Neutrino Signatures of near-critical supernova outflows

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with Alexander Friedland

Based on :
arXiv : 2009.10059
Friedland and Mukhopadhyay (2020)

LOI : Deciphering explosion physics from the supernova neutrino signal

Mini Workshop on
Neutrino Theory - 2020

What's the goal here ?

A core-collapse supernova in our Galaxy is expected to create thousands of ν_e events in the DUNE far detector

It will be possible to track the time evolution of the spectrum with such high statistics.

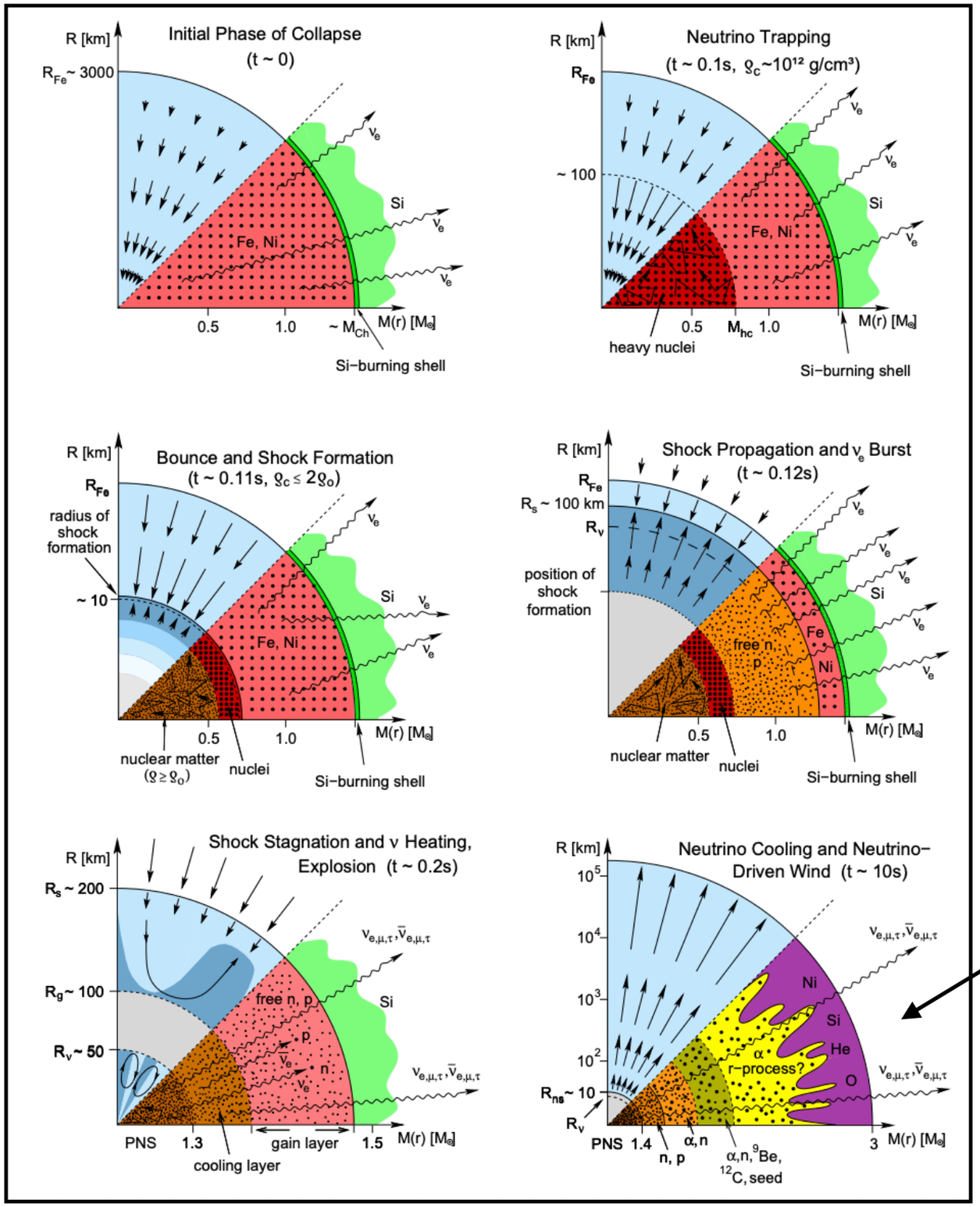
Oscillations will imprint information from the inner regions of the explosion on the observed spectra.

Wind termination shocks in neutrino-driven outflows will play a key role in determining the observable signals in DUNE.

How do wind termination shocks form ?

