

The neutrino-hydro coupling in the hadron-quark flame.

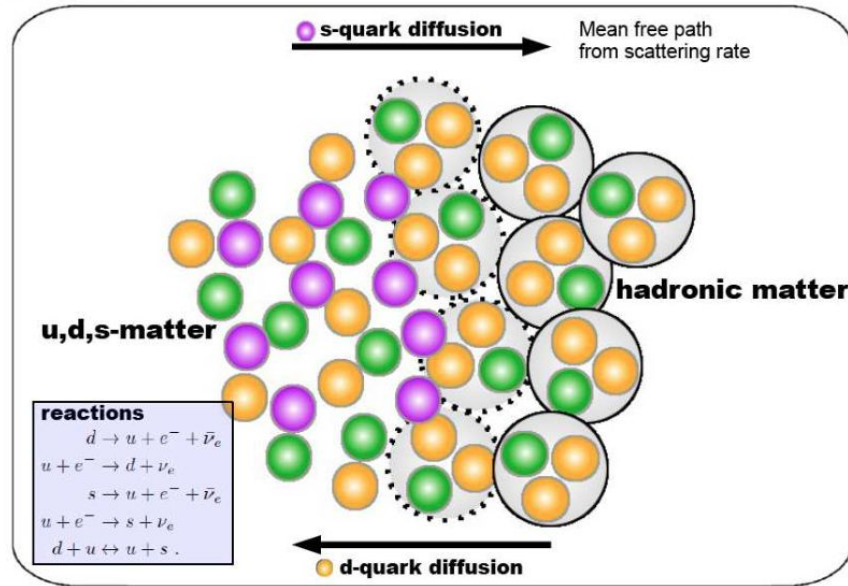
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Outline

- Introduction
- Model
- Results
- Conclusion

If energetically favourable, (u,d) will burn to (u,d,s) through weak interaction (non premixed combustion) which produces neutrinos.

The Interface



Burning front emits and absorbs neutrinos!

Case A: streaming neutrinos

$$d \rightarrow u + e^{-} + \bar{\nu}_e$$

$$u + e^{-} \rightarrow d + \nu_e$$

$$s \rightarrow u + e^{-} + \bar{\nu}_e$$

$$u + e^{-} \rightarrow s + \nu_e$$

$$u + d \leftrightarrow u + s .$$

Case B=trapped neutrinos

$$u + e^{-} \leftrightarrow d + \nu_e$$

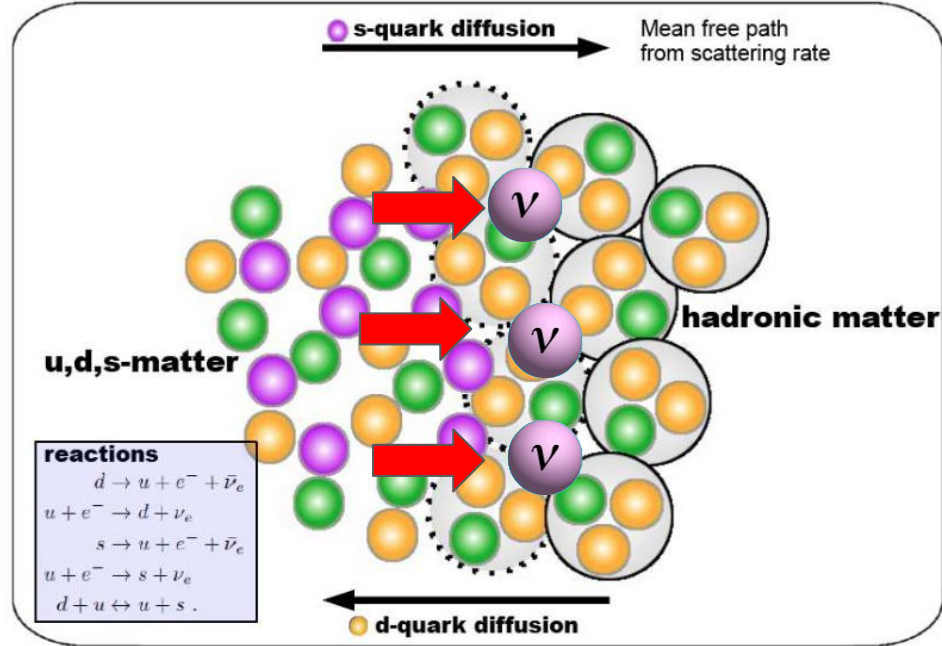
$$u + e^{-} \leftrightarrow s + \nu_e$$

$$u + d \leftrightarrow u + s$$

No antineutrinos!

Burning front emits and absorbs neutrinos!

The Interface



Doing neutrinos and combustion hydrodynamics separately is incomplete.

- Absorption of neutrinos leads to heating of quark matter.
- Emission of neutrinos leads to cooling of quark matter.
- Temperature gradients create complex fluid phenomena.
- We can't just diffuse neutrinos a posteriori of combustion simulation!

Radiation Hydrodynamics in Burn-UD.

