Supernova Physics

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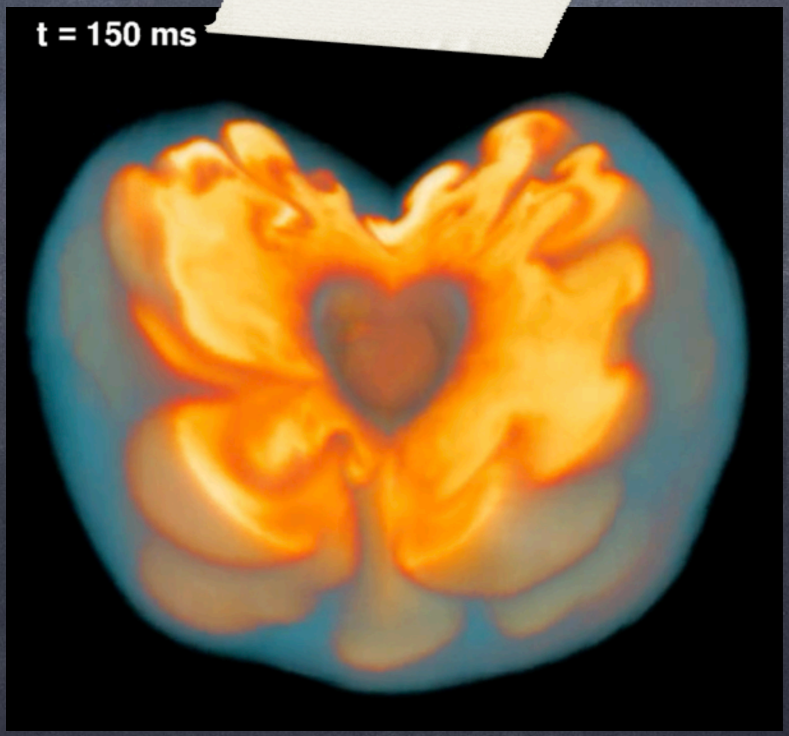
More specifically

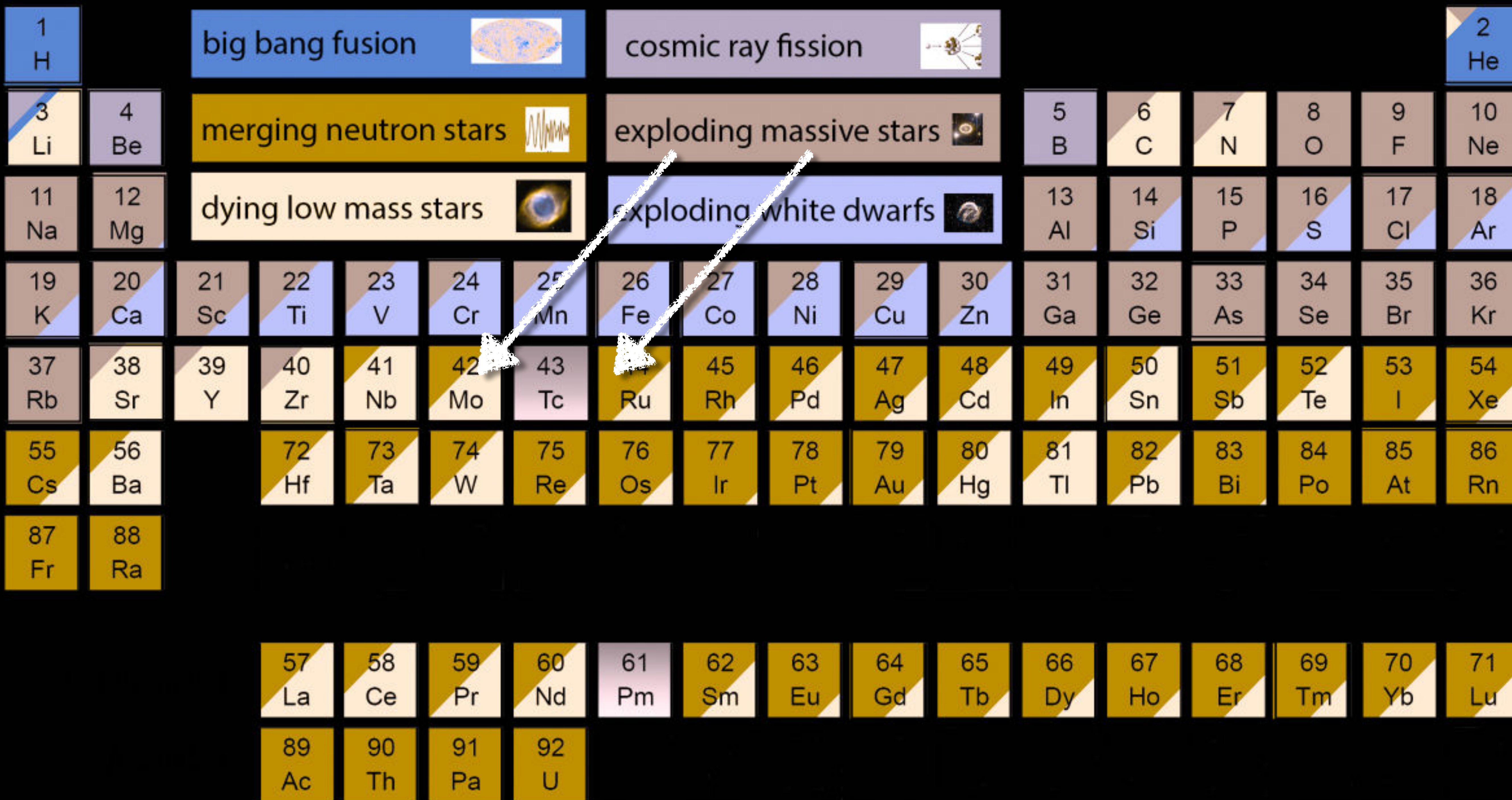
Looking inside a core-collapse supernova at DUNE: are conditions right for $\nu p-$nucleosynthesis?



Why all the interest?

- Core-collapse supernovae are some of the most important players in our universe
  - Create and spread many key elements
  - Seed formation of new stars
  - Make galaxies look like they do
- They are also unique laboratories for particle and nuclear physics, since conditions in a SN core cannot be reproduced in the lab

The Origin of the Solar System Elements



Life of a massive star

- Gravitational contraction paused by nuclear burning

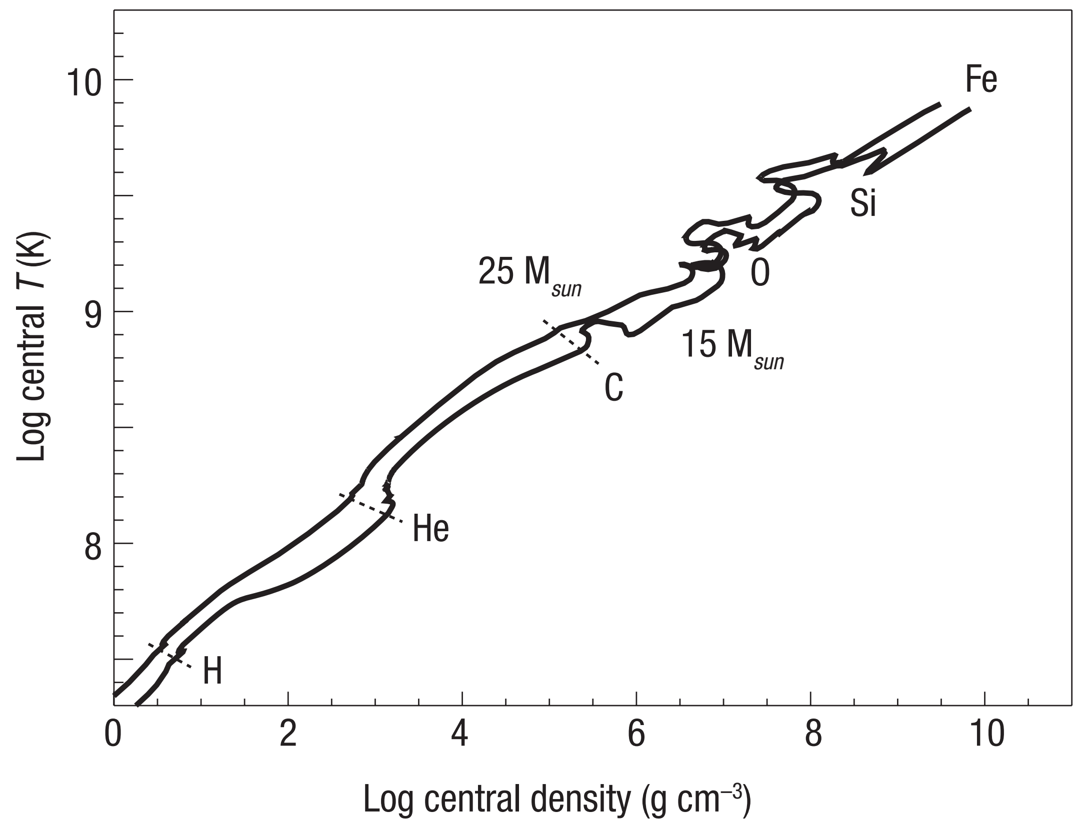


Table 1 Evolution of a 15-solar-mass star.

Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, ...	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse*	$\sim$1 s	Fe, Ni, Cr, Ti, ...	Neutron star	>7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

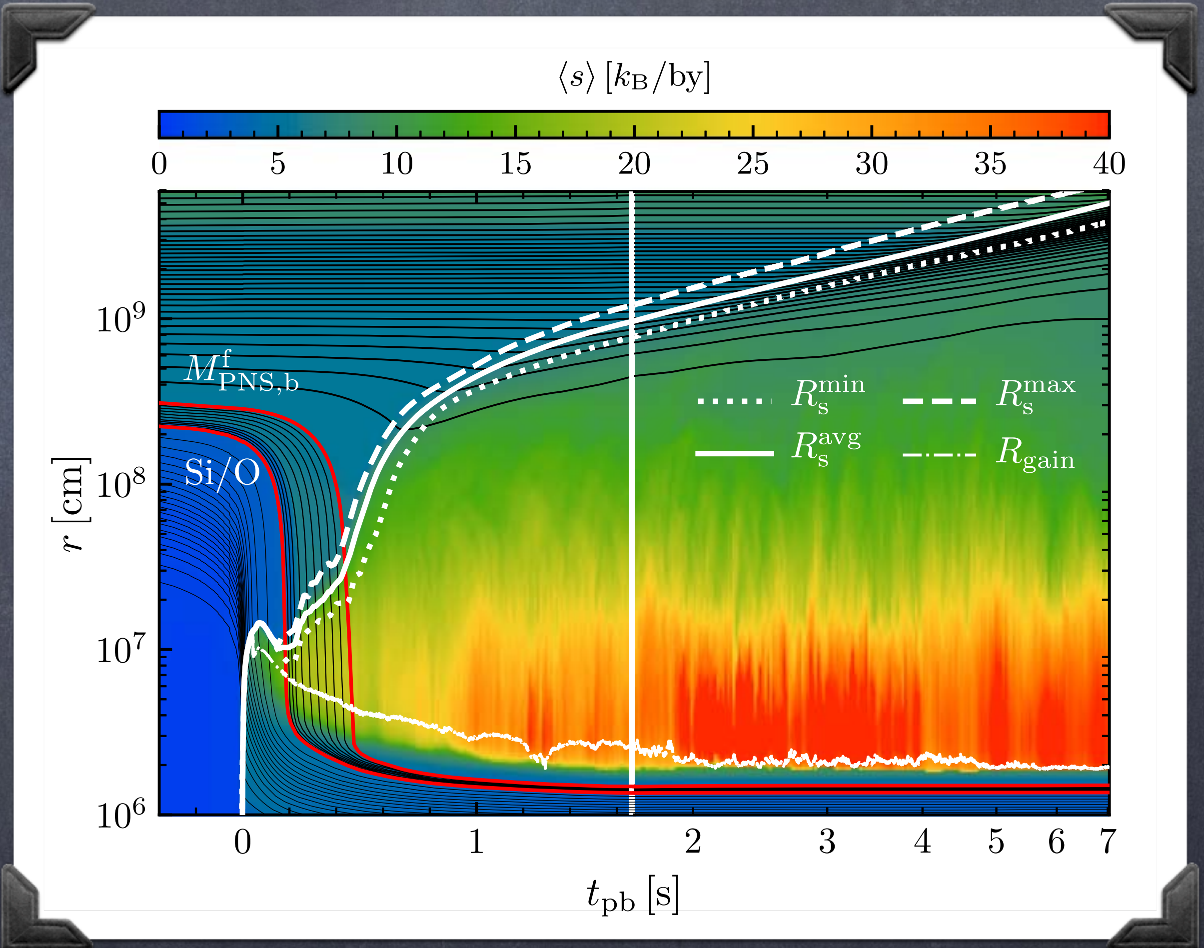
* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.