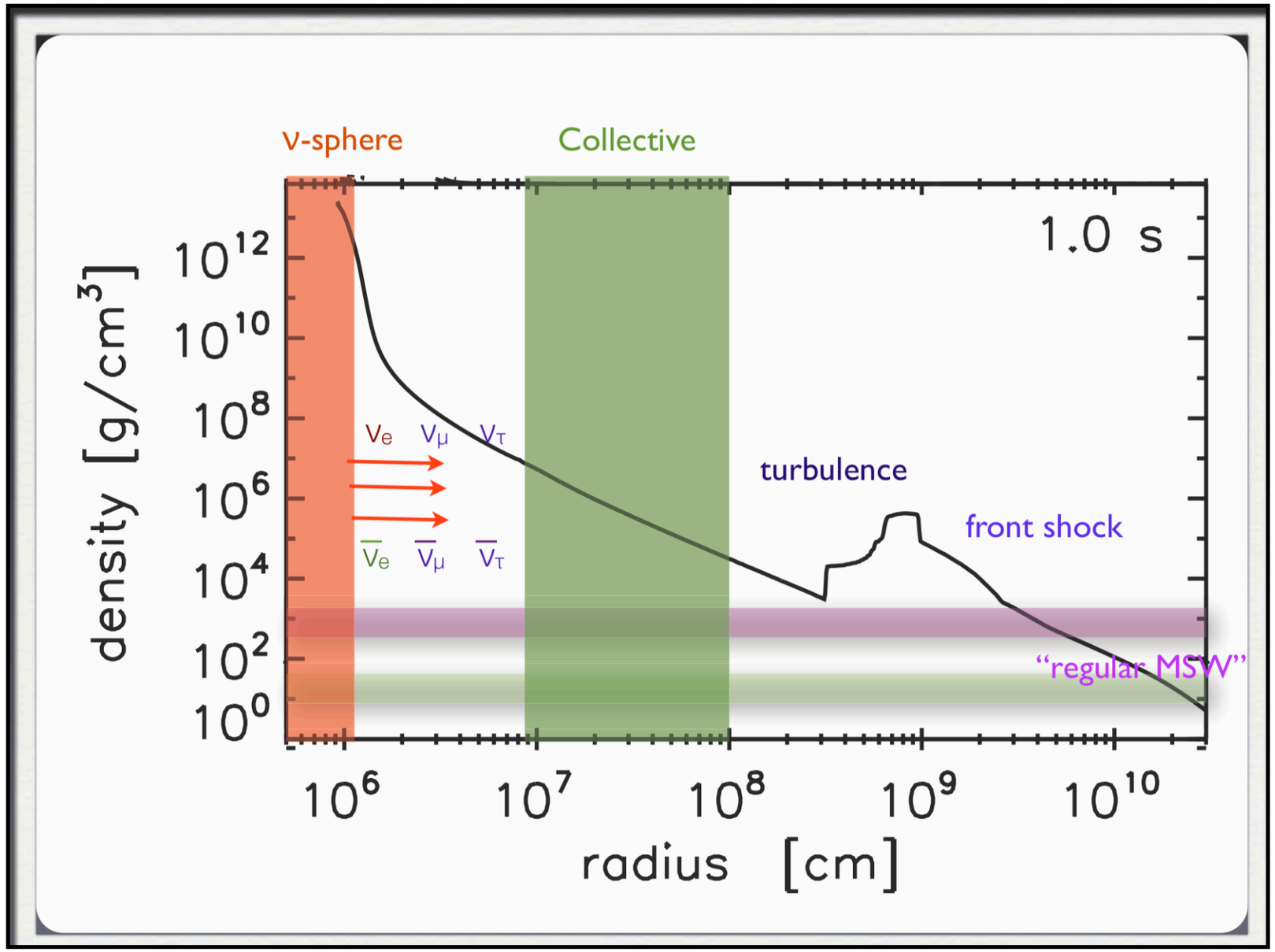
Observable signatures in DUNE ?

Core-collapse supernova explosion



We focus at late times (2-8 s)

