Supernovae neutrino-pasta interaction

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For INT Flavor Observations with Supernova Neutrinos workshop

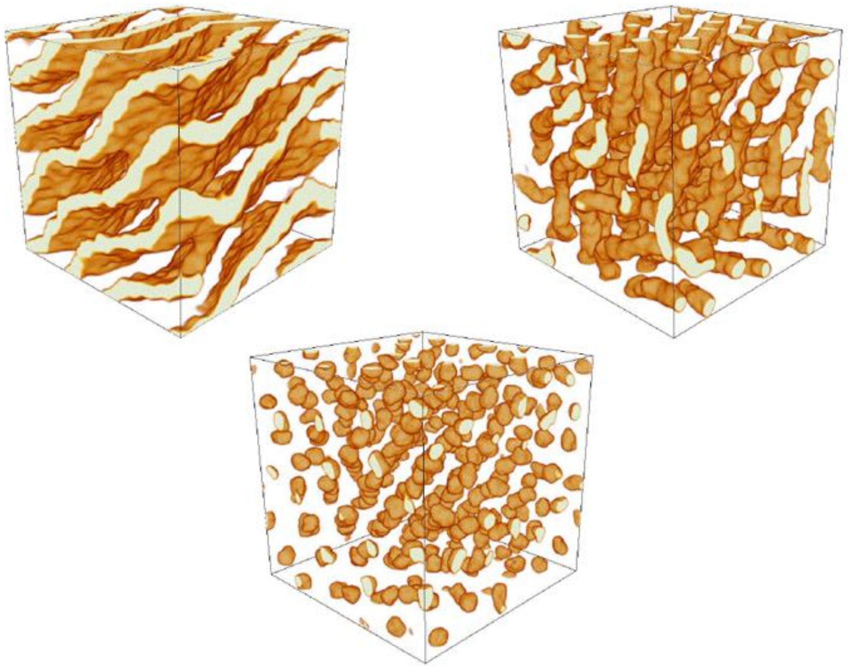
Pasta

Supernovae

Inside

Pasta

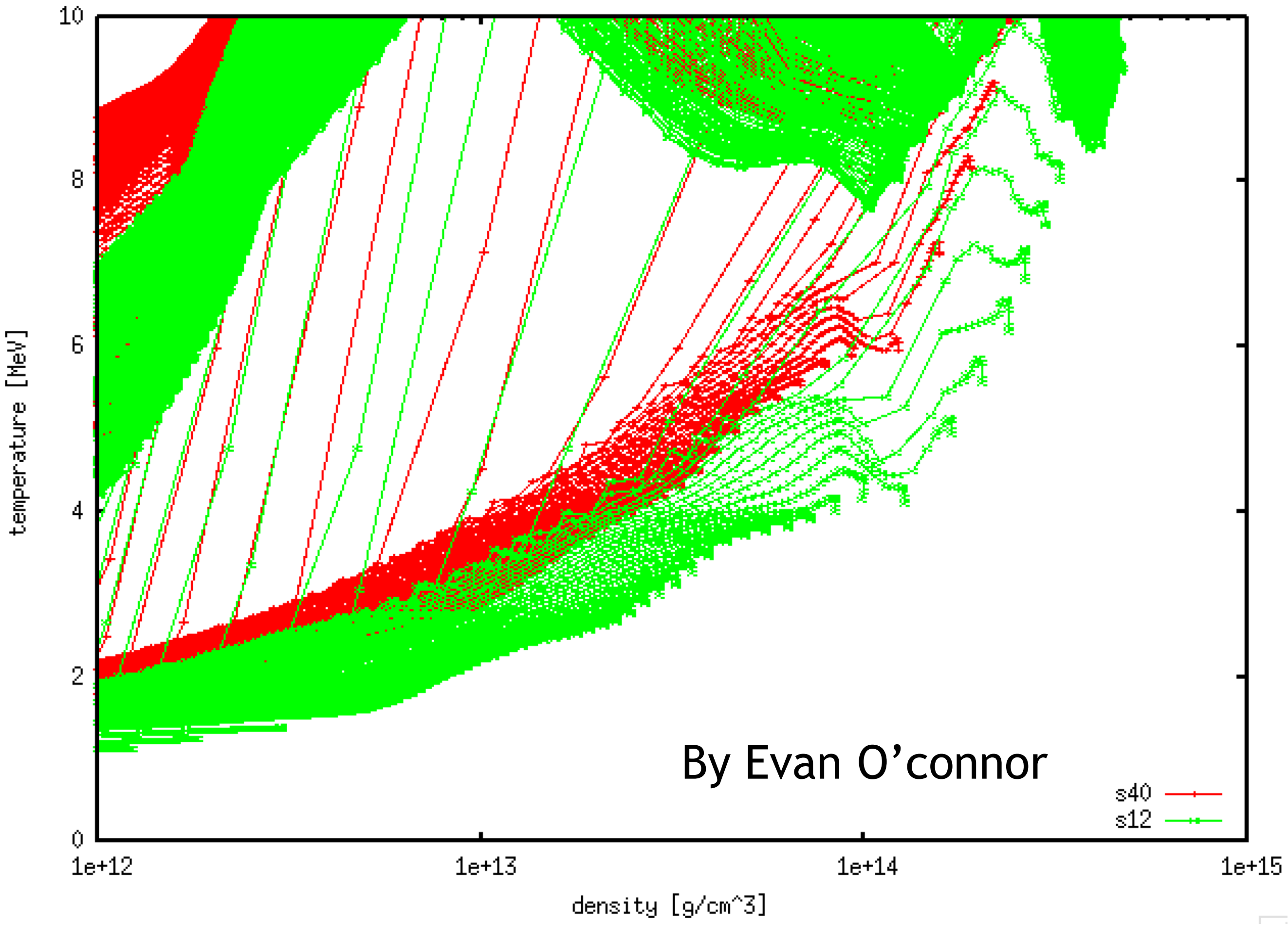
Supernovae



Inside

Density: 0.1 to 0.01 fm^{-3} (sub nuclear density)
Temperature: in the order of several MeV
Result from competition between nuclear attraction and Coulomb repulsion

1D Supernovae Simulation



Pasta might form during collapse and then is melted by the shock wave. Another possible stage for pasta formation is the proto-neutron star cooling phase. When the temperature decreases the pasta will reform.