The last stage is especially dramatic

- As the Fe core mass reaches a critical value, degenerate electrons become relativistic -> unstable to collapse (Chandrasekhar).
- In natural units,
  - $M_{Ch} \sim M_{Pl}^3/M_N^2 \sim M_\odot$ (!!)
  - An accurate calculation keeping all coefficients yields $\sim 1.4\ M_\odot$
- The collapse is interrupted only when nuclei run into each other. The bounce occurs shortly before the object would form a BH.

Energetics

- Core collapse to a neutron star, 10^3 km $\rightarrow 10^1$ km
  - If $1.4 M_\odot \rightarrow \frac{3}{5} G_N M^2 / R$ (neglect GR for a moment)
  - 3 * 10^{53} erg if R~11 km (neutron star radius)
- More than enough energy to unbind the envelope $\gtrsim 10^3$ km and launch with $v \sim c/7$ (?)

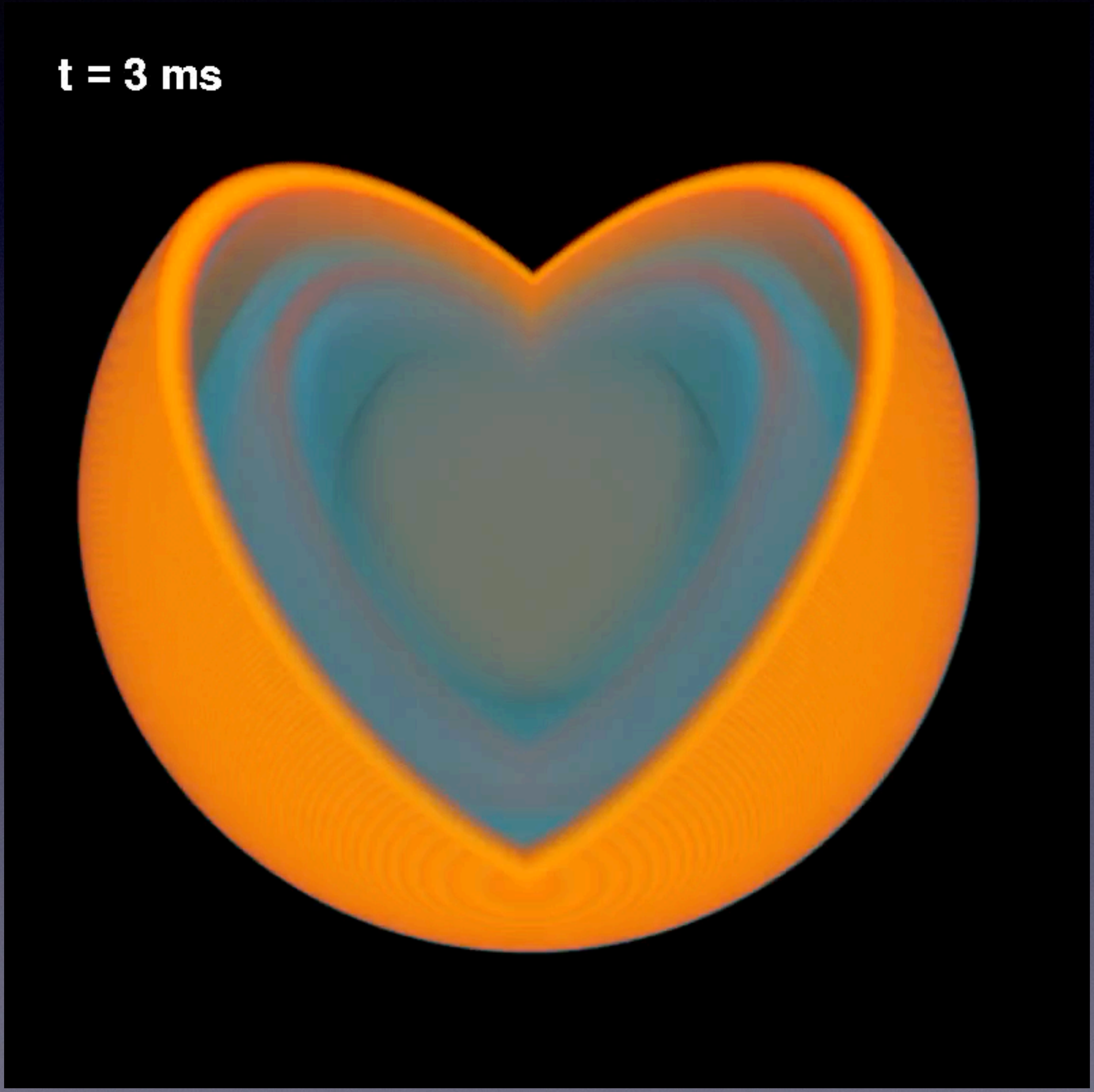


Such explosions are indeed observed, but with v that is smaller by an order of magnitude

The culprit is neutrinos. They freely stream from the surface of the collapsed core ($\rho \lesssim 10^{11}$g/cm^3), sapping energy. Over 99% of it!

3D simulations

- Simulating the heart of the supernova
- Neutrino heating just above the PNS surface diverts ~0.5% of all neutrino energy into the visible explosion!
- Movie by the Garching group (K.Kifonidis http://www.mpa-garching.mpg.de/~kok/)

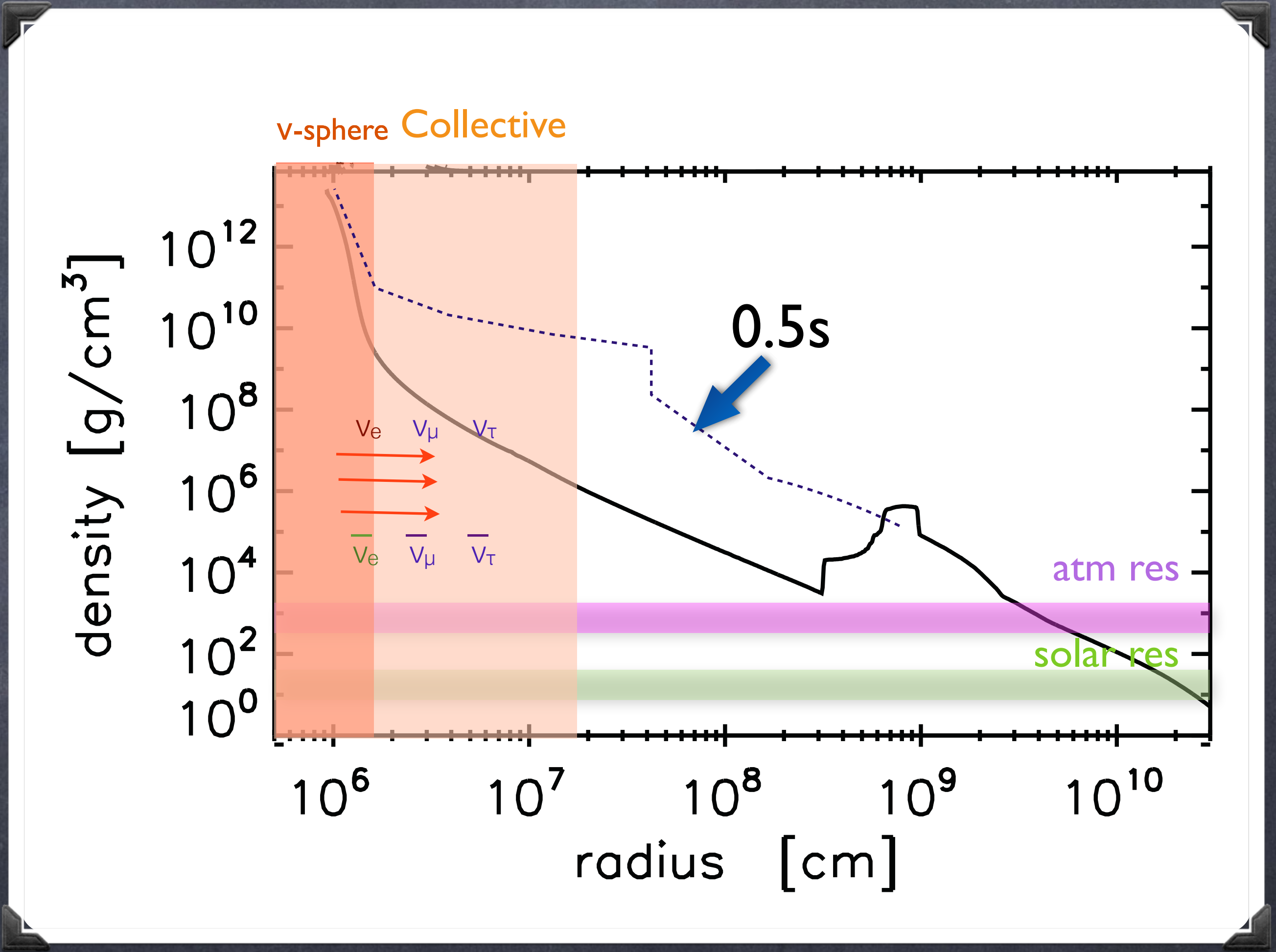


Gravity-powered neutrino bomb

- ν's are the carrier of energy and lepton number, dictate the timescales
- ν's are essential for nucleosynthesis, convert $n \leftrightarrow p$
- CCSN is a laboratory for neutrino oscillations in dense gases
- ν's are a real-time diagnostic of the developing explosion
  - How to read the detected signal?

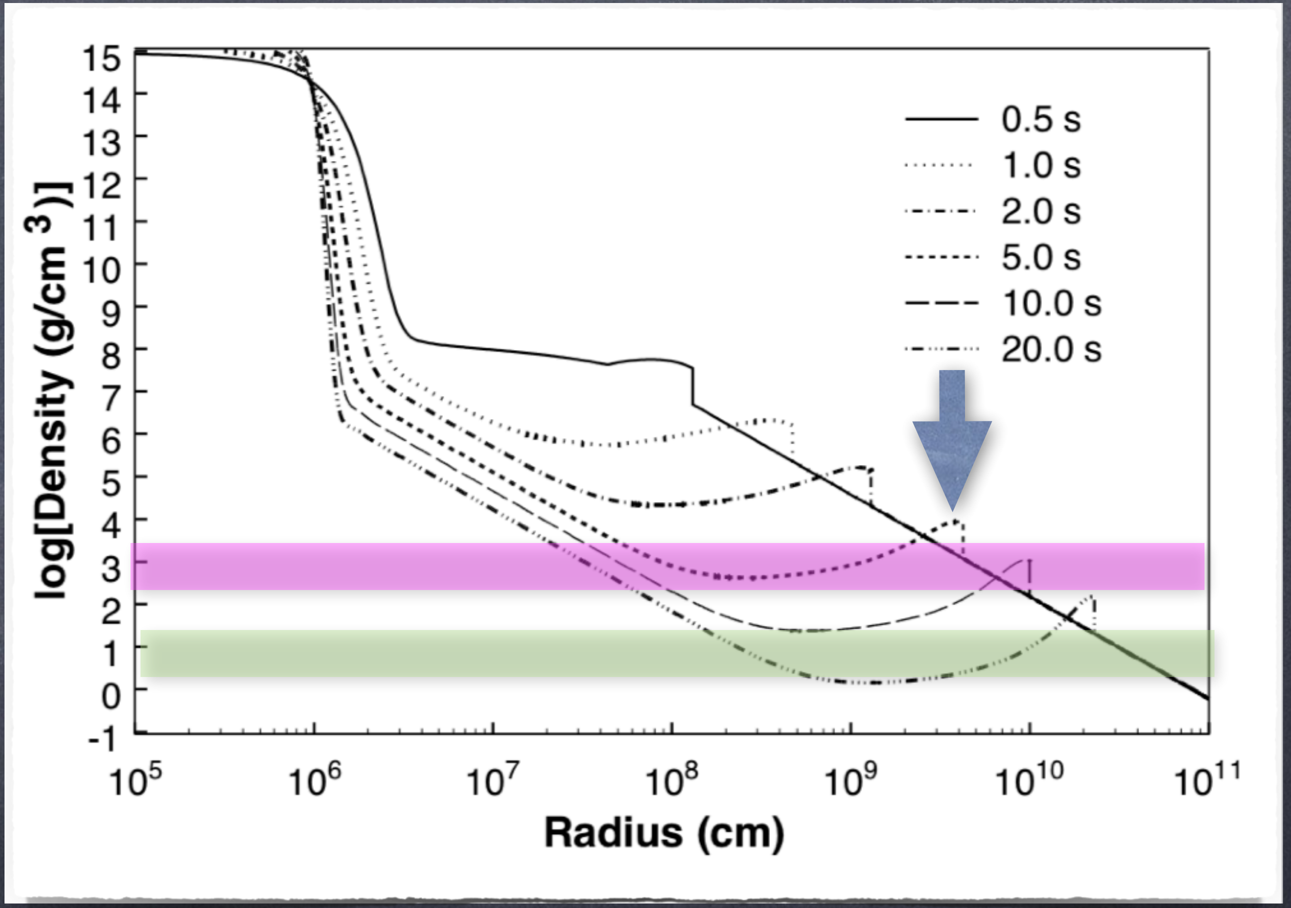
MSW transformations in the envelope

- Neutrinos of all flavors stream from the nu-sphere
- MSW transformations occur at two resonant densities (solar and atm splittings)
- In the beginning, these occur at large radii, where the progenitor profile has not yet been perturbed by the explosion