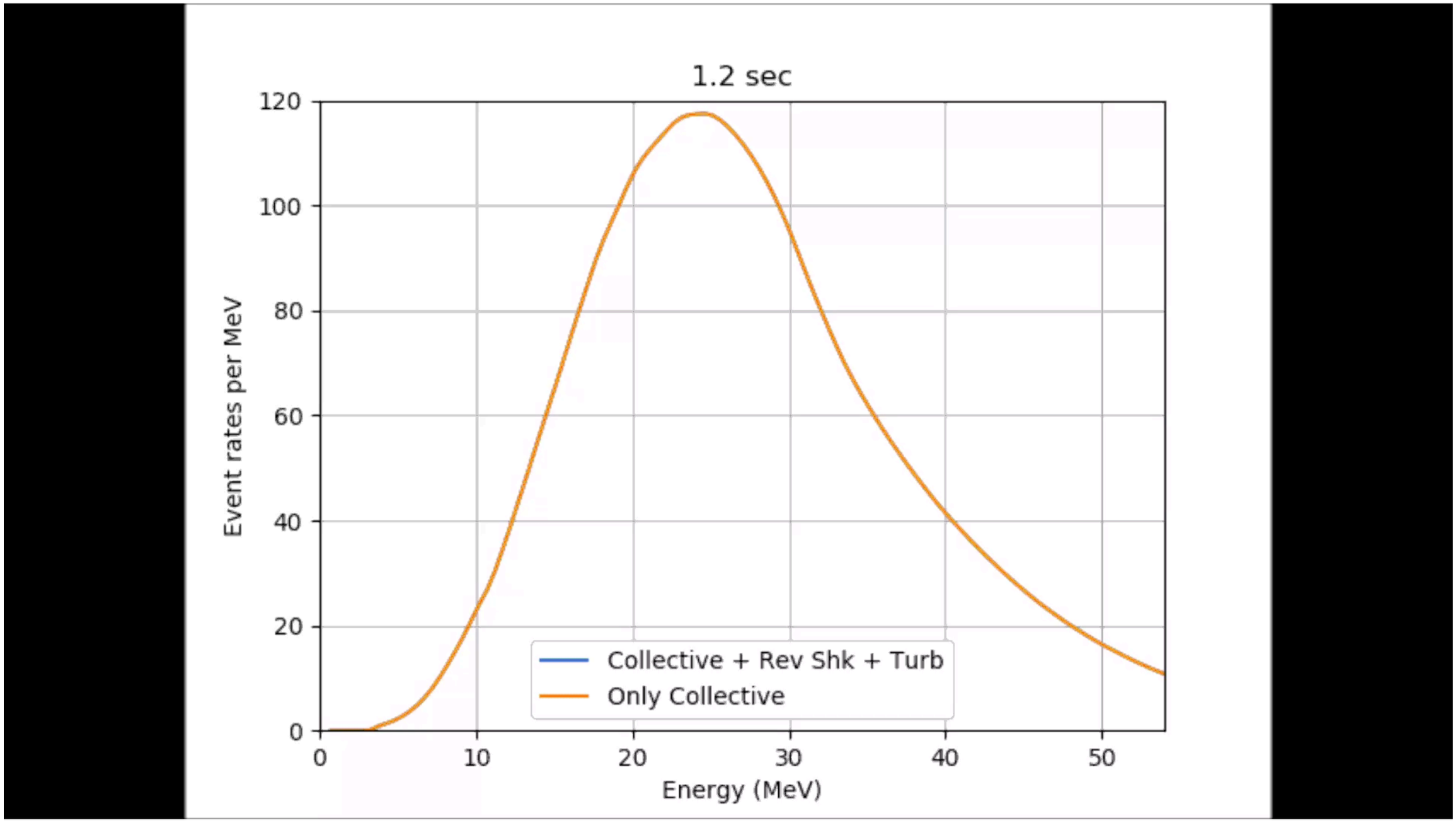
Oscillations within Supernovae



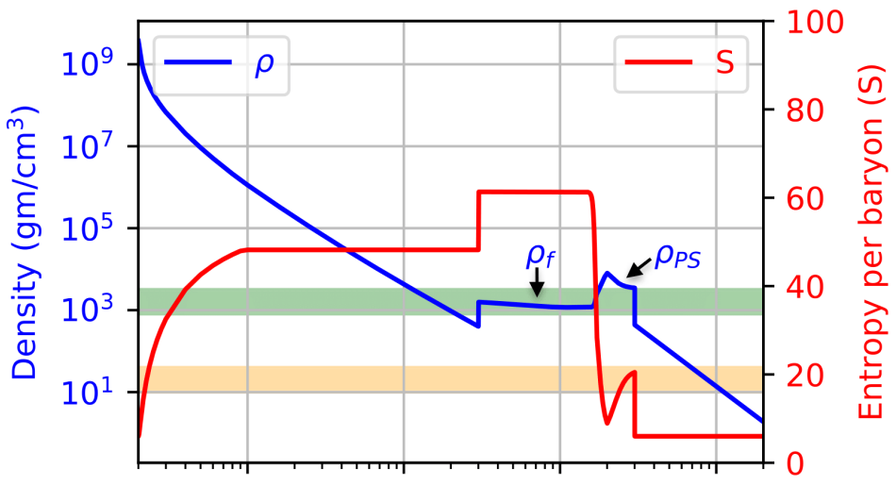
- Neutrinos coming out from neutrinosphere in all flavors.
- Pass through a complicated profile.
- Collective oscillations from $\sim$ 100-1000 km.
- First MSW at H-resonance (atmospheric splitting).
- Encounter front shock , turbulence , reverse shock etc.
- L-resonance at lower densities (solar splitting).

