On the general characteristics of neutrino-driven outflows

Payel Mukhopadhyay

with **Alexander Friedland**

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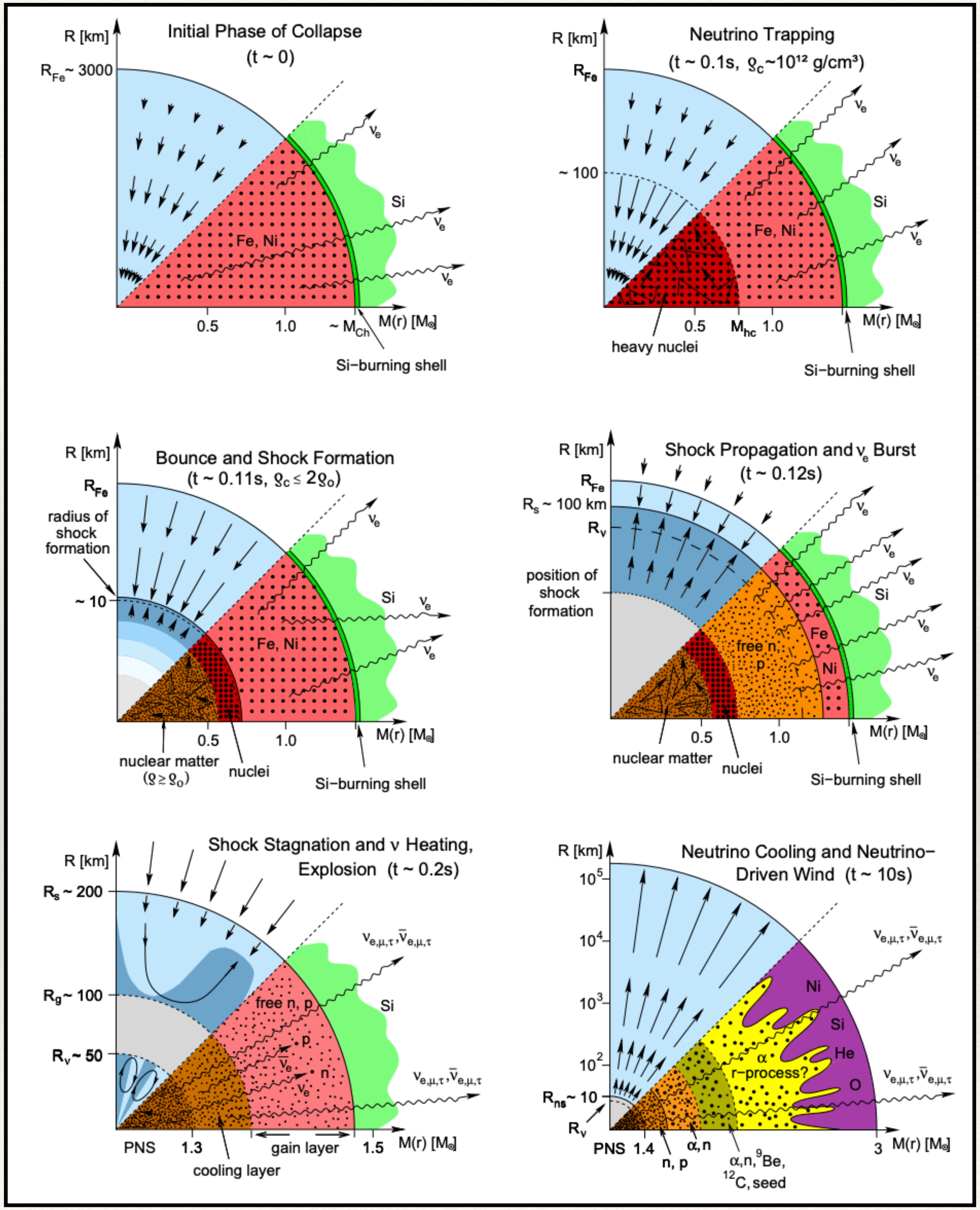
Contact:
payelmuk@stanford.edu

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.
- Neutrino-driven outflows dictate the density profiles at late times that directly impact neutrino oscillations and thereby observable signals.
- In this quest, we discuss the nature of these neutrino-driven outflows.

