Nuclear Pasta in Supernova and Neutron Star Mergers

Matt Caplan
Indiana University

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Summary

Ejecta in SNe and NSMs may have enhanced neutrino opacity just prior to the r-process. Does this change initial conditions and thus yields?

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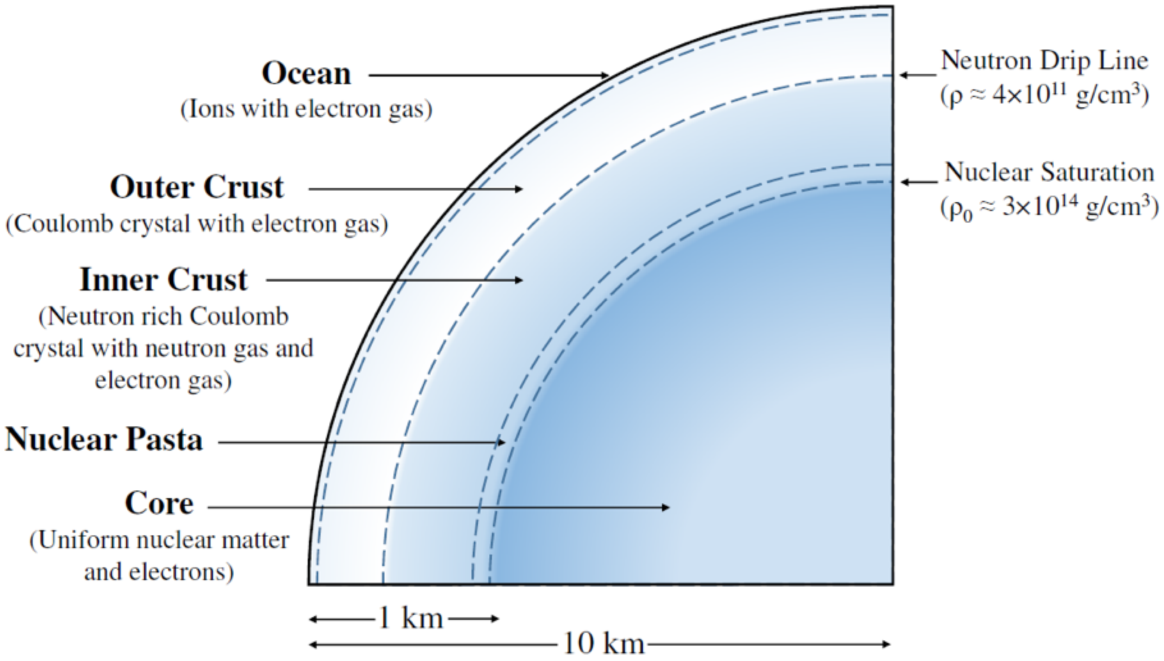
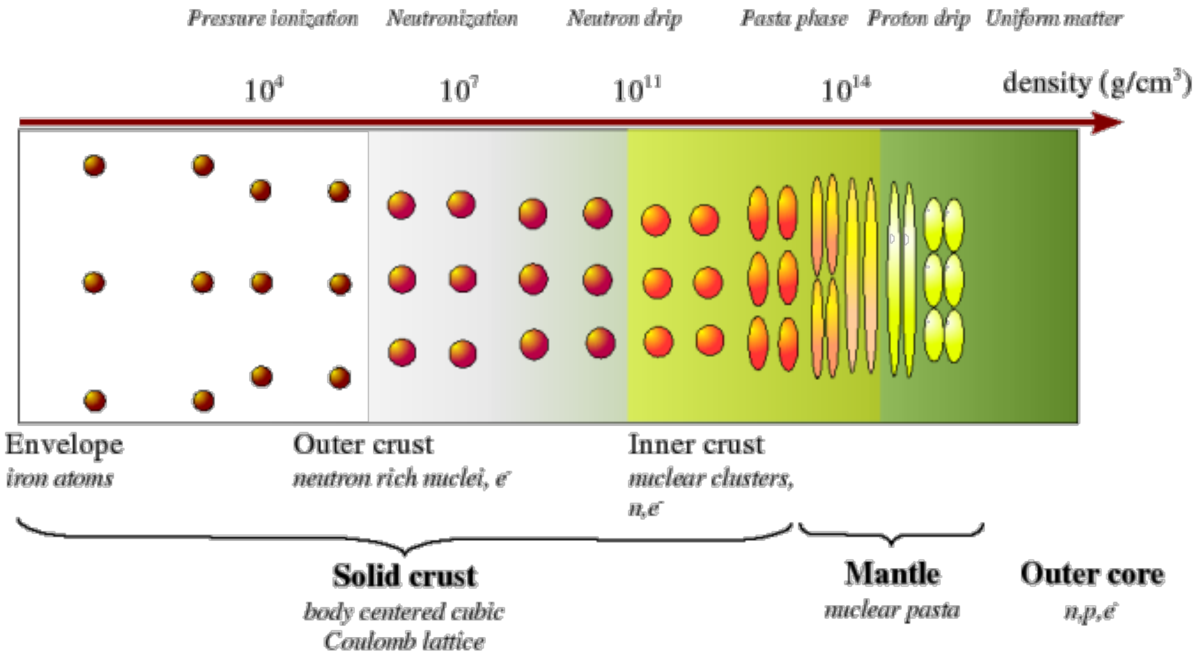
Nuclear Pasta

Neutron Star Structure

- What's inside a neutron star?



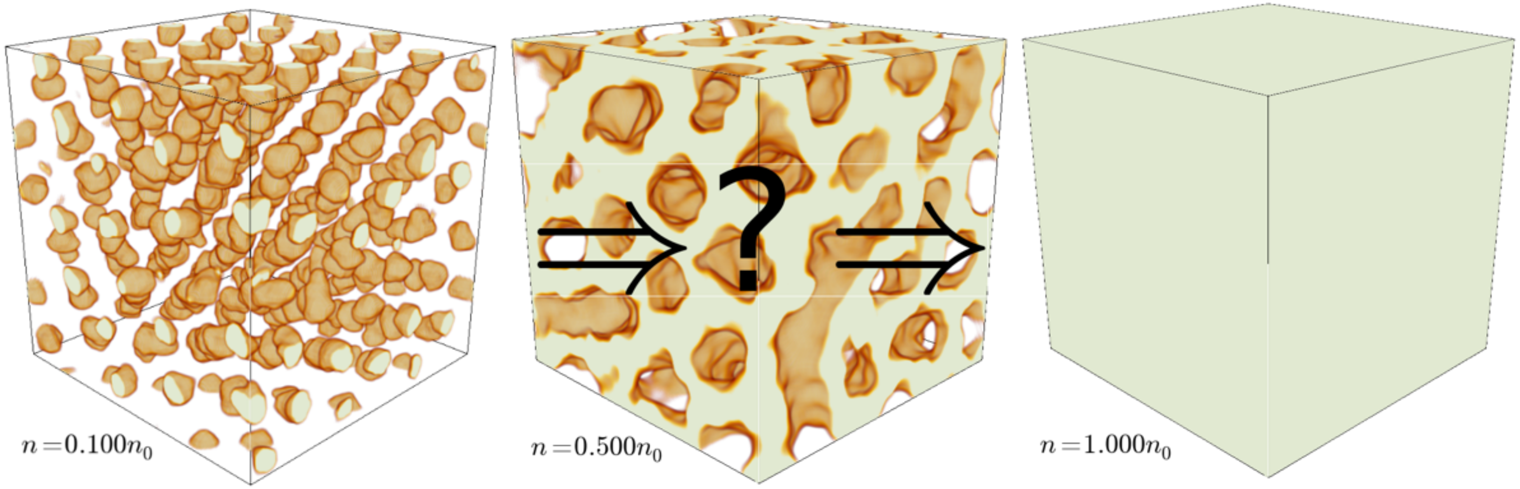


- Not just a "giant nucleus in space!"

