Neutrino-driven outflows inside a supernova I: physical properties and implications for DUNE

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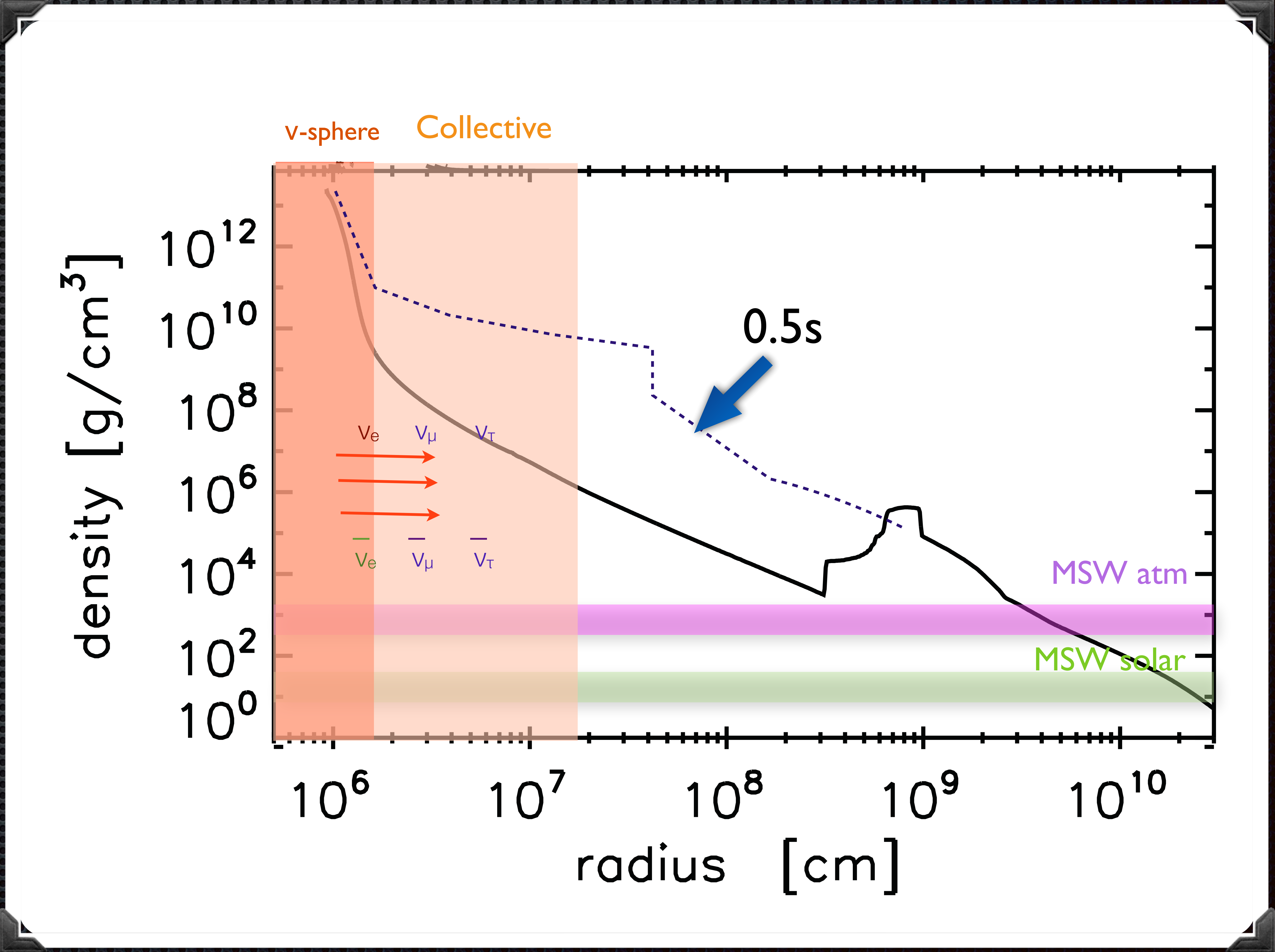
INT Seattle July 26, 2023

CCSN: Gravity-powered neutrino bomb

- Neutrinos are the main carrier of energy and lepton number
  - Carry away >99% of the explosion energy, power the expulsion of the envelope
- Neutrinos provide a laboratory for collective quantum dynamics
  - Collective oscillations of all kinds
- Neutrinos are an essential ingredient in nucleosynthesis
  - Drive the matter outflow from the PNS surface. Set the electron fraction Y_e. Create a subdominant *n* population in a *p*-rich medium. See Part II by Amol + this morning's talk by Yong
- Neutrino signal provides a *diagnostic* of the developing explosion
  - Changing matter profile can imprint features in the neutrino signal by the MSW effect

Reminder: MSW transformations in a CCSN

- MSW flavor transformations occur at two resonant densities, corresponding to the atmospheric and solar splittings
- In the beginning, the resonant conditions occur at large radii, where the progenitor profile has not yet been perturbed by the explosion

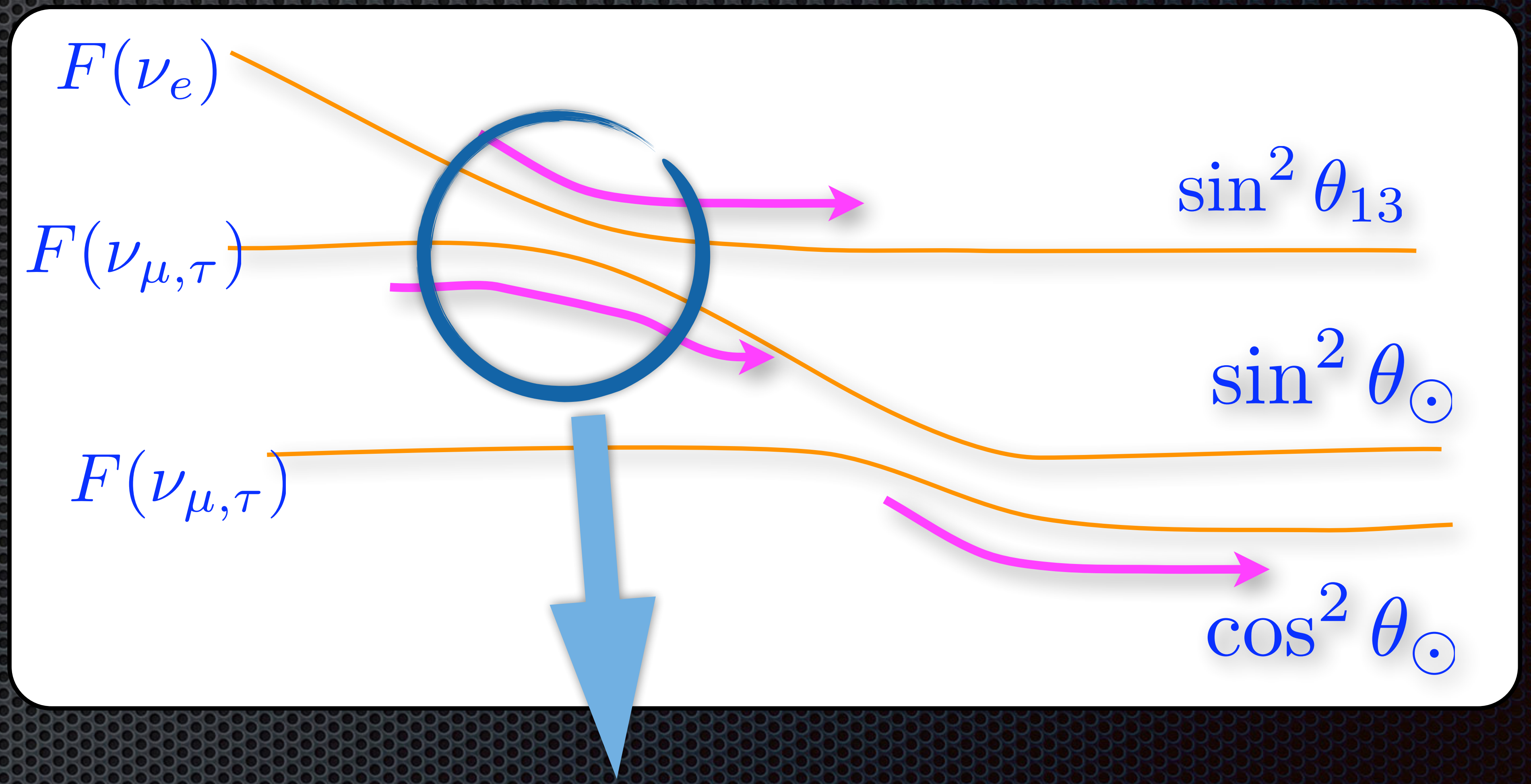


Dighe & Smirnov, Lunardini & Smirnov

MSW transformations, the early stage

- Using measured mixing angles, θ_{13} and θ_{12}, we can verify that both resonances are strongly adiabatic in the progenitor profile
  - $\lambda_{osc} \sim 6\ km$ for E=20 MeV, $\lambda_{profile} \sim 10^4\ km$, $\sin^2 2\theta_{13} \simeq 0.084$

- Illustration for NH

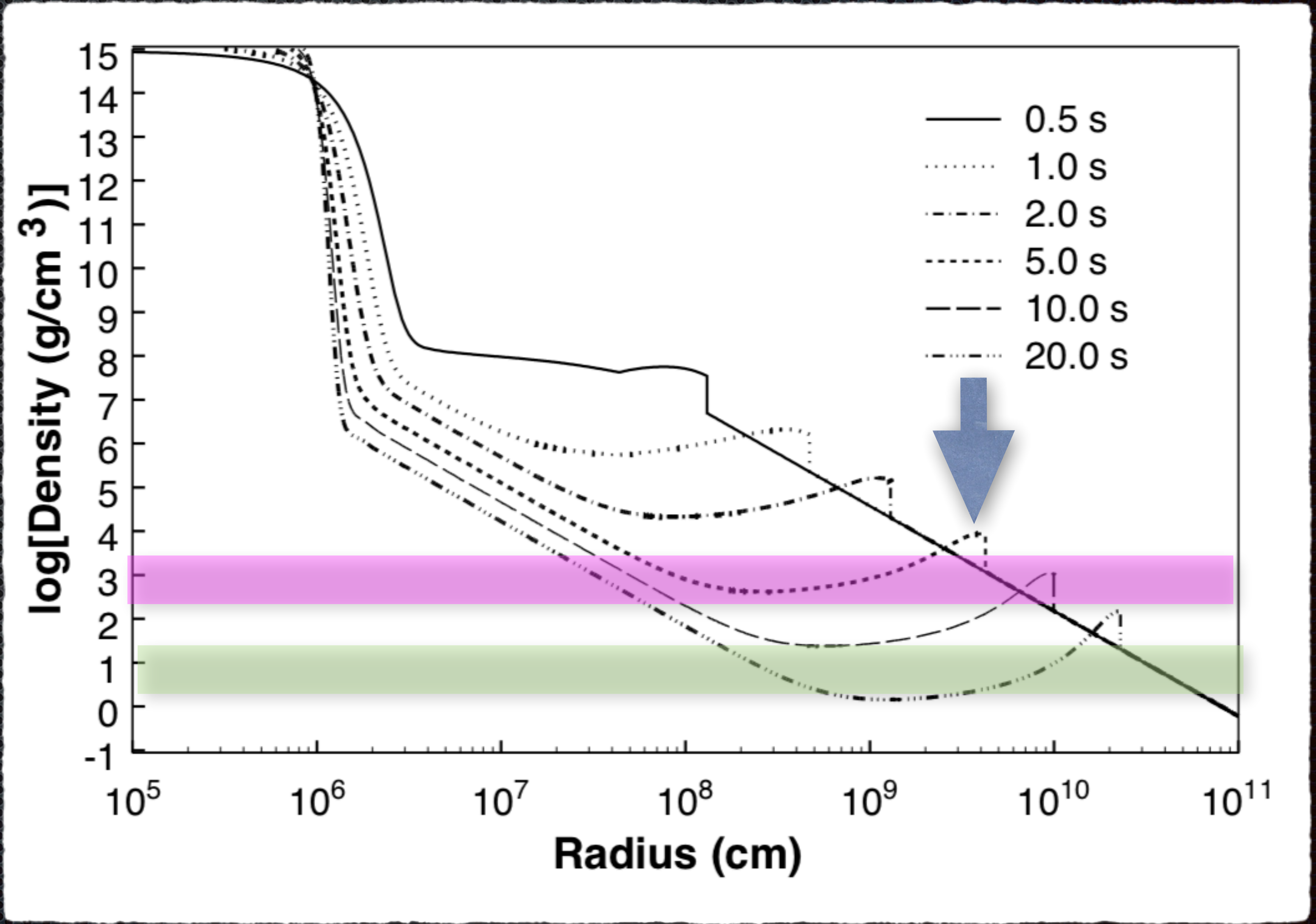


$$P_{jump} = \exp\left(-\frac{\pi\lambda_{profile}}{\lambda_{osc}}\sin^2 2\theta_{13}\right)$$