Core-collapse supernova explosion



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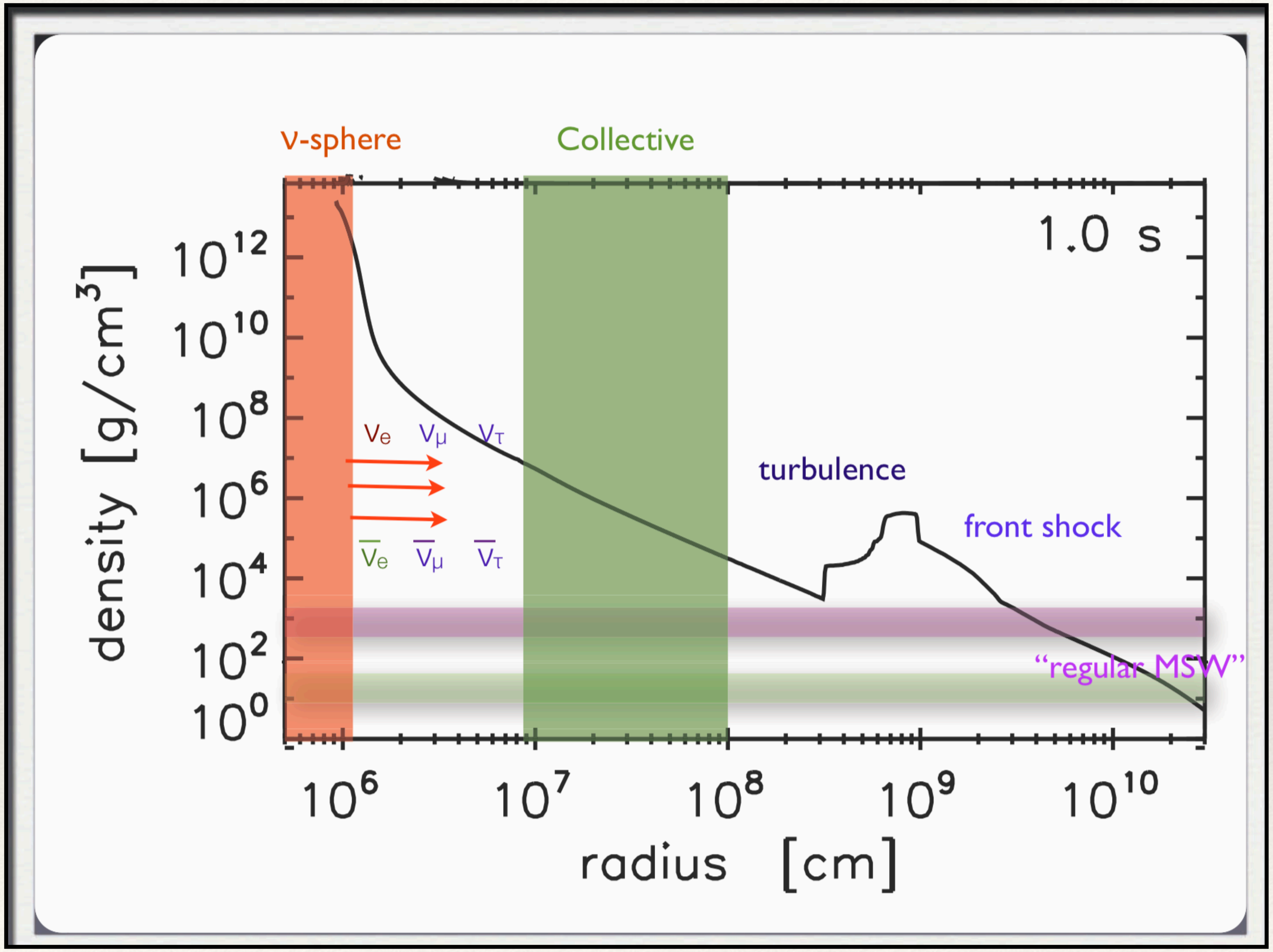
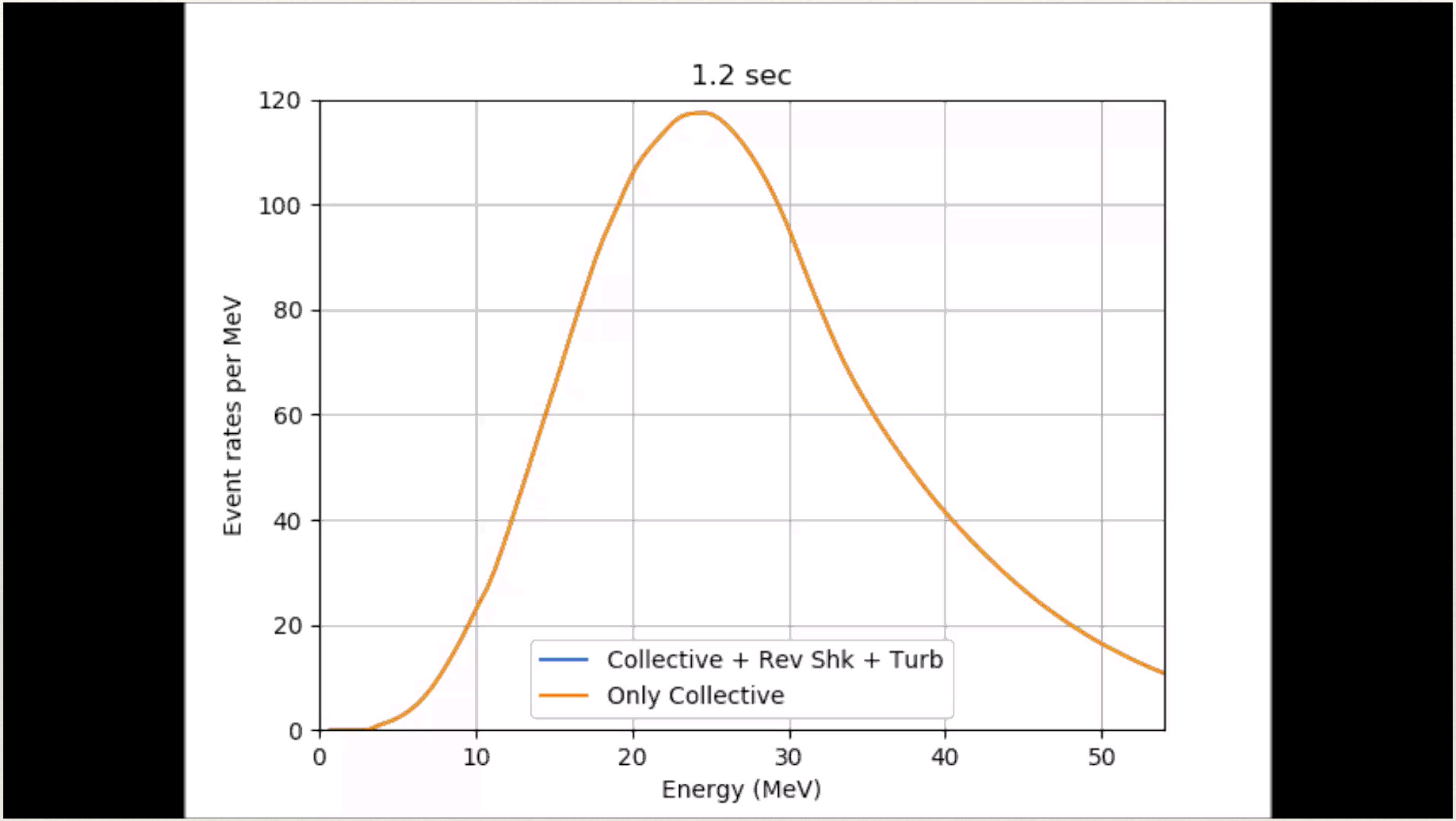
Oscillations within SN are more involved

Arcones (2007)



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

Supernova density profiles affect the observed neutrino spectrum on Earth !