Neutrino-Pasta interaction

The free-space cross section for neutrino-nucleon elastic scattering is given by

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\upsilon^2}{4\pi^2}\left[C_a^2(3 - cos\theta) + C_v^2(1 + cos\theta)\right] \qquad (1)$$

only the contribution from the vector current is coherent. The strong spin and isospin dependence of the axial vector current reduces the coherence. Therefore, in this work we only focus on the **coherence effect of the vector part** and the cross section per neutron can be expressed as

$$\frac{1}{N}\frac{d\sigma}{d\Omega} = S(q)\frac{G_F^2 E_\upsilon^2}{16\pi^2}(1 + cos\theta) \qquad (2)$$

$S(q)$

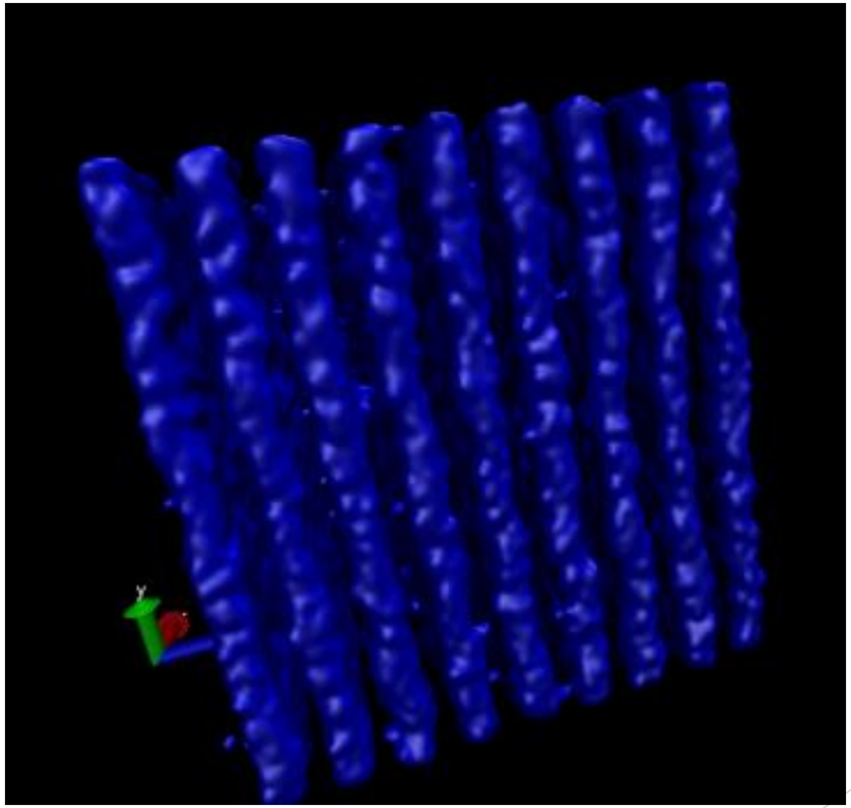
↑

Classical Molecular Dynamics simulation for nuclear Pasta at different densities and temperatures

Static Structure factor S(q) for pasta at density 0.05 fm^{-3} and temperature 1 MeV

$$S(\boldsymbol{q}) = \frac{1}{N}\int_0^\infty S(\boldsymbol{q},w)dw = \frac{1}{N}\left(\langle 0|\hat{\rho}^{+}\hat{\rho}|0\rangle - \langle 0|\hat{\rho}|0\rangle^2\right) \quad \textbf{(3)}$$

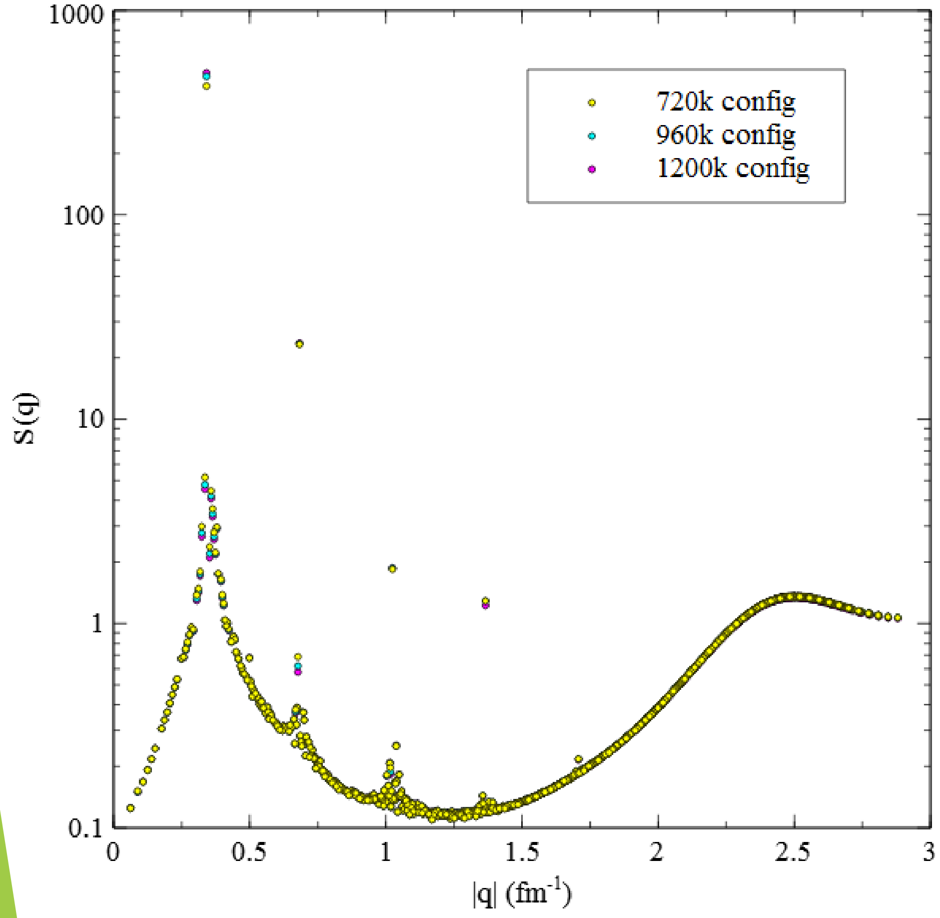
$$\rho(\mathbf{q}) = \sum_{i=1}^{N} \exp(i\mathbf{q}\cdot\mathbf{r}_i)$$