Oscillations modulated by changing matter profile

- Several seconds into the explosion, the front shock reaches the MSW layers.
- The shock changes flavor oscillation probabilities (maximally nonadiabatic)
    - R. Schirato and G. Fuller (2002)
    - Using simulations by J. Wilson group of a heavy progenitor



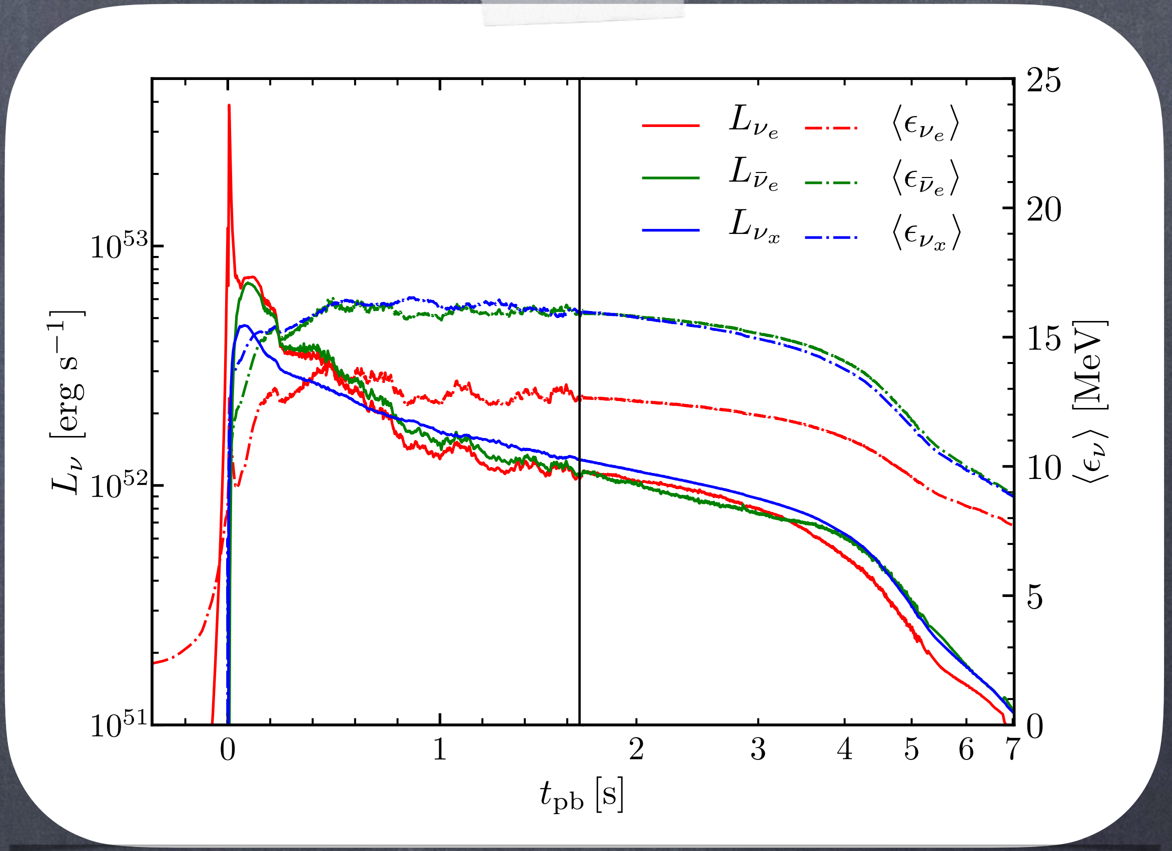
Is this observable?

- Do emitted spectra of all flavors become the same at several seconds? Then oscillations wouldn't leave a visible imprint

- Actual results from modern simulations [Bollig et al 2021]

    - Antineutrinos are indeed close. But ν_e are sufficiently different from ν_x. -> Oscillation effects visible

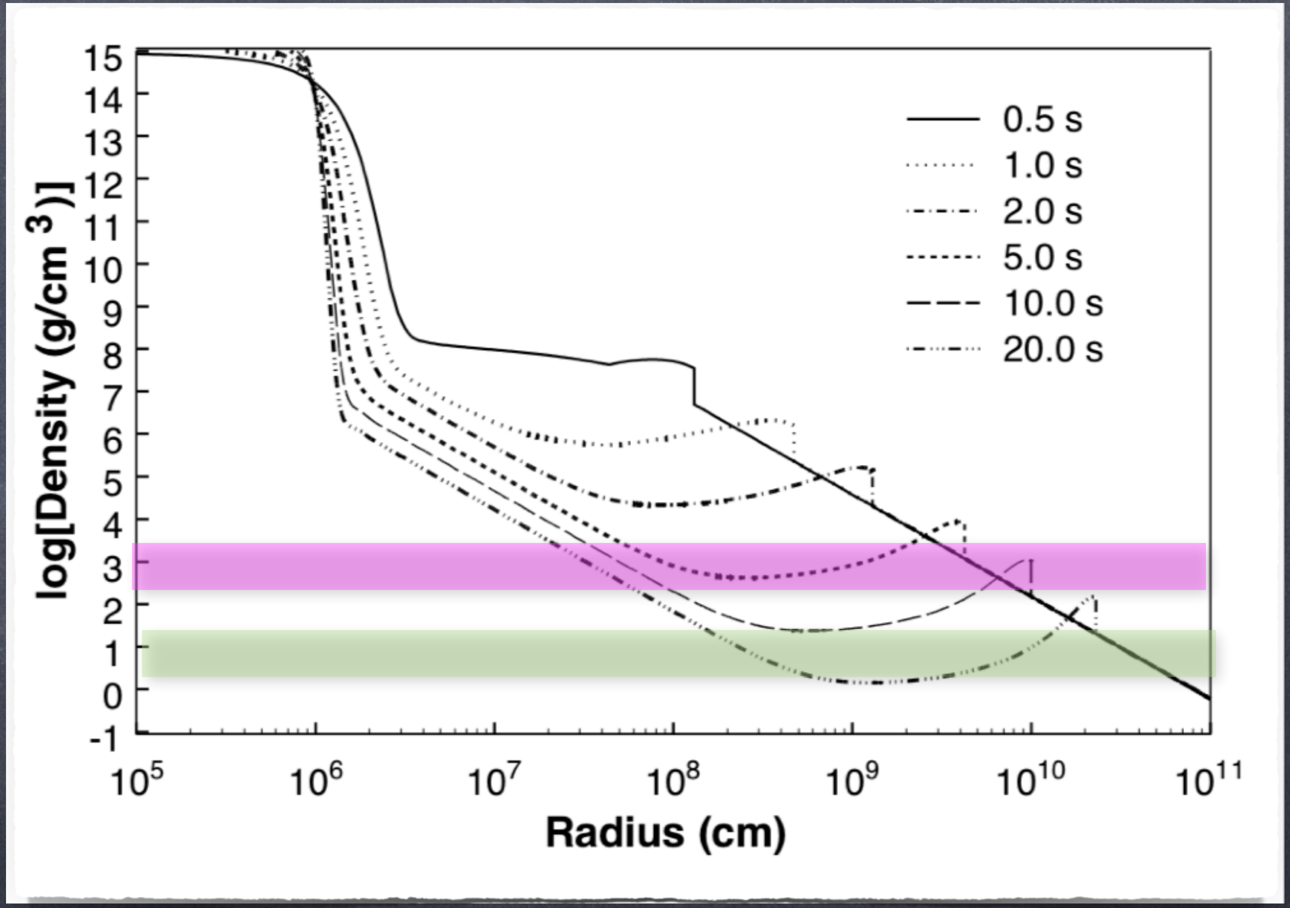
- ν_e's are a specialty of DUNE. DUNE is uniquely positioned to study physics that may be revealed with oscillation effects



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

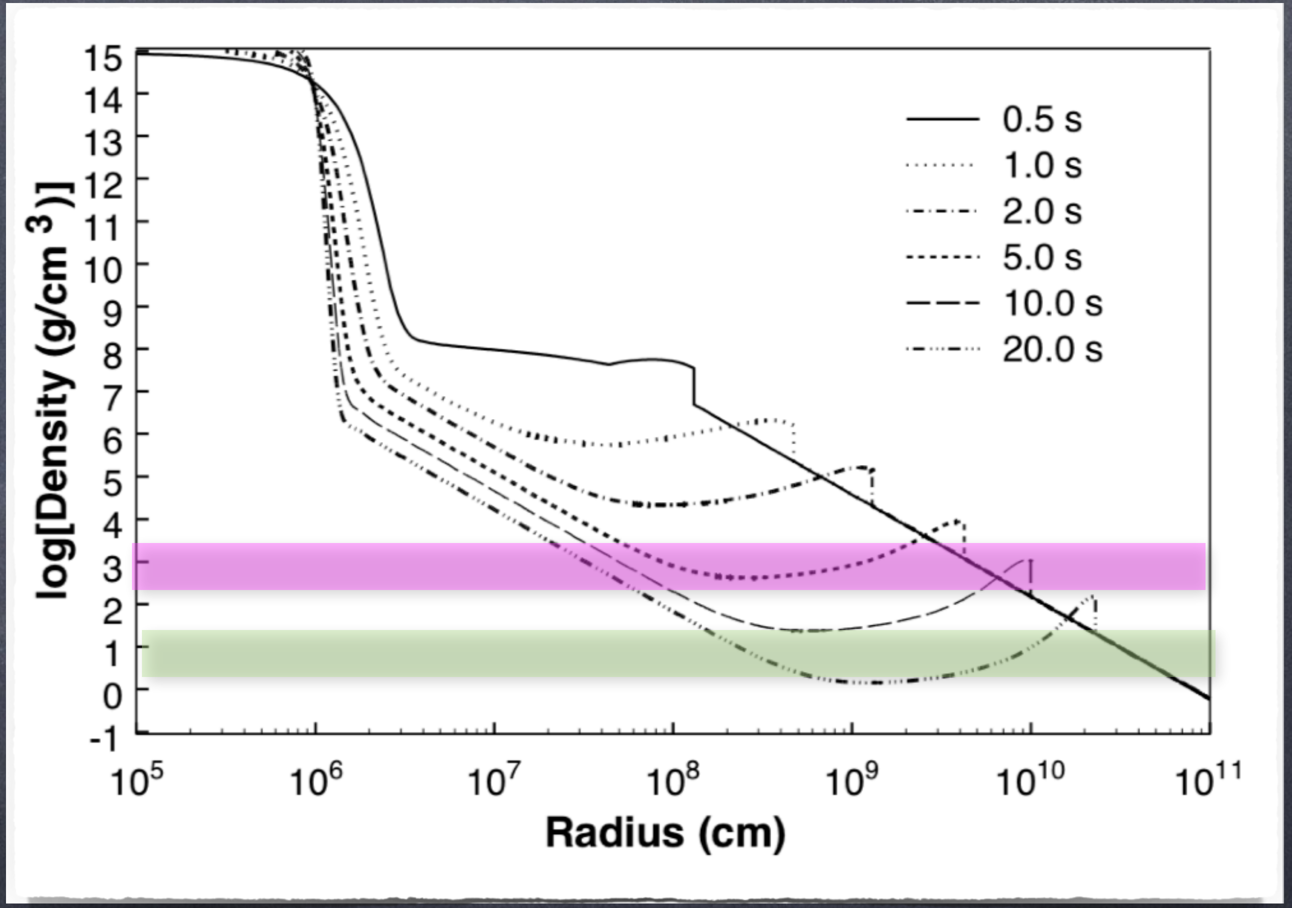
Density behind the shock

- We should also ask what happens behind it
- The resonant density crossed multiple times there
- Why is there rarefied region?
- Are the crossings adiabatic?