Video file shown in the recorded talk !

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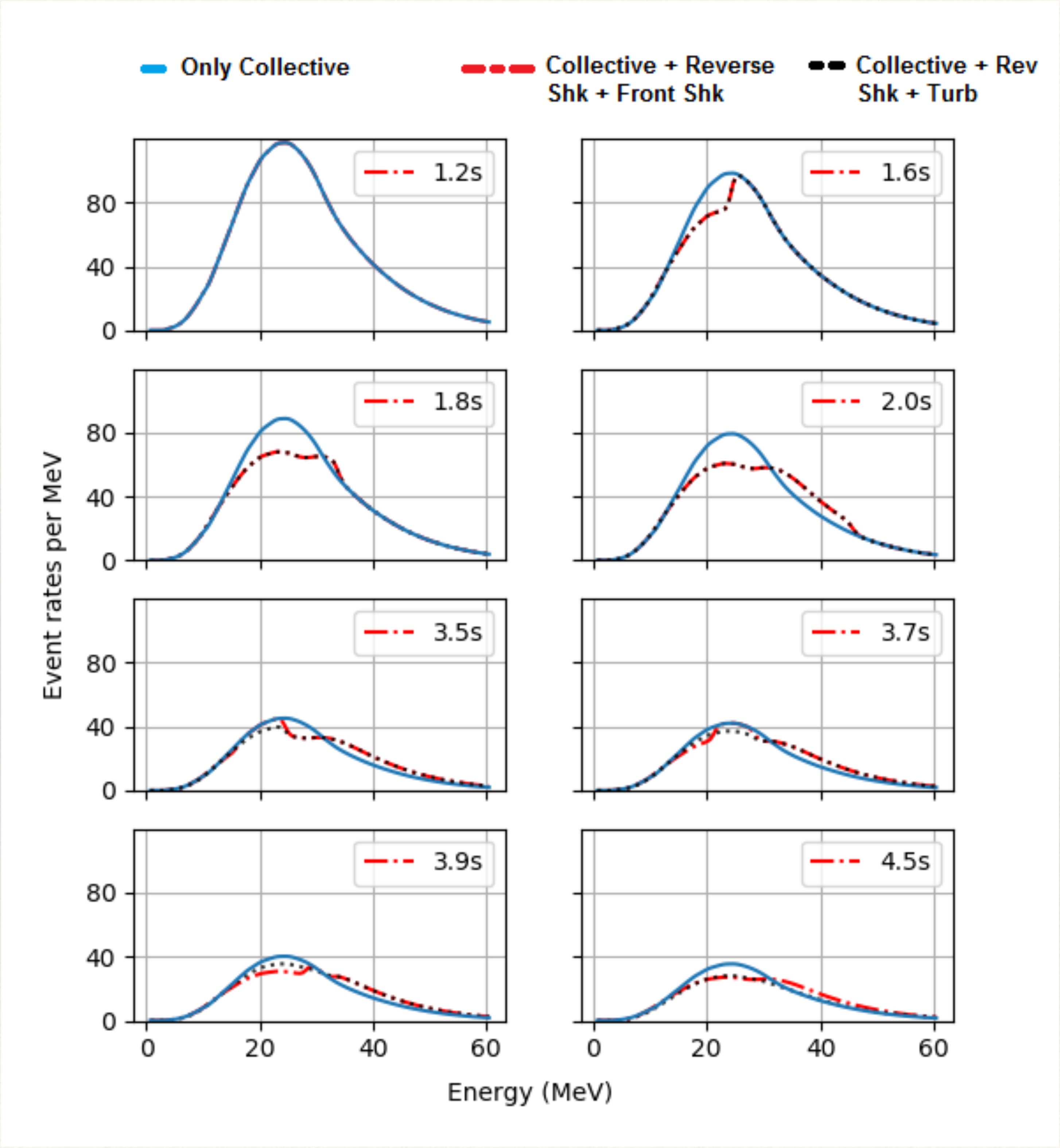
Shocks induce non-thermal features observable in DUNE !