- E.g., neutralization burst

But neutrinos keep streaming for ~10 s

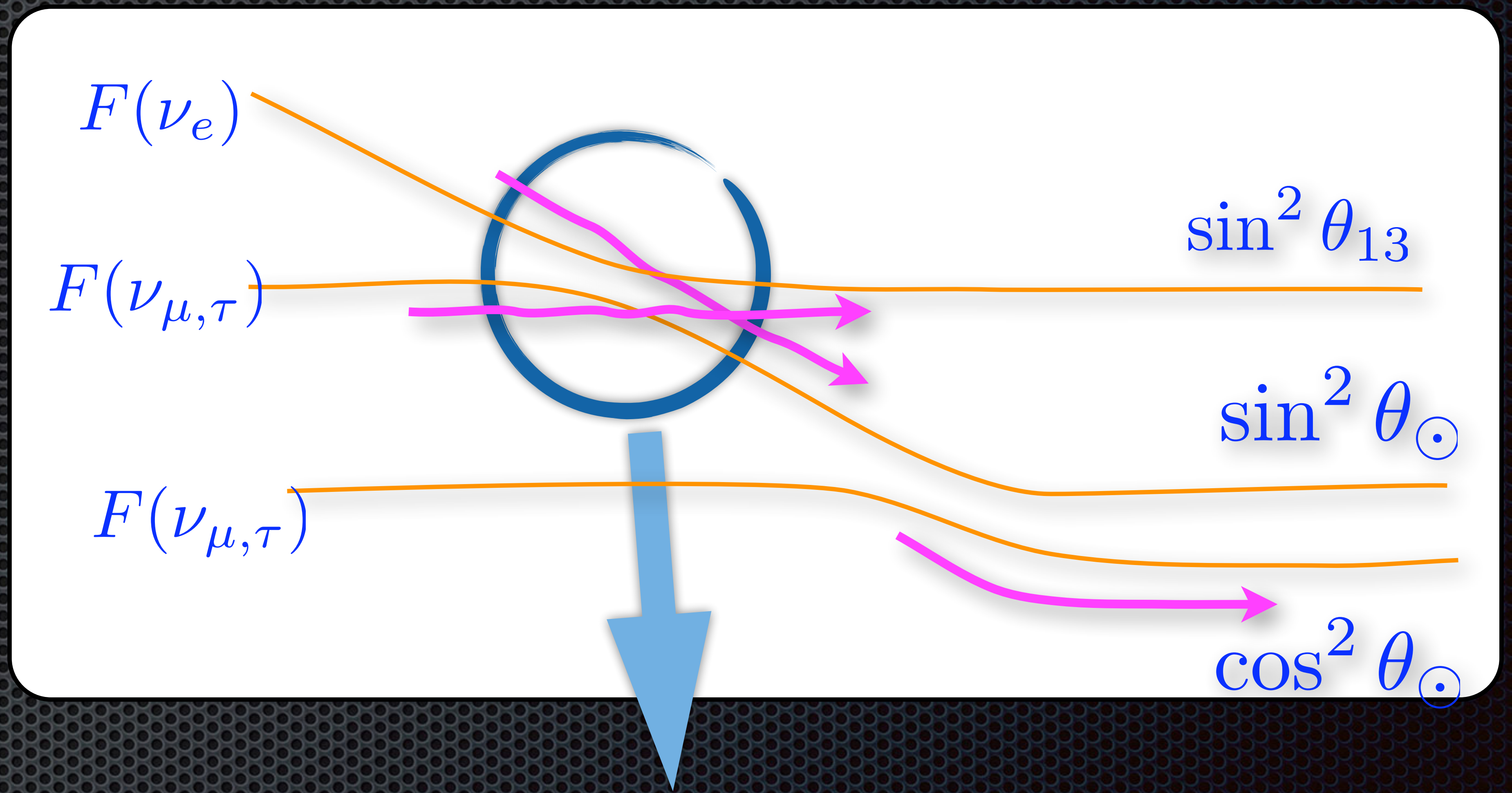
- Several seconds into the explosion, the front shock reaches the MSW layers.
- R. Schirato and G. Fuller (2002)
- At this point, the flavor evolution at the shock becomes maximally nonadiabatic and the oscillation probabilities change



Simulation by Jim Wilson
(heavy progenitor)

Oscillations after the shock gets to the H-resonance

- H-res is now completely non-adiabatic
- Electron neutrinos, which before went into ν_3, now go into ν_2
- ν_2 has a higher probability of being measured as ν_e than ν_3
  - $\sin^2\theta_{12}$ *vs* $\sin^2\theta_{13}$
- e.g., if the original ν_e flux was colder than ν_x, observed ν_e flux gets colder

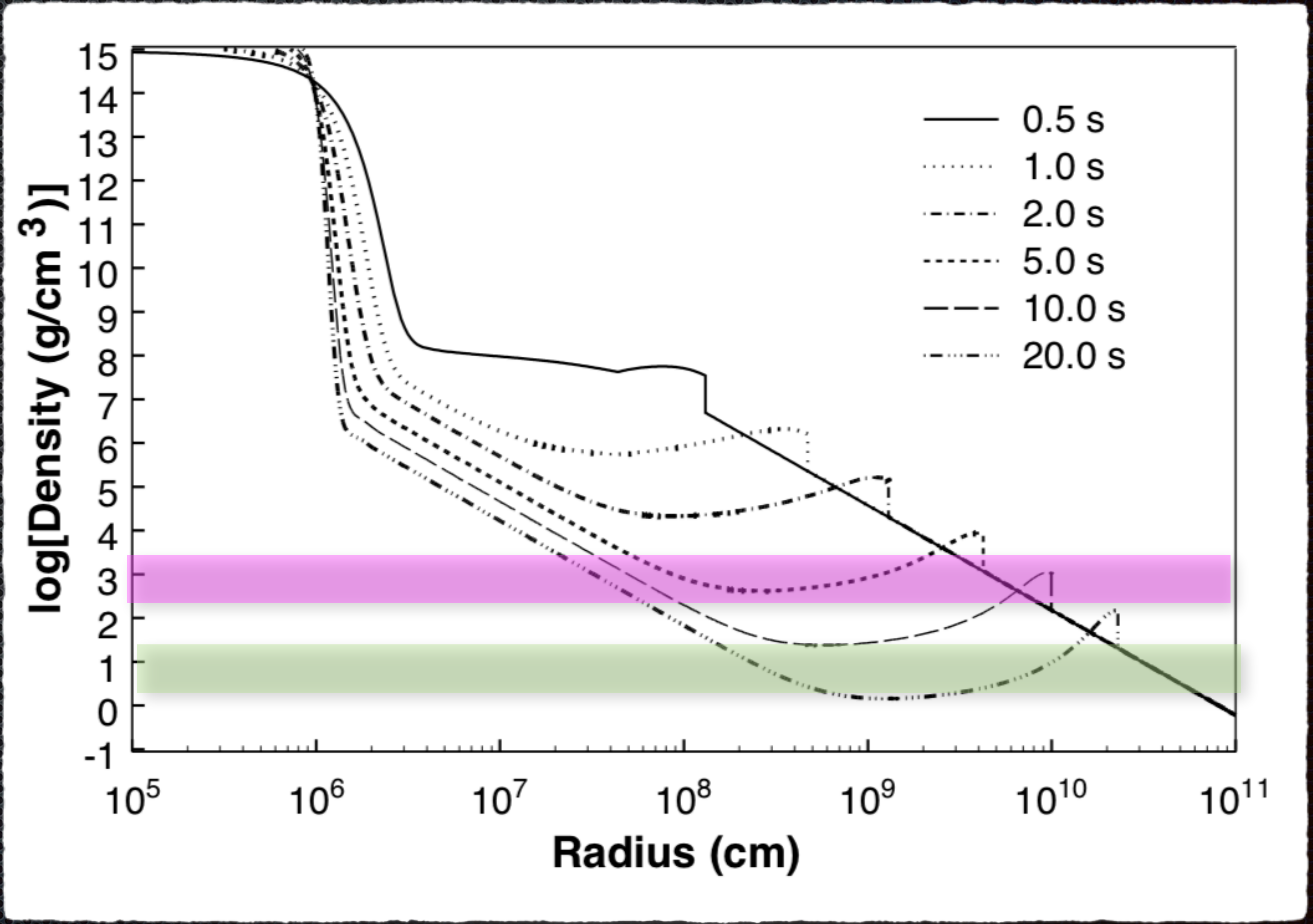


$$P_{jump} = \exp\left(-\frac{\pi\lambda_{shock}}{\lambda_{osc}}\sin^2 2\theta_{13}\right)$$

- Note: to be combined with collective later!

Density behind the shock

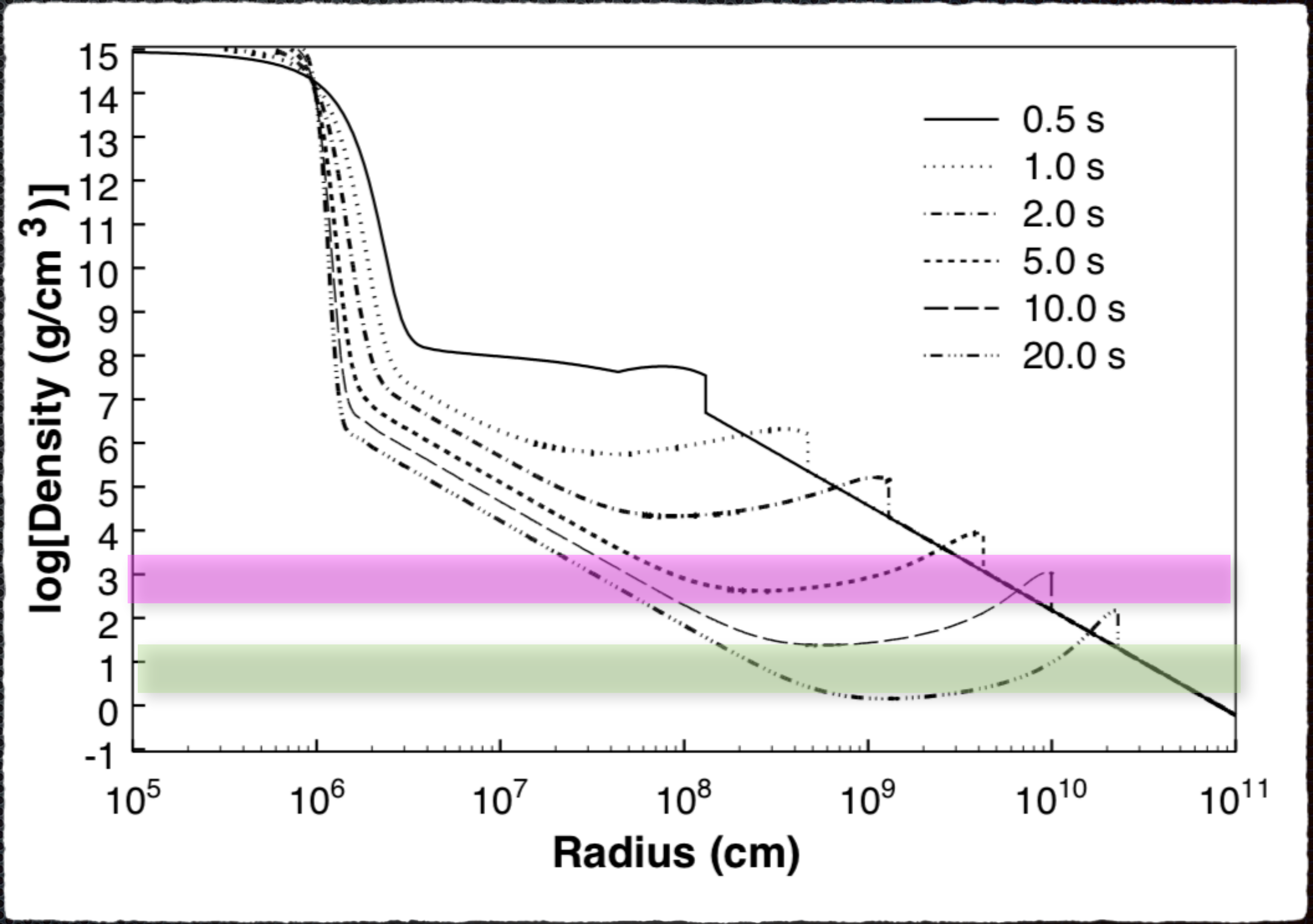
- So far, we focused on the front shock, but we should also ask what happens behind it
- The resonant density can be crossed multiple times there
- Why is there a rarefied region?
- Are the crossings in it adiabatic?



cf. Tomas et al, 2004

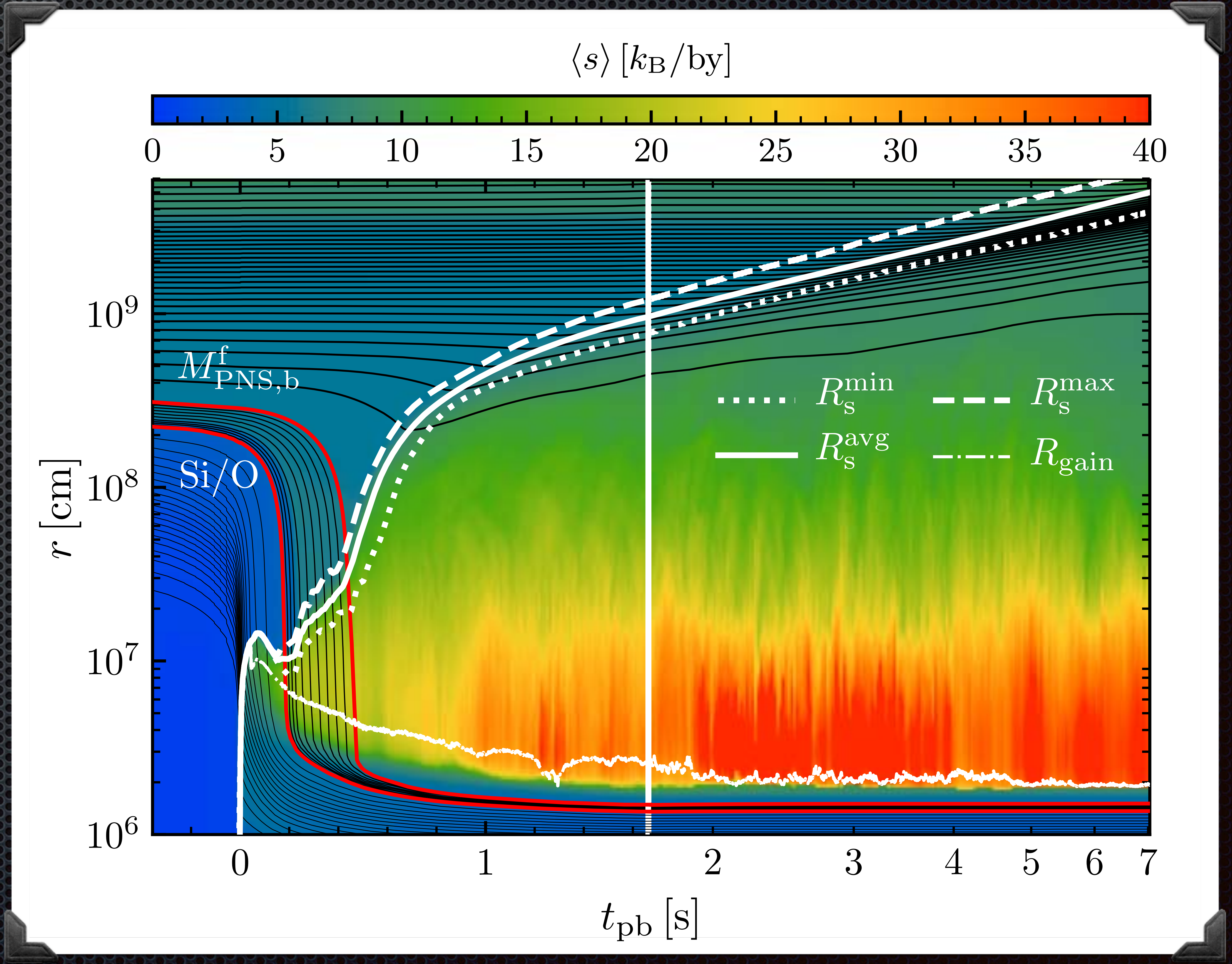
Hot bubble

- The low-density region around the PNS is called the "hot bubble" [H. Bethe]
- If neutrinos could probe density features in the hot bubble, it would be very much of interest!
- Especially important because *the hot bubble is a nucleosynthesis site!*