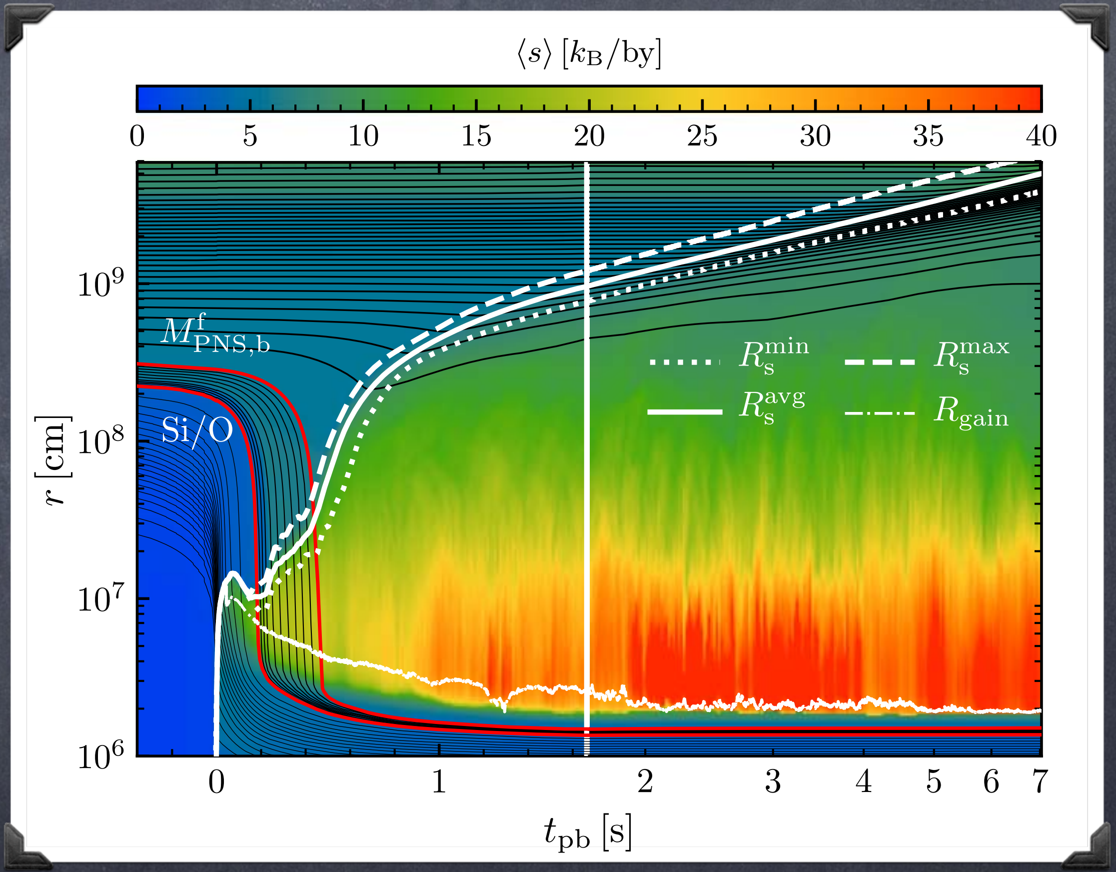
Hot bubble

- The low-density region around the PNS is called the "hot bubble" [H. Bethe, S. Woosley, others]
- It is formed by neutrino heating, the same mechanism that launches the explosion
- The hot bubble could be a nucleosynthesis site
- Can neutrinos probe density features in the hot bubble?

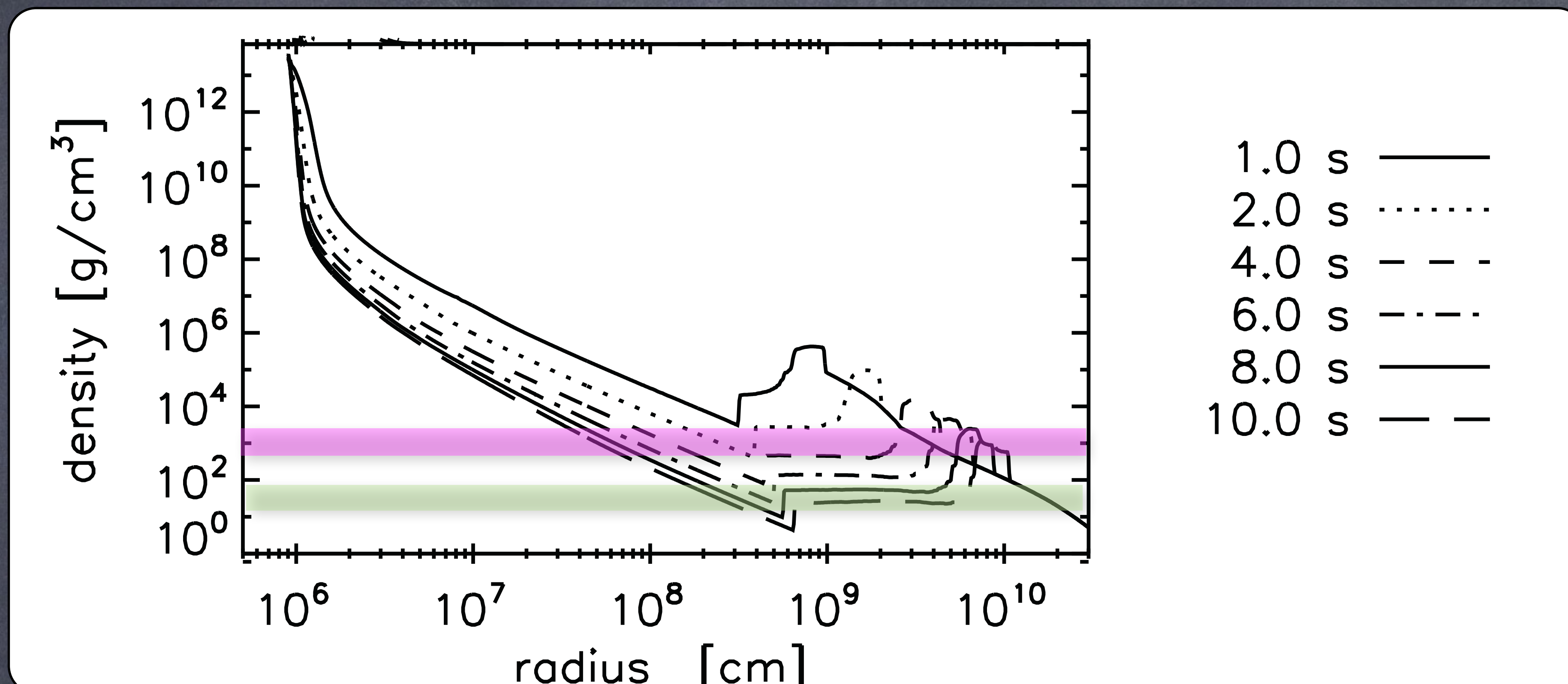


Why hot bubble?

- Neutrino heating, $\sim G_F^2 T_\nu^6$, 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, $m_N G_N M_{PNS}/R_{PNS} \sim T^4/n_N$
- entropy per baryon, $S \sim T^3/n_N$
- $S \sim (m_N/T)(G_N M_{PNS}/R_{PNS}) \gtrsim 50$

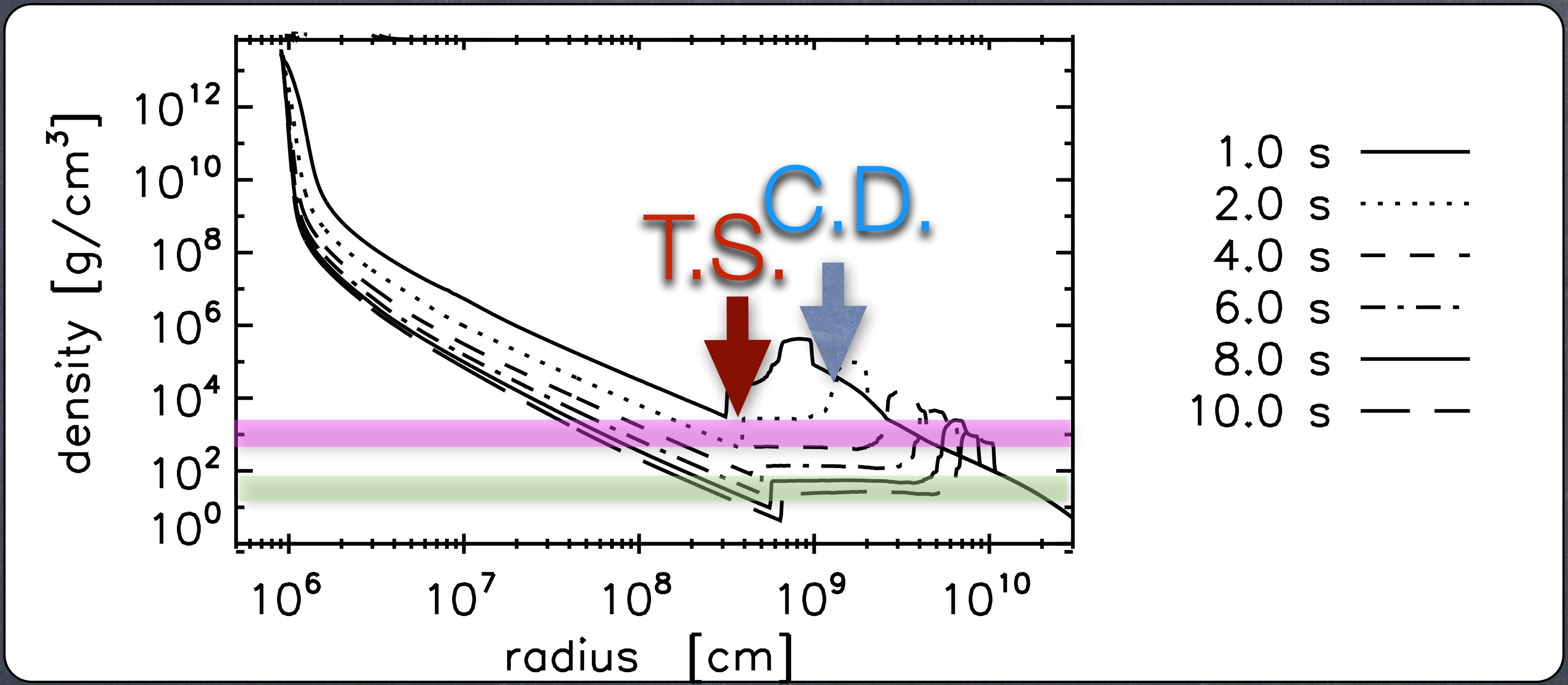


Densities features in the hot bubble



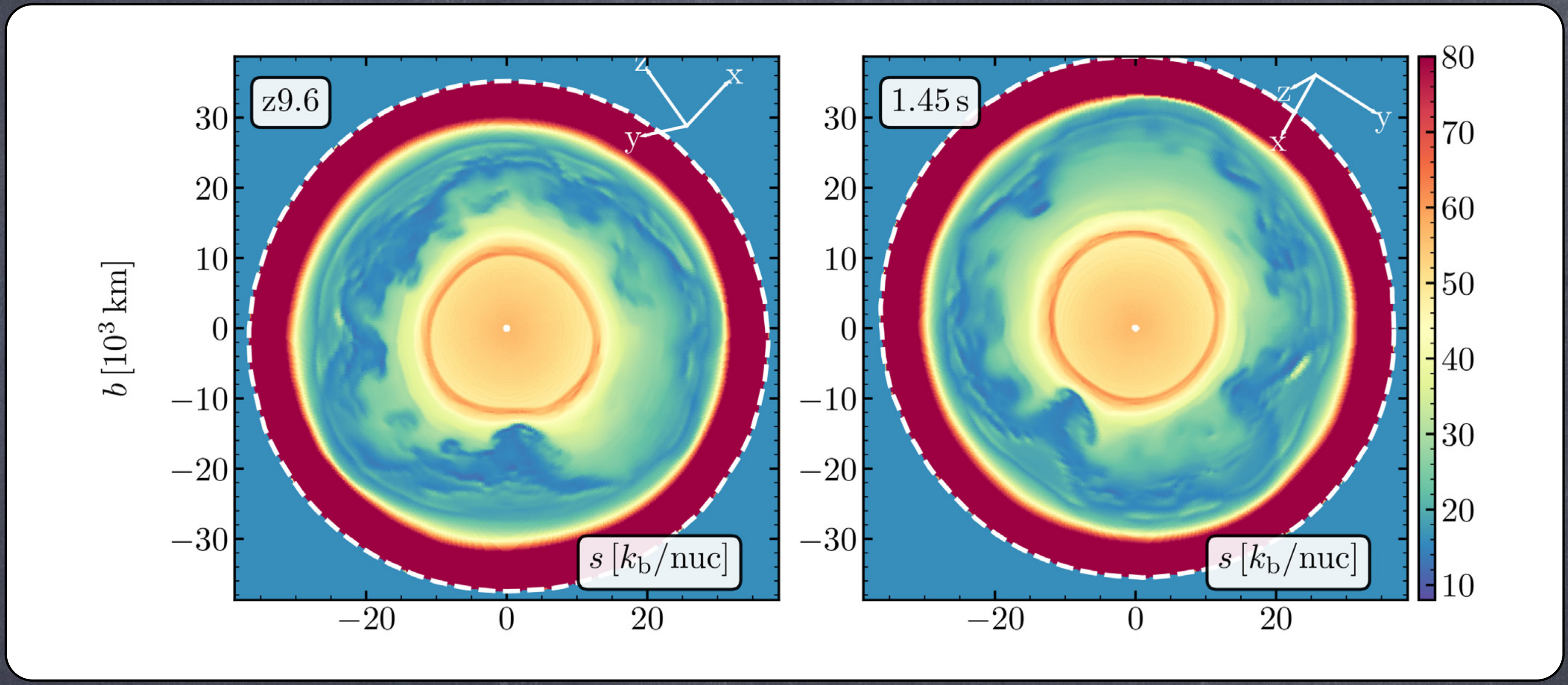
- The profiles of Wilson were pretty smooth
- However, not so for other simulations [Arcones et al, 2006]:
  - Notice the wind termination shock

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 washed out 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 modern simulations