Arcones (2007)

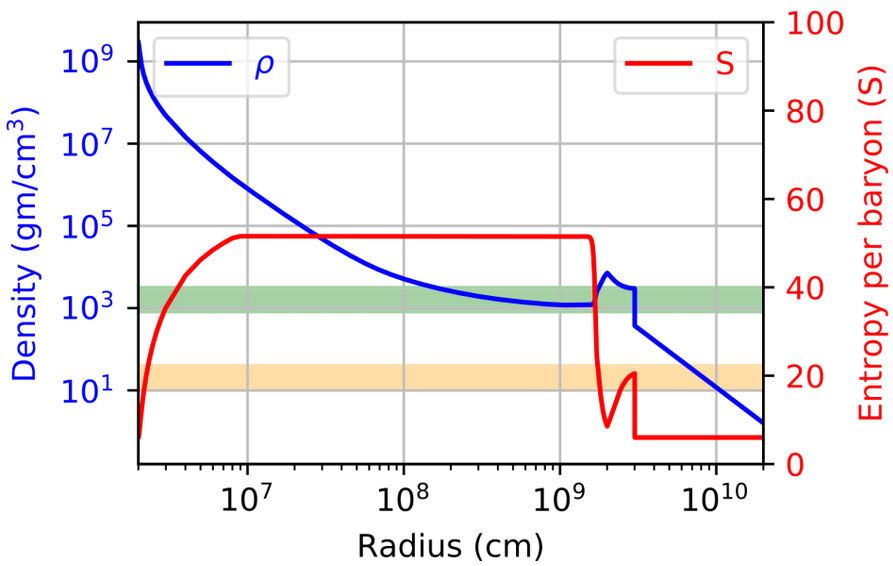
Experimental signatures of wind termination shock



Neutrino-Driven outflows



→ **Supersonic**



→ **Subsonic**

Studied since 1990s, still an active field:

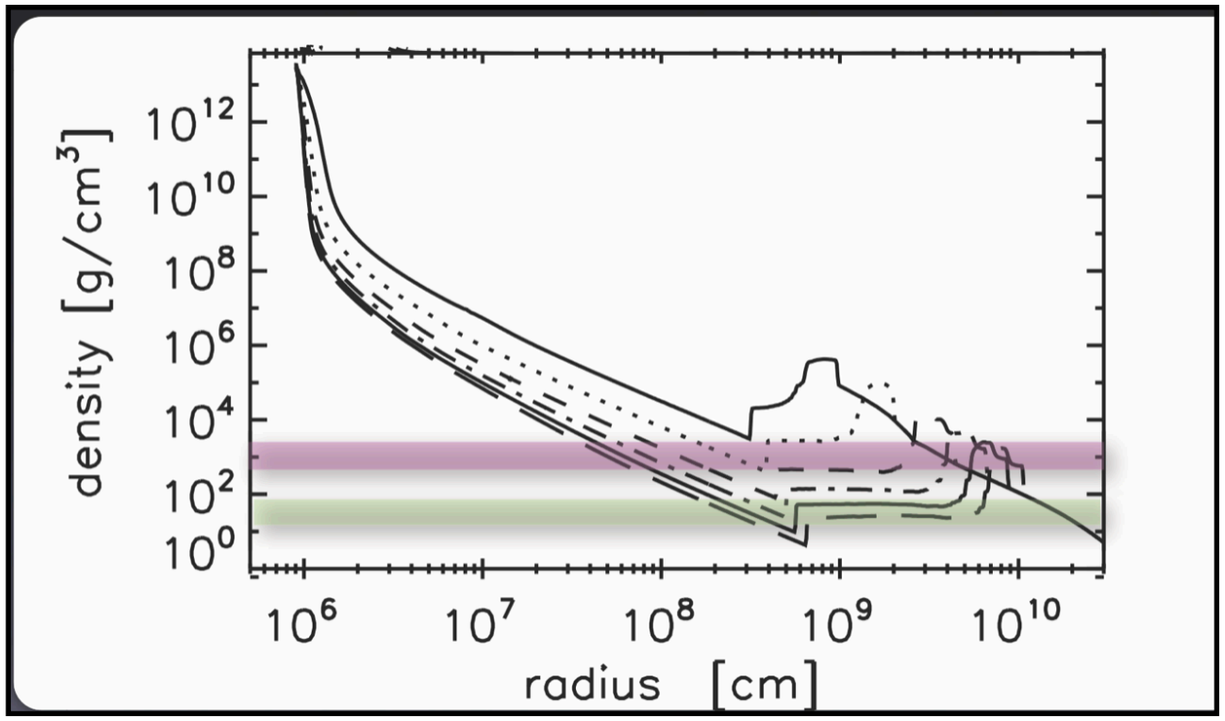
Studied in the context of general outflow properties,

Nucleosynthesis sites, sterile neutrinos etc.