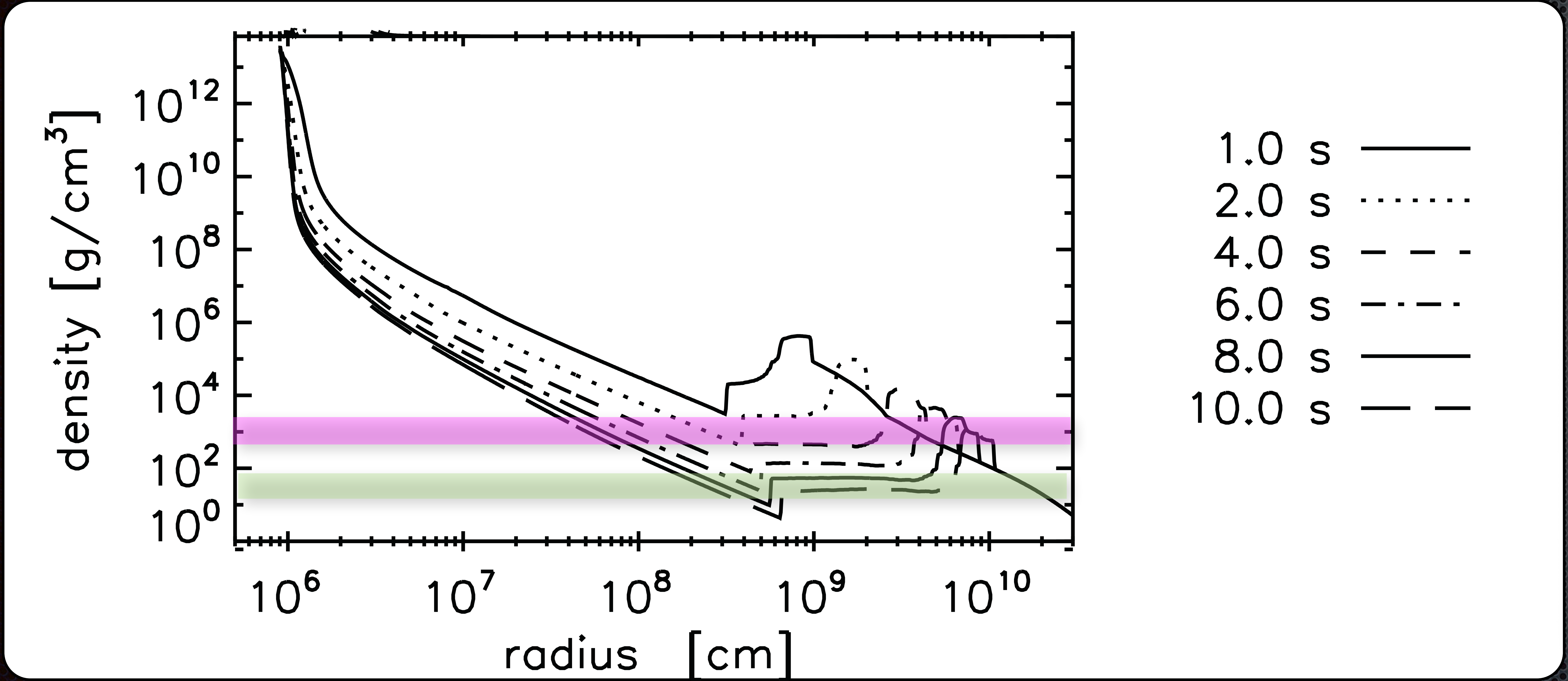
Why hot bubble?

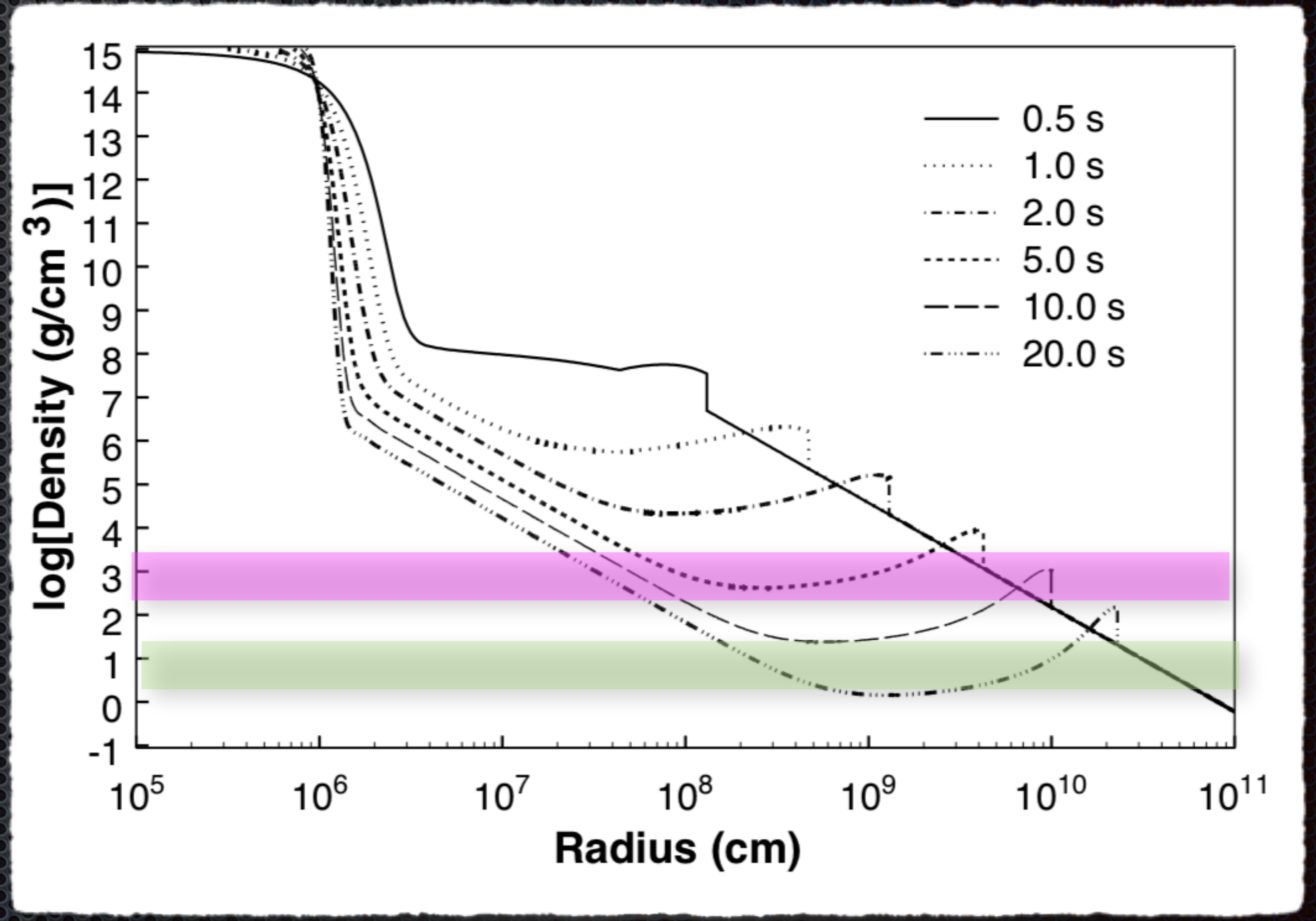
- Neutrino heating in the outer layers, $\sim G_F^2 T_\nu^6$, is not balanced by reemission, $\sim G_F^2 T^6$.
    - *Gain radius, essential for understanding the explosion mechanism*
- Energy deposited is removed by matter outflow
- To unbind a nucleon, $G_N m_N M_{PNS}/R_{PNS} \sim T^4/n_N$
- entropy per baryon, $S \sim T^3/n_N$
- $S \sim (m_N/T)(G_N M_{PNS}/R_{PNS}) \gtrsim 50$
    - Seconds after the explosion is launched



