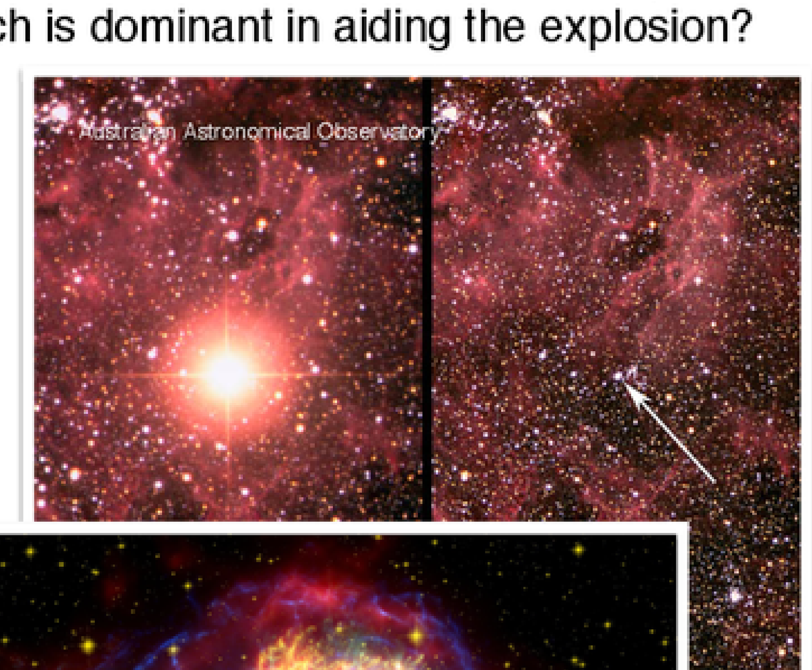
To produce explsions and neutron stars, the shock wave must revive, but how?



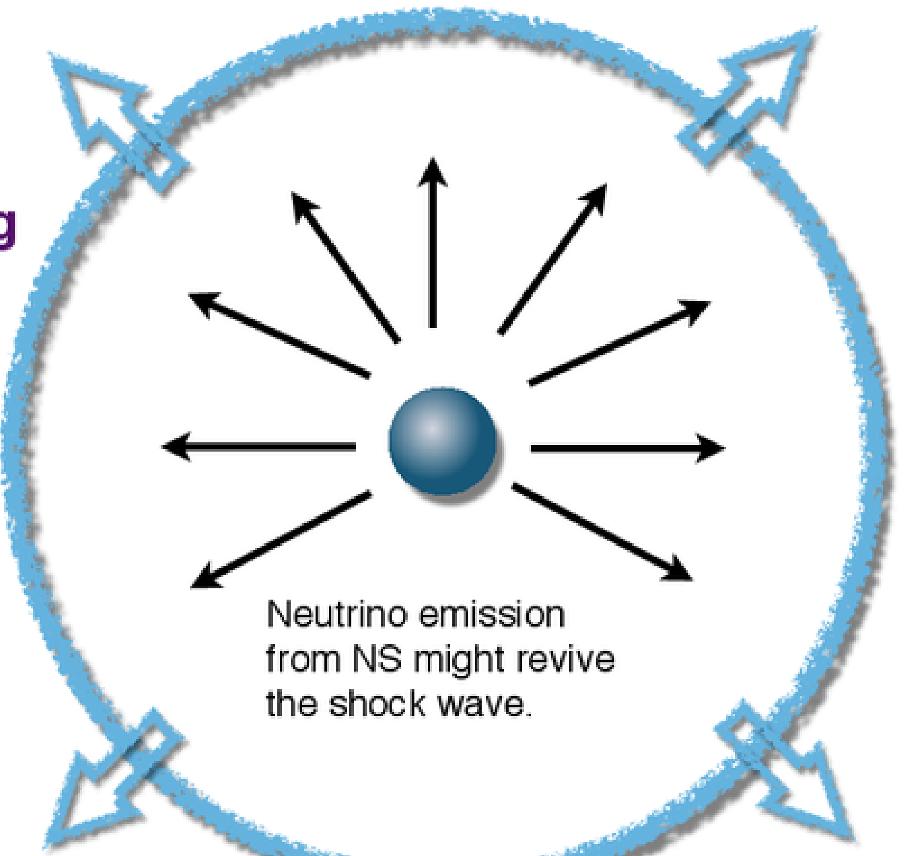
Hypothesis (Neutrino heating helps to relaunch the Shock):