Nuclear Pasta

- Neutron star core is uniform nuclear matter (n_0 = 2.4 × 10^{14} g cm^{-3})
- The crust is conventional, isolated nuclei
- What sort of nuclear phase transition must occur between these two phases of matter?

n << n_0 **n ≈ n_0** **n > n_0**



Non-Spherical Nuclei

- First theoretical models of the shapes of nuclei near n_0

  1983: Ravenhall, Pethick, & Wilson
  1984: Hashimoto, H. Seki, and M. Yamada

- *Frustration*: Competition between proton-proton Coulomb repulsion and strong nuclear attraction
- Nucleons adopt non-spherical geometries near the saturation density to minimize surface energy

Shape of Nuclei in the Crust of Neutron Star 321

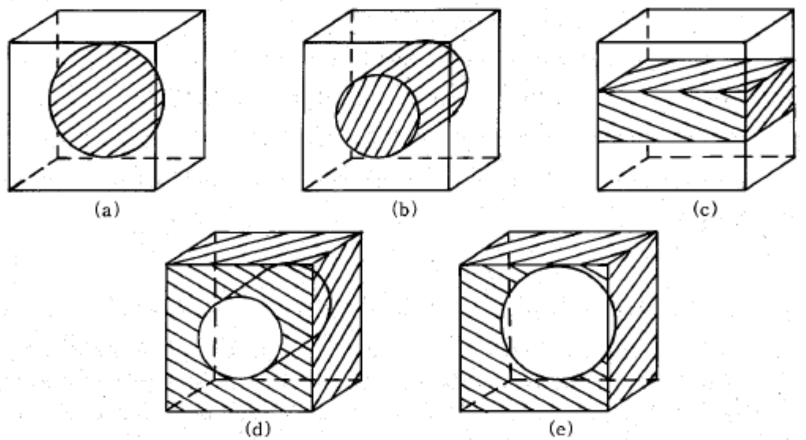
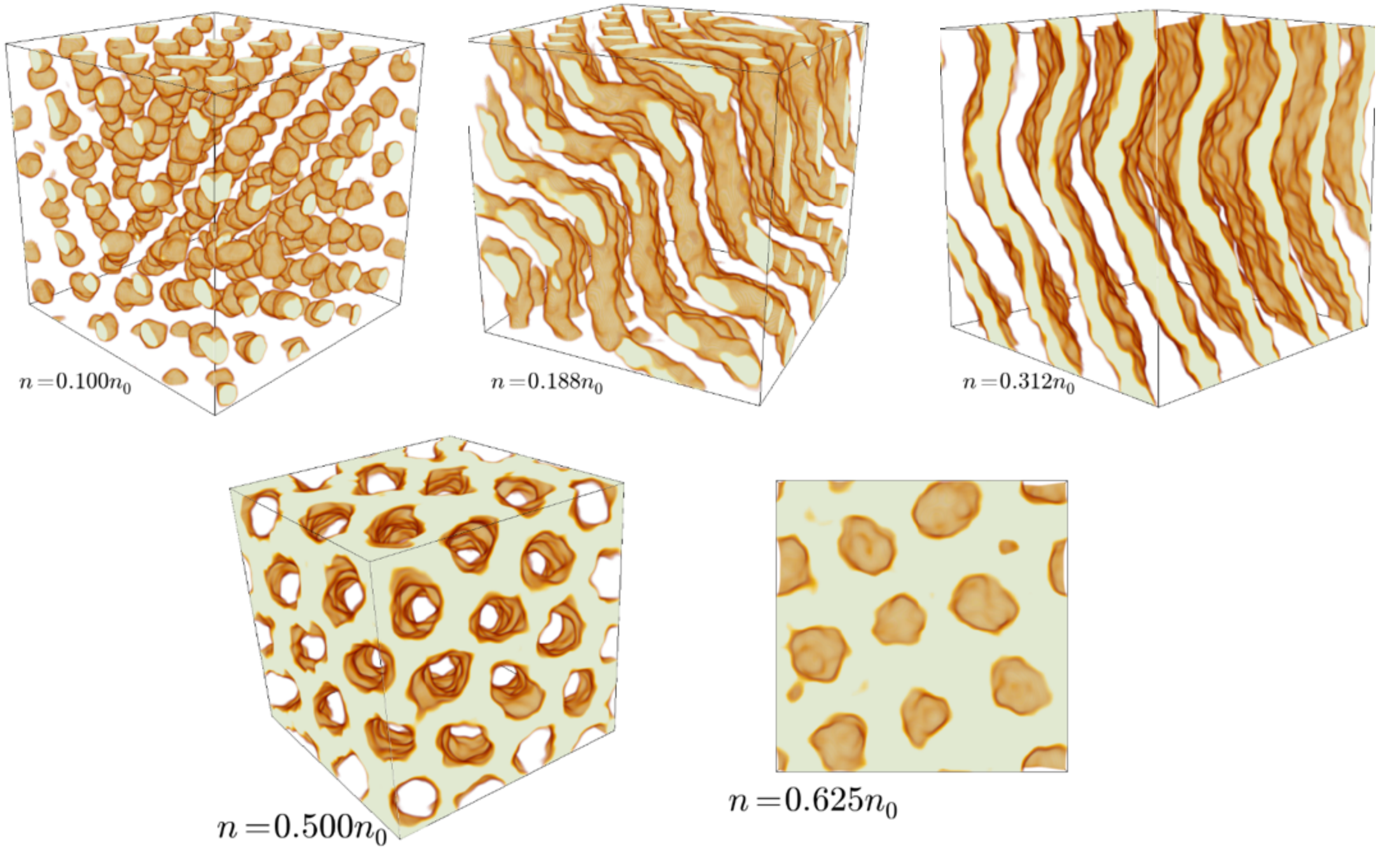


Fig. 1. Candidates for nuclear shapes. Protons are confined in the hatched regions, which we call nuclei. Then the shapes are, (a) sphere, (b) cylinder, (c) board or plank, (d) cylindrical hole and (e) spherical hole. Note that many cells of the same shape and orientation are piled up to form the whole space, and thereby the nuclei are joined to each other except for the spherical nuclei (a).