Bollig et al 2021

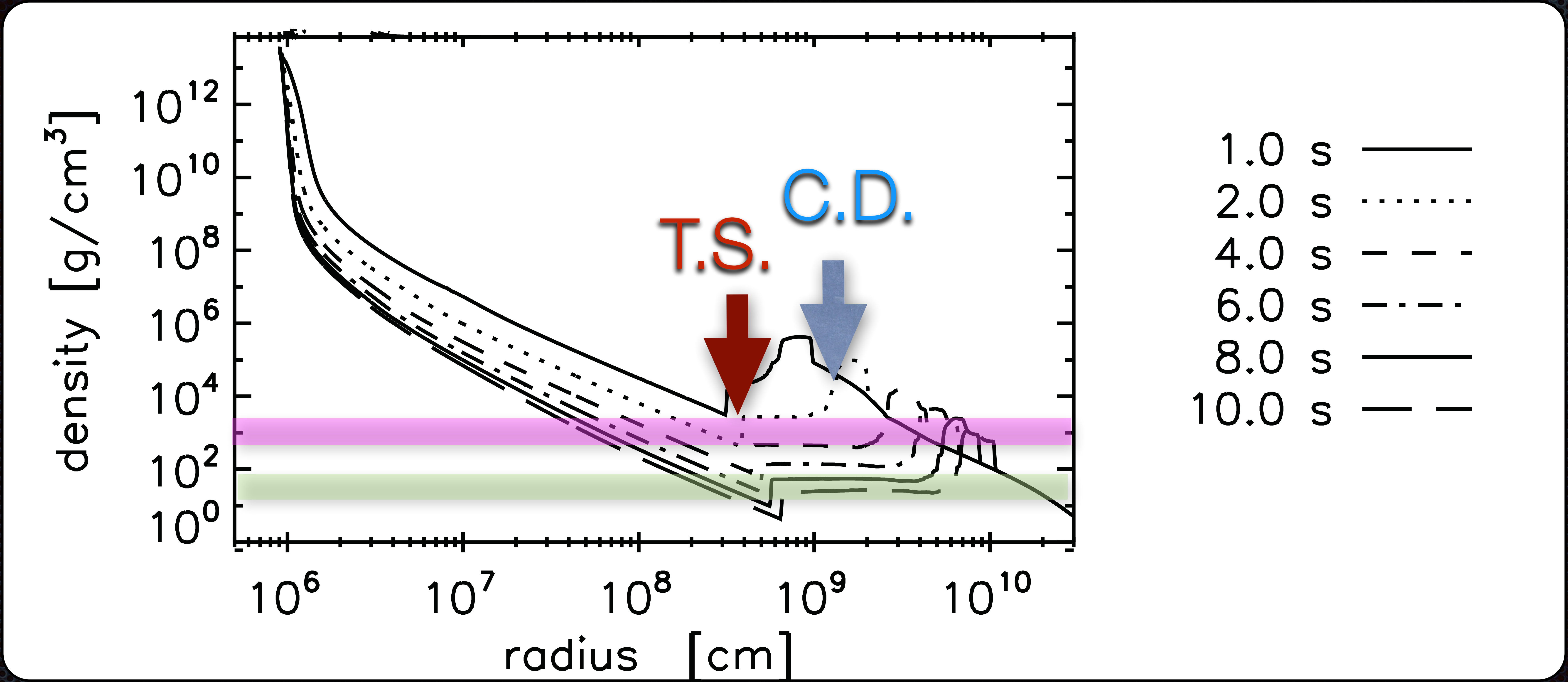
Densities features in the hot bubble





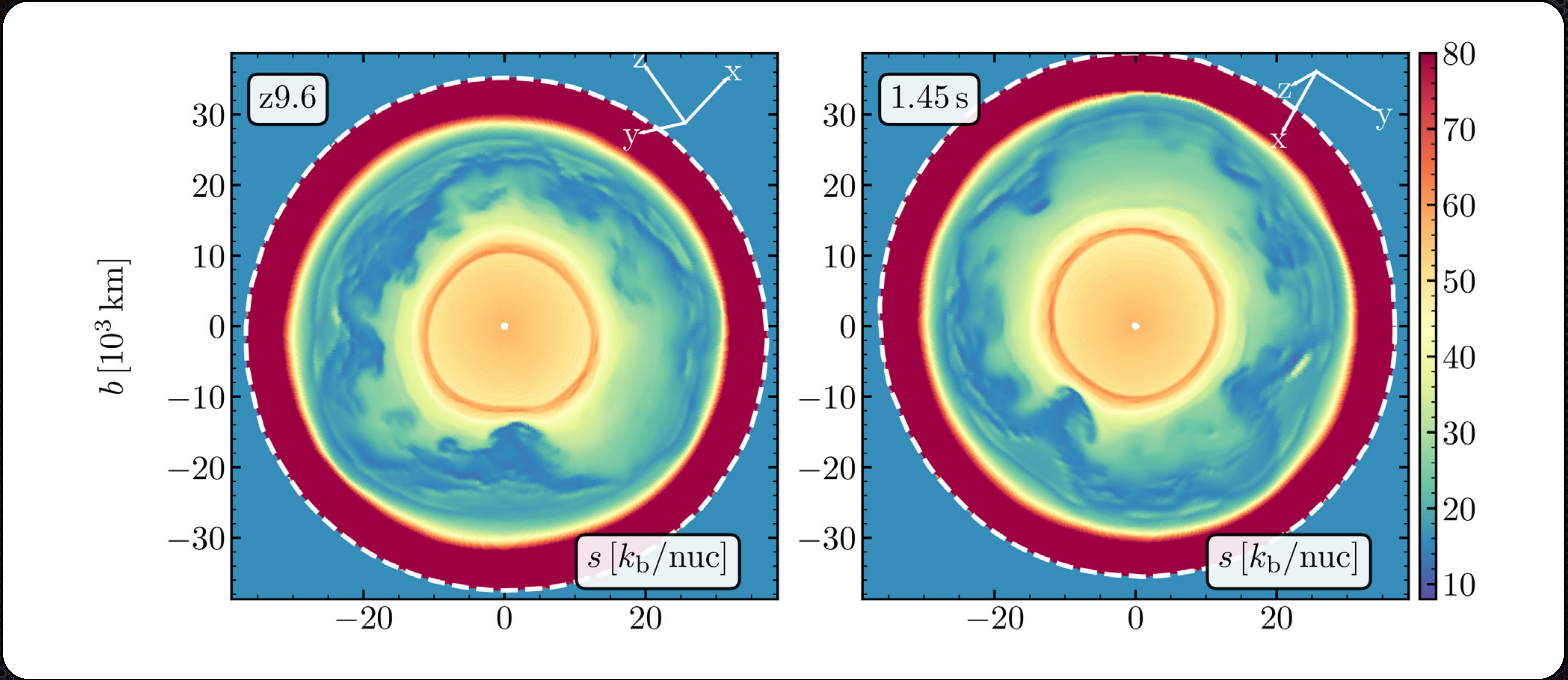
- The profiles of Wilson are pretty smooth in the hot bubble
- In contrast, in the simulation by Arcones et al, 2006, two new features:
  - contact discontinuity and wind termination shock

Densities features in the hot bubble



- Contact Discontinuity (C.D.): pressure matching between the inside and outside of the hot bubble requires T=const, $\rho_2/\rho_1 = S_1/S_2 \gtrsim 10$. It is unstable to convection and turbulent in multi-D.
- Wind termination shock (T.S.) arises when the outflow is accelerated to supersonic speeds and plows into the slowly expanding ejecta. Can be present in multi-D

Wind termination shock in 3D



- 3D simulation from Stockinger et al (2020)

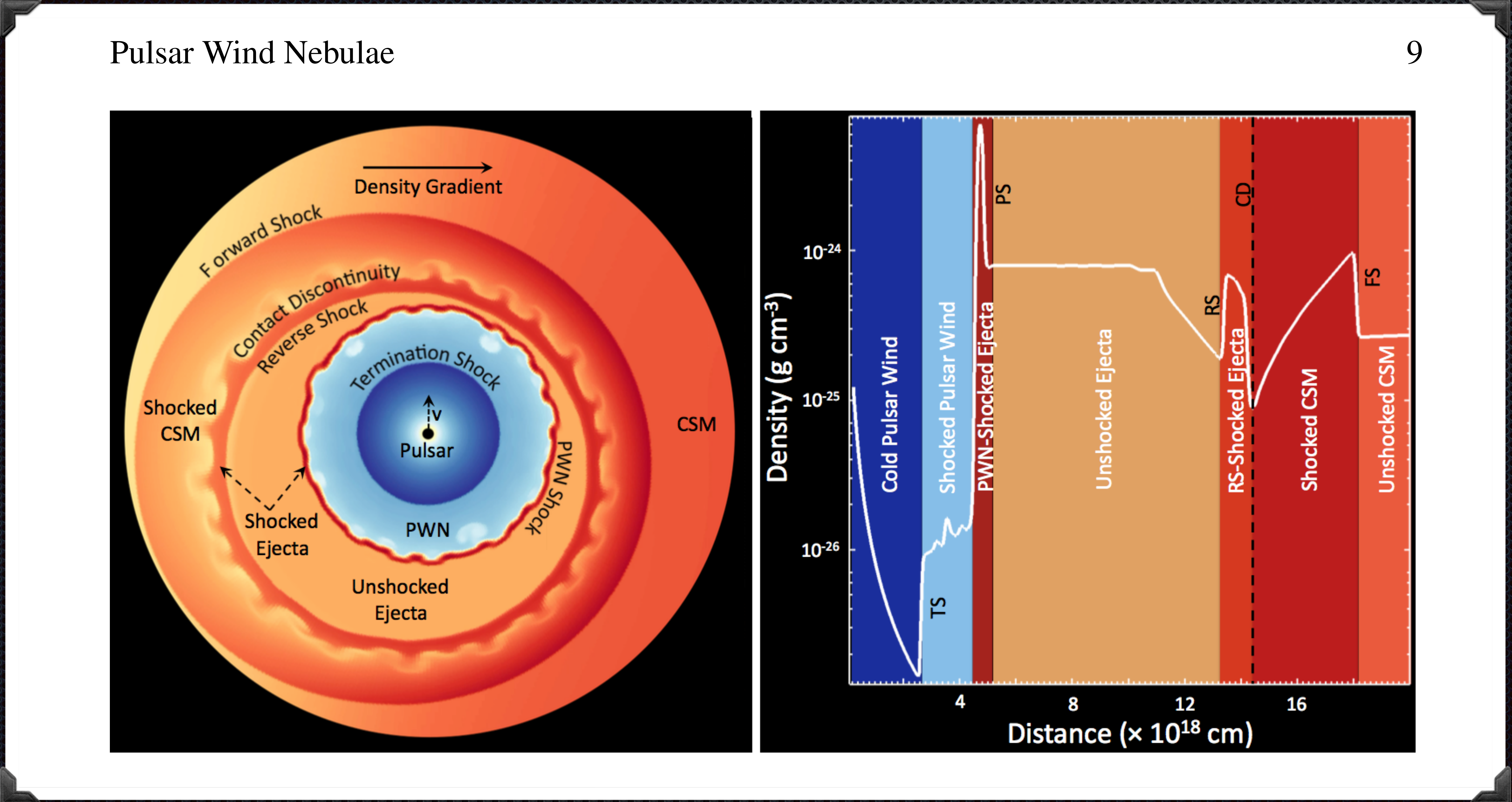
So are there wind termination shocks?

- In some simulations, yes, in others, no
- We already saw the examples of Wilson vs Arcones
- It gets worse. For example, Fischer et al 2009 has cases with intermittent shocks.
- Stockinger et al $9.6M_{\odot}$ 3D has a pronounced shock, but Bollig et al $19M_{\odot}$ does not.
- Who's right? Or is something very special going on?

Outflows in supernova are near-critical!

- Because of its importance to understanding the neutrino signal (and nucleosynthesis!), we have analyzed the physics of the outflow termination shock formation in detail.
- The results are fascinating: the conditions in a supernova are indeed special and the *system is on the edge of shock formation*.
- This is extremely unusual in astrophysical systems! For example, the solar wind is very supersonic and has a termination shock at 94 AU.

Another example: pulsar wind nebula



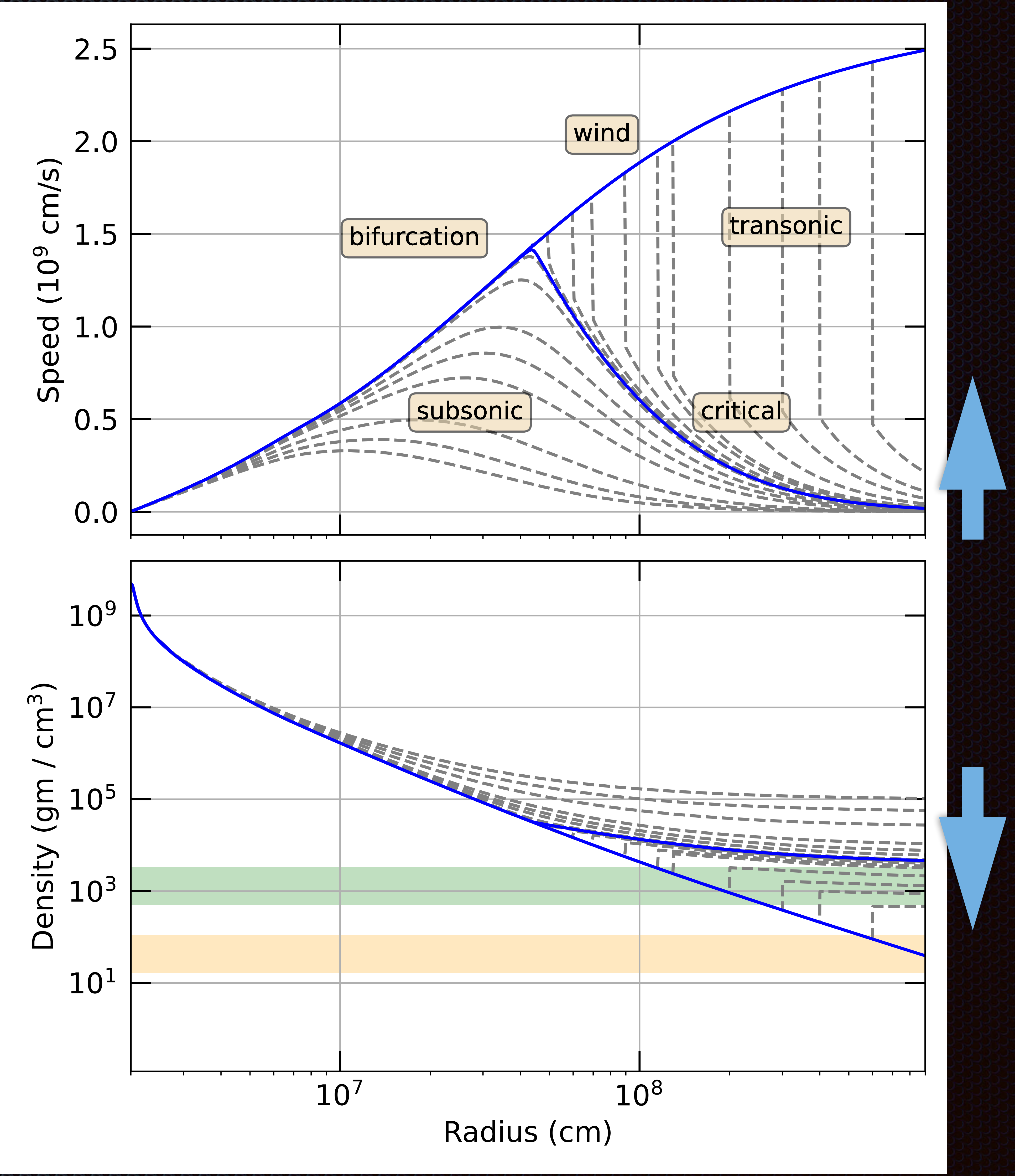
- arXiv: 1703.09311

Factorization assumption

- In all these systems, the problems of outflow acceleration and termination separate (factorize)
- This is typical for stellar winds. This influenced the seminal paper by Duncan, Shapiro, Wasserman (1986) on neutrino-driven outflows. Their method *presupposes* supersonic outflow.
- Literature also describes subsonic solutions, obtained with a completely different method.
- What is not discussed is how to determine whether the outflow is subsonic or supersonic. And this is what crucially matters for the neutrino signal and for the nu-p process.

Mathematics of the outflow problem

- Fixing the neutrino heating and the PNS gravity, one can look for solutions as a function of the far pressure P
- At high P, one can match the far pressure by “shooting" the initial velocity. This gives a family of smooth subsonic curves. Below a certain finite P, however, no solutions can be found with this method
- As P approaches this critical value, the velocity curve develop a kink
- As P is further reduced, the kink turns into a step: a termination shock. In this regime, one shoots the location of the termination shock.
- The two regimes meet at the kinky curve, which is *the critical flow*, separating the subsonic and transonic regimes. The corresponding P is critical confining pressure.