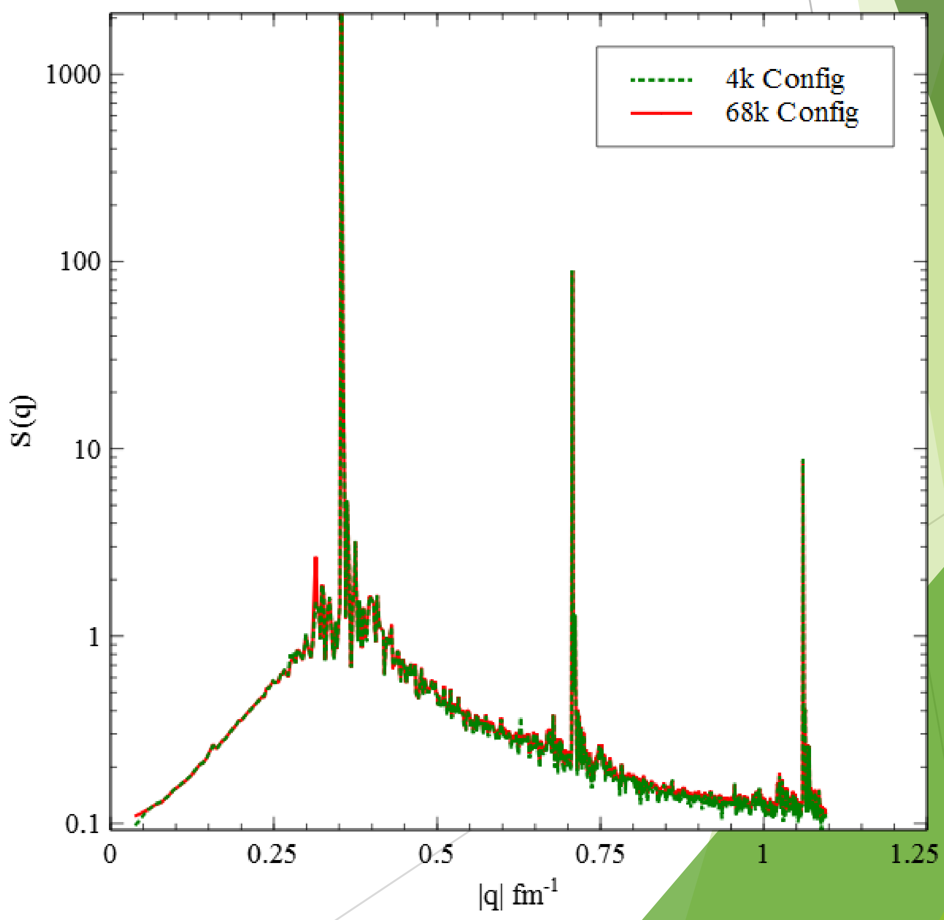
204,800 nucleons simulation at 1 MeV, 0.05 fm $^{-3}$

Static Structure factor S(q) for pasta at density 0.05 fm^{-3} and temperature 1 MeV

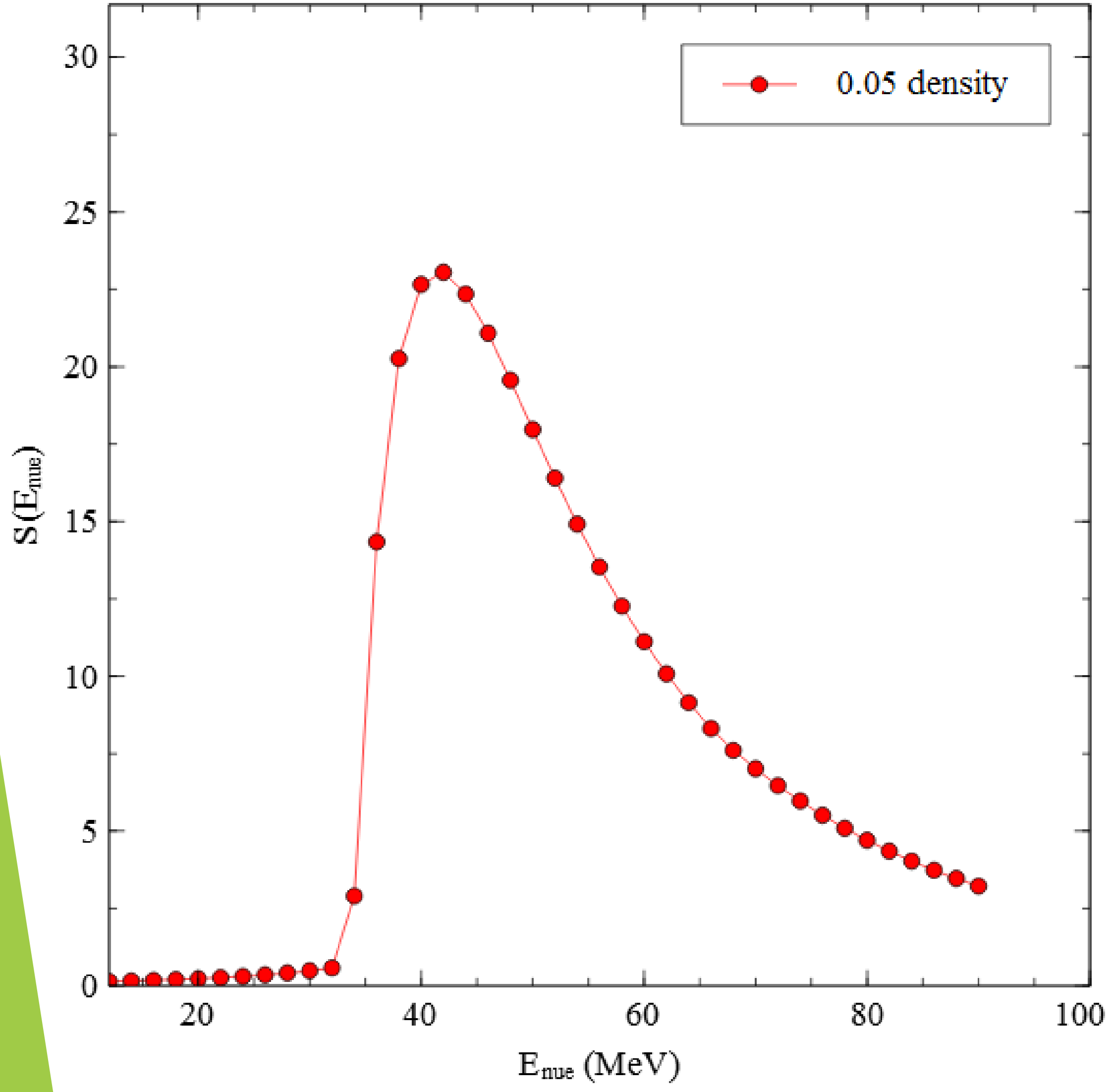
Angle averaged S(q) based on the simulation of 51,200 nucleons