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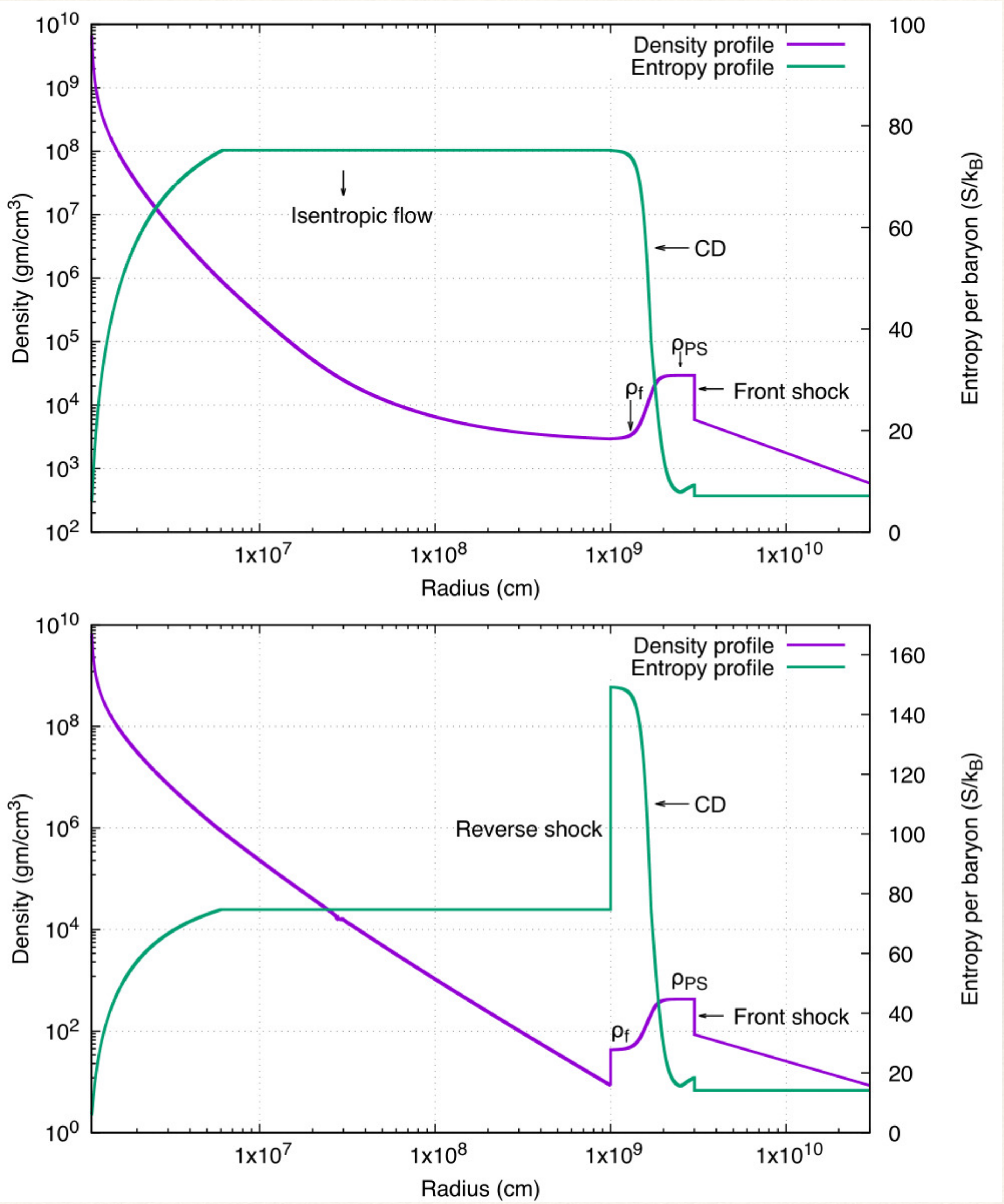
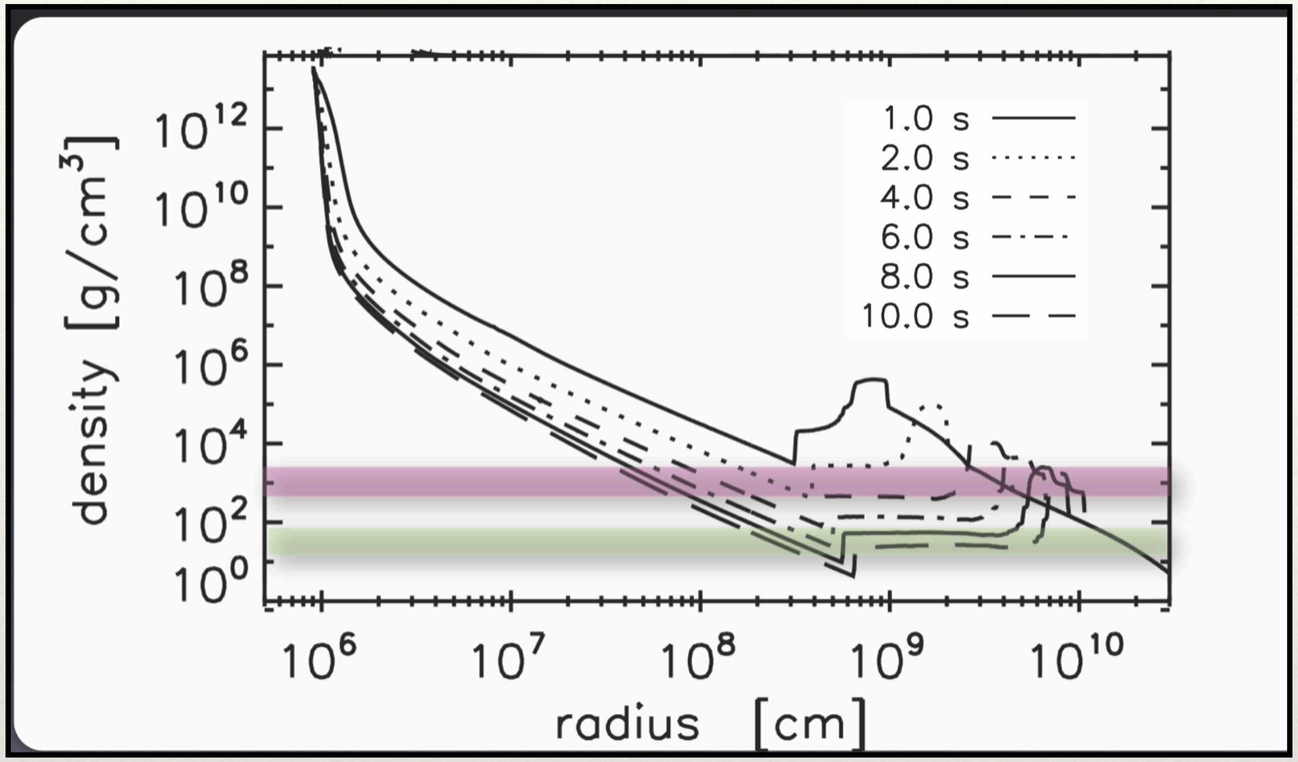
Neutrino-driven outflows: Subsonic and Supersonic