Nuclear Pasta



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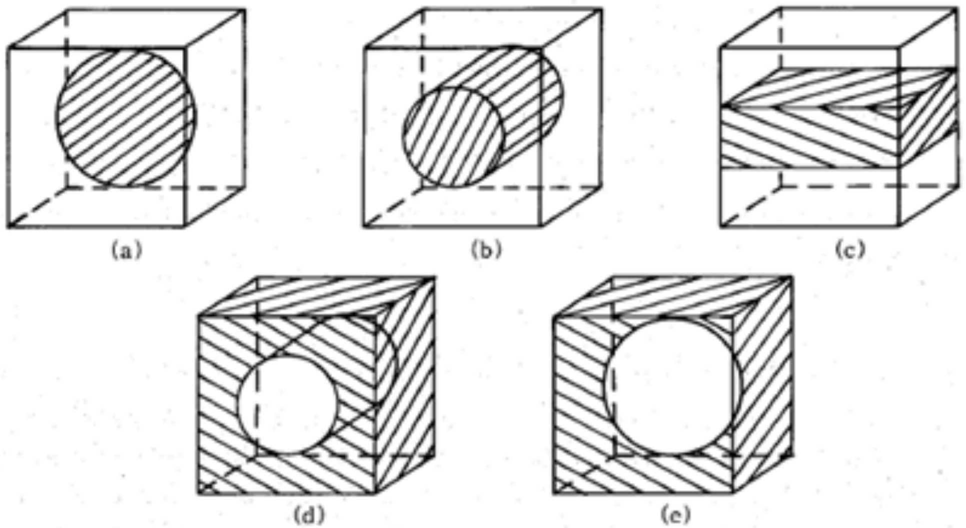

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Classical Pasta Formalism

- **Classical Molecular Dynamics** with IUMD on Big Red II

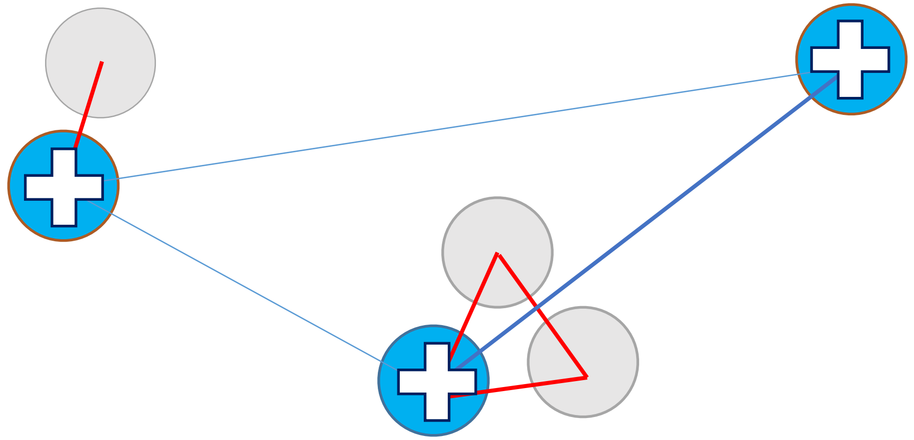
a	b	c	Λ	λ
110 MeV	-26 MeV	24 MeV	1.25 fm^2	10 fm

$$V_{np}(r_{ij}) = a e^{-r_{ij}^2/\Lambda} + [b - c] e^{-r_{ij}^2/2\Lambda}$$

$$V_{nn}(r_{ij}) = a e^{-r_{ij}^2/\Lambda} + [b + c] e^{-r_{ij}^2/2\Lambda}$$

$$V_{pp}(r_{ij}) = a e^{-r_{ij}^2/\Lambda} + [b + c] e^{-r_{ij}^2/2\Lambda} + \frac{\alpha}{r_{ij}} e^{-r_{ij}/\lambda}$$

- Short range nuclear force
- Long range Coulomb force



Nucleus	Monte-Carlo $\langle V_{tot} \rangle$ (MeV)	Experiment (MeV)
^{16}O	-7.56±0.01	-7.98
^{40}Ca	-8.75±0.03	-8.45
^{90}Zr	-9.13±0.03	-8.66
^{208}Pb	-8.2 ±0.1	-7.86

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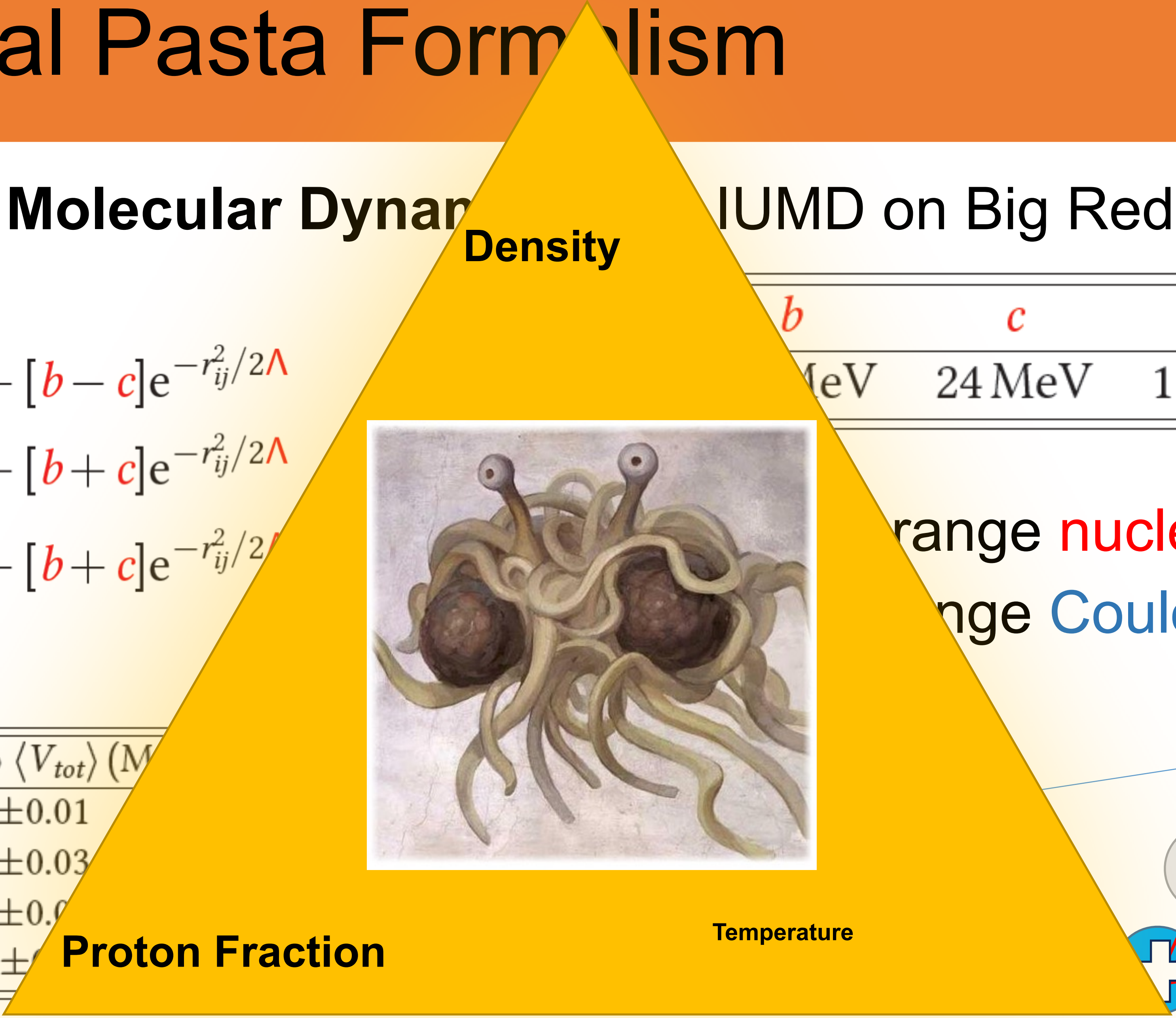
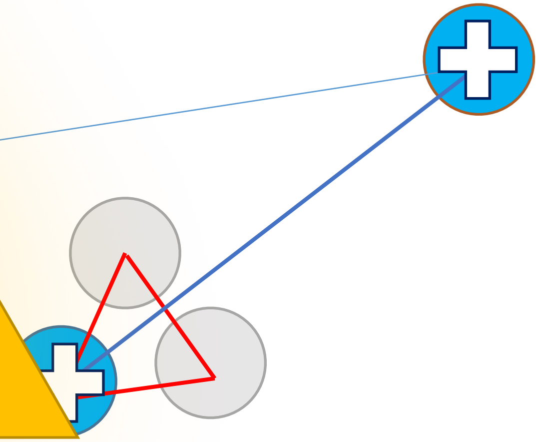
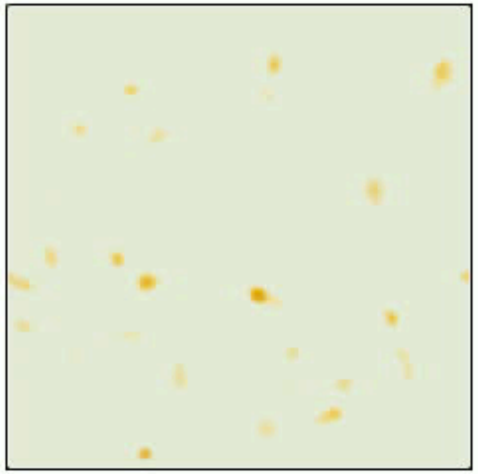