Reaction-Diffusion-Advection eqns:

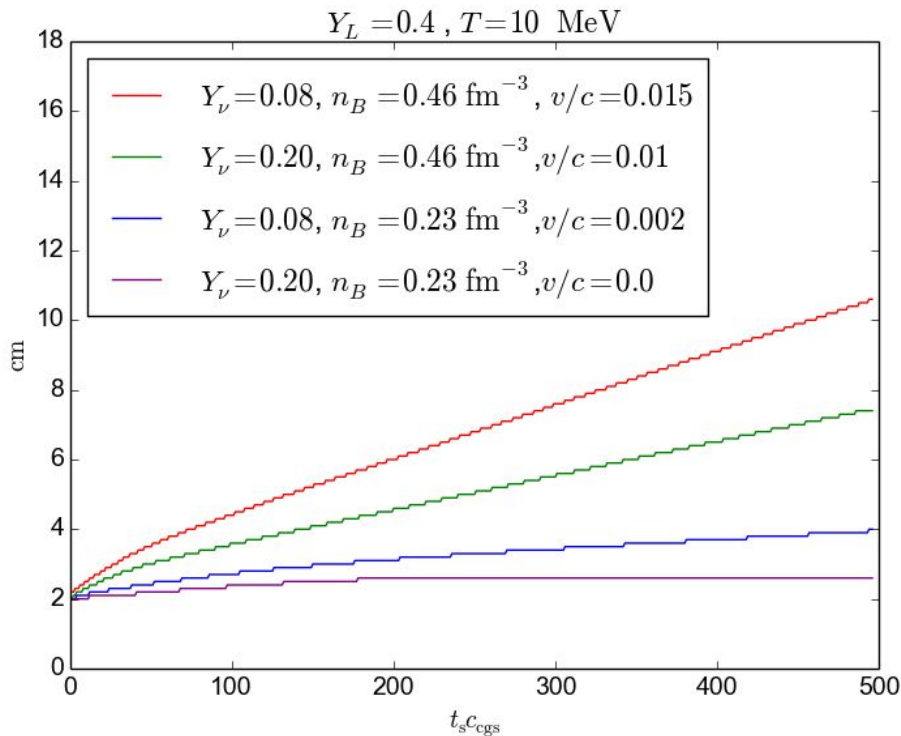
$$\begin{aligned}\frac{\partial n_i}{\partial t} &= -\nabla \cdot (n_i \mathbf{v} - D_i \nabla n_i) + R_i \\ \frac{\partial n_{\text{total}}}{\partial t} &= -\nabla \cdot (n_{\text{total}} \mathbf{v} - D_{\text{total}} \nabla n_{\text{total}}) \\ \frac{\partial h\nu}{\partial t} &= -\nabla \cdot (h\nu \cdot \mathbf{v}) - \nabla P \\ \frac{\partial s}{\partial t} - \nabla \cdot (s\mathbf{v}) - \frac{1}{T} \sum_i \mu_i \frac{\partial n_i}{\partial t} &= \frac{j_\nu}{T} \\ & i = u, d, s\end{aligned}$$

Flux-limited diffusion of electron neutrinos:

$$\begin{aligned}\frac{\partial n_\nu}{\partial t} &= \nabla \cdot (D_\nu \nabla n_\nu) + R_\nu \\ \frac{\partial E_\nu}{\partial t} &= \nabla \cdot (D_\nu \nabla E_\nu) + j_\nu \\ n_\nu &= n_L - n_\nu\end{aligned}$$

Neutrino trapping (degenerate neutrinos) leads to... contained burning?