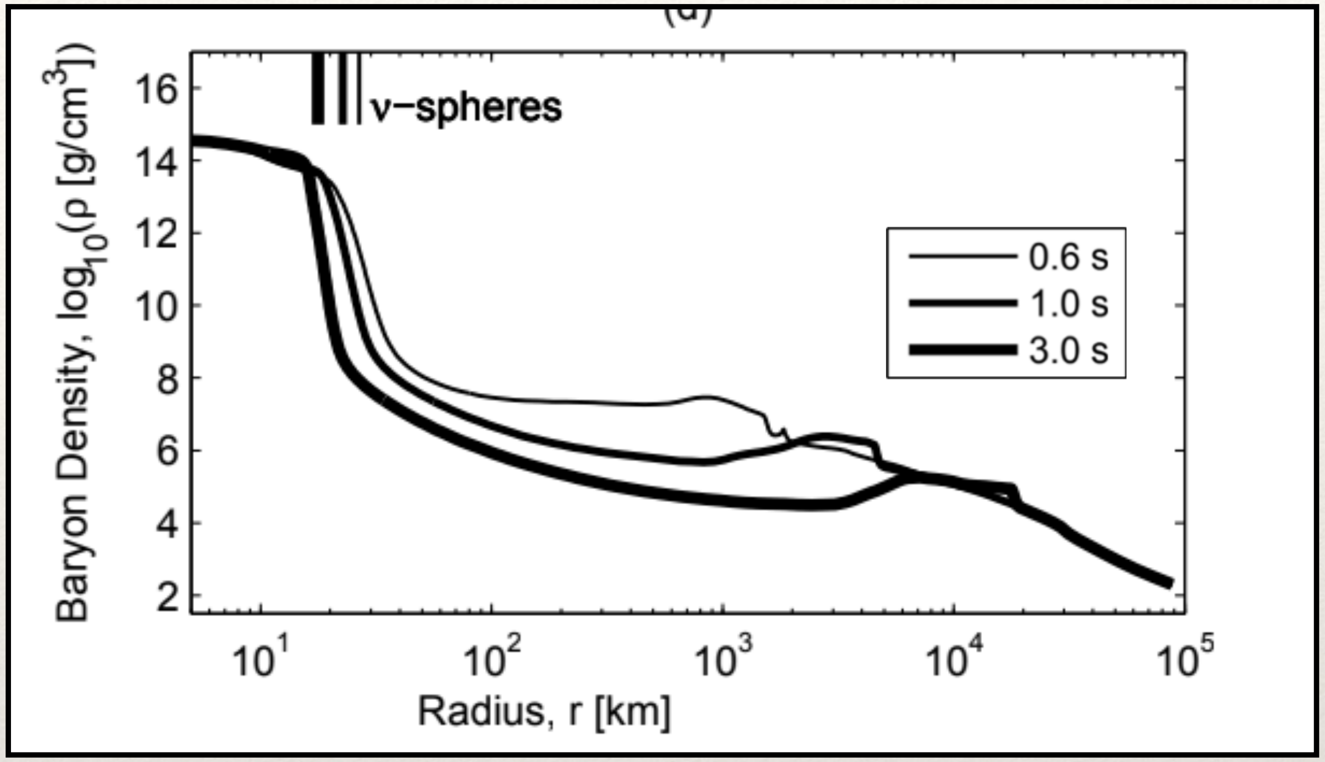
Wind vs. Breeze

Winds - Termination shock



Arcones 15 M⊙ (2007)

Breezes



Fischer 18 M⊙ (2010)

Main question : What is the condition of formation of termination shock ?

Governing equations

1

$$\left(v-\frac{v_s^2}{v}\right)\frac{dv}{dr}=\frac{2v_s^2}{r}-\frac{GM}{r^2}-\frac{\dot q}{3v}.,$$
$$\dot q = v\frac{d}{dr}\left(\frac{v^2}{2}+3v_s^2-\frac{GM}{r}\right).,$$
$$v\frac{dS}{dr}=\frac{\dot q m_N}{T}.$$

3 non-linear ODE

Specify T_i, S_i, ρ_f

Boundary-value problem

2

$$\dot q \approx \dot q_{\nu N} - \dot q_{eN} - \dot q_{e^+e^-} \propto \left(L_{\bar\nu_{e,51}} E^2_{\bar\nu_{e,MeV}} \frac{1-x}{R^2_{\nu 6}}\right) - C_1 T^6 - C_2\frac{T^9}{\rho_8}$$

$T < 0.5$ MeV

(Nuclear Recombination)

$$\dot q = 0$$

3

$$\left(v-\frac{v_s^2}{v}\right)\frac{dv}{dr}=\frac{2v_s^2}{r}-\frac{GM}{r^2}.$$

$$I = \frac{v^2}{2}+3v_s^2-\frac{GM}{r}$$

4

Single non-linear ODE with an algebraic constraint

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Boundary value problem

$$\left(v - \frac{v_s^2}{v}\right)\frac{dv}{dr} = \frac{2v_s^2}{r} - \frac{GM}{r^2} - \frac{\dot{q}}{3v}.,$$