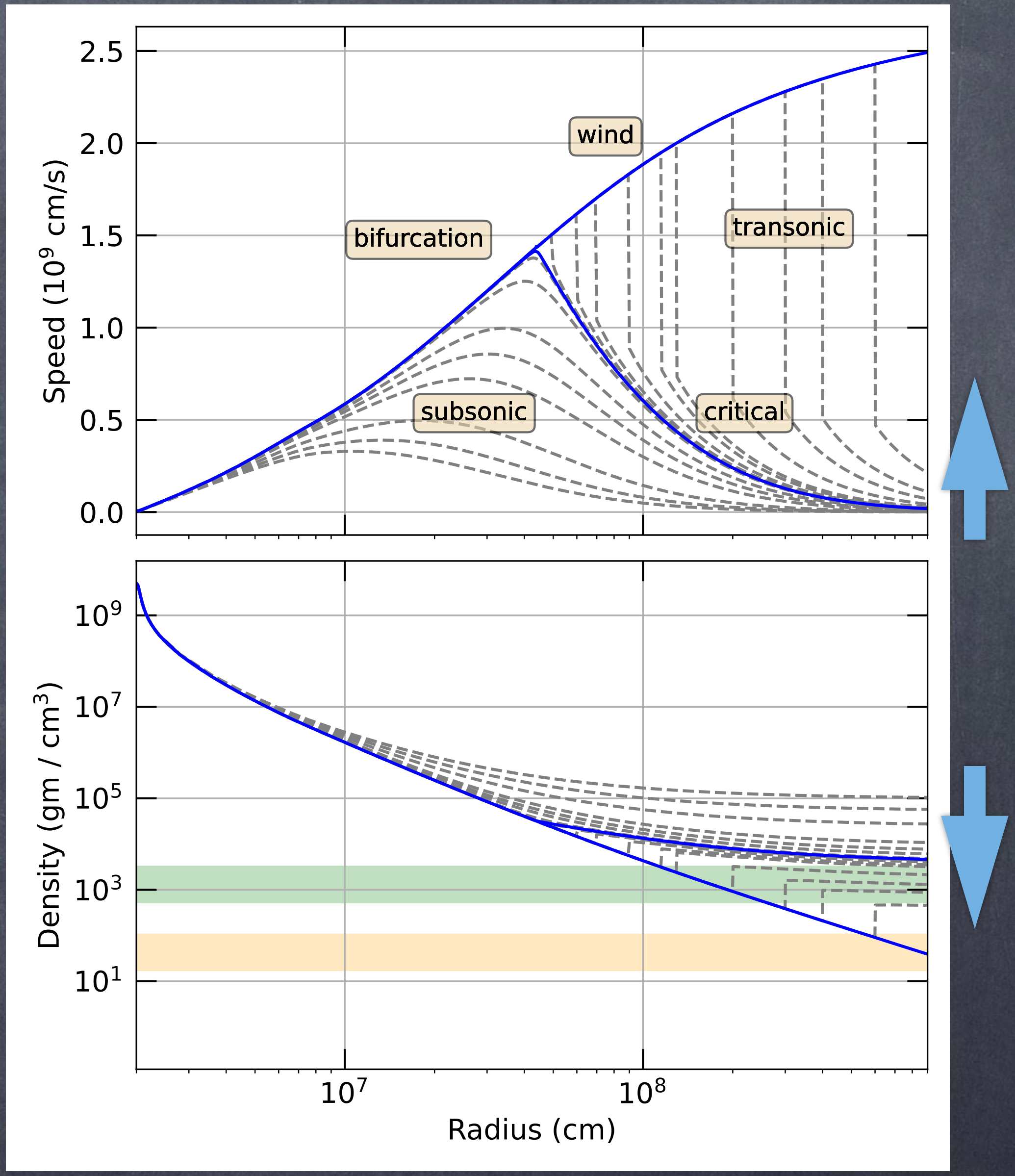
- 3D simulation from Stockinger et al (2020)

What do we make of these simulations?

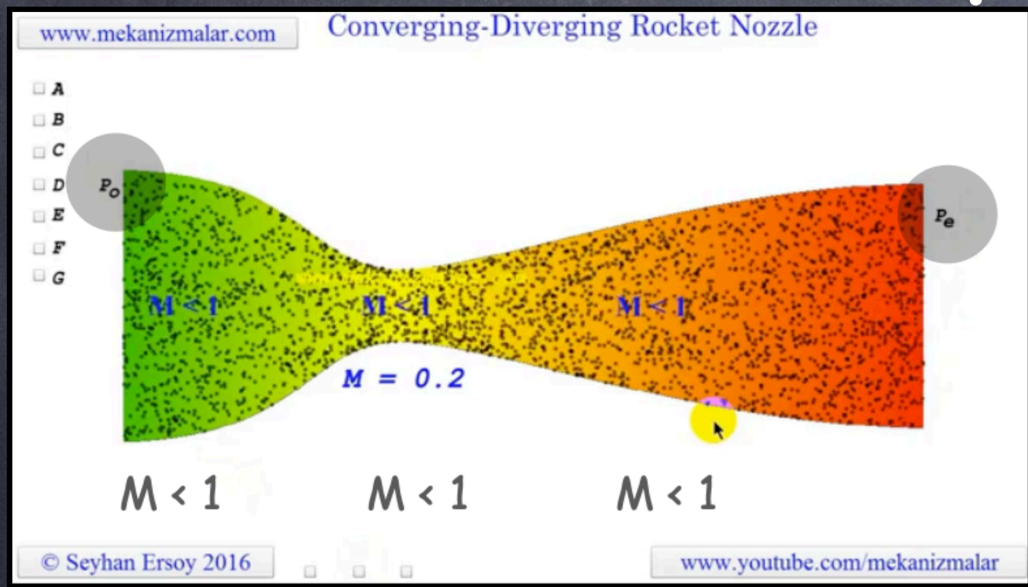
- Some simulations show termination shocks and some don't. It's not a priori obvious that the different simulations could be reconciled.
- If we could understand the physical criterion for the shock formation, it would make the neutrino signatures of the termination shock a sensitive probe of the physical conditions near the PNS.
    - Its neutrino signals could serve as a new diagnostic of the explosion!

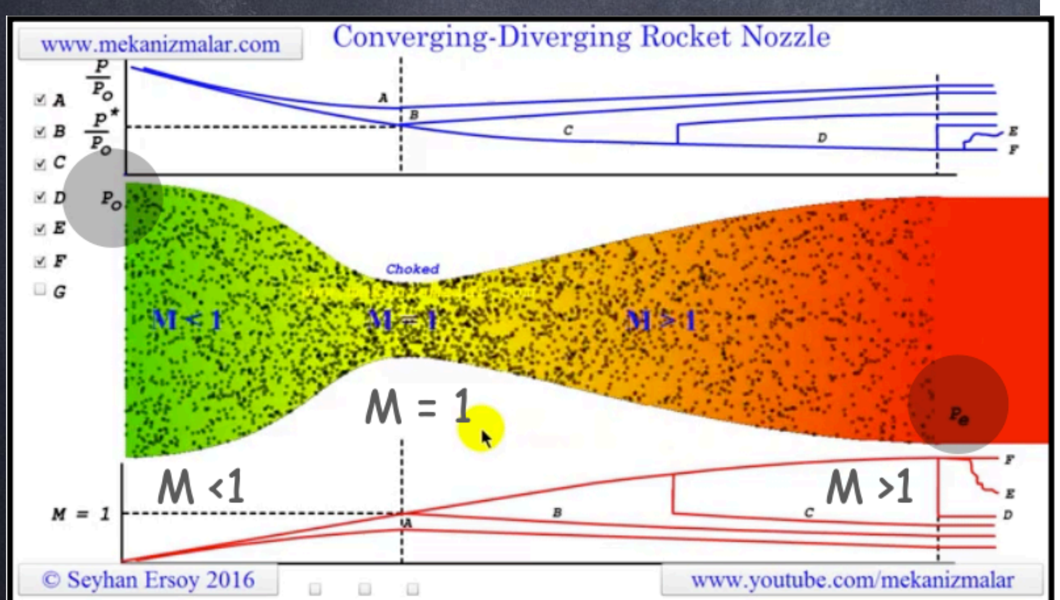
Key physics: a phase transition

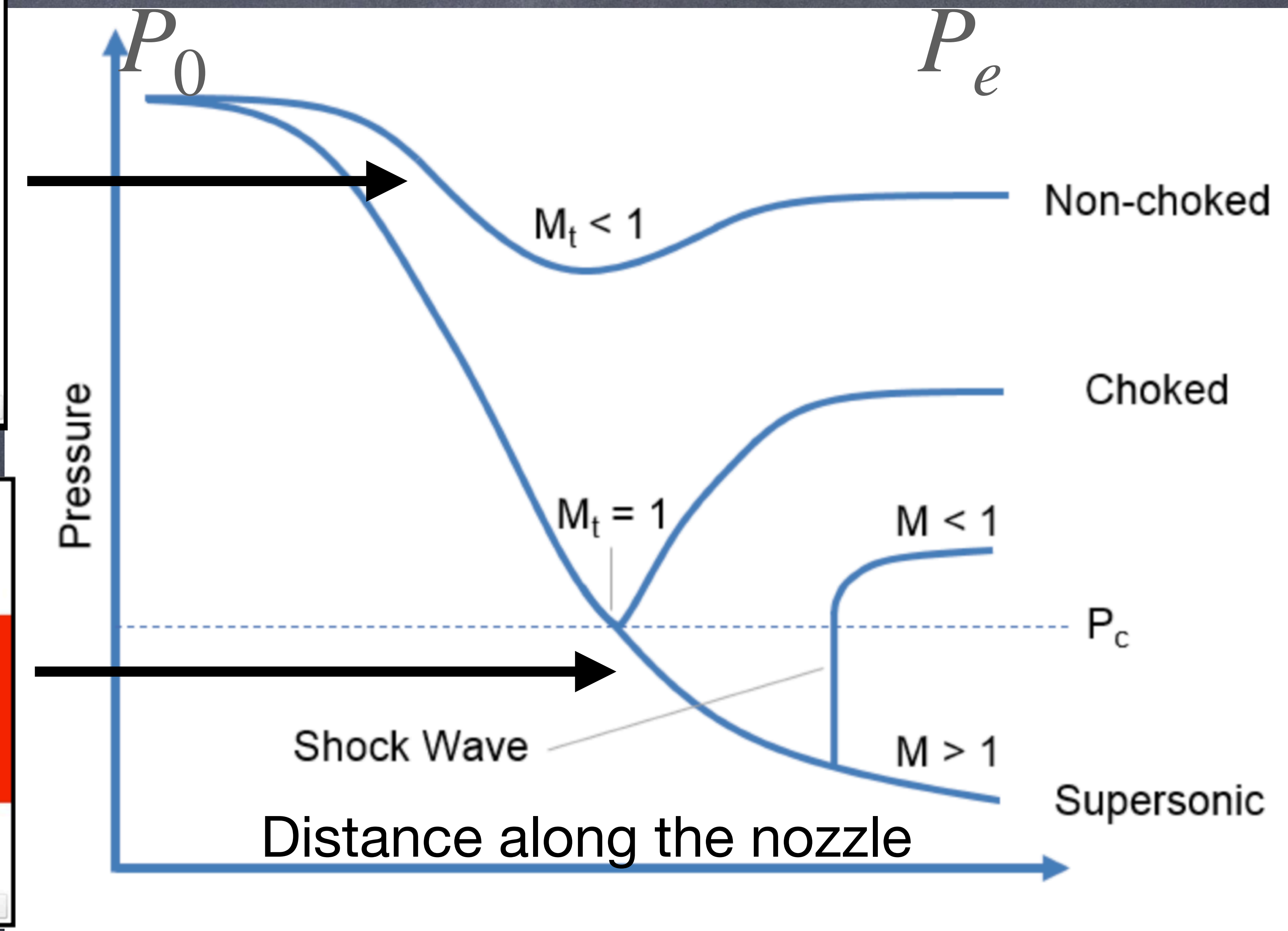
- Fixing neutrino heating and gravitation, we look for solutions as a function of the surrounding pressure P
- At high P, a family of smooth subsonic curves
- As P is reduced, the smooth velocity curves develop a kink
- As P is further reduced, the kink turns into a step -> termination shock!
- The kinky curve is the critical flow, separating the subsonic and transonic regions



Rocket engine nozzle dynamics - similar to supernovae systems





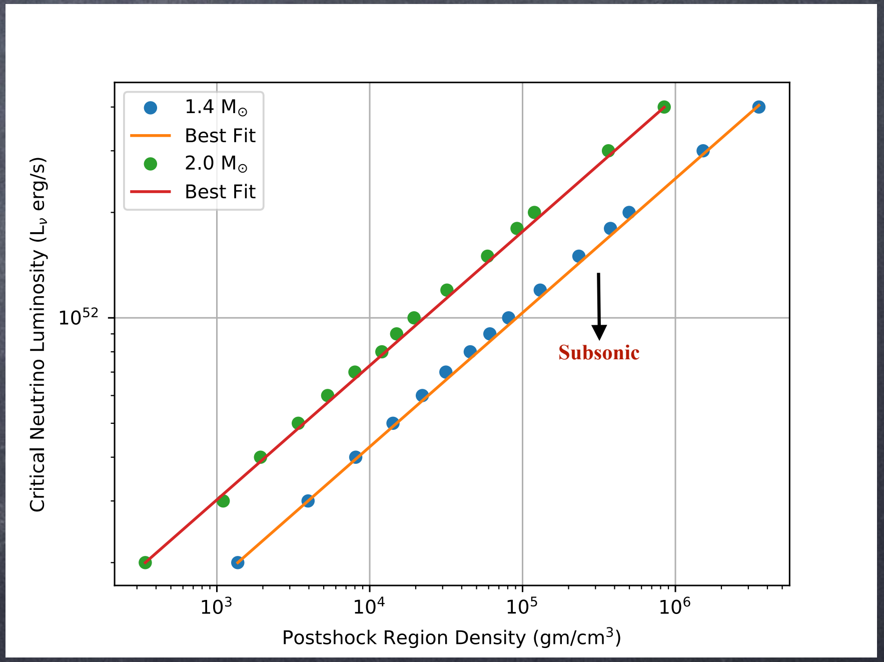


Outflows in supernova are near-critical!