Angle averaged S(q) based on the simulation of 204,800 nucleons



Angle averaged S(E_ν) for pasta at 1 MeV and 0.05 fm^{-3}



$$\langle S(E_\nu)\rangle \equiv \frac{3}{4}\int_{-1}^{1} dx(1-x^2)S\big(q(x,E_\nu)\big)$$

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

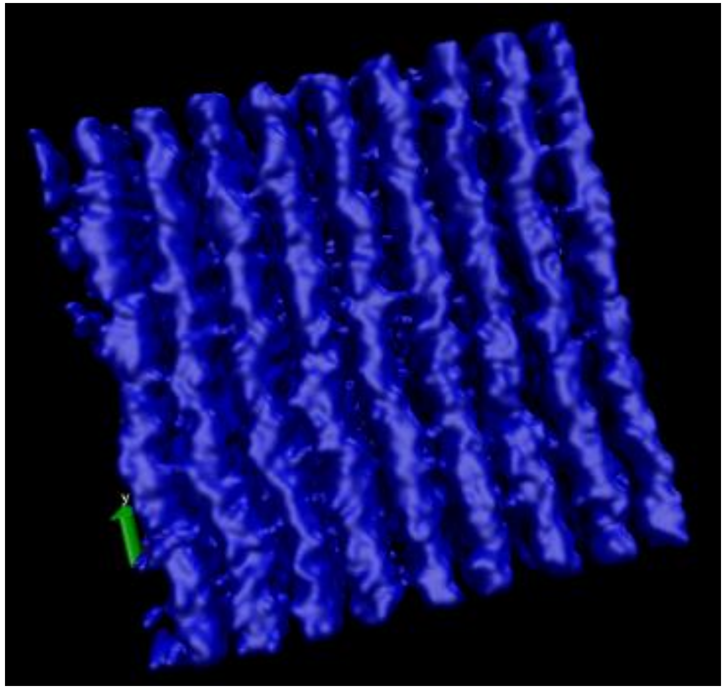
The S(E_υ) calculation for lasagna pasta phase is very sensitive on the delicate S(q) peak structure. To have a precise calculation for S(E), maybe a larger MD simulation giving more detail of the S(q) structure is necessary.

What will happen in higher temperature??

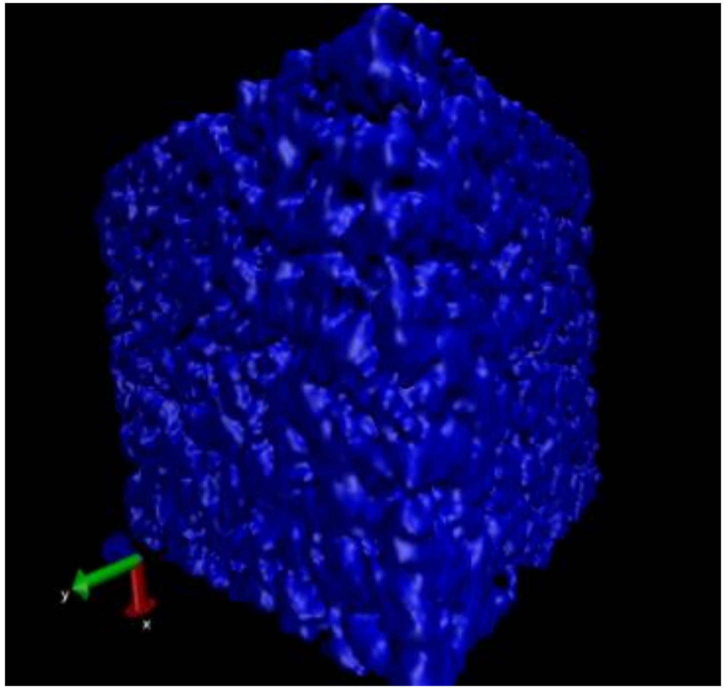
Melted Pasta??