$$\dot{q} = v\frac{d}{dr}\left(\frac{v^2}{2} + 3v_s^2 - \frac{GM}{r}\right).,$$

$$v\frac{dS}{dr} = \frac{\dot{q}m_N}{T}.$$

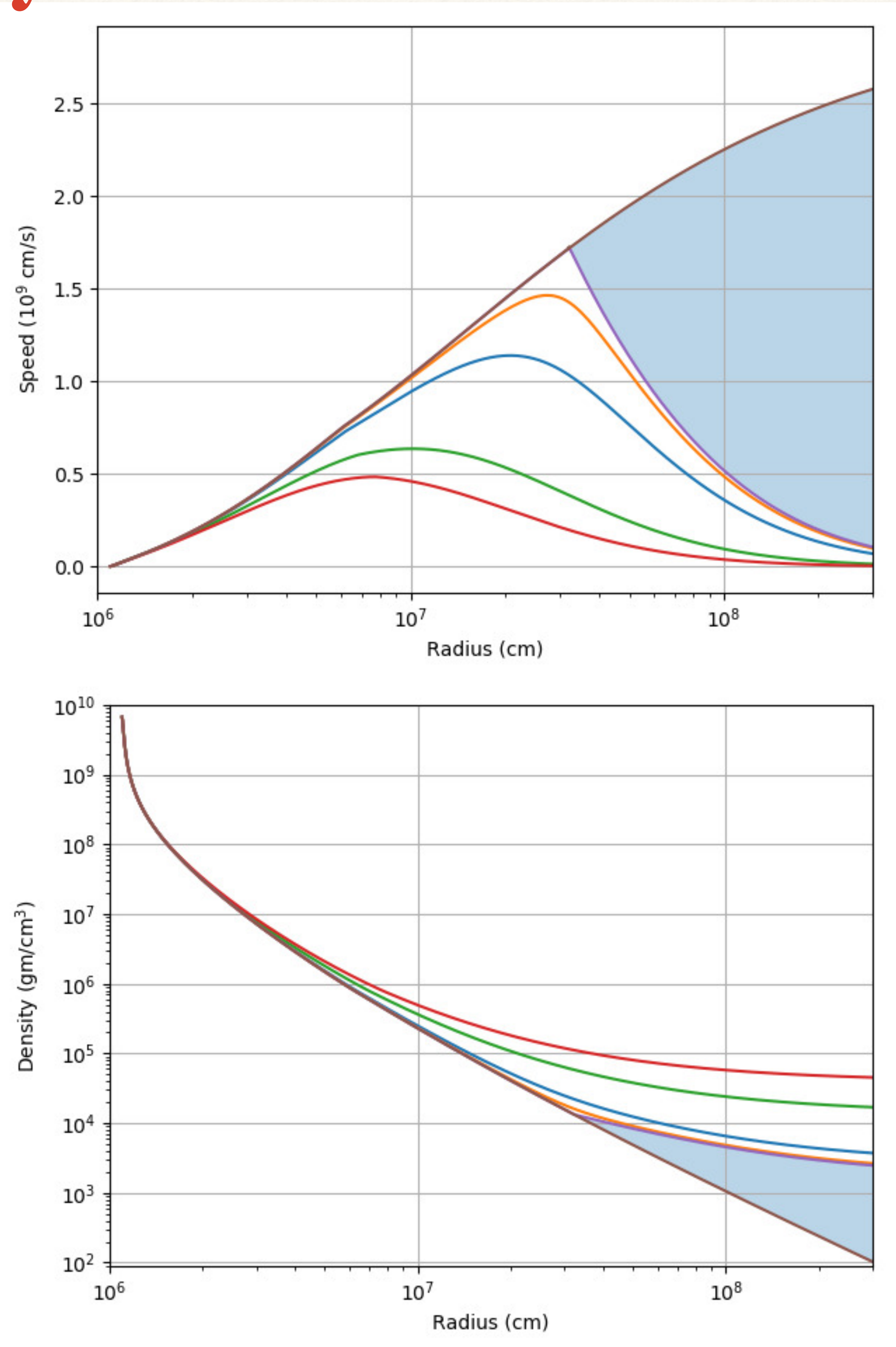
T_i, S_i at PNS radius R

What is the right third boundary condition ?