Gold Nucleus
For Scale

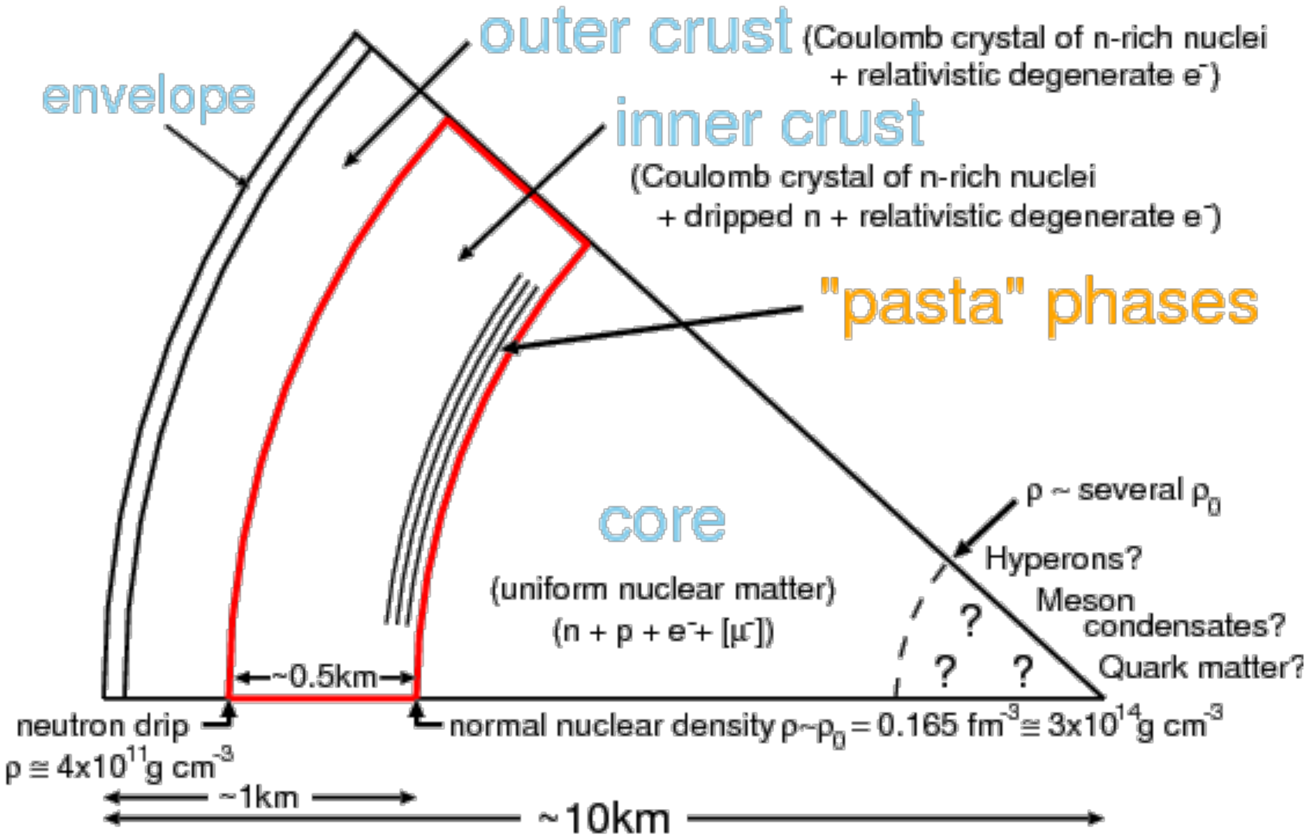


$$n = 0.1200 \mathrm{fm}^{-3}$$

Phases of Pasta

- Where does pasta form?

1) Inner crust of neutron stars



(Watanabe et al. 2011)