pasta at 0.05 fm^{-3} and at different temperatures

1.5 MeV



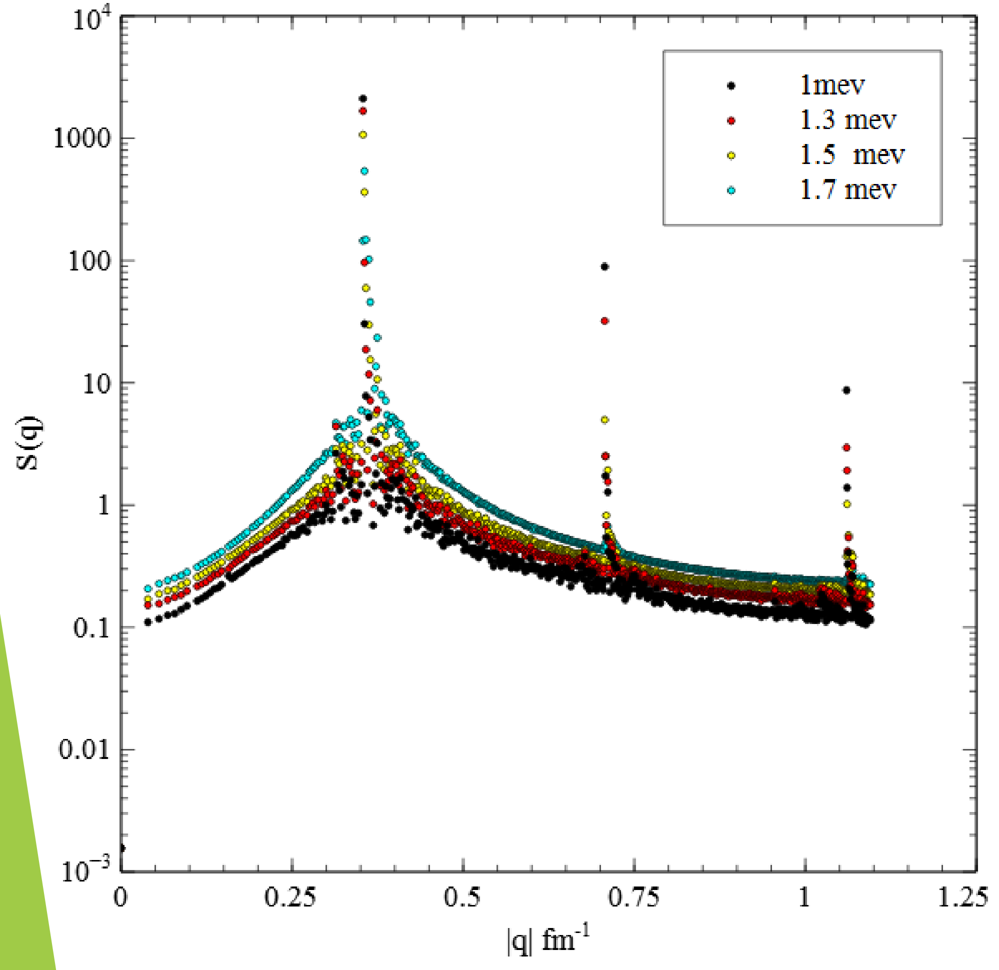
1.9 MeV

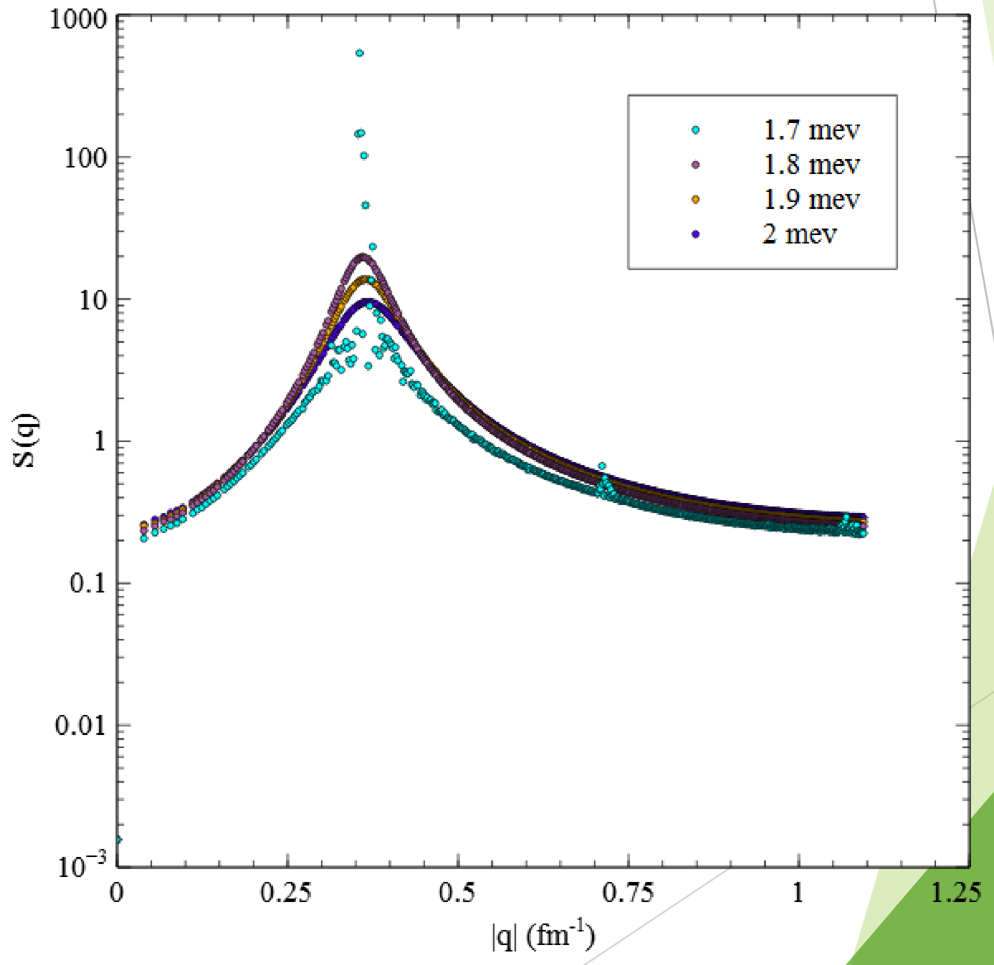


It seems that classical heat capacity is too large. So instead we use a lower effective temperature in classical MD simulations that roughly corresponds to a higher temperature for a full quantum calculation.

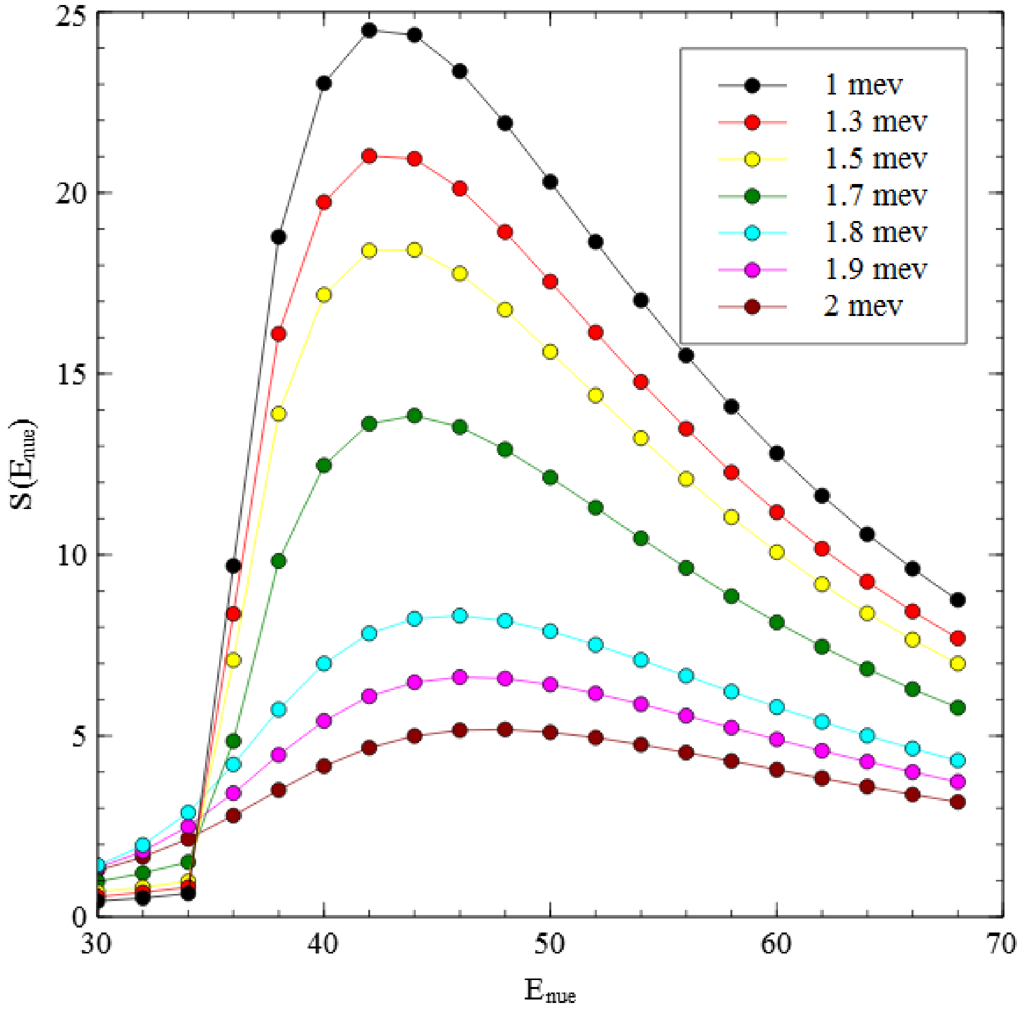
Quantum (mean filed) calculations find melting temperatures for pasta of order 10-14 MeV. However hard to calculate S_q directly from quantum calculation.