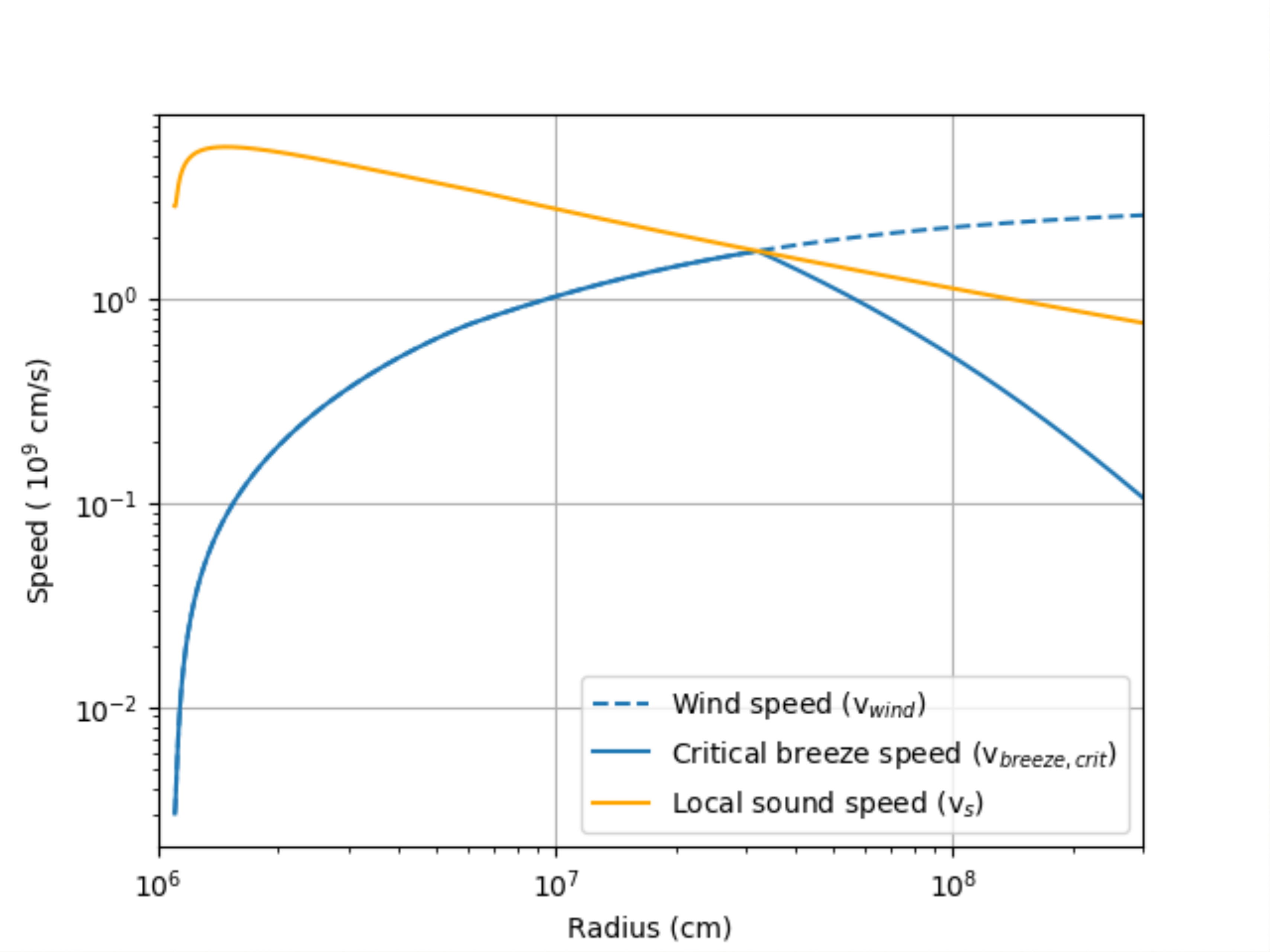
- Historically, various approaches used.
- T = 0.1 MeV at R = 10,000 km (Qian & Woosley 1996, Otsuki 2001)
- Boundary condition at the sonic point itself. (Thompson 2001)
- $\dot{M}$ as inner boundary condition. (Wanajo 2001)
- Confusing literature…
- We propose using far density ρ_f as the third boundary.

Criticality !

- Below a certain ρ_f, no subsonic solutions exist !
- After this point, the curve directly goes to supersonic
- The corresponding far end density ρ_f is the minimum density that can be achieved by a breeze solution
- We call this the critical density ρ_{crit}

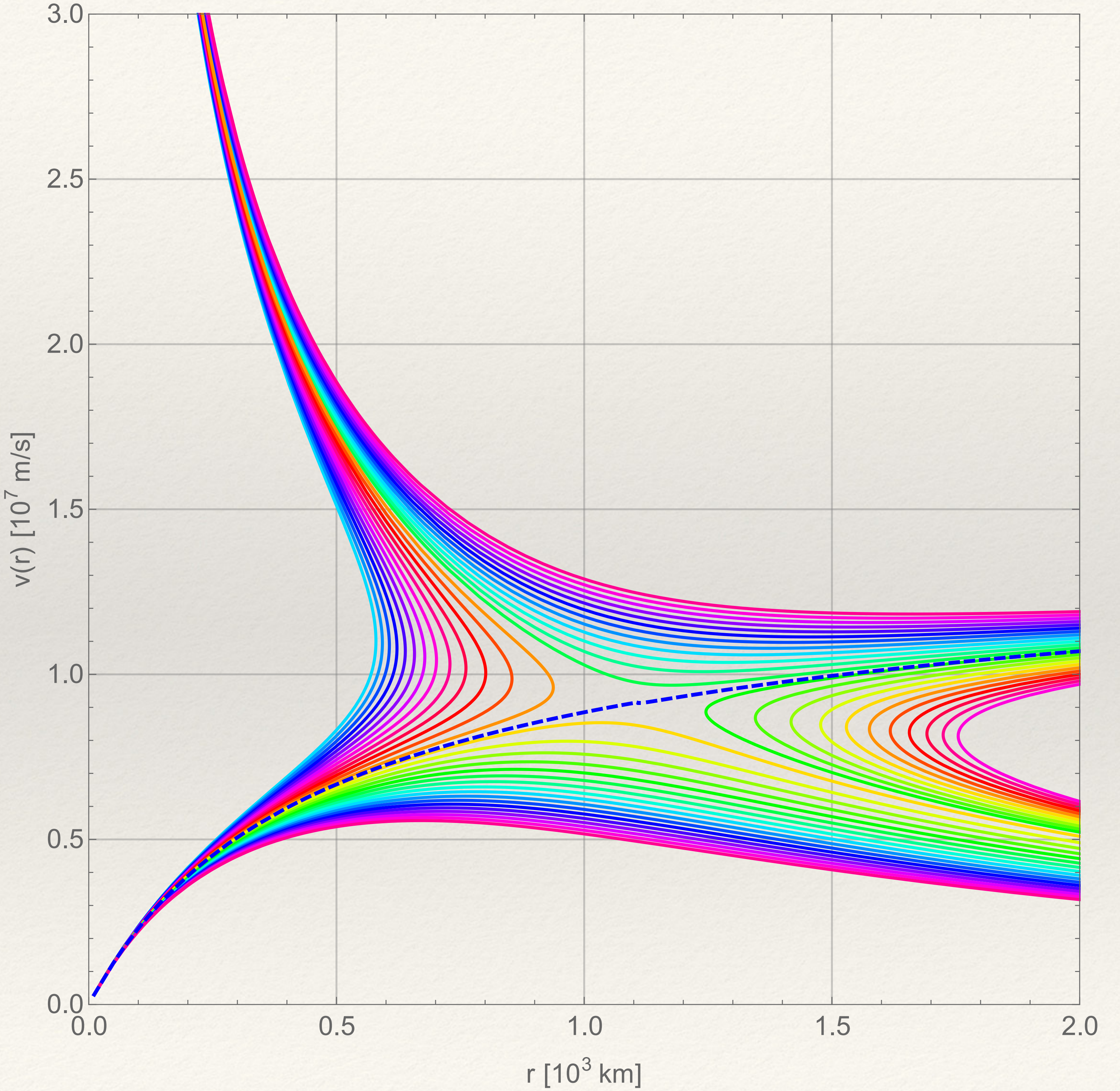


Criticality



System has a saddle point !