A.F., Mukhopadhyay, PLB (2022)

Nozzle flows

- A qualitatively similar phenomenon occurs in an entirely different physical system: a flow of a compressible gas through a nozzle
  - Different geometry, no gravity
- By regulating ambient pressure in the lab, can go from subsonic to transonic flows
- Of course, in the lab, conditions can be fine-tuned to be near-critical

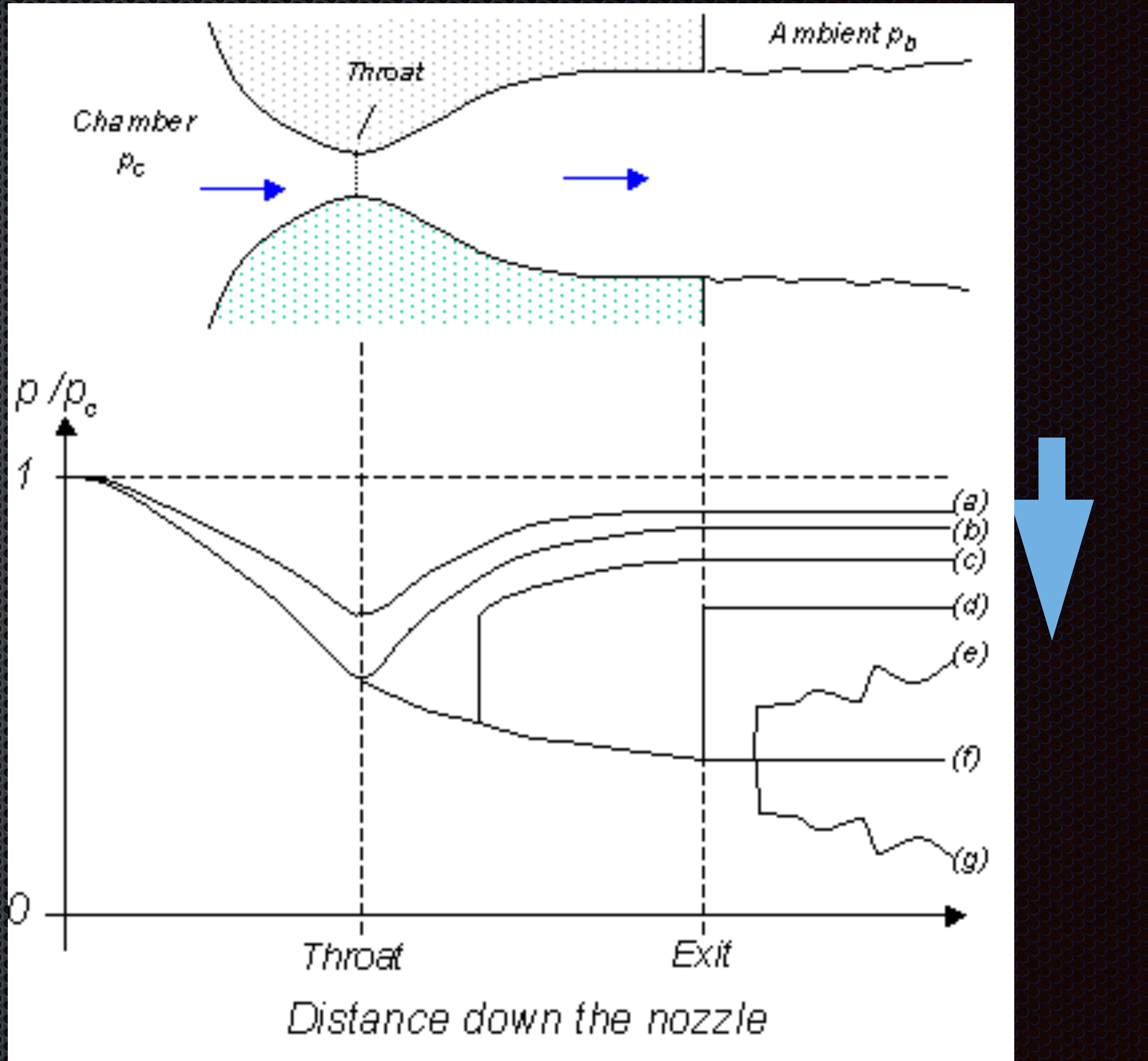
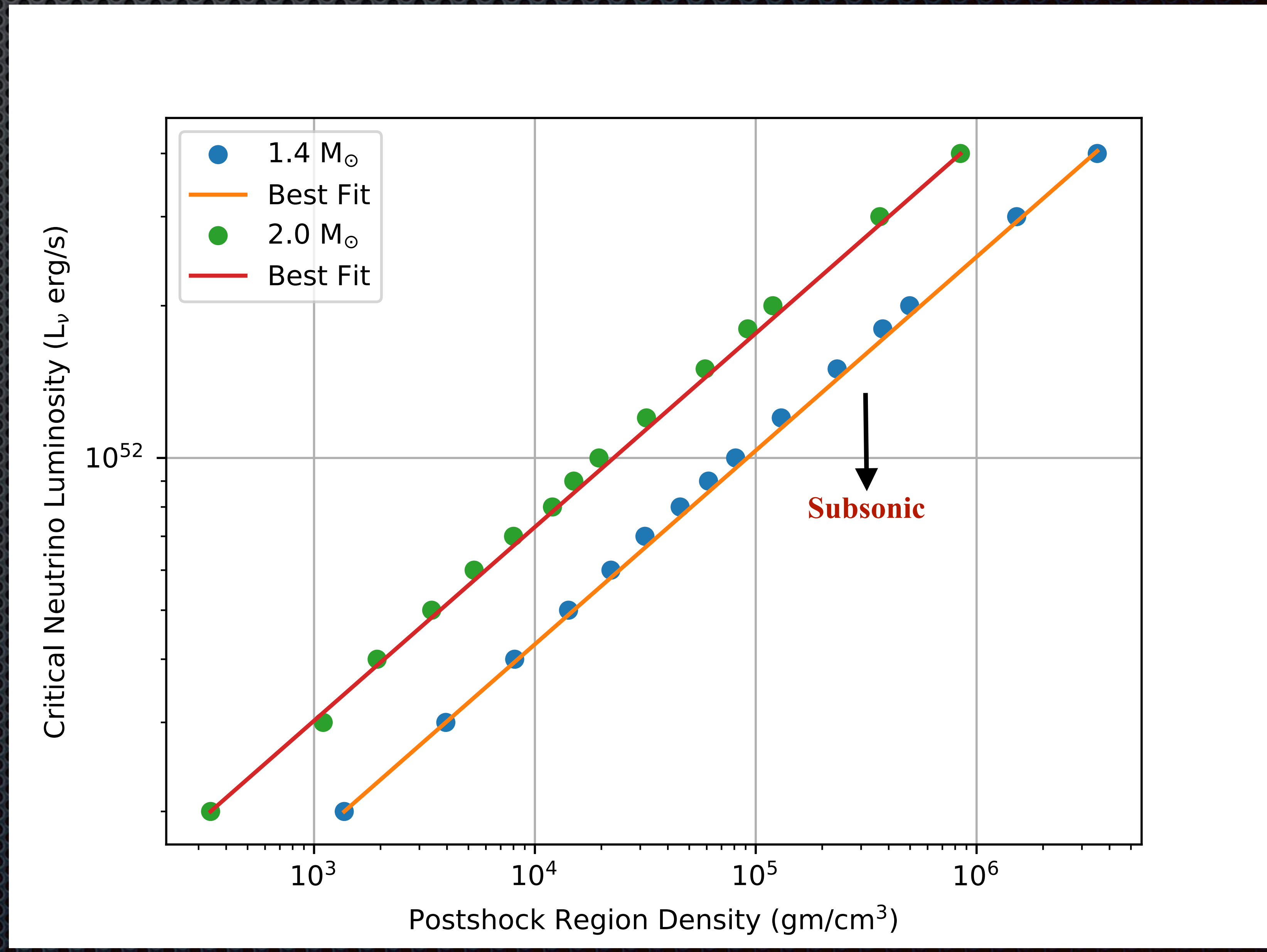


Figure 4 Pressure distribution along the nozzle. Labels refer to flow regimes in figure 3.

Condition for critical flow

- $T_{f,crit} \simeq (112\ \text{keV}) L_{52}^{0.702} E_{\nu 20}^{1.404} M_{1.4}^{-0.96} R_{20}^{0.08},$
- $\rho_{f,crit} \simeq (8.1 \times 10^3\ \text{g/cm}^3) L_{52}^{2.61} E_{\nu 20}^{5.2} M_{1.4}^{-4.0} R_{20}^{1.03}$
- Allow us to relate the existence of the termination shock to the fundamental parameters of the problem: $M_{plowed}(R)$, neutrino L and E, and PNS M and R
    - In particular, you may infer the mass of the PNS
- Can be understood analytically



* the scaling laws obtained here include the actual variation of $g_\star$ with T

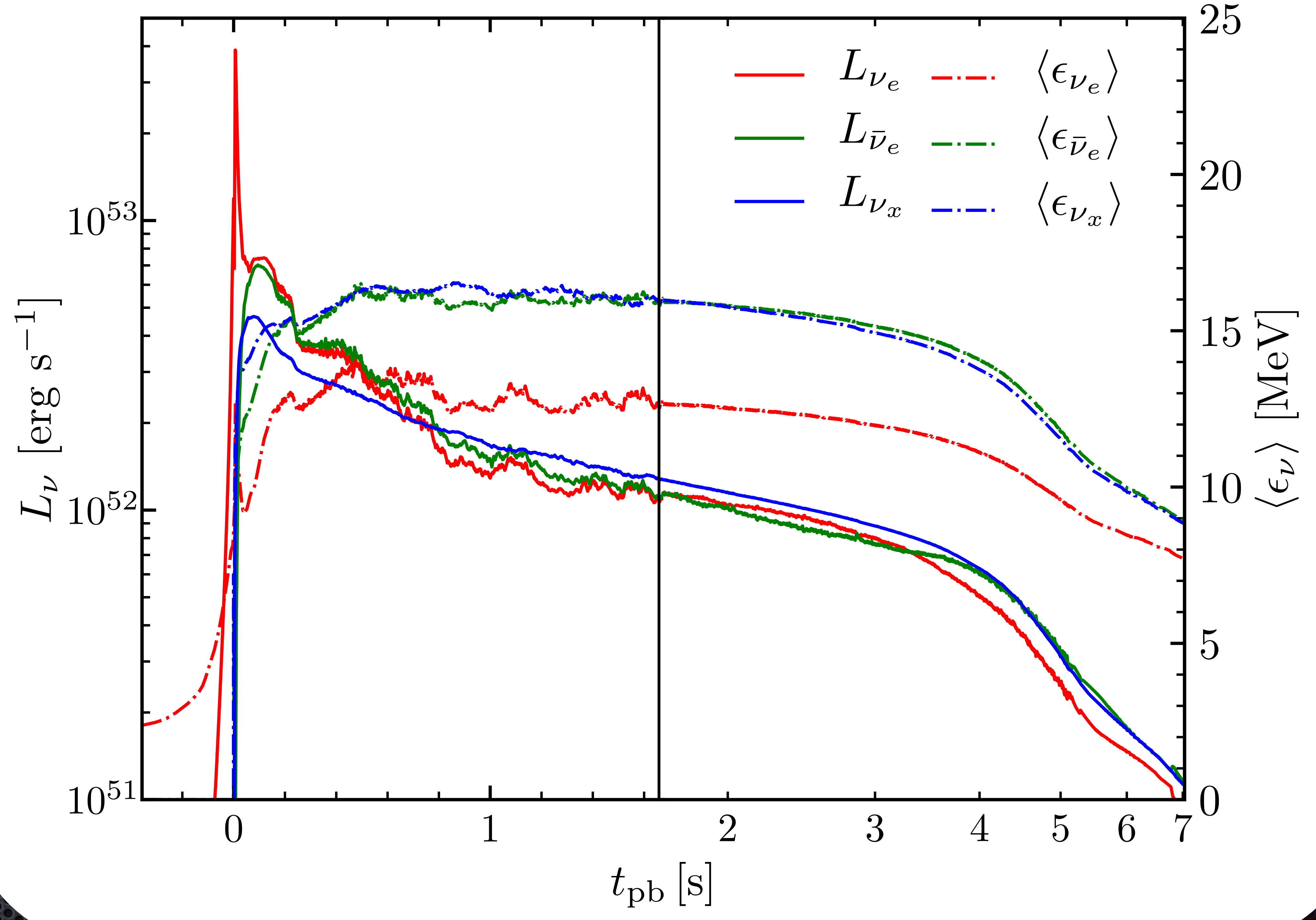
Reconciling simulations in the literature

- These allow us to reconcile published simulations, make predictions for future simulations
- For example, with luminosities and PNS parameters of Fischer et al 2009, termination shock formation is expected for progenitors of $\lesssim 12 M_\odot$.

What are the signatures at DUNE?

Why DUNE?

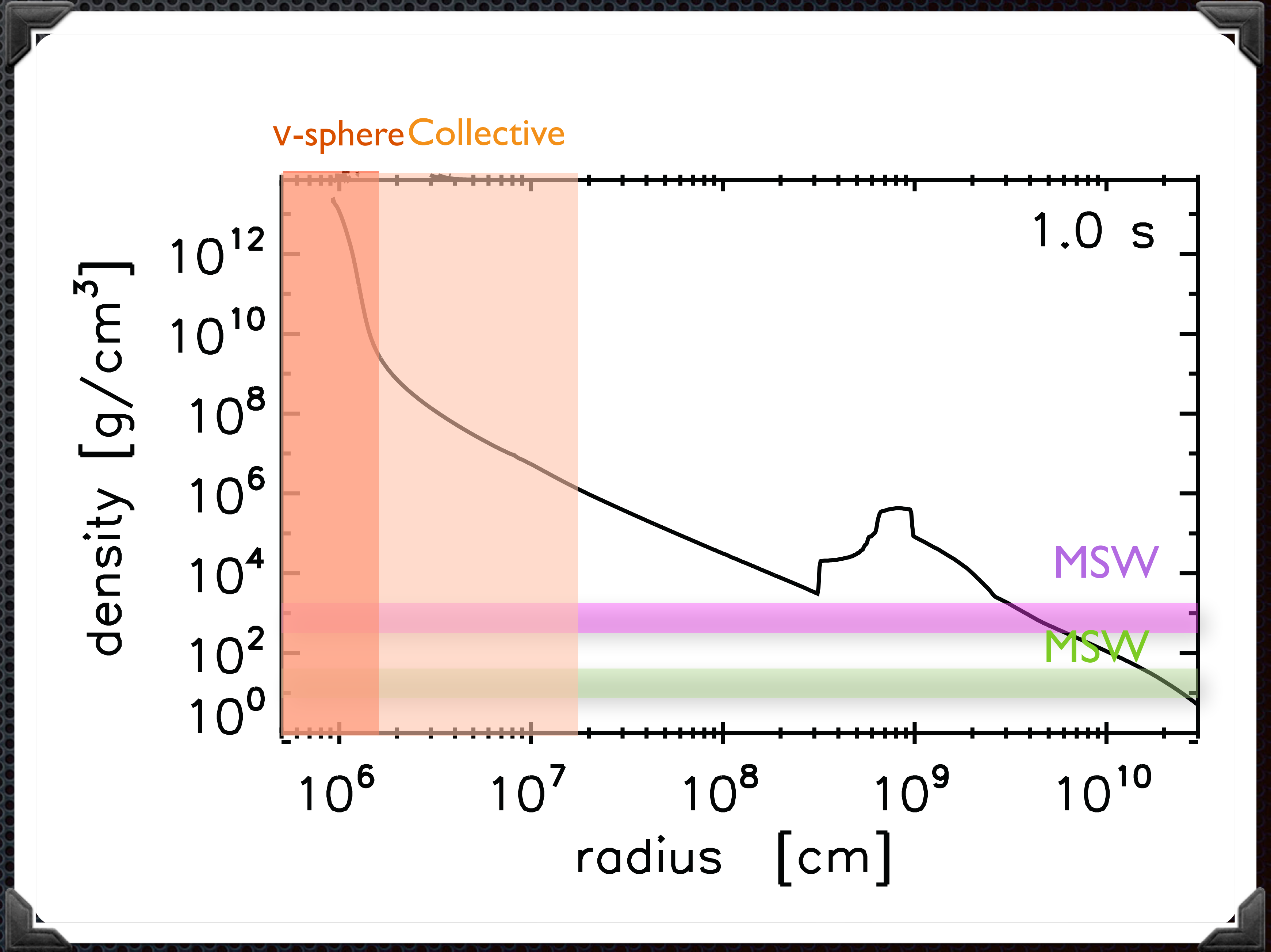
- It is often stated that at several seconds, the spectra of all neutrinos converge. Then oscillations don't leave a visible imprint.
- Here are actual results from modern simulations [Bollig et al 2021]
  - The antineutrinos are indeed close. But ν_e are sufficiently different from ν_x. -> Oscillation effects in the neutrino channel could be observable.
- ν_e's are the specialty of DUNE. Hence, it's interesting what signals of this physics one might expect in DUNE