Angle averaged S(q) for pasta at 0.05 fm^{-3} and at different temperatures





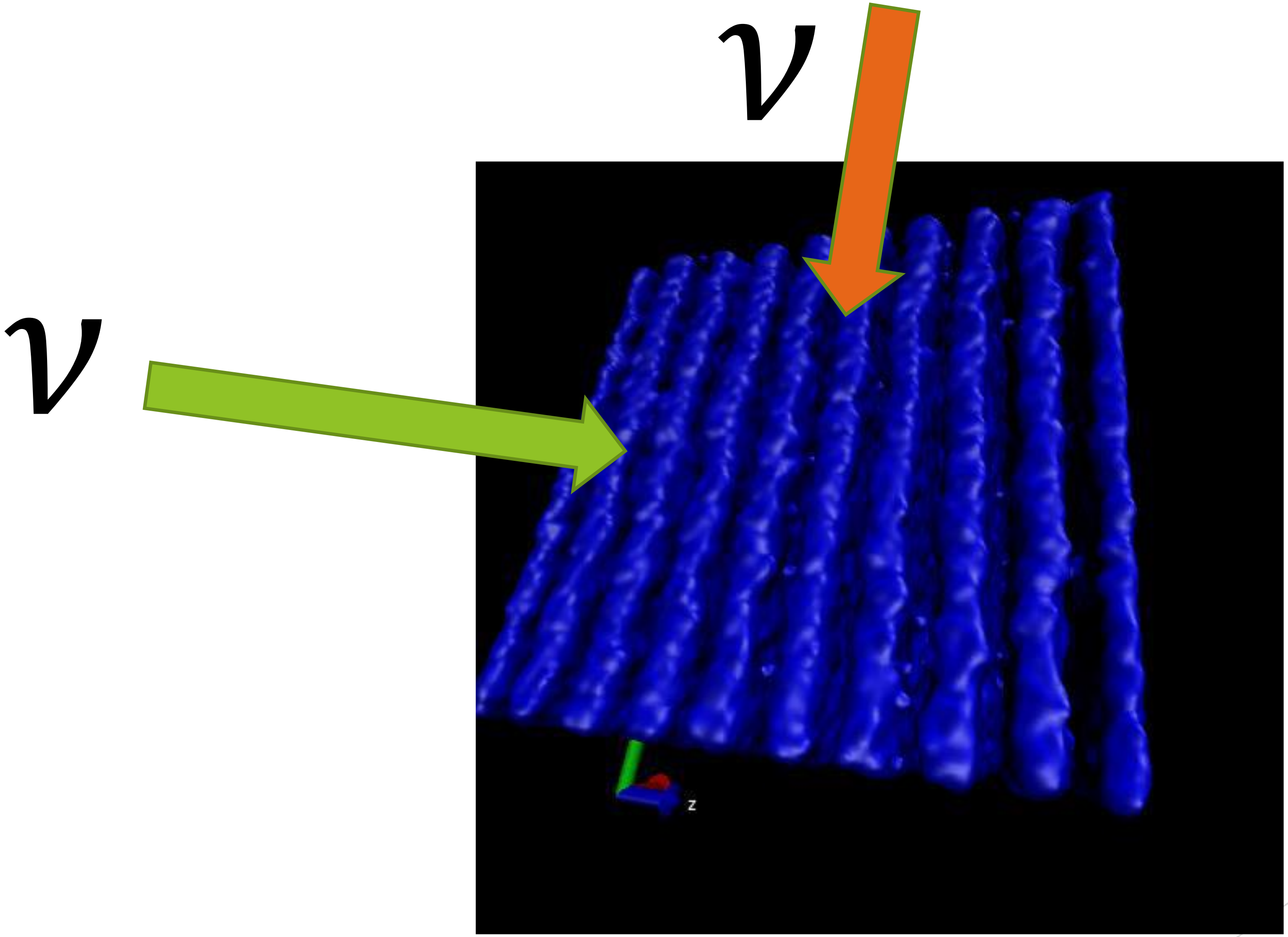
Angle averaged S(E_ν) for pasta at different temperatures and 0.05 fm^{-3}