$$\frac{dv}{dr} = \frac{v}{r}\frac{2v_s^2 - GM/r}{v^2 - v_s^2}$$



Critical parameters

For a given final density ρ_f, there exists critical values of the basic parameters like Luminosity (L_ν), average energy ($\epsilon_{avg,\nu}$), radius (R) and mass of the protoneutron star (M_{PNS})

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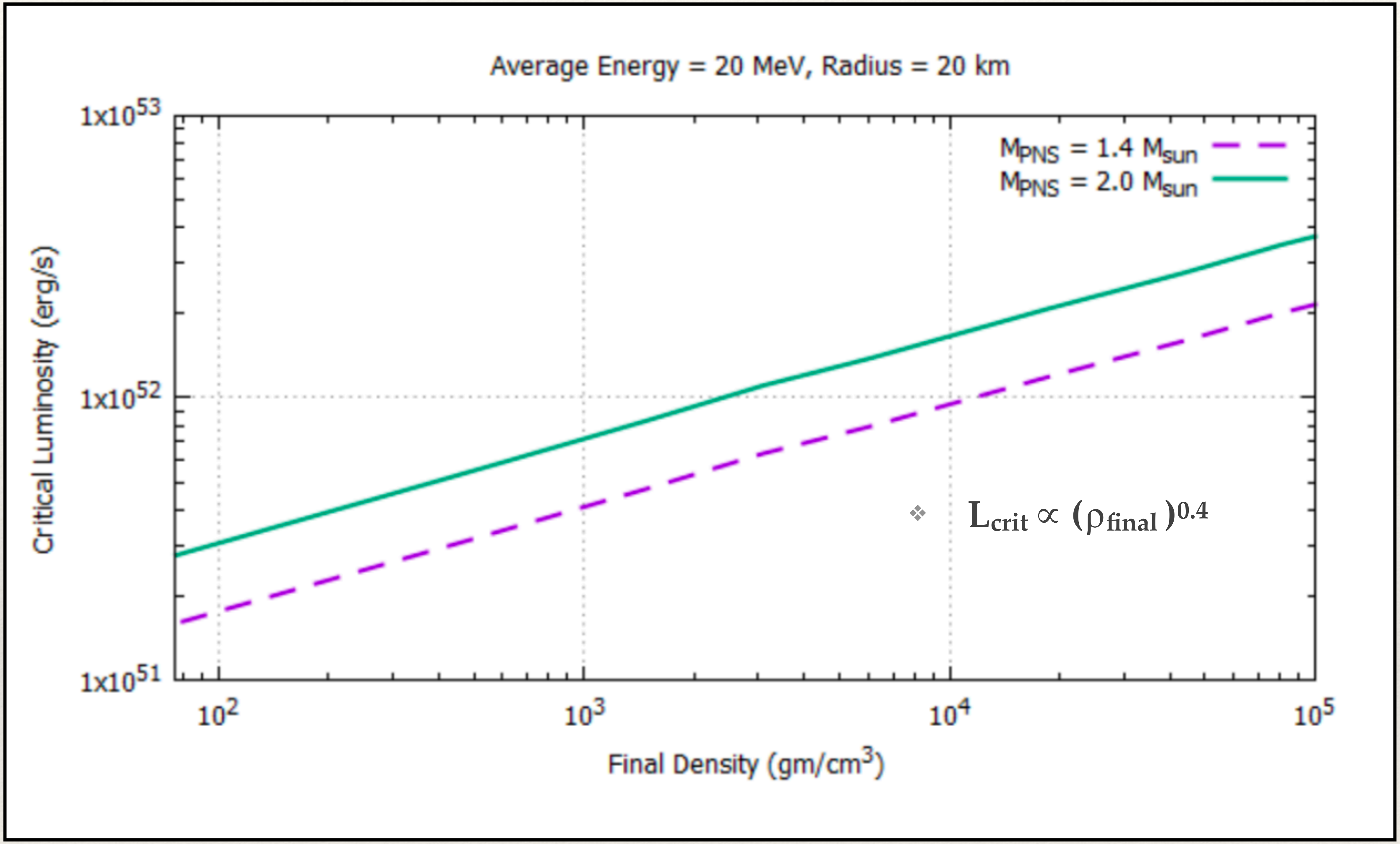
Critical curves



Critical Luminosity curve for reaching subsonic to supersonic transition point

- For $L \sim 10^{52}$ erg/s, final densities of at least 10^4 gm/cm^3 needed

Approximate scaling law for critical density

Similar critical curves exist for average energy (E) and radius of the protoneutron star. Numerically, then one obtains a scaling law for the critical density in terms of the basic governing parameters :

$$\rho_{crit} \propto L^{2.69} R^{0.9} E^{5.1} M^{-4}$$

Friedland and Mukhopadhyay (in prep)

Practical applications

- Presence or absence of termination shocks directly impact MSW flavor transformations !
- Direct impact on observable neutrino signals !
- Essential for understanding nucleosynthesis ?

Thank you !