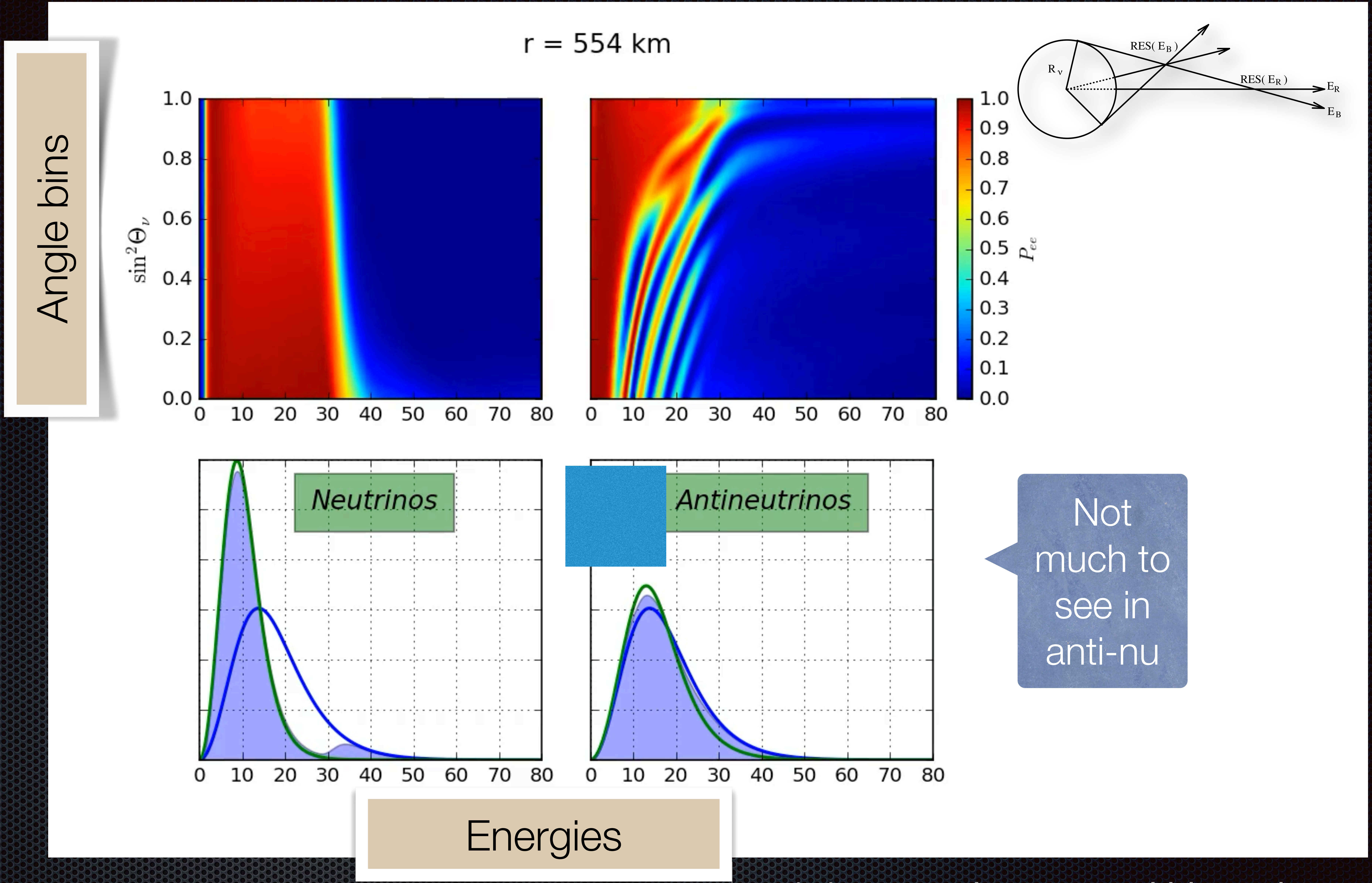


$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

Collective oscillations

- These are very complicated and are not yet fully understood. (See talks yesterday!) Need to decide how to include them.
- We adopt an approach that allows us to *illustrate* an important physical behavior which comes from combining time-modulated MSW and collective.
- Consider multiangle, spherically symmetric calculations. We compute it using well-understood numerical techniques.

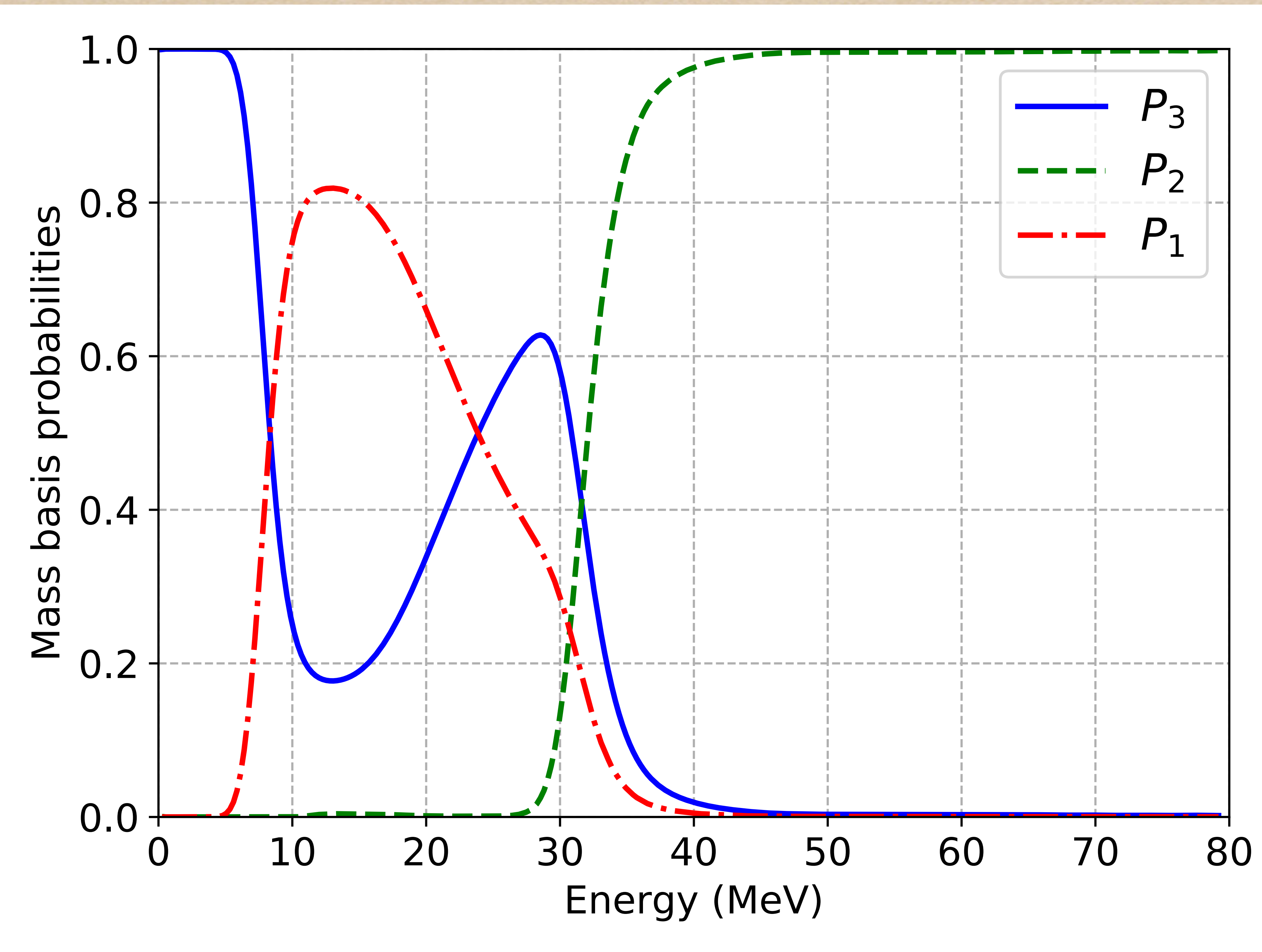




Radial development of collective oscillations

t=1.4 s snapshot, normal hierarchy
Multiangle, spherical symmetry

A snapshot of Collective Oscillations



$P_1 : P(\nu_e \rightarrow \nu_1)$

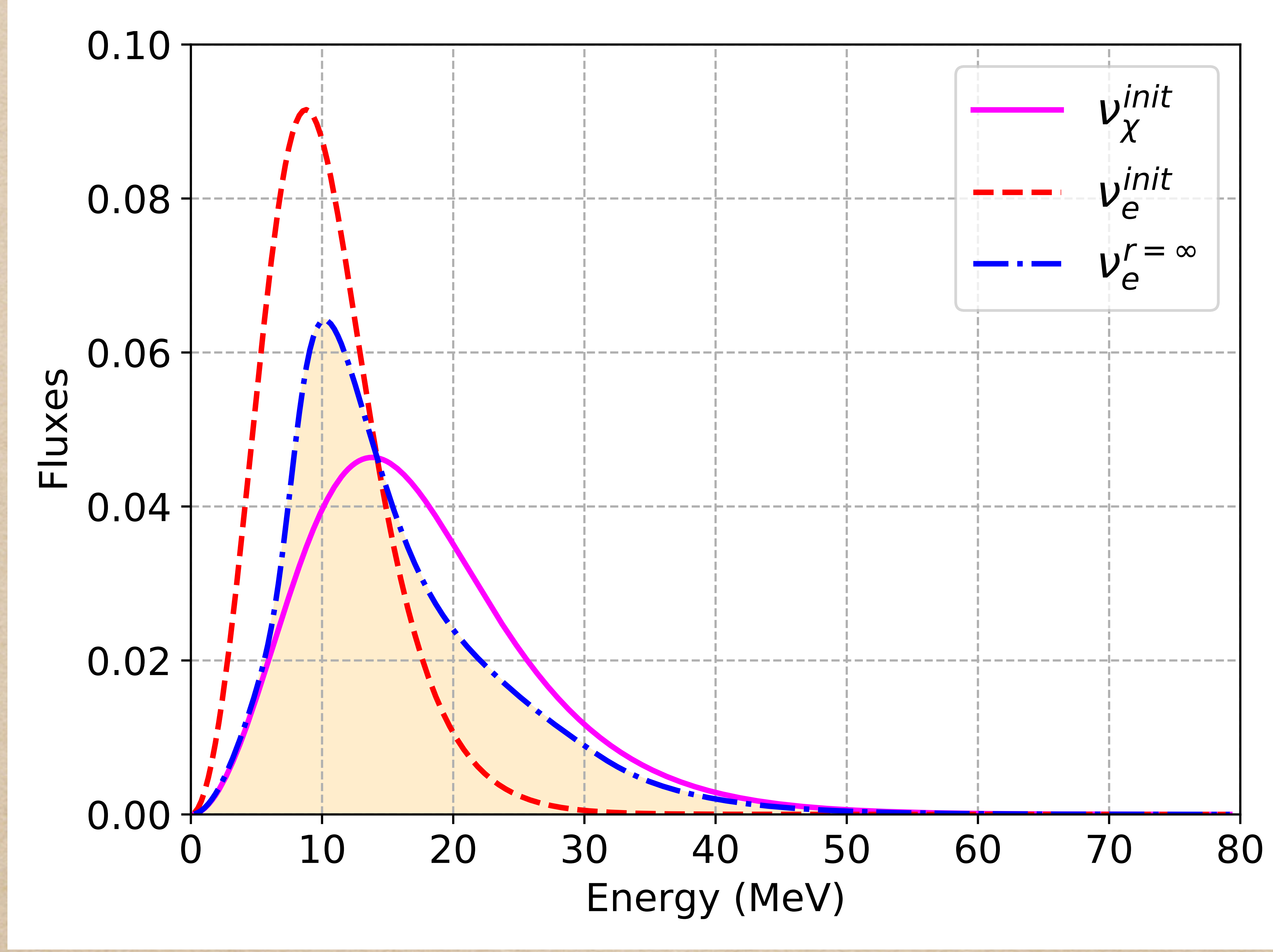
$P_2 : P(\nu_e \rightarrow \nu_2)$

$P_3 : P(\nu_e \rightarrow \nu_3)$

$$F_{\nu_e}^{vac} \approx F_{\nu_\chi}^{init} + (F_{\nu_e}^{init} - F_{\nu_\chi}^{init})\ (0.68\ P_1 + 0.29\ P_2 + 0.02\ P_3)$$