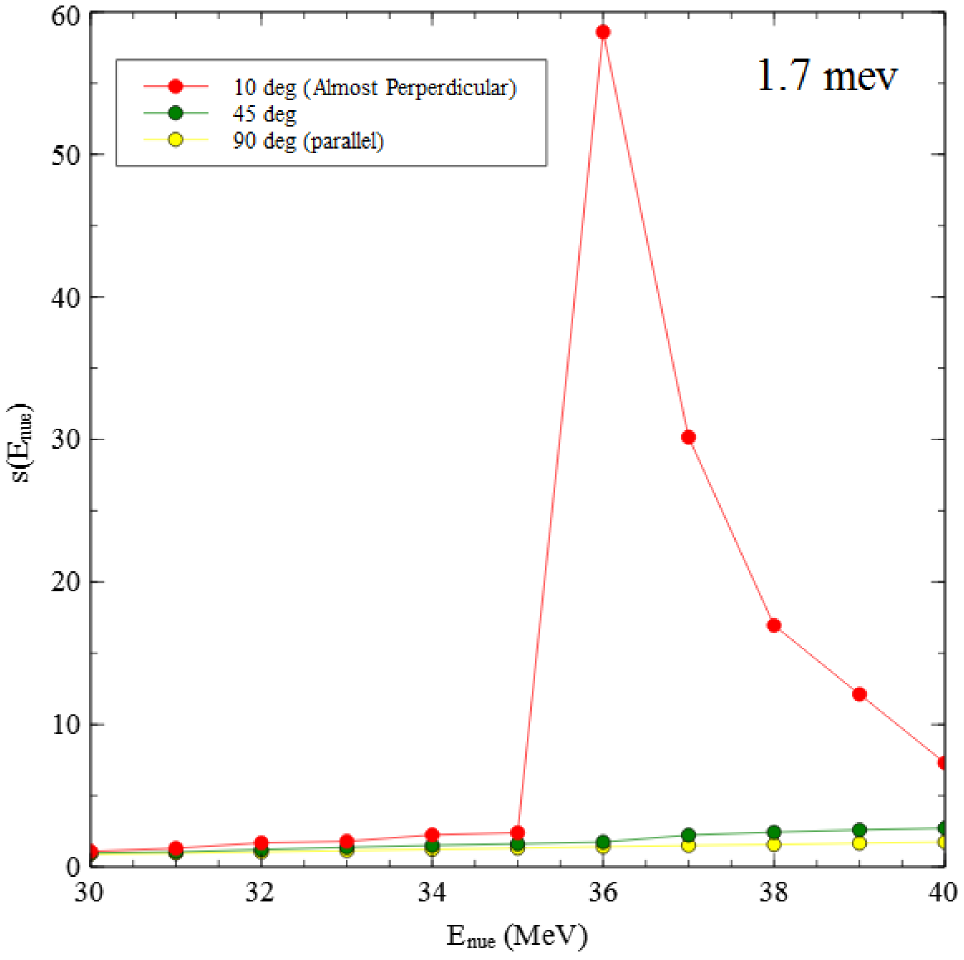
Asymmetric Pasta??

Neutrinos with different incident Directions experience different Opacities in the lasagna pasta

Angle dependent S(E_ν)



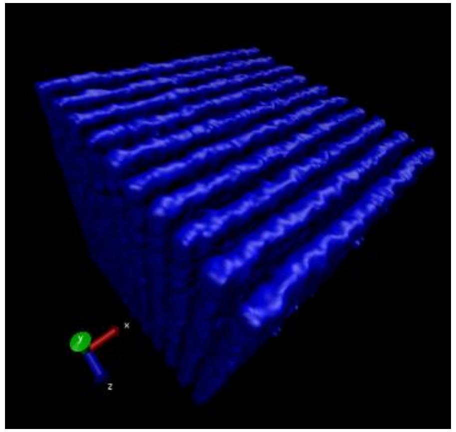
Angle dependent S(E_ν) for pasta at 1.7 MeV and 0.05 fm^{-3}



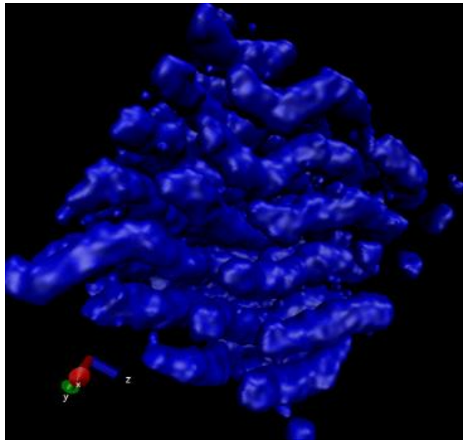
Pasta at different densities?