Motivated by observable signatures, we revisit the problem.

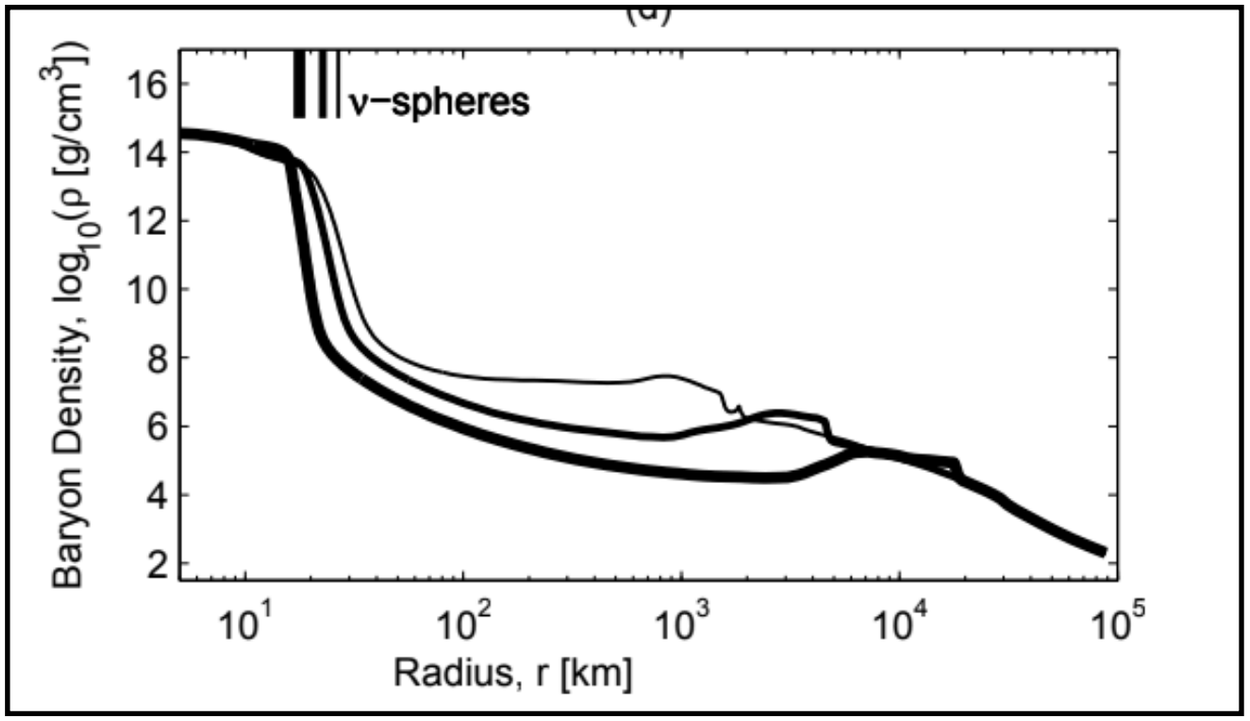
Wind vs. Breeze

Winds - Termination shock



Arcones 15 $M_\odot$ (2007)

Breezes



Fischer 18 $M_\odot$ (2010)

Some simulations get winds, some get breezes - Are these consistent ?

How can these numerical results be understood analytically ?

Semi-analytical formulation of neutrino winds

1) Steady-state spherically symmetric equations with mass conservation, Newton's 2nd law and entropy generation. 3 Coupled differential equations needs 3 boundary cond.

2) First two b.c : Initial Temperature (T) and entropy (S) at starting radius R.