- In the lab, the far pressure can be fine-tuned to the critical value
- The real surprise is that the conditions in a supernova are also fine-tuned and the system is on the edge of shock formation.
- This is extremely unusual in astrophysical systems. For example, the solar wind has termination shock at 94 AU.

Condition for critical flow

- $T_{f,crit} \simeq (112 \text{ keV}) L_{52}^{0.702} E_{\nu 20}^{1.404} M_{1.4}^{-0.96} R_{20}^{0.08},$
- $\rho_{f,crit} \simeq (8.1 \times 10^3 \text{ g/cm}^3) L_{52}^{2.61} E_{\nu 20}^{5.2} M_{1.4}^{-4.0} R_{20}^{1.03}$
- Can be understood analytically
- 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



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

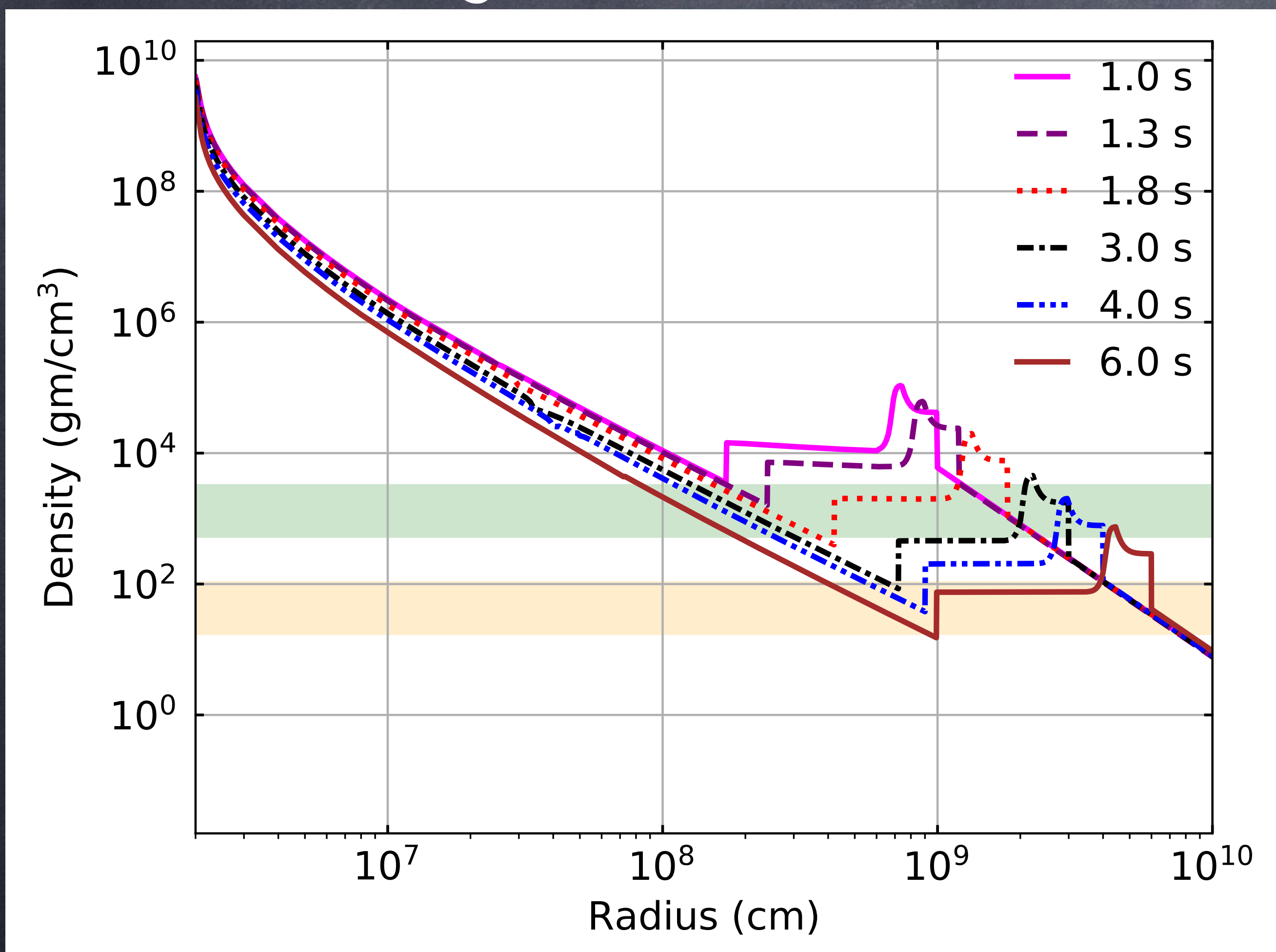
Reconciling simulations

- 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 $\lesssim 12 M_\odot$.