Clear spectral splits in the mass basis

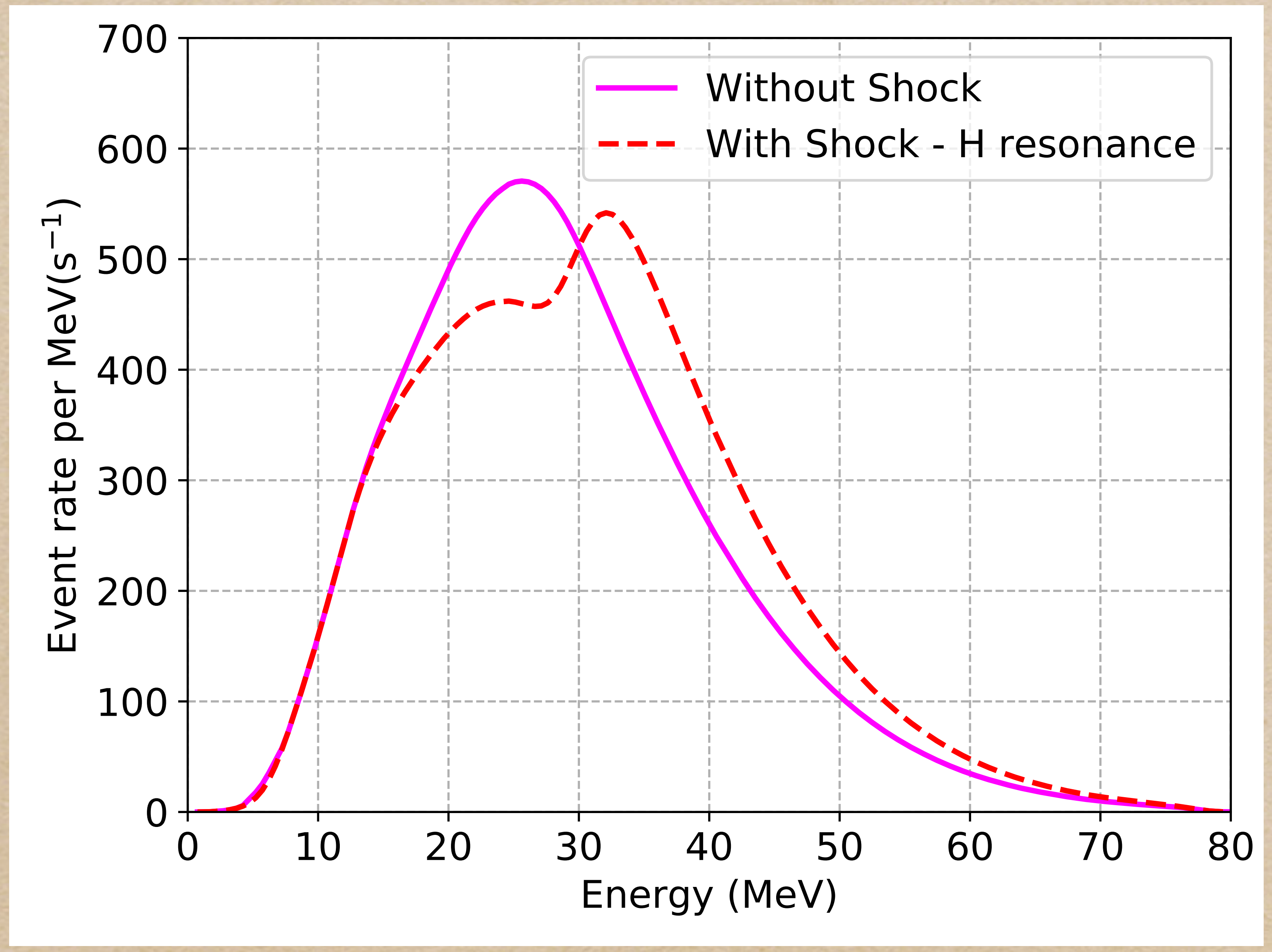
Neutrino flavor fluxes after collective oscillations

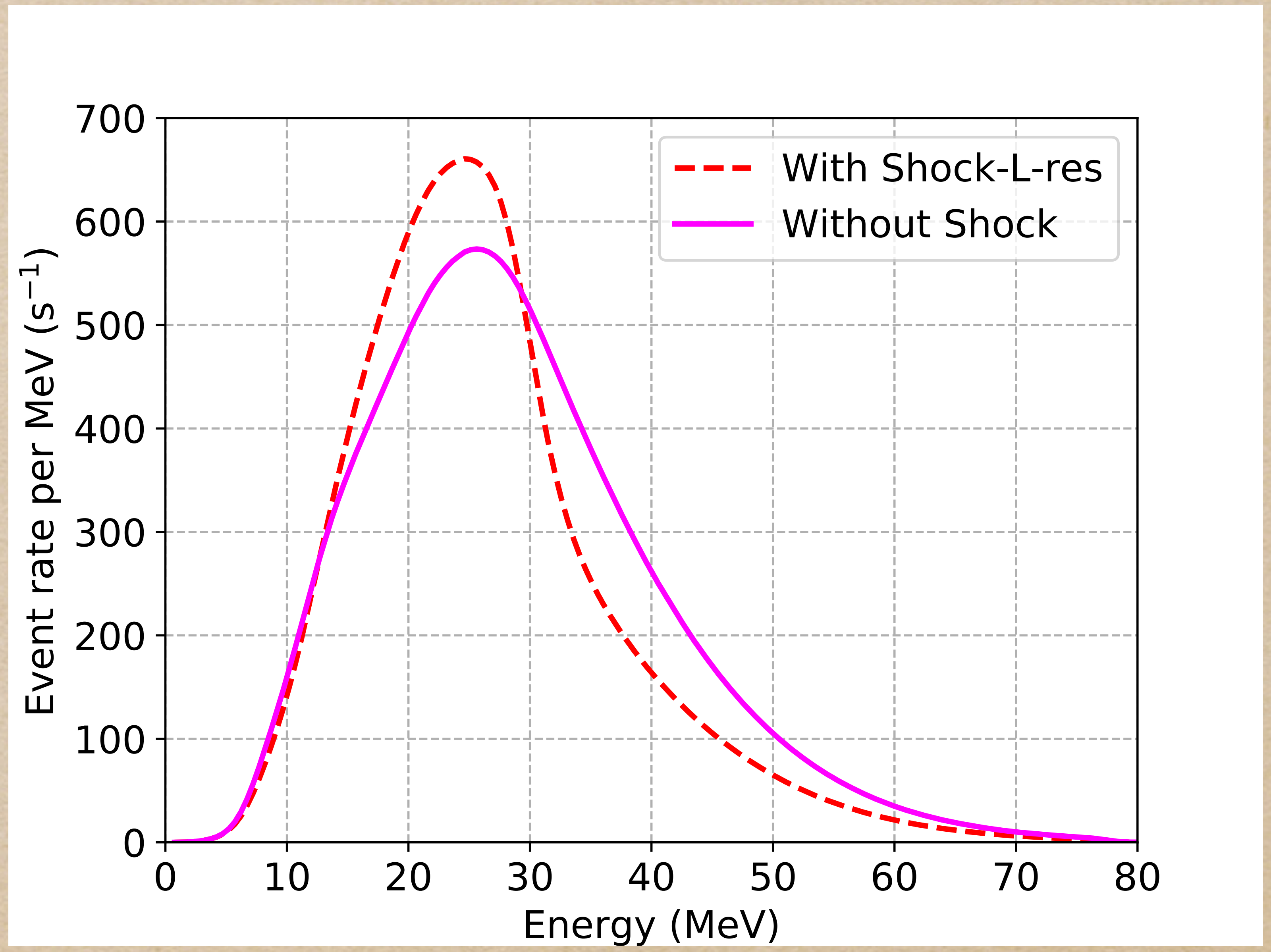


No obvious sign of a spectral split in flavor fluxes

Note that there are no shocks in the picture yet.

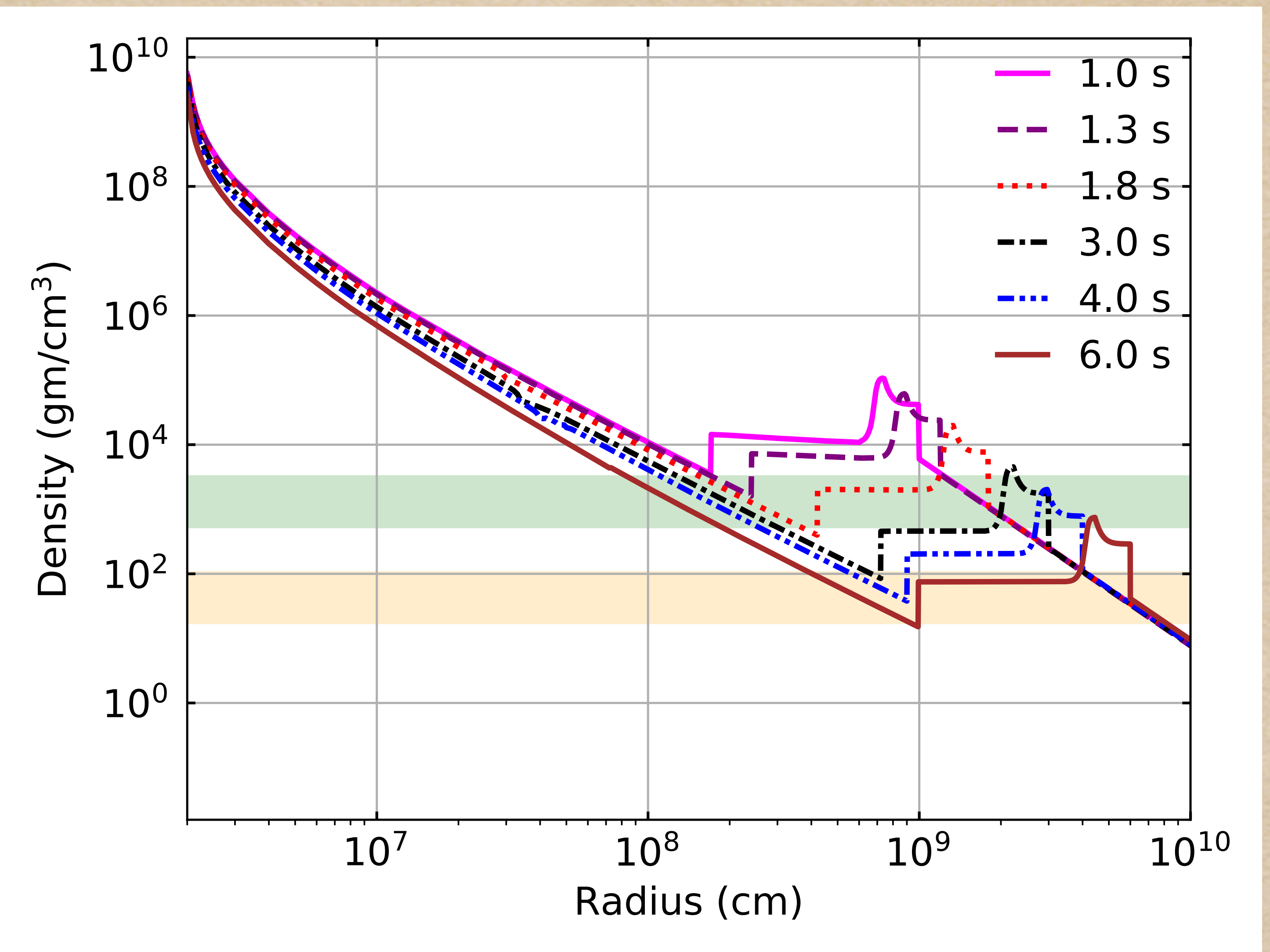
Impact of shock passage through H- and L- layer on detected events In DUNE (40 kt)