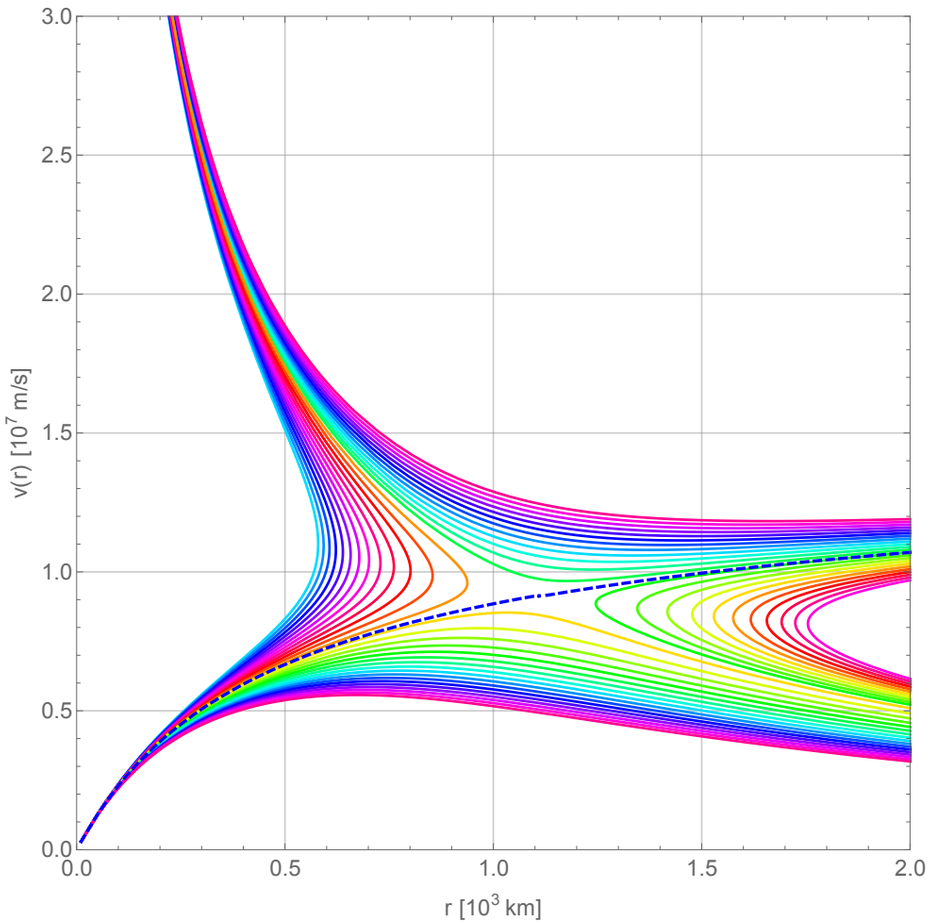
3) What should the third boundary condition (b.c) be ?

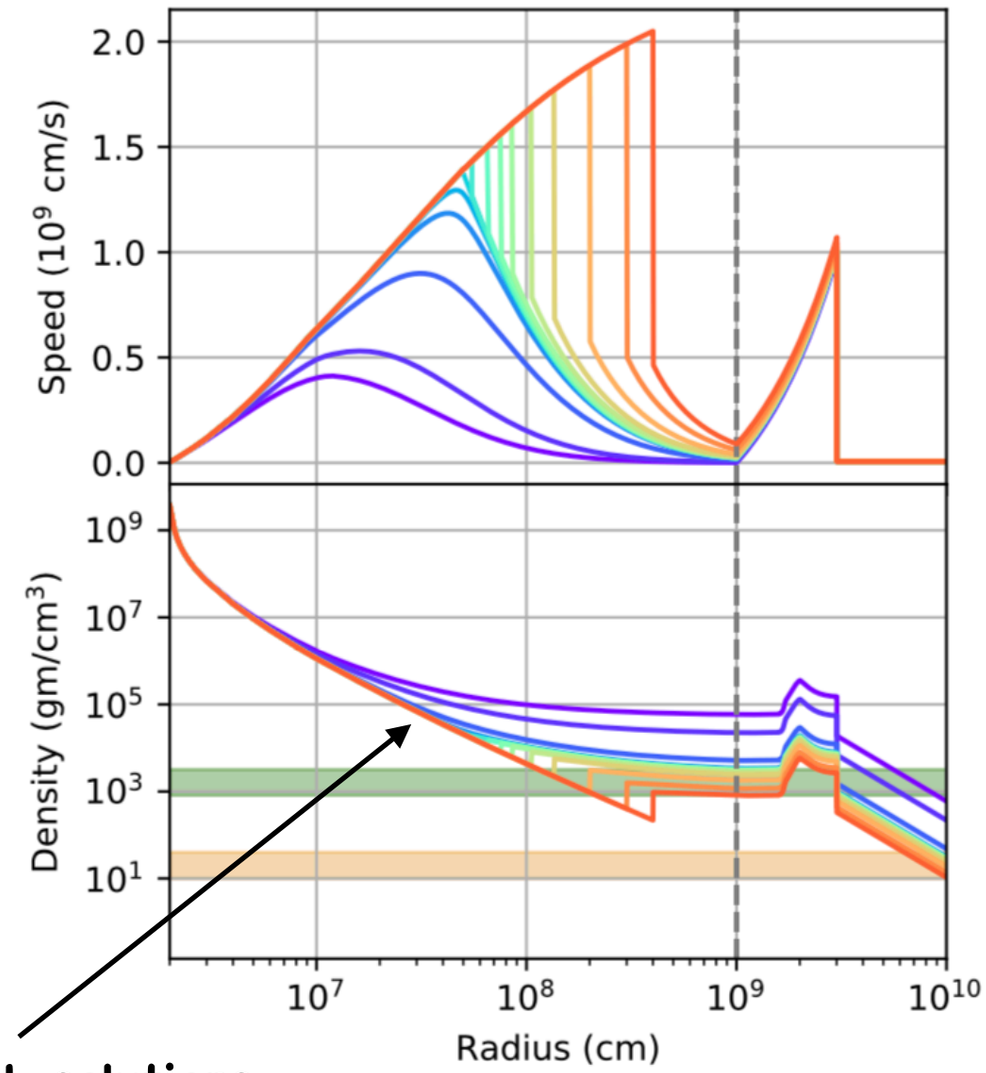
4) Existing literature : presupposes supersonic solutions (Thompson 2001) ,
Outer boundary pressure for subsonic solutions (Qian Woosley 1996, Otsuki 2001)