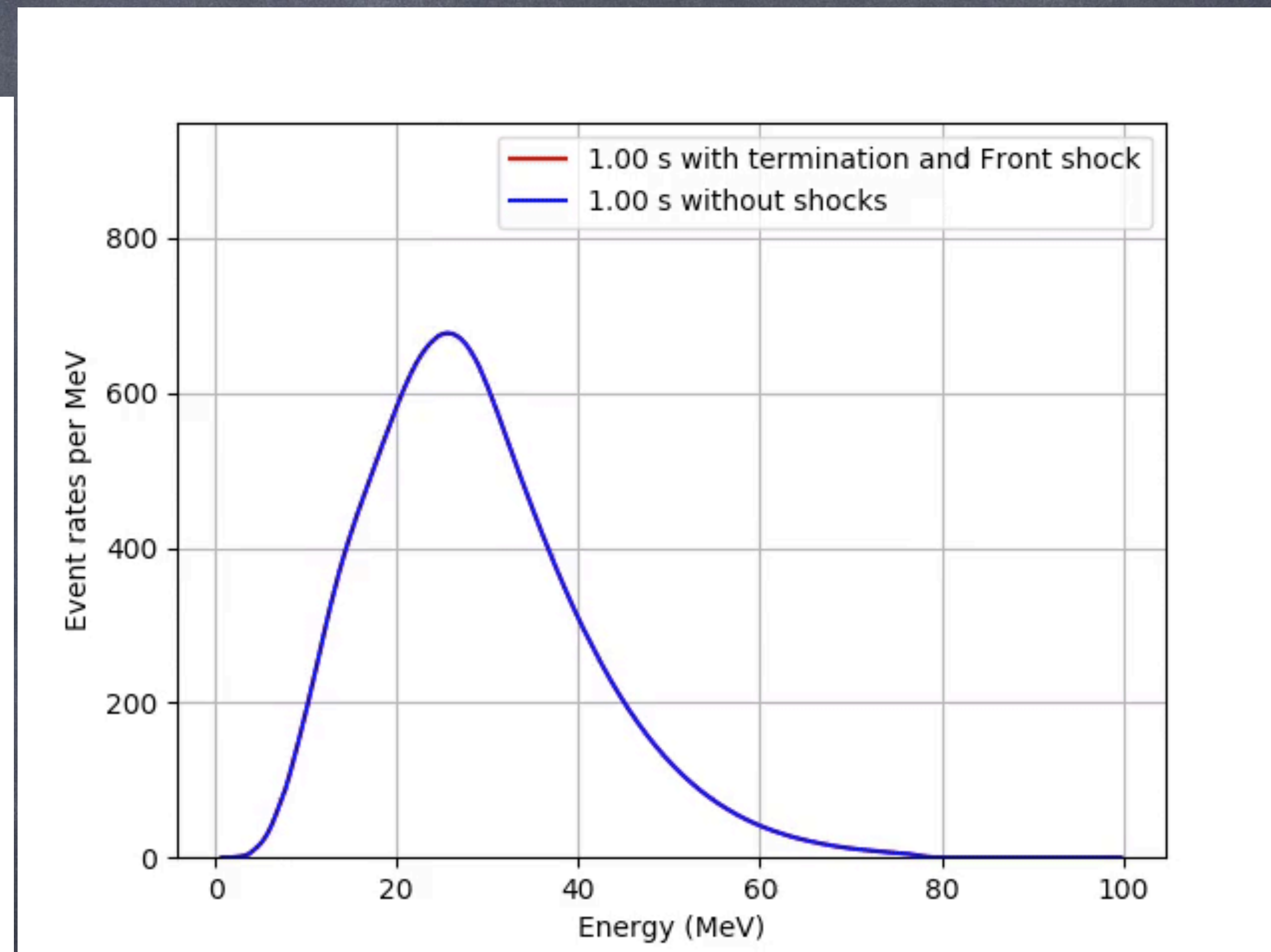
Shock passage signatures at DUNE

Neutrino signals of shocks in DUNE

Strong termination shocks



Event rates in 40 Kt DUNE detector

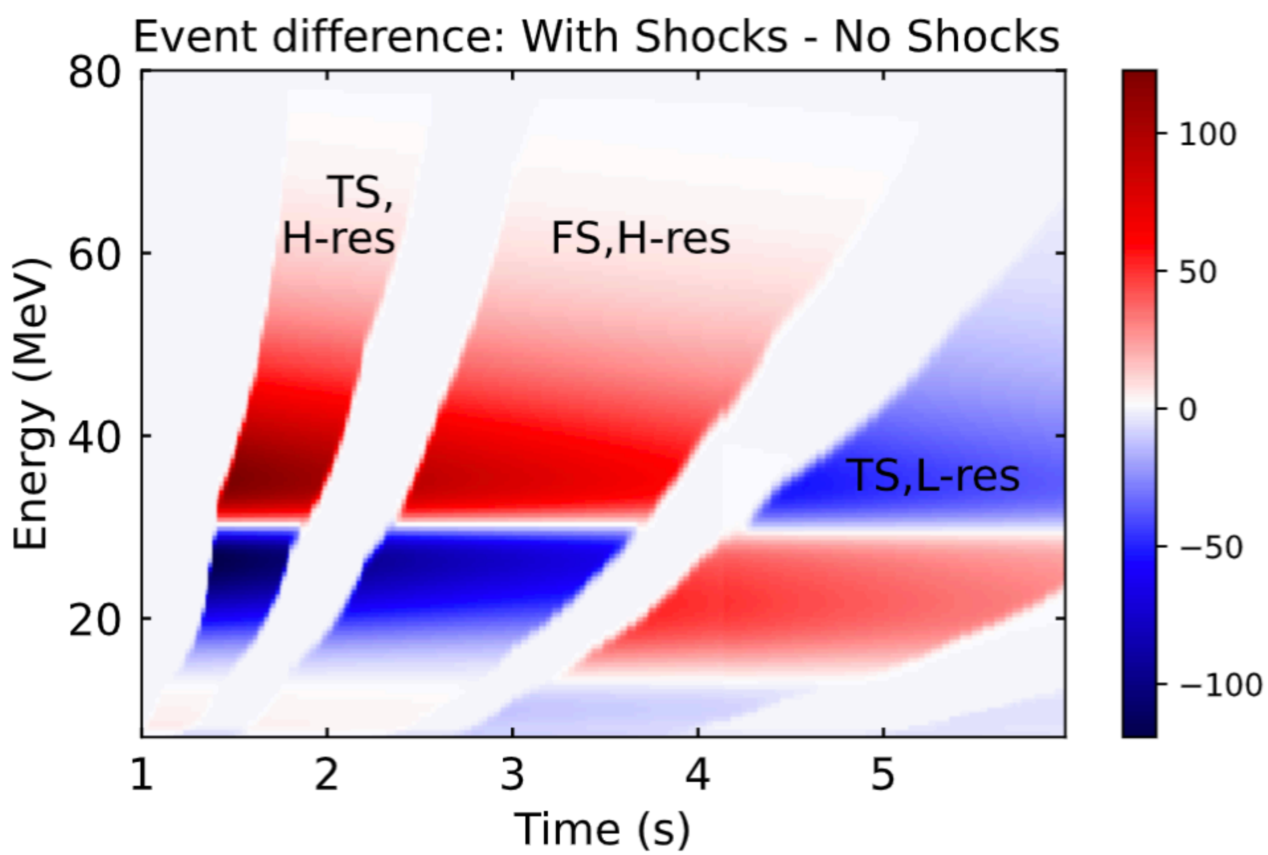


High neutrino luminosities

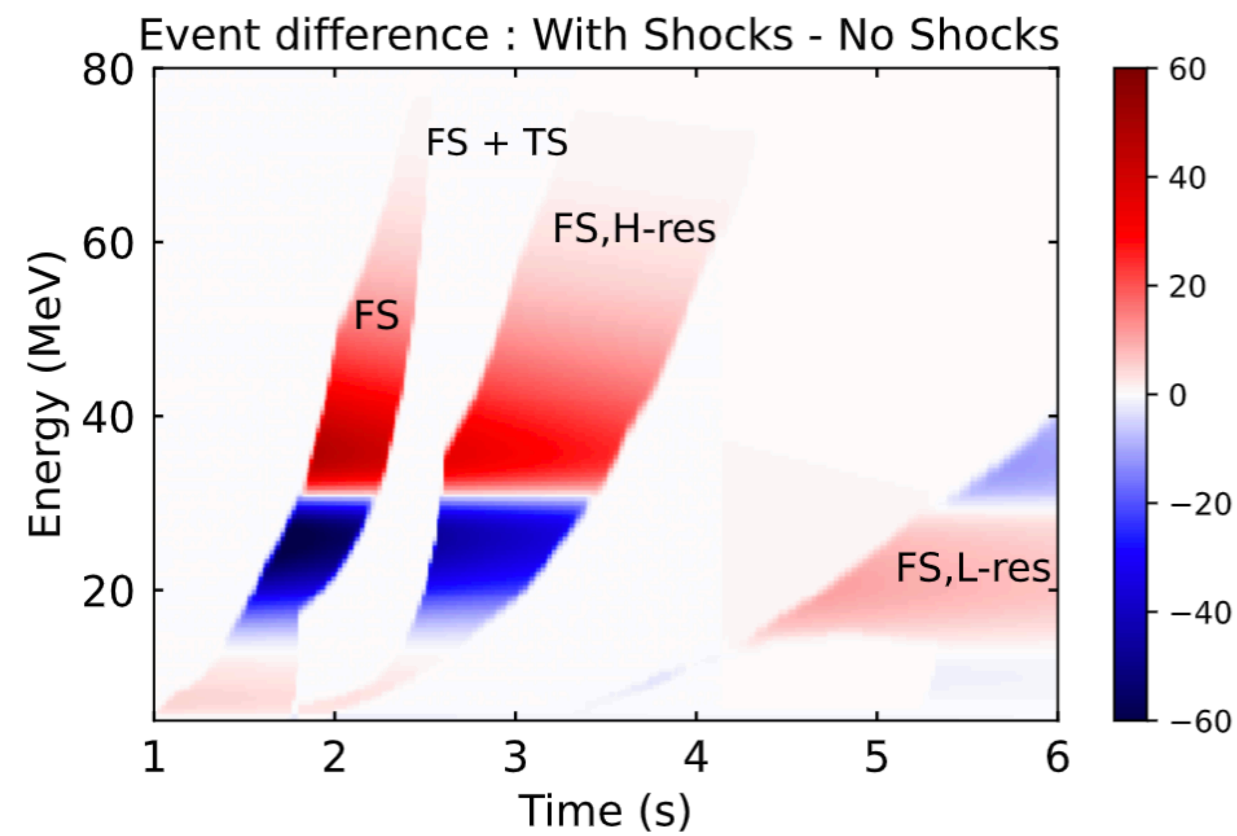
A.F., P. Mukhopadhyay (2022), to appear

Modulation signal can appear as early as 1.3 sec and continue for the burst duration !

Time-energy signature of modulation signals



Strong termination shocks



Subsonic breezes and intermittent shocks

Neutrino time signatures in DUNE sensitive to outflow hydrodynamics

Can be observed with 5-sigma confidence for any SN in the galaxy

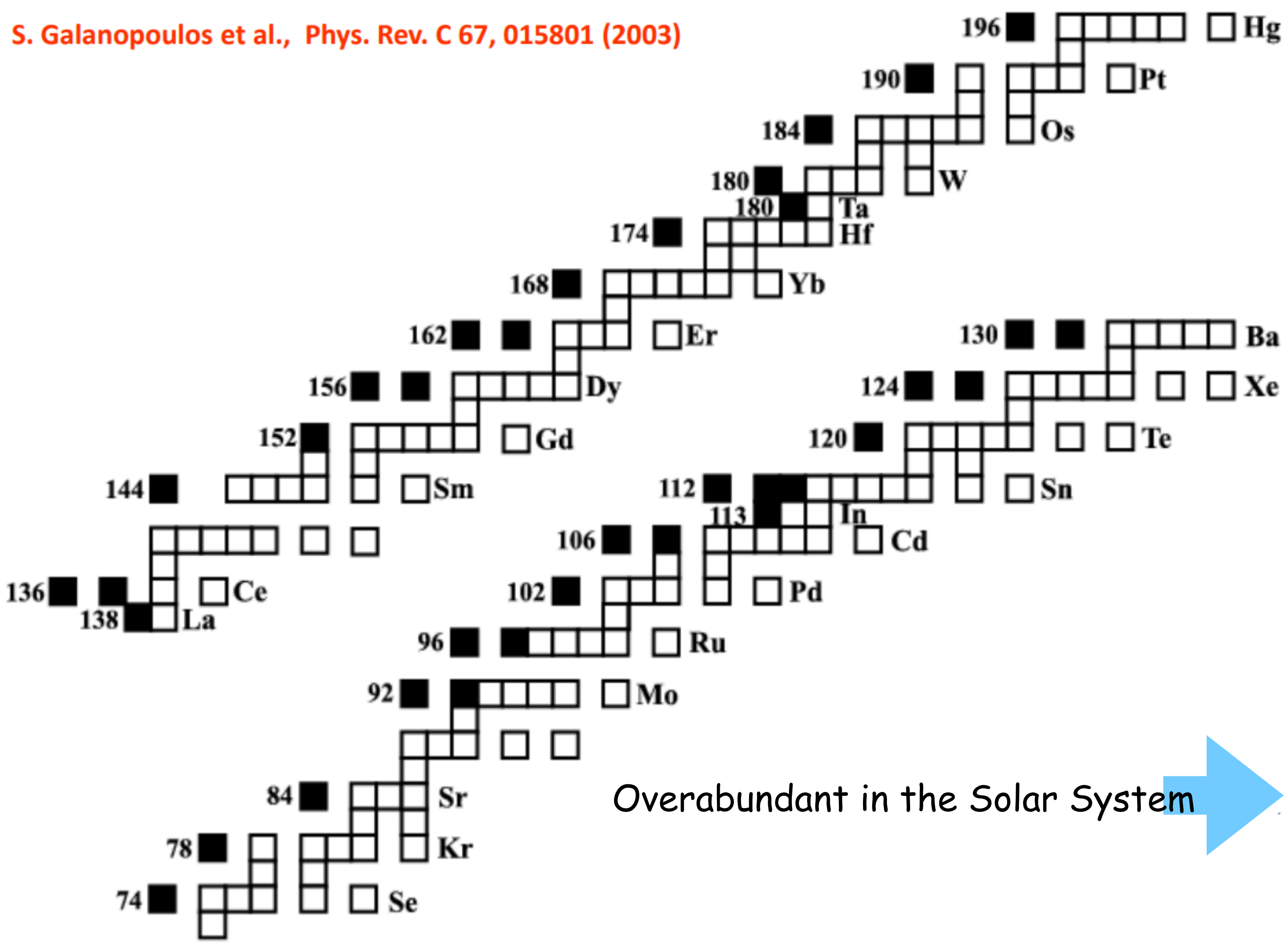
Finally, a few words on nucleosynthesis

Nu-p process

- While most of the elements heavier than iron are synthesized by the s- and r- processes, a number of naturally occurring, proton-rich isotopes must be produced by different mechanisms [Rauscher (2013)]
- νp-process is an attractive proposal [Frohlich et al (2005), Pruet et al (2005), Wanajo (2006)]. Site: in a neutrino-driven outflow from the surface of PNS
  - The outflow is proton-rich and expands in the presence of a large flux of neutrinos

Proton-rich ($p-$)nuclei

S. Galanopoulos et al., Phys. Rev. C 67, 015801 (2003)



Overabundant in the Solar System

p-nuclei solar abundances

p nucleus	(%)	p nucleus	(%)	p nucleus	(%)
74_Se	0.89	114_Sn	0.65	156_Dy	0.06
78_Kr	0.35	115_Sn	0.34	158_Dy	0.10
84_Sr	0.56	120_Te	0.096	162_Er	0.14
92_Mo	14.84	124_Xe	0.10	164_Er	1.61
94_Mo	9.25	126_Xe	0.09	168_Yb	0.13
96_Ru	5.52	130_Ba	0.106	174_Hf	0.162
98_Ru	1.88	132_Ba	0.101	180_Ta	0.012
102_Pd	1.02	138_La	0.09	180_W	0.13
106_Pd	1.25	136_Ce	0.19	184_Os	0.02
108_Cd	0.89	138_Ce	0.25	190_Pt	0.01
113_In	4.3	144_Sm	3.1	196_Hg	0.15
112_Sn	0.97	152_Gd	0.20		

State-of-the-art results on the $\nu p-$process

nature

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Article | Published: 02 December 2020

Enhanced triple-α reaction reduces proton-rich nucleosynthesis in supernovae

Shilun Jin, Luke F. Roberts, Sam M. Austin & Hendrik Schatz

Nature **588**, 57–60 (2020) | Cite this article

State-of-the-art calculations argue that the $\nu p-$process in CCSN neutrino driven outflows does not work

Field in crisis

MSUTODAY

Dec. 2, 2020

Supernova surprise creates elemental mystery

Michigan State University researchers have discovered that one of the most important reactions in the universe can get a huge and unexpected boost inside exploding stars known as supernovae.

This finding also challenges ideas behind how some of the Earth's heavy elements are made. In particular, it upends a theory explaining the planet's unusually high amounts of some forms, or isotopes, of the elements ruthenium and molybdenum.

But accelerating the triple-alpha reaction also puts the brakes on the supernova's ability to make heavier elements on the periodic table, Roberts said. This is important because scientists have long believed that proton-rich supernovae created Earth's surprising abundance of certain ruthenium and molybdenum isotopes, which contain closer to 100 protons and neutrons.

"You don't make those isotopes in other places," Roberts said.

But based on the new study, you probably don't make them in proton-rich supernovae, either.

"What I find fascinating is that you now have to come up with another way to explain their existence. They should not be here with this abundance," Schatz said of the isotopes. "It's not easy to come up with alternatives."

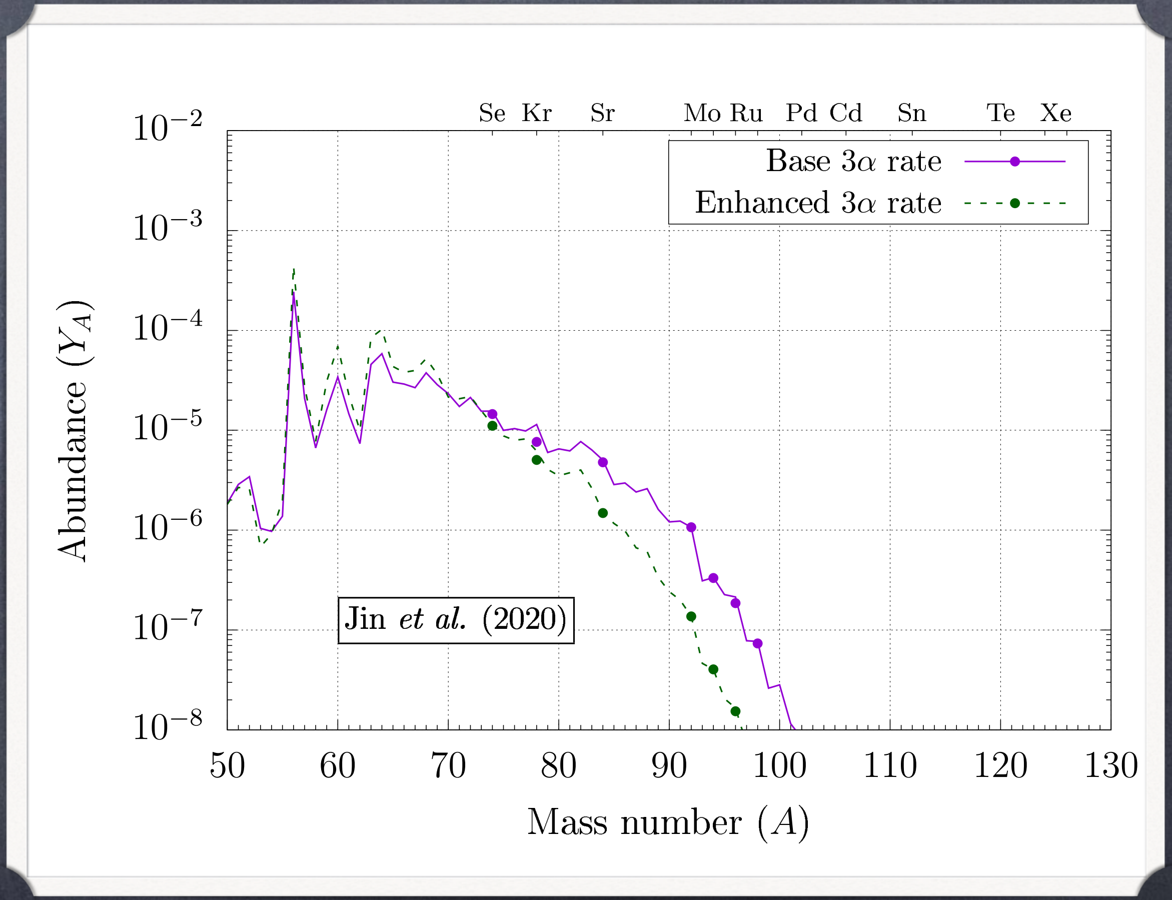
Link for the press release: MSU Nature

Near-criticality to the rescue

- We have studied the profiles in the hot bubble for modeling neutrino signals. Can this help with the nucleosynthesis?
- We learned that the outflow profiles in the hot bubble can have qualitatively different character, depending on the details of the explosion (near-criticality!) Hence, it's dangerous to draw conclusions based on a single ansatz of the outflow.
  - We should see if any of them works!