Phases of Pasta

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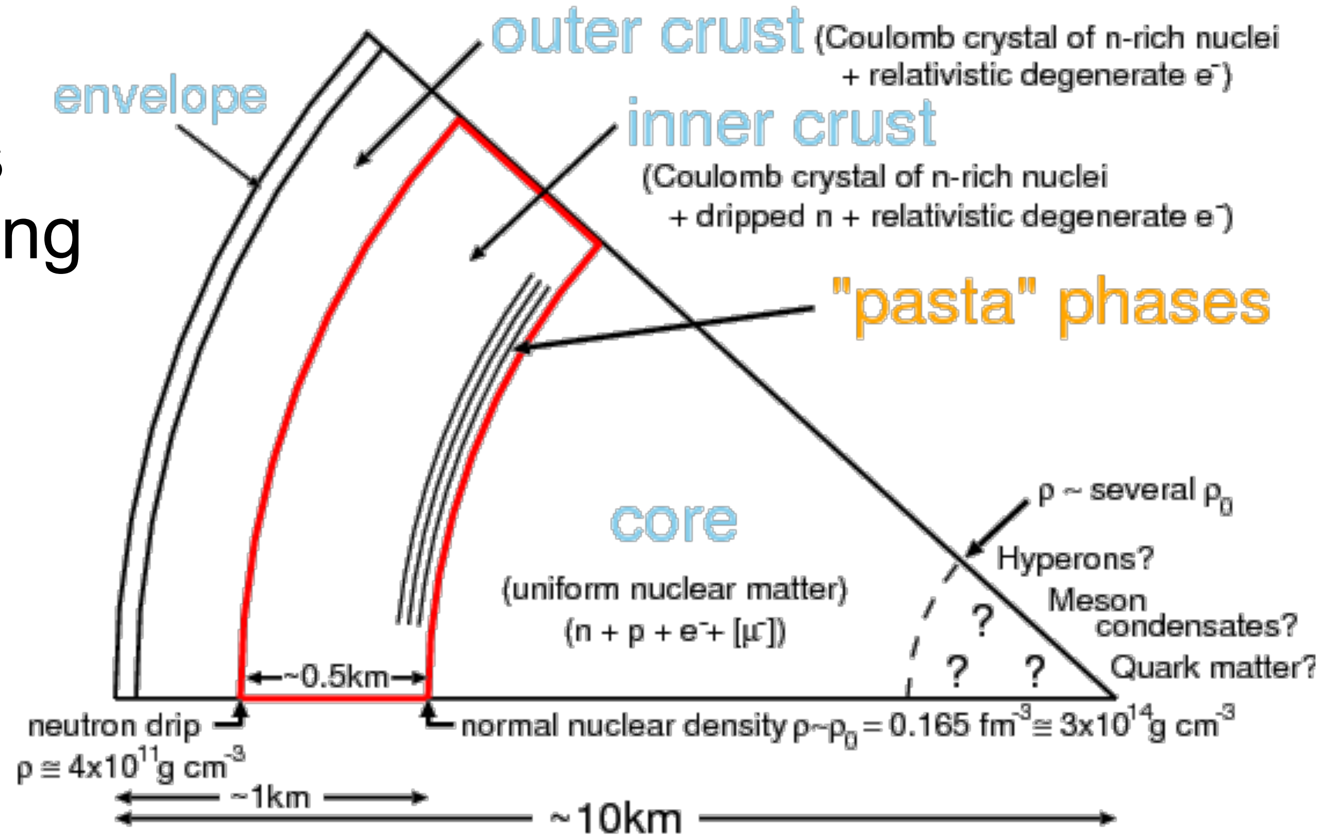

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1) Temperature: T $\lesssim$ 10 MeV
2) Density: 0.1 $n_0 \lesssim n \lesssim 1.0\ n_0$
3) Proton Fraction: 0.1 $\lesssim$ Ye

(Sonoda et al., 2008)
(Schuetrumpf et al. 2013)
(Caplan et al., in prep)

Phases of Pasta

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   … but that's not interesting
2) Supernova?
3) Neutrons star mergers?

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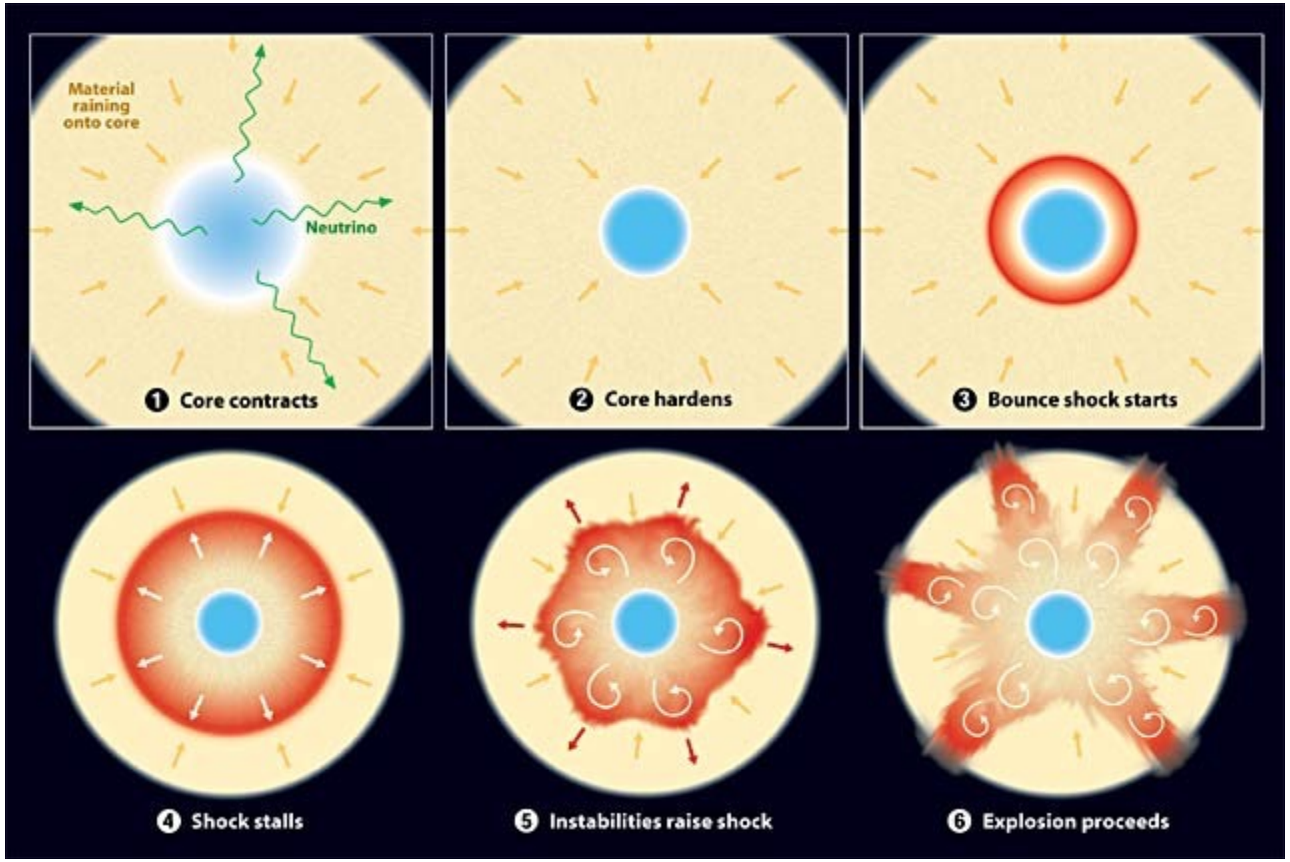
Where in these do we find these conditions?