5) Different boundary conditions used for supersonic and subsonic outflows.
Supersonic and subsonic solutions treated differently.

6) Our approach : Use outer boundary pressure for both Supersonic and Subsonic.
Change far end pressure (P) from very high to zero continuously

Outflow solutions in neutrino-driven outflows





1) Critical density below which solutions are supersonic.

2) Above critical density, solutions are subsonic.

3) Both supersonic and subsonic described using outer boundary pressure as the far condition

Scaling law for critical density :

Numerical estimate

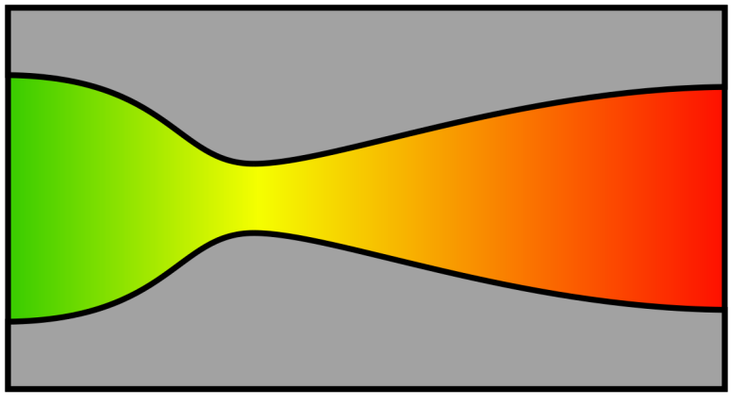
$$\rho_{f,crit} \propto L^{2.69} M^{-4} R^{0.9} \epsilon^{5.1}.$$

Analytical estimate :

$$\rho_{f,crit} \propto L^{8/3} \epsilon^{16/3} R^{2/3} M^{-4}.$$

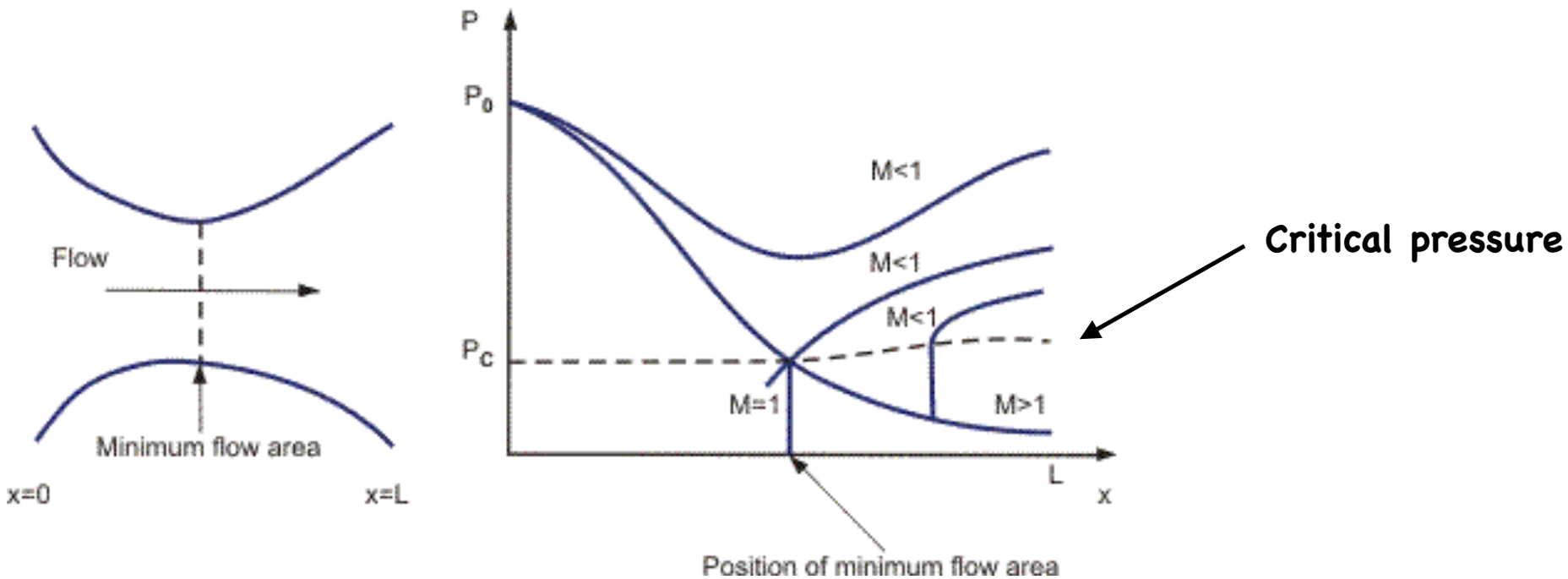
- Termination shocks form only for densities below the critical value.
- Critical progenitor mass 12 M. Termination shocks between 2-4 sec.
- Existing numerical simulations can be reconciled with this approach.
- Supernova neutrino driven outflows are naturally close to critical.
- Running present day simulations for longer times can give shocks.