Angle averaged S(q) for pasta at different densities and at 1 MeV

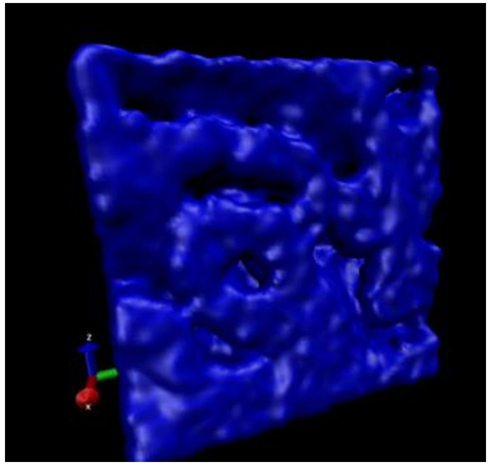
0.05 fm^{-3}

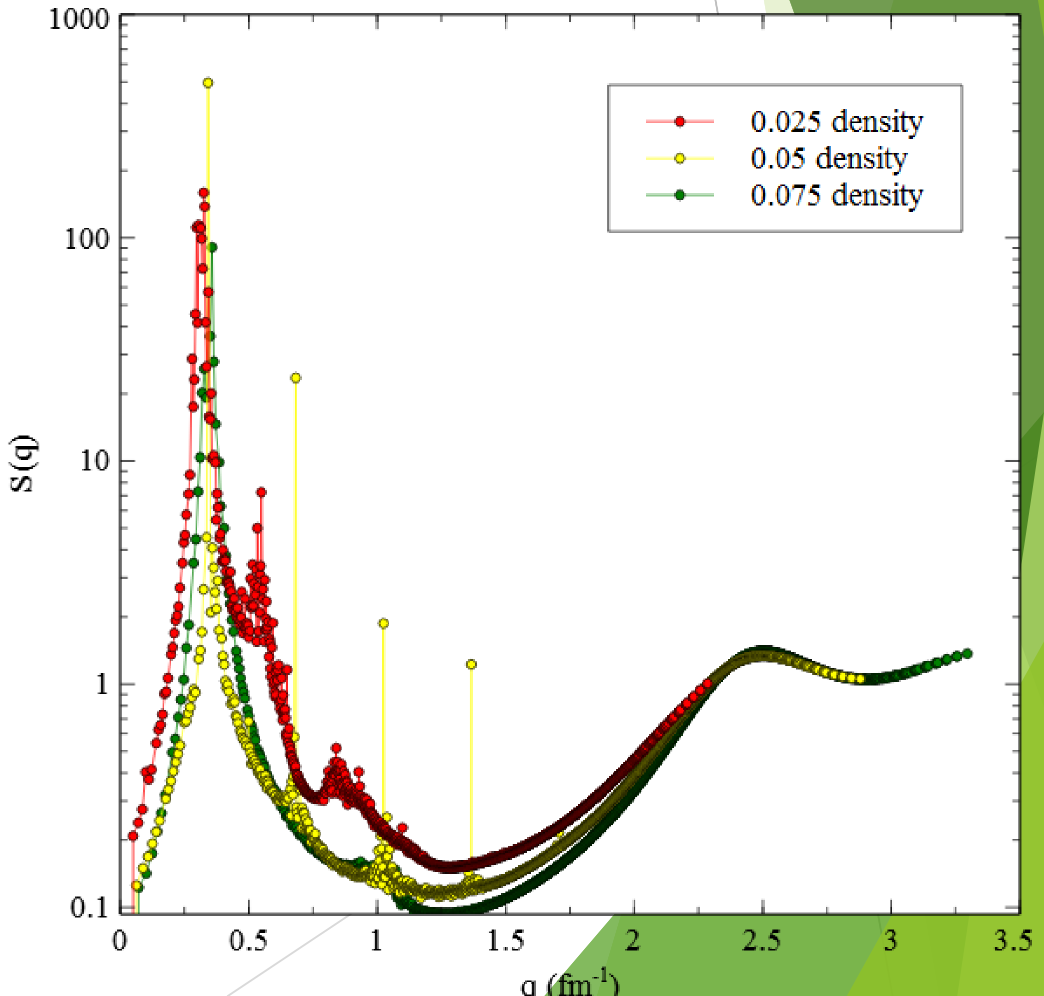


0.025 fm^{-3}

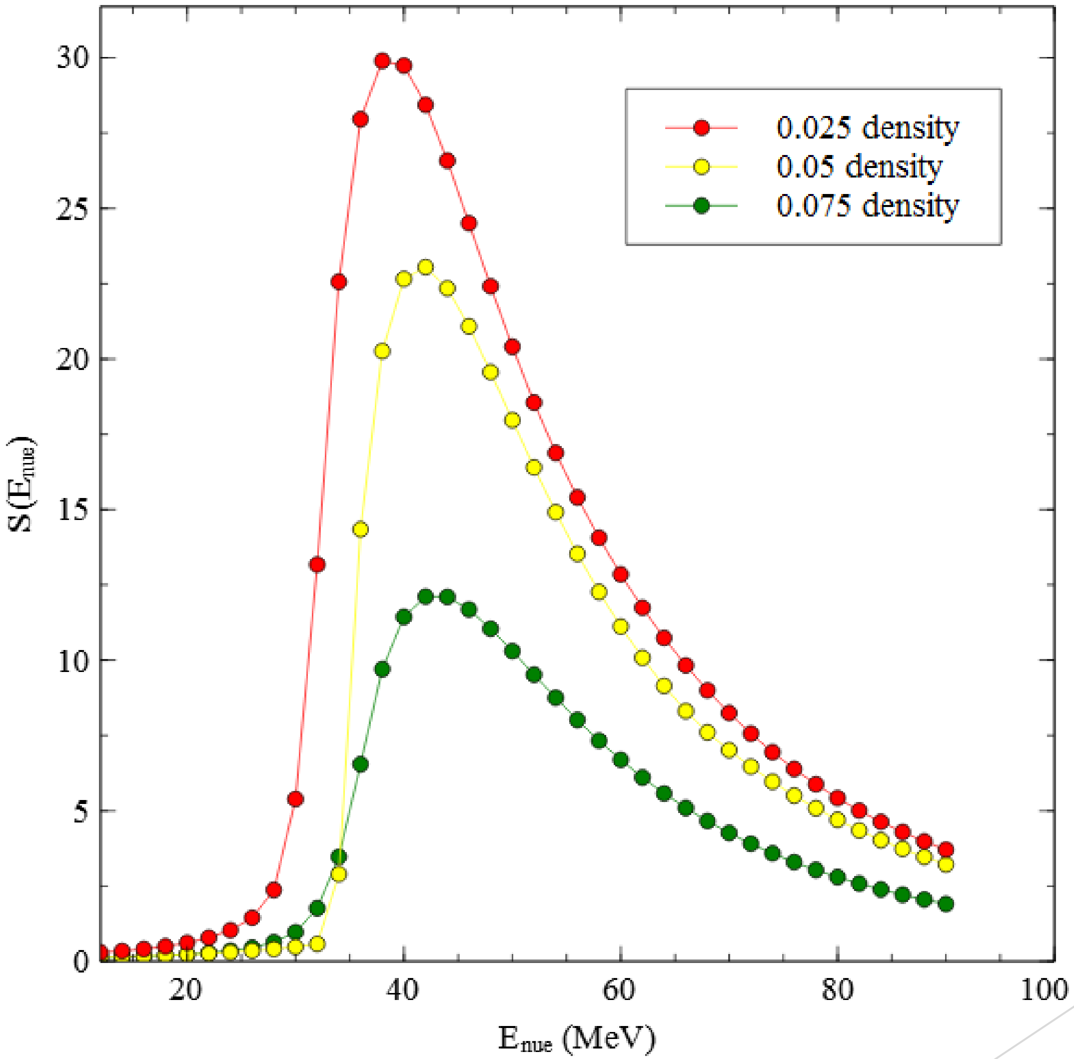


0.075 fm^{-3}





Angle averaged S(E_υ) for pasta at different densities and at 1 MeV



What if pasta opacities are asymmetric in the supernovae simulation??

A simple toy model for supernovae simulation with asymmetric neutrino opacities:

1. Define region in temperature and density space with Tanh functions.
2. Additional scattering opacity equal to 50 times of the standard value
3. Pasta opacities varies with polar angles

By Evan O'connor and Luke Roberts

In Preparation

Conclusion

- Nuclear Pasta possibly exist just before the core-bounce or during the supernova cooling phase
- Neutrino-pasta interaction gives big variations on the neutrino opacity inside the supernova
- Trials to see the impact of neutrino-pasta interactions on the supernova simulations is interesting and is going on…

Collaborators:

- C. J. Horowitz
- D. K. Berry
- M. E. Caplan
- Evan O'connor
- Luke Roberts

Thank You !