The NS is emitting prodigious amounts of neutrinos and the hope is that these neutrinos will heat the material behind the shock, energize it, and relaunch the outward propagation of the shock wave into an explosion. Detailed 1D radiation-hydrodynamic simulations show that the delayed neutrino mechanism does not work. Yet, we know that stars explode. So, we're still left with the question, "How does the stalled accretion shock transition into a dynamic explosion?"

Multi-dimensional instabilities seem to aide the neutrino heating toward explosion. There are two dominant instabilities: neutrino-driven convection and the standing accretion shock instability (SASI). In the former, neutrino heating from below drives buoyant plumes to rise, leading to convection. In the latter, the standing accretion shock is susceptible to an acoustic-vortical acoustic cycle. It can grow to nonlinear amplitudes and cause significant turbulence just below the shock. In both cases, the turbulence might aide the neutrino mechanism toward explosion. Which is dominant in aiding the explosion?



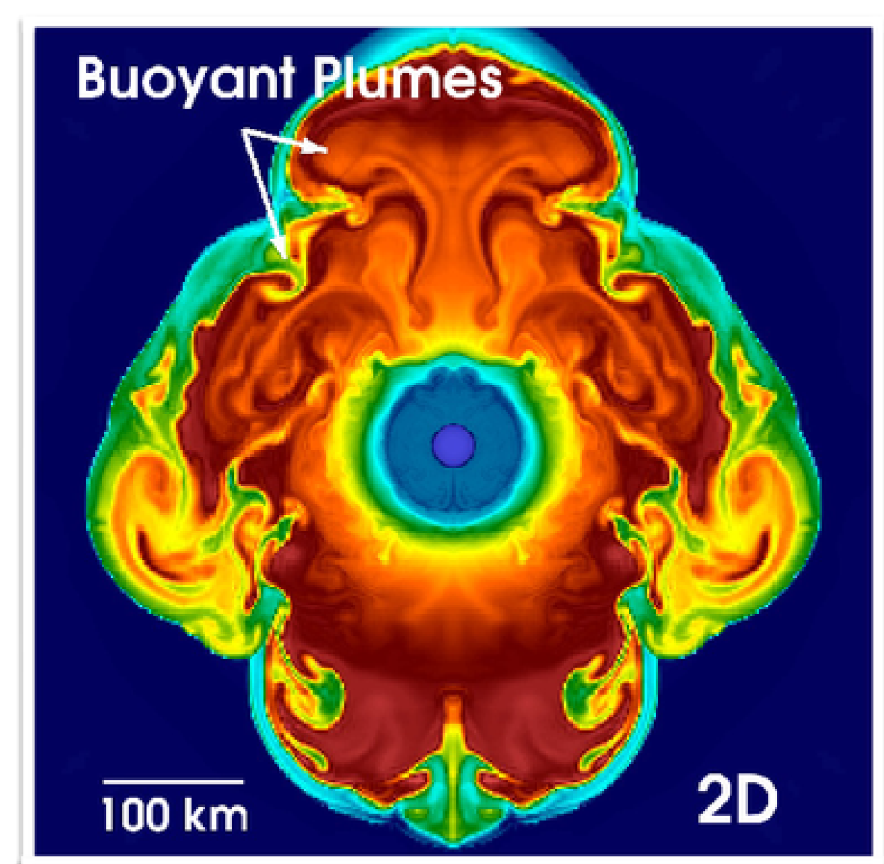
Top: SN 1987A
Middle: SN remnant Cassiopeia A
Bottom: Crab Pulsar
These are all observational manifestations of supernova explosions.