Analogy : De laval nozzle theory



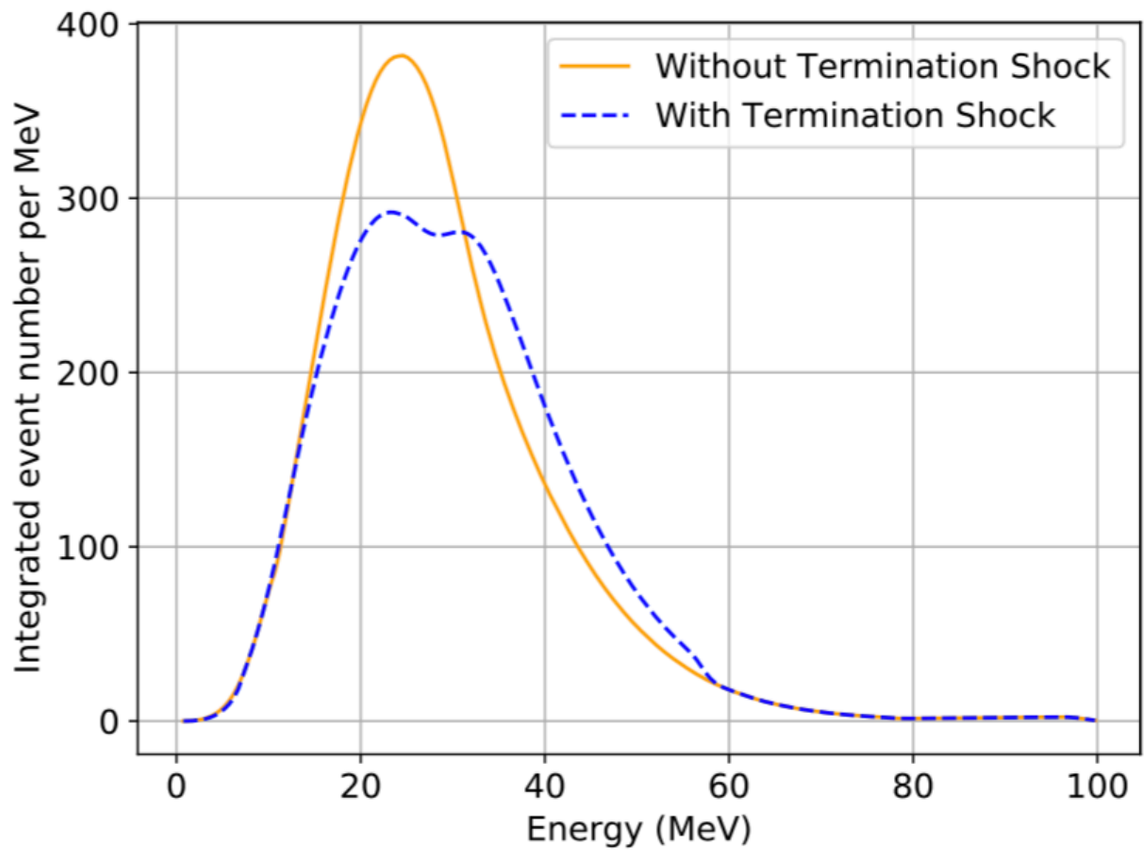
Flow

Ref : Landau Lifshitz (Fluid mechanics)



In astrophysical settings : Bondi accretion, jets etc.

Observable signatures of termination shocks ?



Termination shocks have observable signatures in DUNE

5-sigma detection possible for 3 kpc

Probe of the inner workings of supernovae

SUMMARY

- Supersonic and subsonic outflows can both be consistently solved with outer pressure boundary condition.

- Below the critical far boundary pressure, wind termination shocks will form.

- Neutrino-driven outflows are close to critical for a range of supernova masses.

- Termination shock signatures can be quite substantial.

- Tight collaborative efforts with experimentalists needed for assessing detectability.

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Thank you !