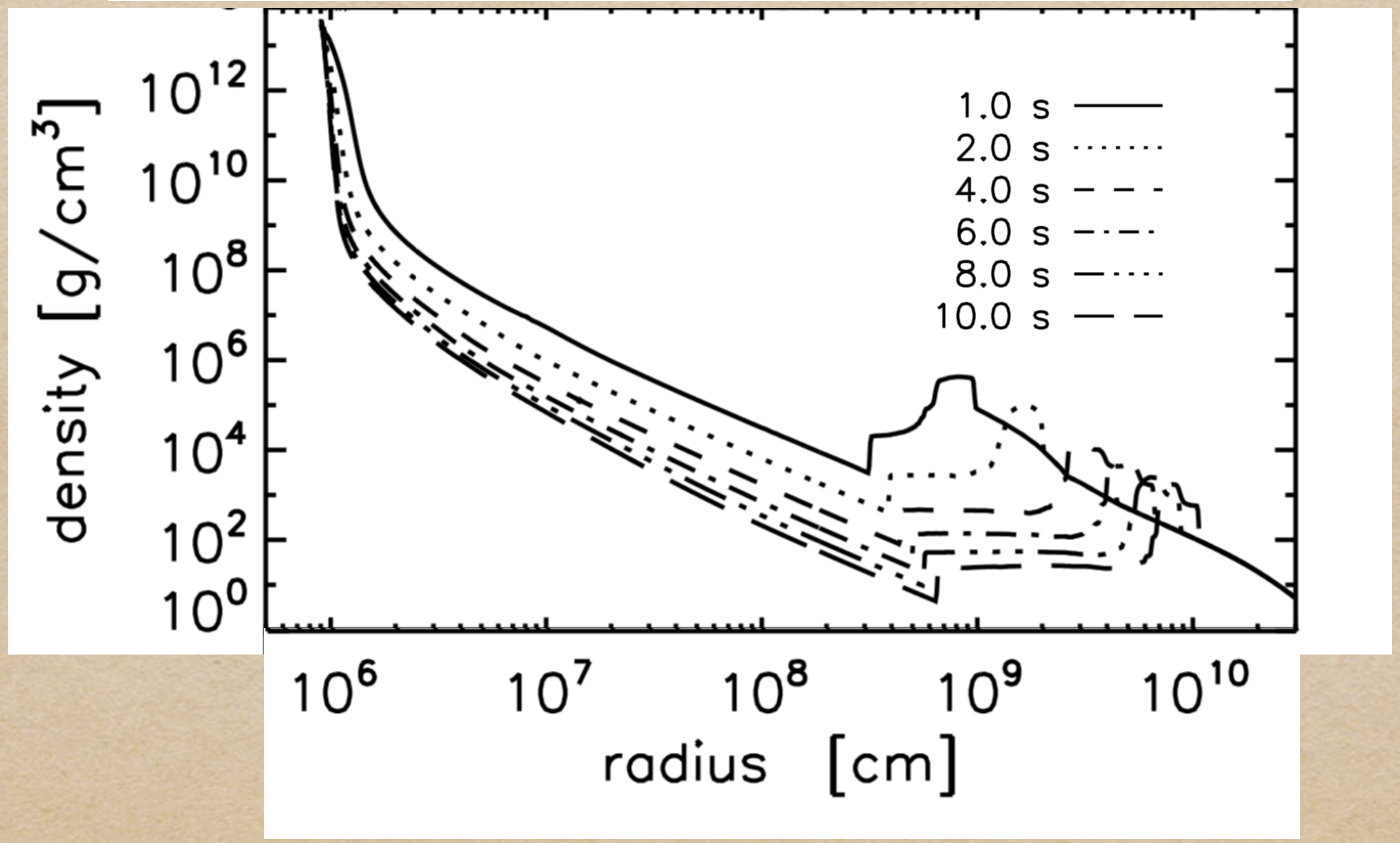


Shocks reveal hidden splits

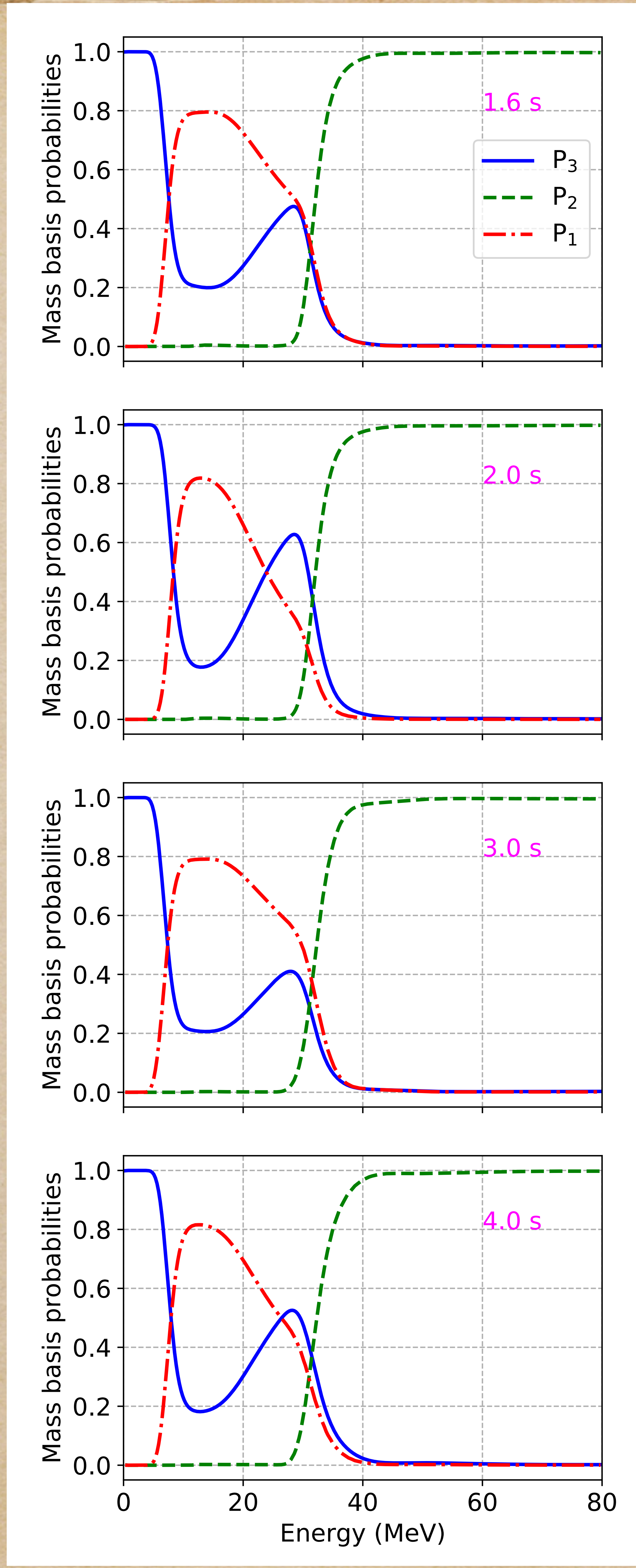
Case study : ~ 10 $M_{\odot}$ progenitor with high luminosities



Our model



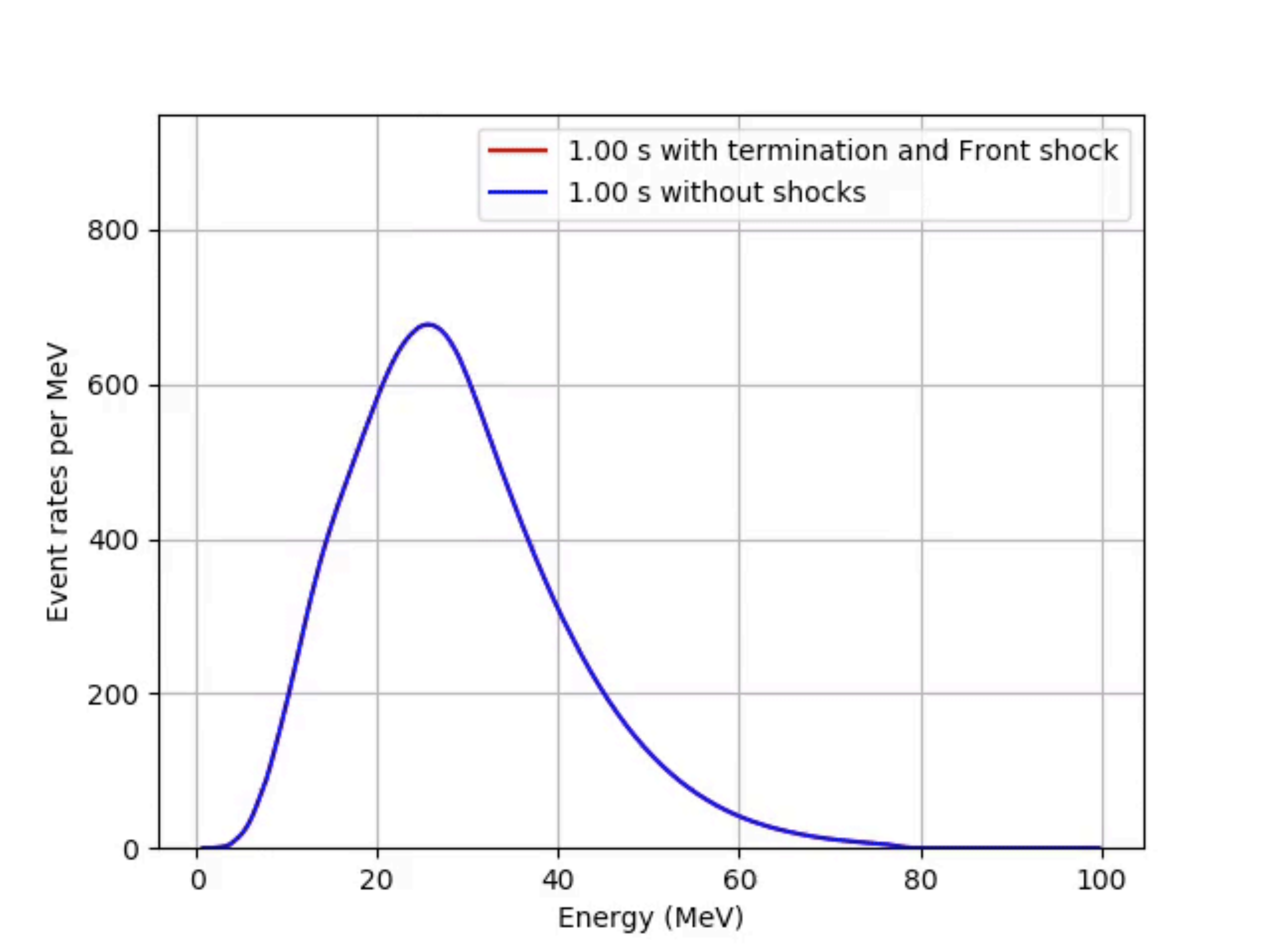
Arcones et al (2006)



Collective oscillations at different times

Evolving density profile and
and luminosities make the
collective oscillation pattern vary slightly.
Overall, the pattern
is quite stable

Signal as a function of time



Signals can appear as early as 1.3 sec !

And continues throughout the burst duration !

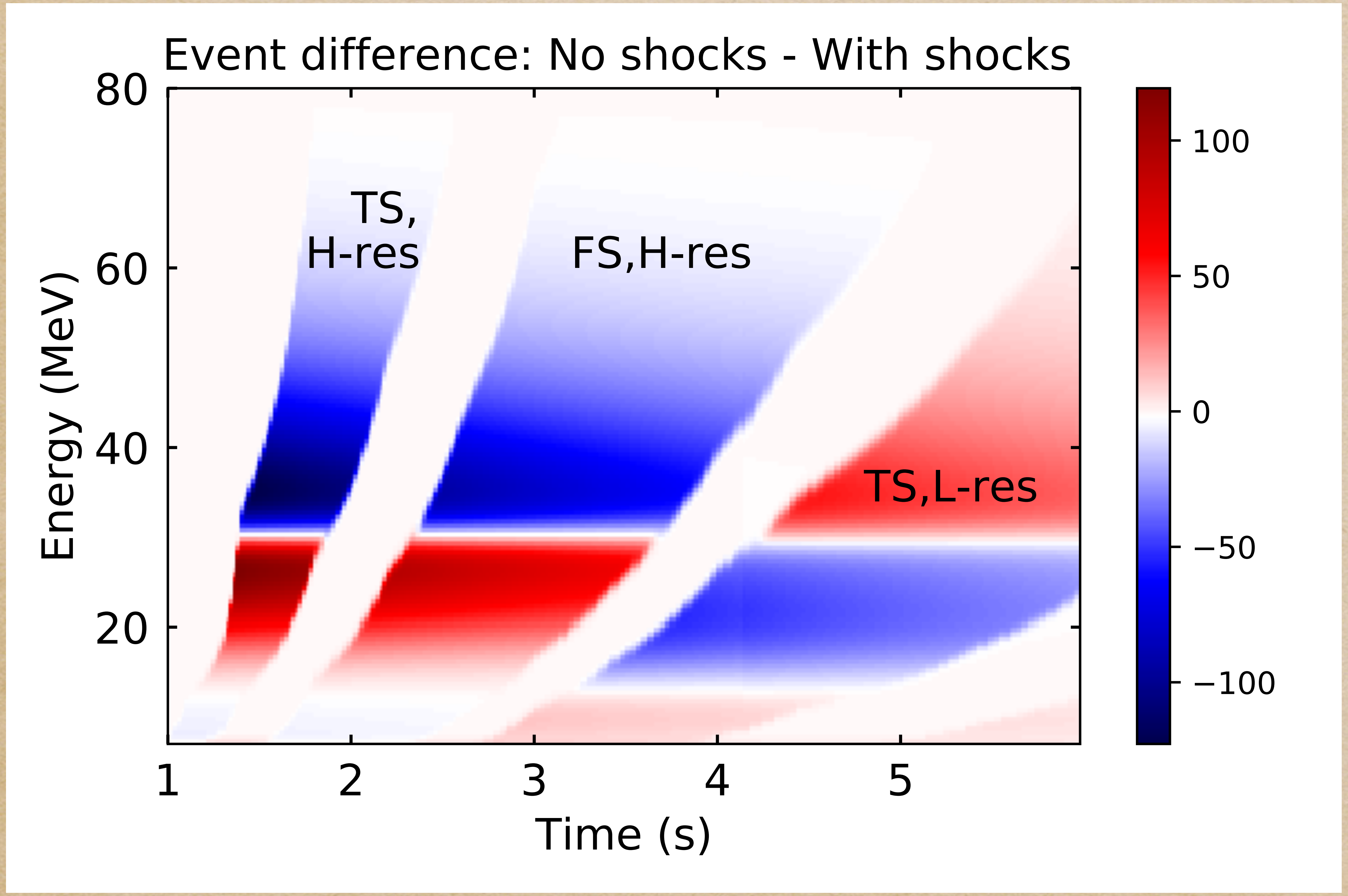
Spectacular non thermal features

Why do features roll across the spectrum?

- Flavor transformation condition: $\sqrt{2} G_F n_e^{res} \sim \frac{\Delta m^2}{2E_\nu}$
- Resonant density depends inversely on neutrino energy
  - the passage of the shock from high to low densities results in a feature moving across the neutrino spectrum from low to high energies
- A smoking-gun signature of this phenomenon

Energy-Time Binning

Idea : modulation has characteristic time-energy correlations.



Can be detected at DUNE
from anywhere
in the Galaxy
with good energy resolution

A.F., Mukhopadhyay, PLB (2022)

Conclusions

- Neutrino-driven outflows in a supernova possess a special property of near-criticality
- Near-criticality makes neutrino signatures of termination shocks a powerful diagnostic of the physical conditions in the hot bubble
- Combining modulated MSW effects and collective oscillations could reveal spectral split features that otherwise may stay hidden
- A quarter of molybdenum in the solar system comes in the form of two neutron-poor isotopes, 92Mo and 94Mo. This fact is very hard to explain. We proved that our subsonic profiles can solve this mystery -> See Amol's talk!
- Our study points out a possibility to connect neutrino observations and optimal nucleosynthesis conditions