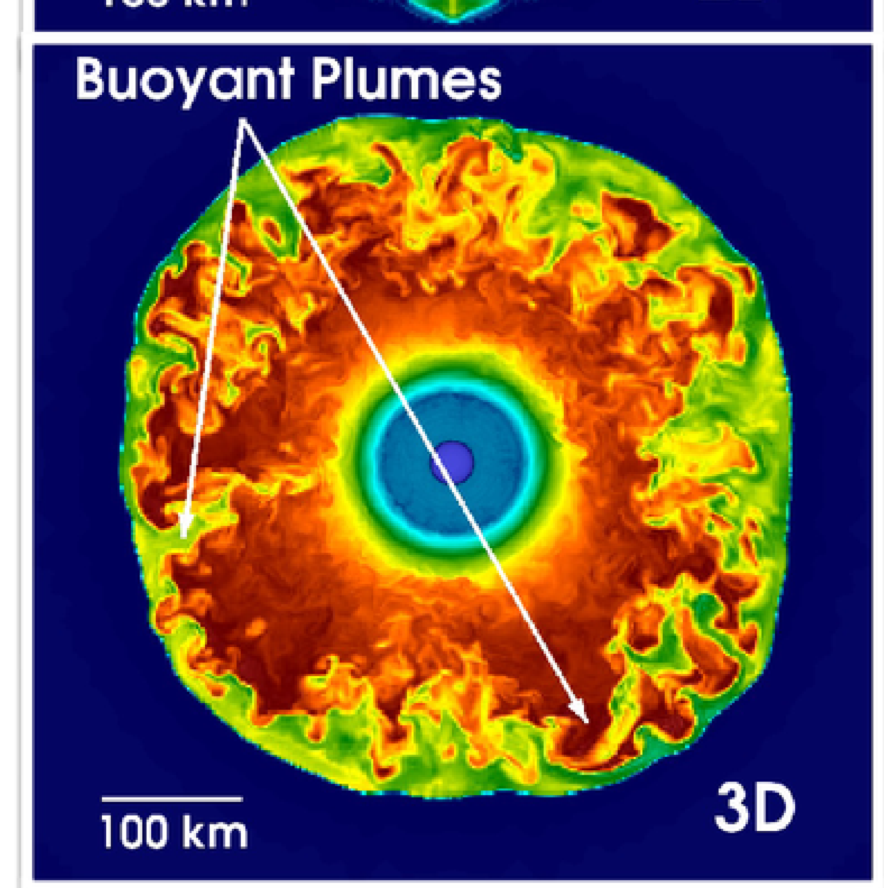


Two Methodologies:

1) Detailed Numerical Solutions: To predict accurate explosion energies, NS masses, nucleosynthetic yields, etc. we must run 3D radiation-hydrodynamic simulations, but these are computationally expensive, so in the meantime we must make approximations, and learn what we can.

2) Approximate Analytic Solutions Eventually we would like a deeper understanding of the mechanism. Finding approximate analytic solutions can often illuminate the important physics.