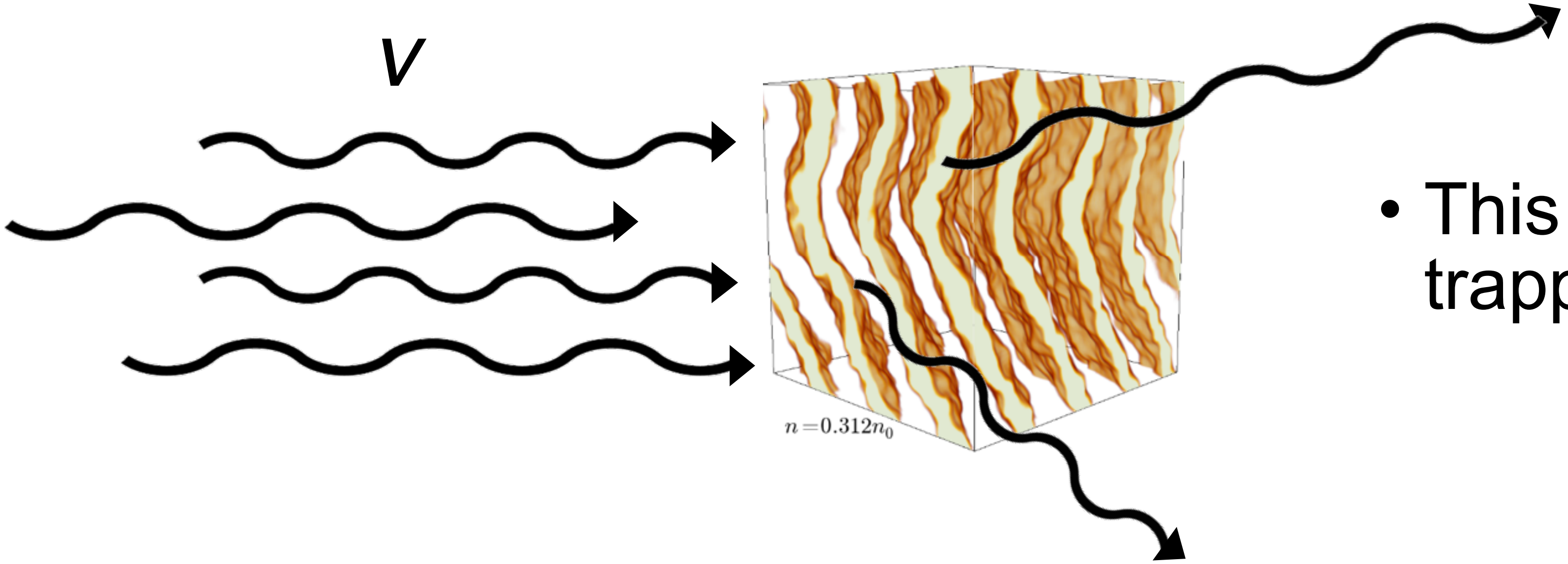
Supernova

- Pasta has been studied for its role in supernova
- When the core collapses to form a proto-neutron star, it *deleptonizes*.
- The flux of 10^{58} neutrinos from the core interacts with the infalling gas, blowing off the outer layers



Supernova

- Pasta has been studied for its role in supernova
- Pasta ‘pieces’ have a separation comparable to neutrino wavelengths, so neutrinos can scatter coherently from pasta



- This makes pasta opaque, trapping neutrinos

Supernova

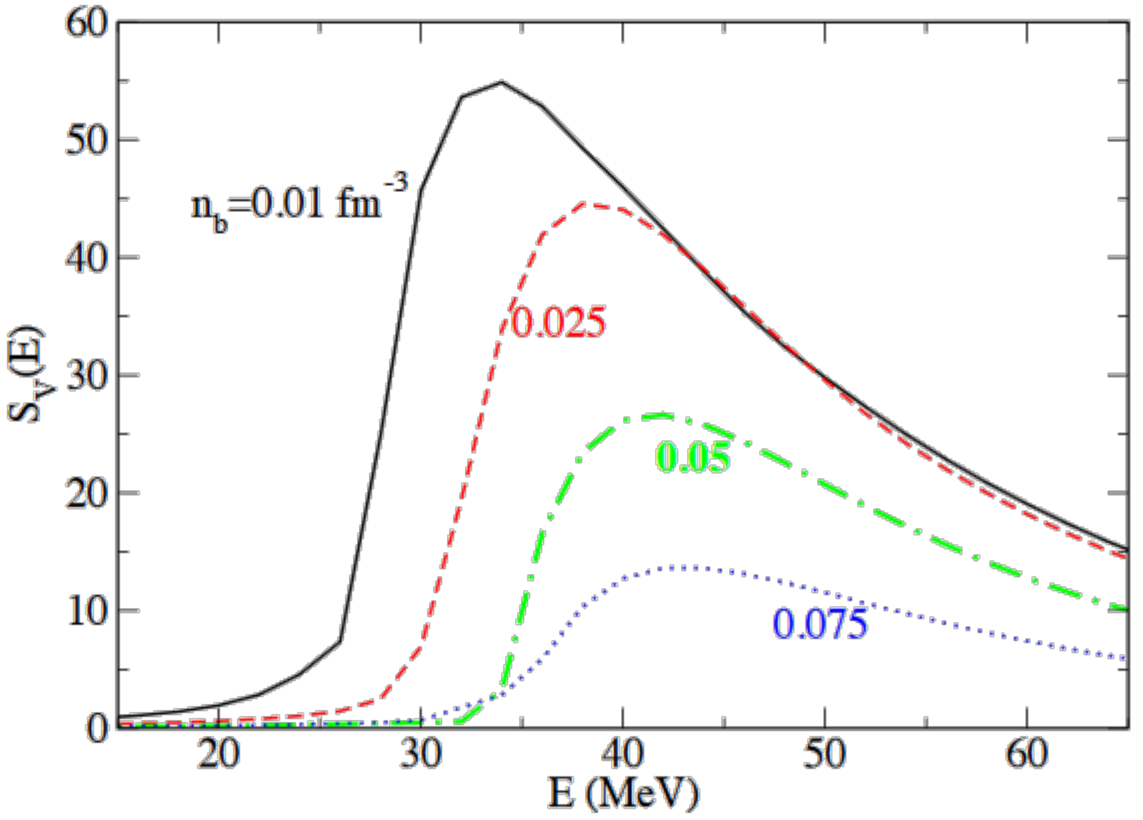
- We calculate the opacity of pasta, or mean free path, from molecular dynamics simulations

$$S_i(\boldsymbol{q}) = \langle \rho_i^*(\boldsymbol{q},t)\rho_i(\boldsymbol{q},t)\rangle_t - \langle \rho_i^*(\boldsymbol{q},t)\rangle_t \langle \rho_i(\boldsymbol{q},t)\rangle_t$$

$$\rho_i(\boldsymbol{q},t) = N_i^{-1/2} \sum_{j=1}^{N_i} e^{i\boldsymbol{q}\cdot\boldsymbol{r}_j(t)}$$