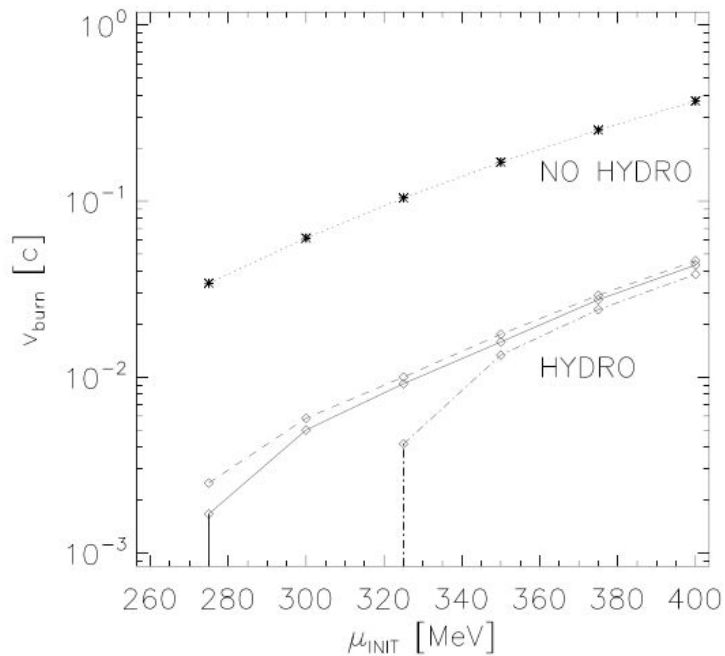
Front position vs time



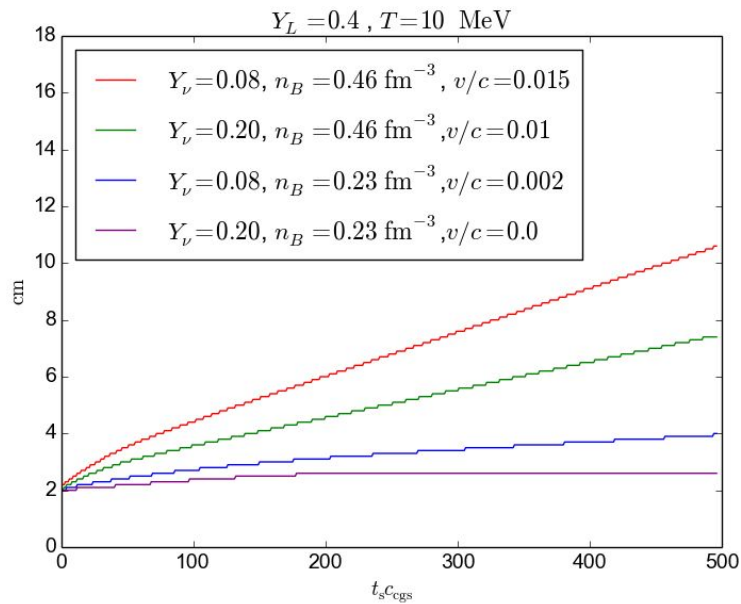
Inward pressure gradient halts burning (Animation).

Inhibition of leptonic reaction rate (Animation).

Multidimension leads to two types of neutrino driven instabilities which halt burning.

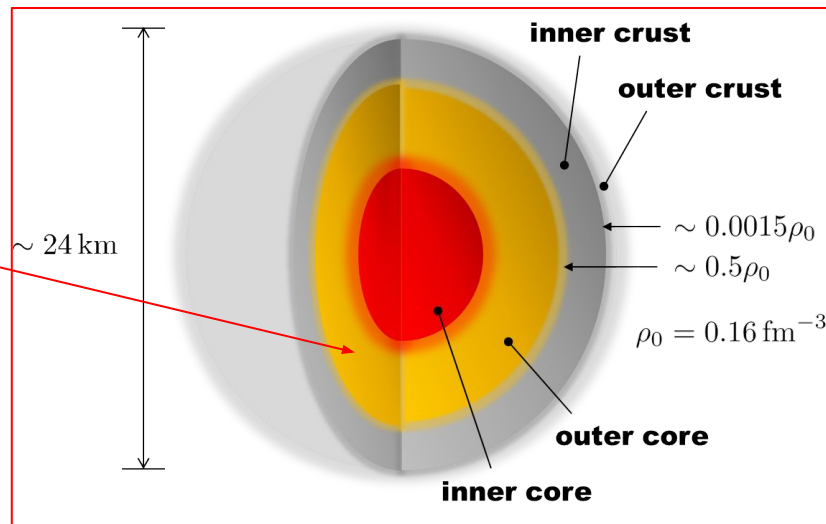
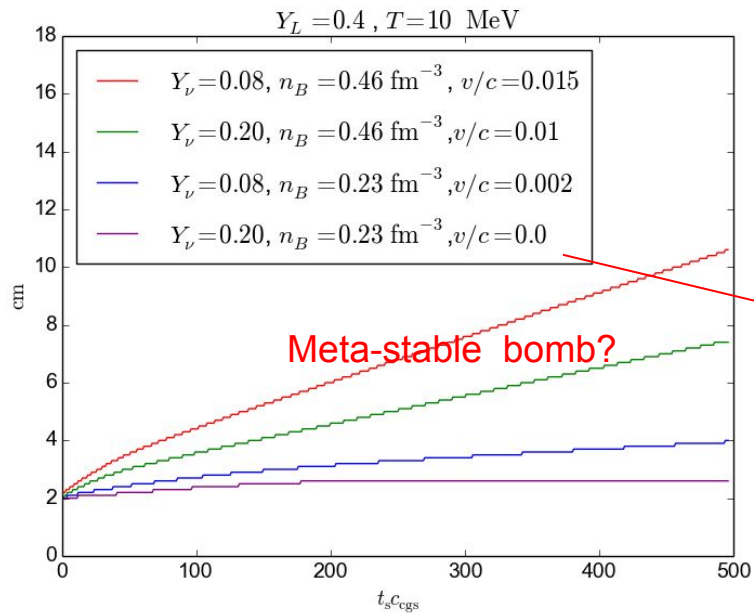


Deleptonization (free streaming) (Niebergal et al. 2010)



Neutrino trapping

Astronomical implications: neutron stars as ticking bombs?



Summary and Future Work.

- Hadron-quark burning is a laboratory for unique neutrino driven instabilities.
- Neutrinos and hydro talk to each other! Cannot be done separately.
- I am turning Burn-UD into a radiation-hydro code.
- Neutrinos can halt the burning through chemical/hydro means.
- Astrophysical implications in explosive astrophysics (e.g. r-process, Fast Radio Bursts, etc.)
- Future Work: Add different EOS to Burn-UD.