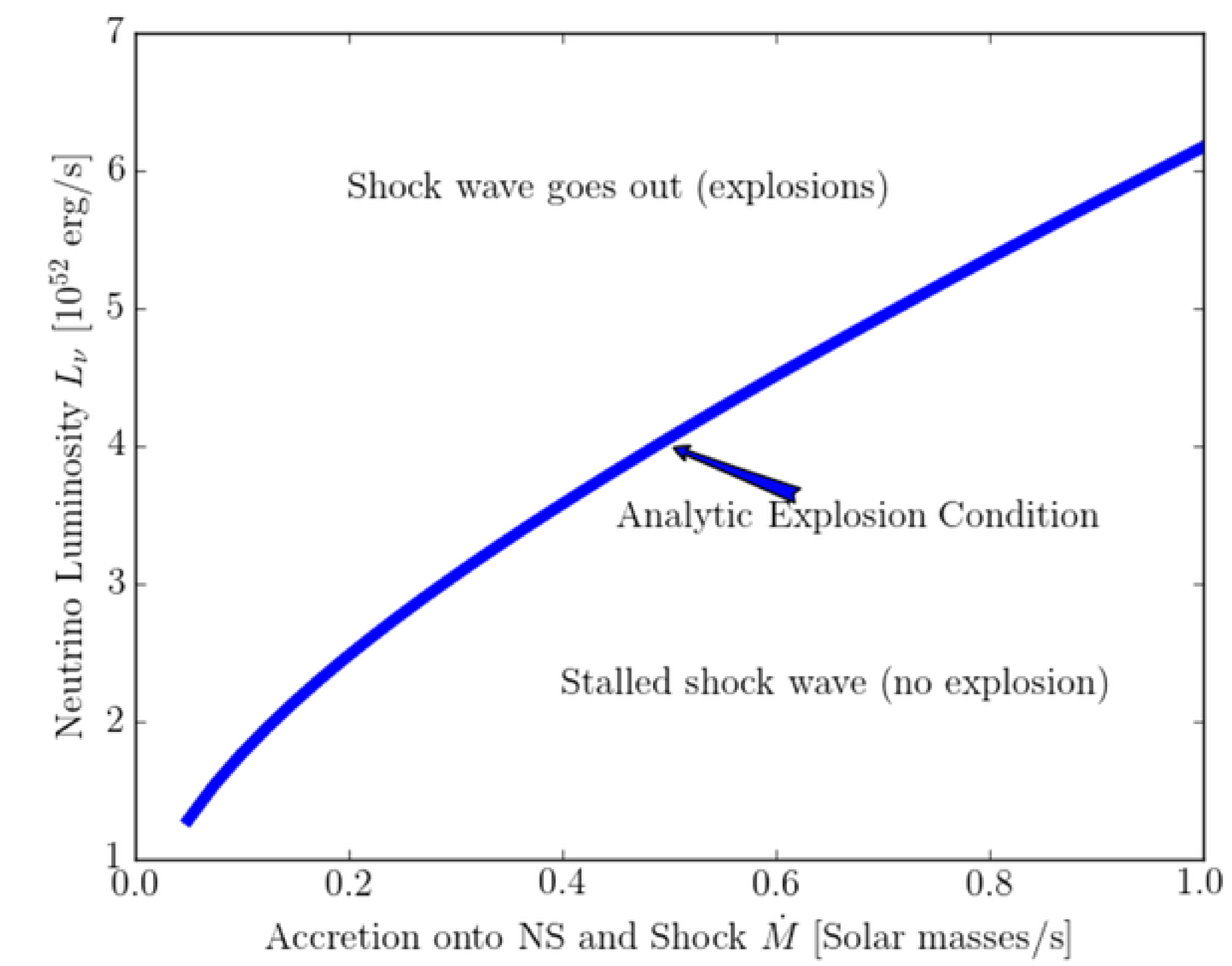


Hypotheses and Questions:

- **Is there a critical condition that divides steady-state accretion shock from explosive solutions? (Yes)**
- **Is the critical condition lower when multi-dimensional instabilities are present? (Yes)**
- **What dominates the instabilities: convection or SASI? (convection is consistent, but we need better nonlinear theories for SASI to test it.)**
- **Can we derive the critical condition? (FYAP progress, in prep)**

Results:

- **Derivation of an analytic solution to the conditions for explosion**



An analytic Critical Condition for Explosion: For a given accretion rate, there is critical neutrino luminosity, above which there is no steady state solution, but an explosion. In this work, we derive this dividing line, and show that it indeed corresponds to an expansion of the shock wave, leading to an explosion.

Relevant Bibliography:
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