$$\lambda_t^{-1} = \sigma_t^0 \rho_n \langle S(E_\nu)\rangle$$

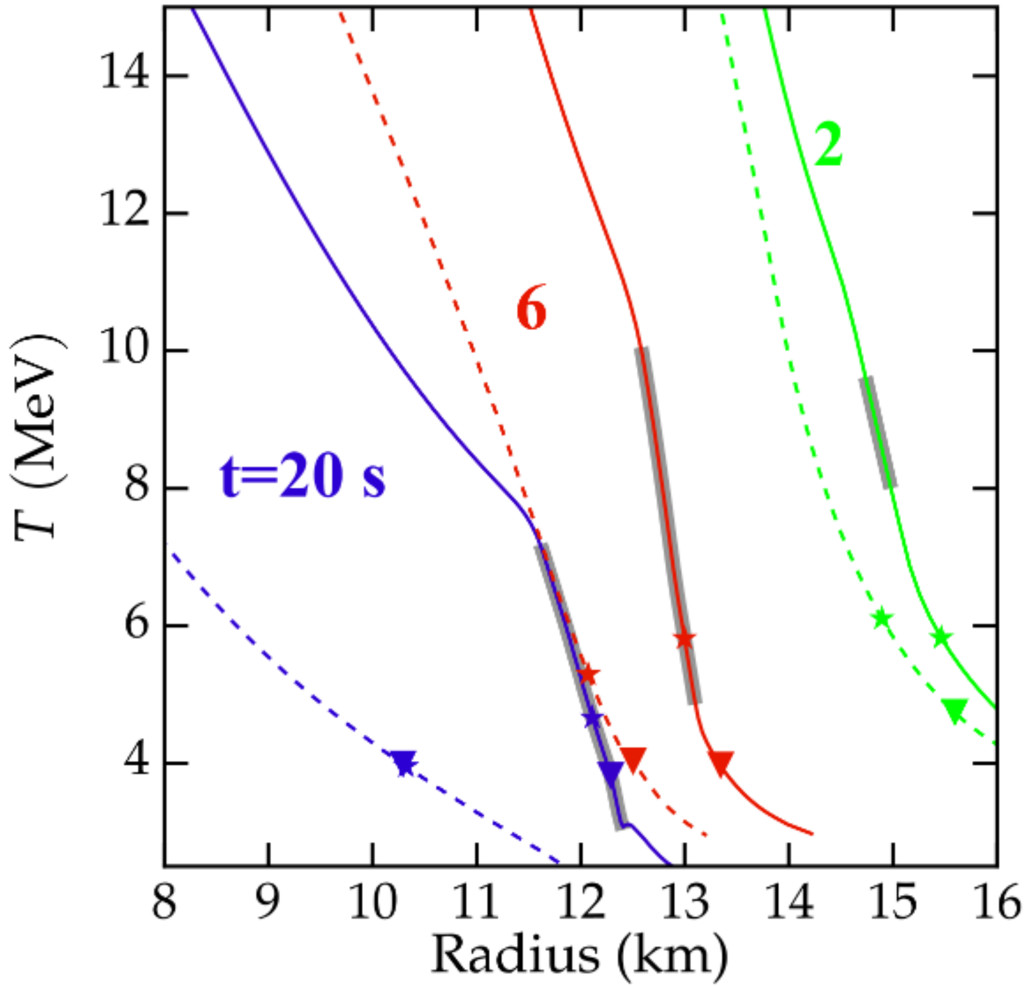
(Horowitz et al., 2004)
(Caplan et al., 2017)



(Horowitz et al., 2016)

Supernova

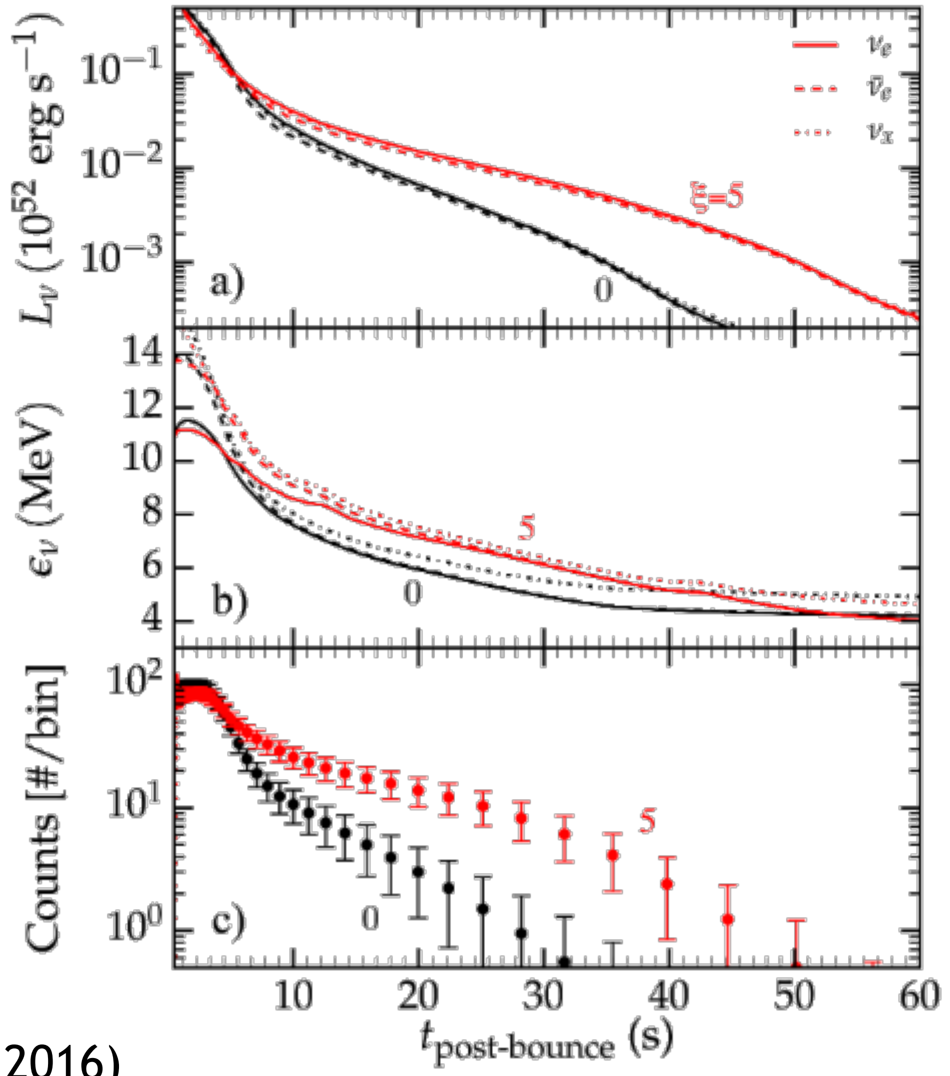
- What happens when you include pasta opacity in supernova simulations?
- 1D Simulation of supernova with pasta (solid) and without pasta (dashed)
- Pasta gives supernova a hotter, extended atmosphere.
- What does this do to neutrino luminosities?