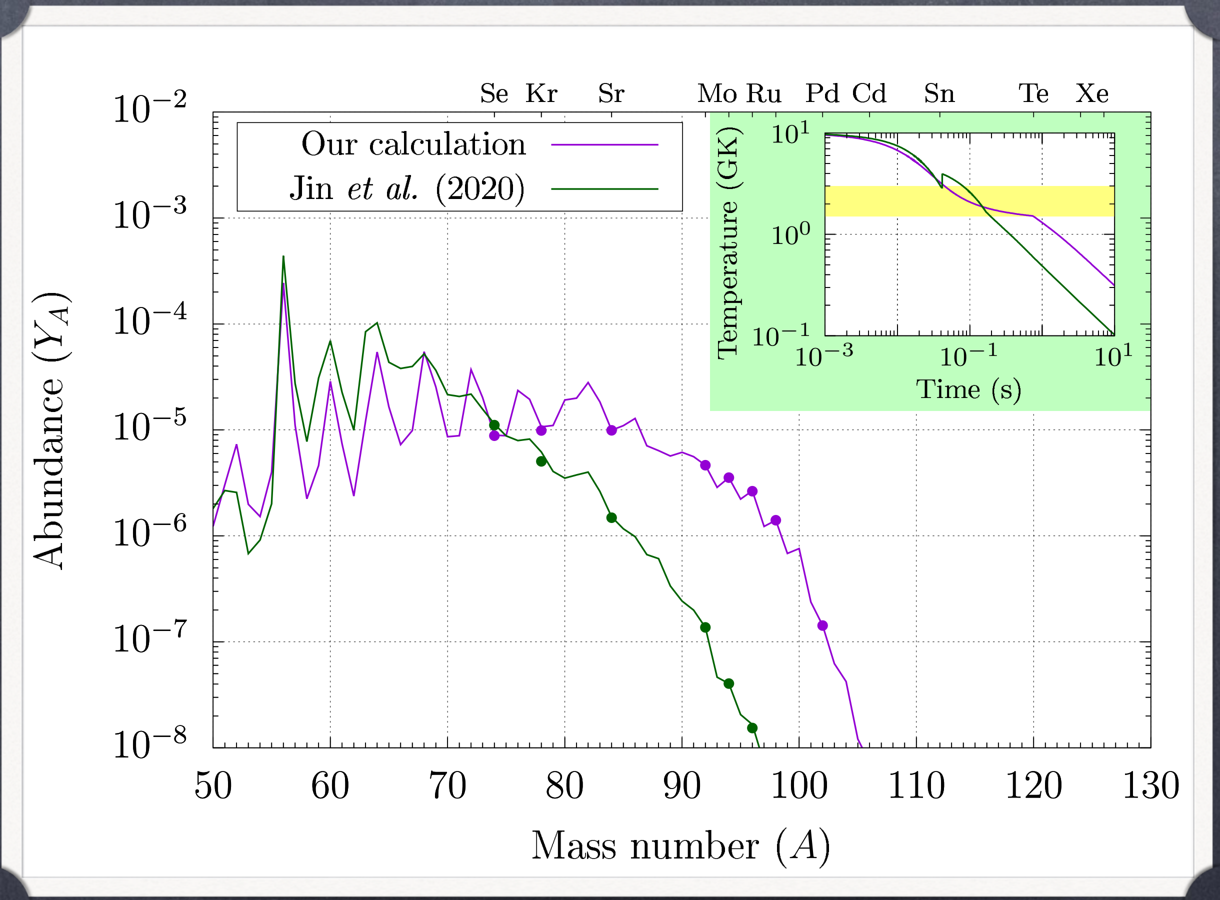
Reproducing results of Jin et al (2020)

- Yields obtained for parametrized outflow profile with entropy ($S = 80$) that has been used in Jin et al (2020)
  - Huge thanks goes to Jonas Lippuner and the authors of of the Nature paper for making their codes public



Here are the results in our subsonic outflow

- Subsonic outflows do the trick!
- They can enhance yields by more than 2 orders of magnitude
- Both the absolute and relative abundances of $^{92,94}Mo$ and $^{96,98}Ru$ agree with Solar System measurements.



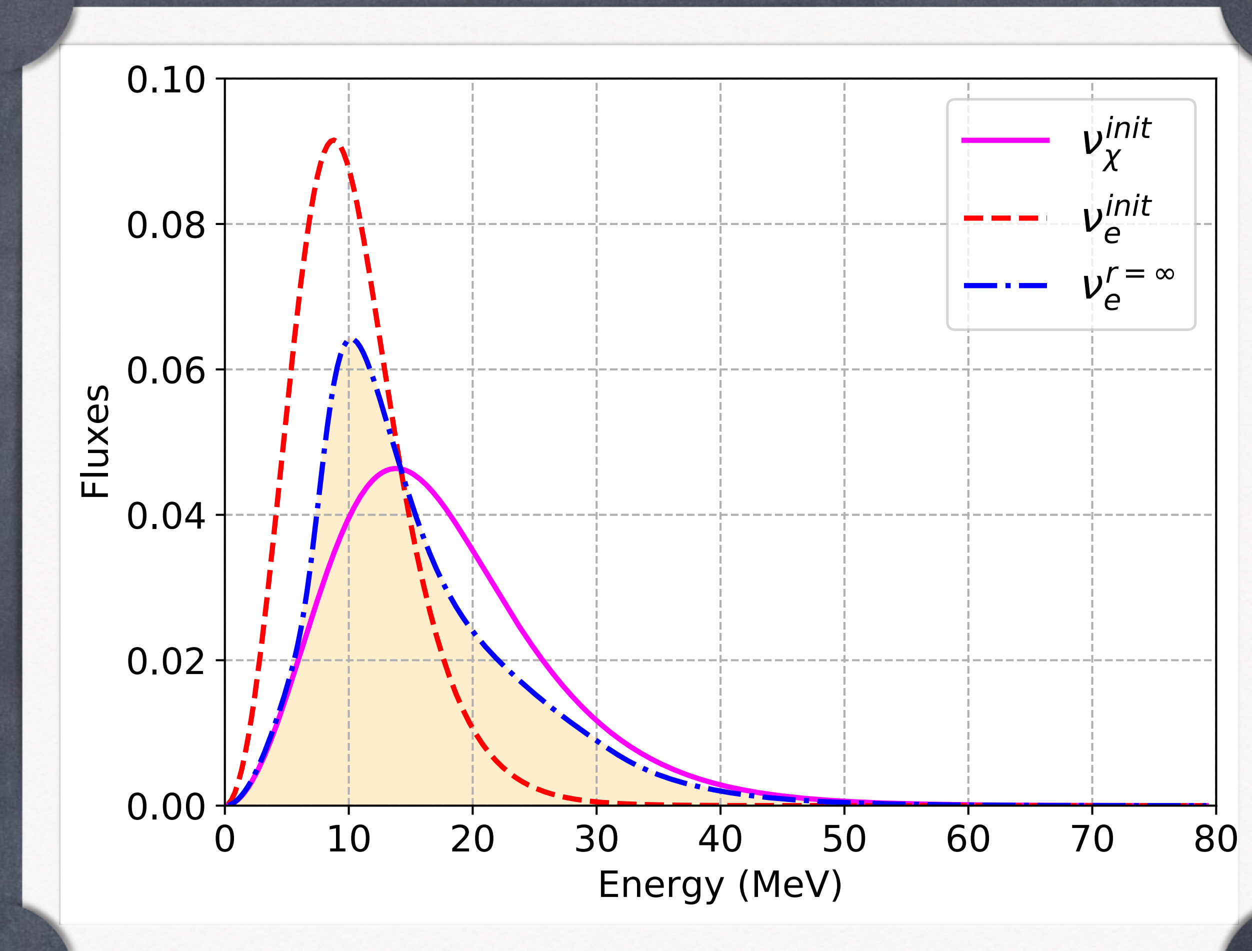
A.F., P. Mukhopadhyay, A. Patwardhan, *to appear*

Further observations

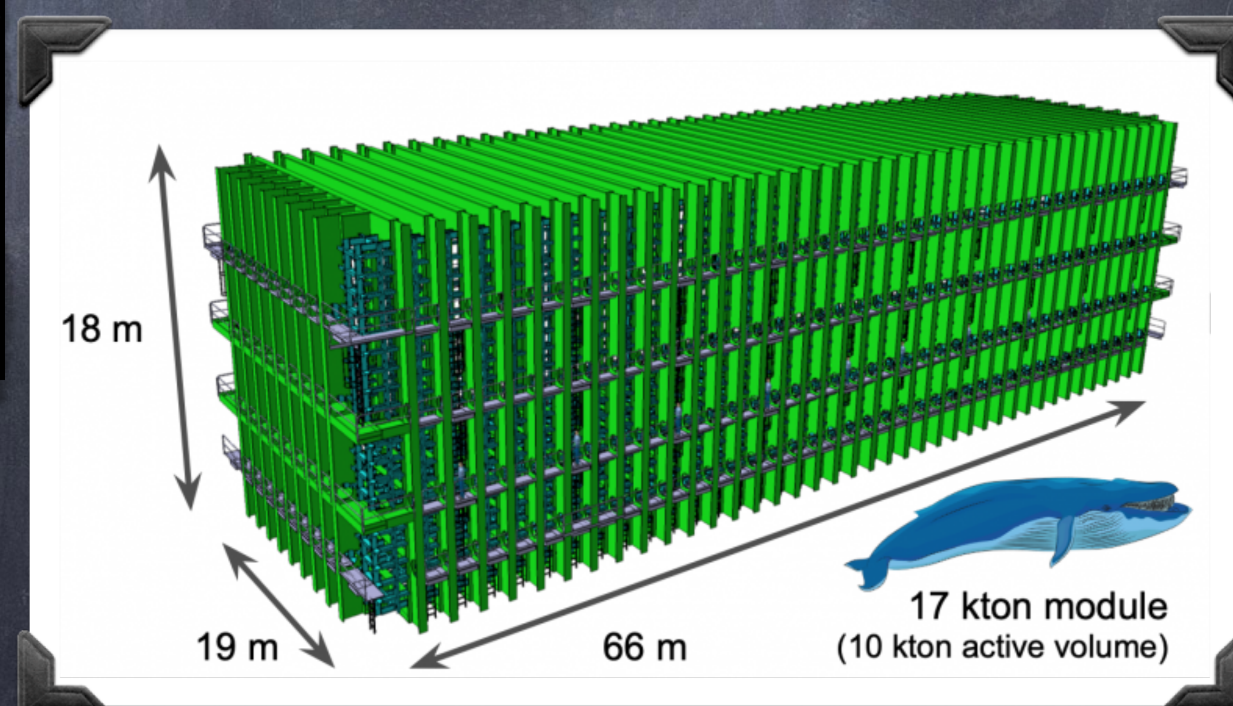
- The desired entropy per baryon indicate the mass of the PNS above the Chandrasekhar value, $\gtrsim 1.7 M_{\odot}$
- This is exactly what is seen in recent simulations of massive progenitors, $\gtrsim 13 M_{\odot}$
- These are the progenitors that we predict will have subsonic flows -> a nontrivial check!
- The radius of the hot PNS has implications for the nuclear equation of state. Also agree with recent trends in the field.

Conclusions

- Neutrino-driven outflows in a supernova possess a special property of near-criticality
- Near-criticality makes neutrino signatures of termination shocks at DUNE a powerful diagnostic of the physical conditions in the hot bubble
- Our study points out a possibility to infer from neutrino observations whether the conditions in the hot bubble are optimal nu-p nucleosynthesis



Fluxes
Energy (MeV)
0.00
0.02
0.04
0.06
0.08
0.10
0
10
20
30
40
50
60
70
80
ν_χ^{init}
ν_e^{init}
$\nu_e^{r=\infty}$



18 m
19 m
66 m
17 kton module
(10 kton active volume)