(Horowitz et al., 2016)

Supernova

- What does this do to neutrino luminosities?
- Well, we observed ~20 neutrinos from SN1987A. With SuperK, we expect several thousand detections.
- Pasta has a distinct effect on supernova neutrino signals:
    - More energetic neutrinos at later times
    - More neutrinos at late times after core collapse



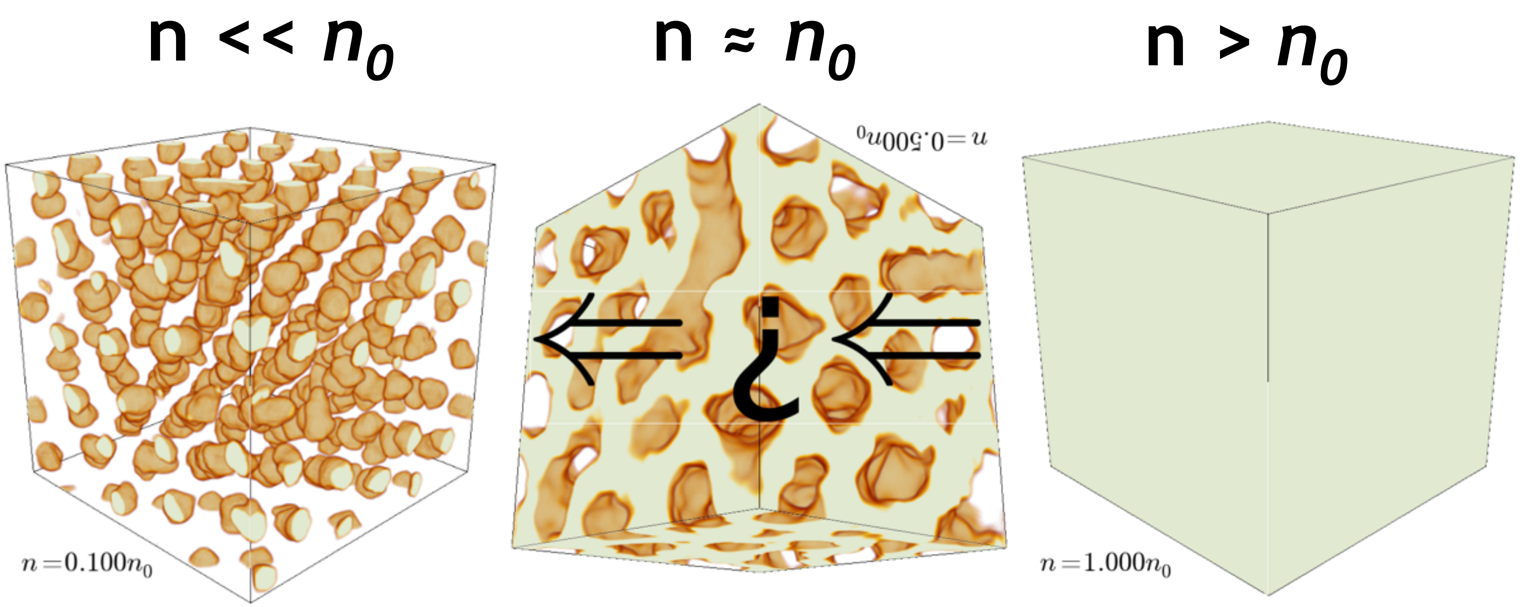
(Horowitz et al., 2016)

Open Questions

- What is the neutrino opacity of pasta?
- What effect does this neutrino opacity have on supernova?
- Certainly, the enhanced neutrino opacity should affect the proton fraction of the pasta. This is material that is hot, dense, and neutron rich, and may undergo the r-process. How does pasta change the r-process?

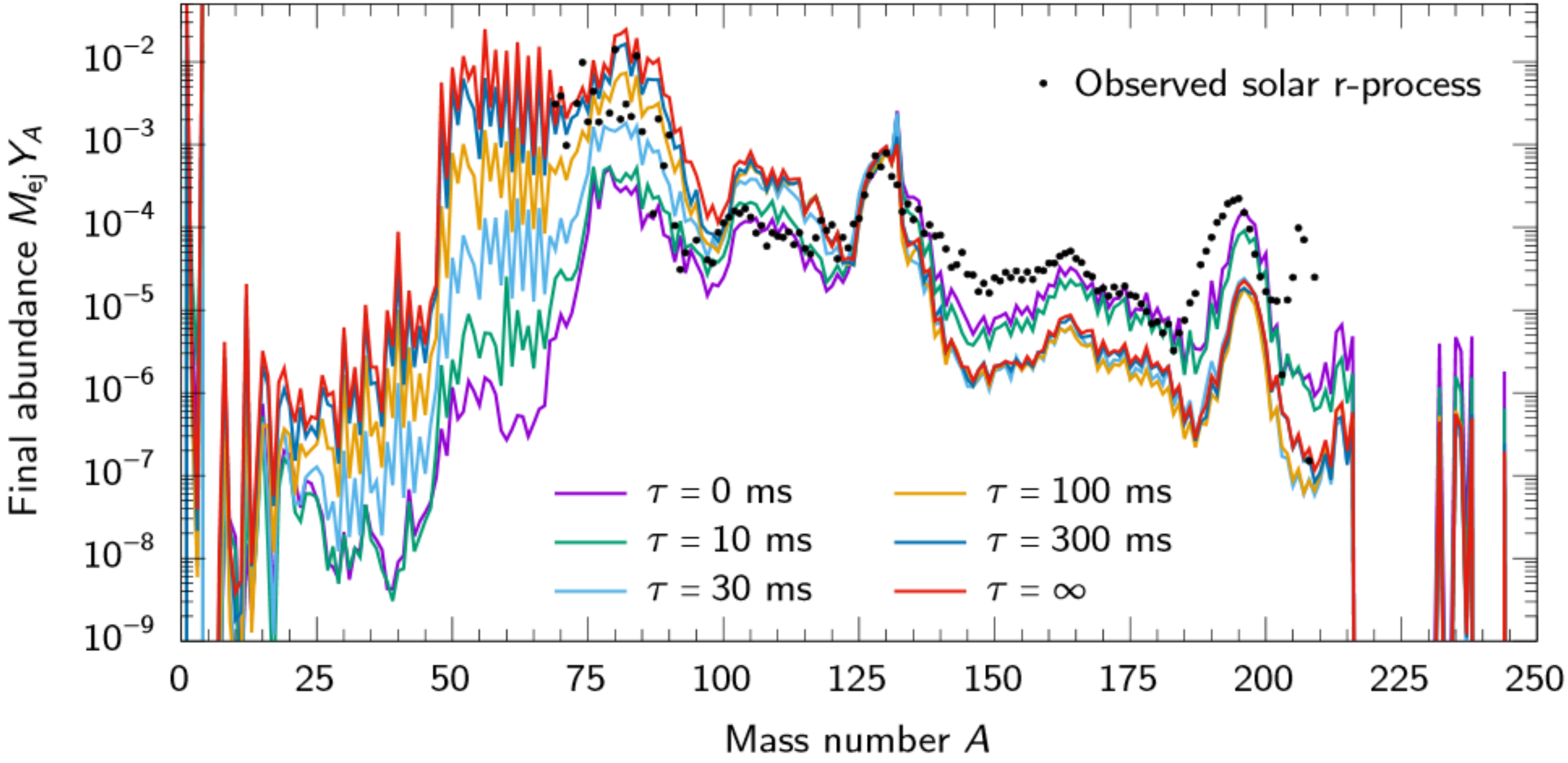
Neutron Star Mergers

- What about neutron star mergers?
- It's like a supernova run in reverse…
- Ejecta may pass through pasta phases



Neutron Star Mergers

- One recent result (Lippuner, 2017), the lifetime of the hypermassive NS in a merger strongly effects r-process yields



Forging Connections

- Theory can provide the modified neutrino opacities for pasta matter.
- Can simulation/nuclear reaction network codes be modified to study the effect that pasta plays on the ejecta?