Neutrino response in Supernova Matter from Transport Models

Chuck Horowitz, Indiana University
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- With Liliana Caballero, Achim Schwenk, **Matt Caplan, Zidu Lin**, Don Berry, Farrukh Fattoyev, Andre Schneider, Luke Roberts, Evan O'Connor, Tobias Fischer,W. Newton…

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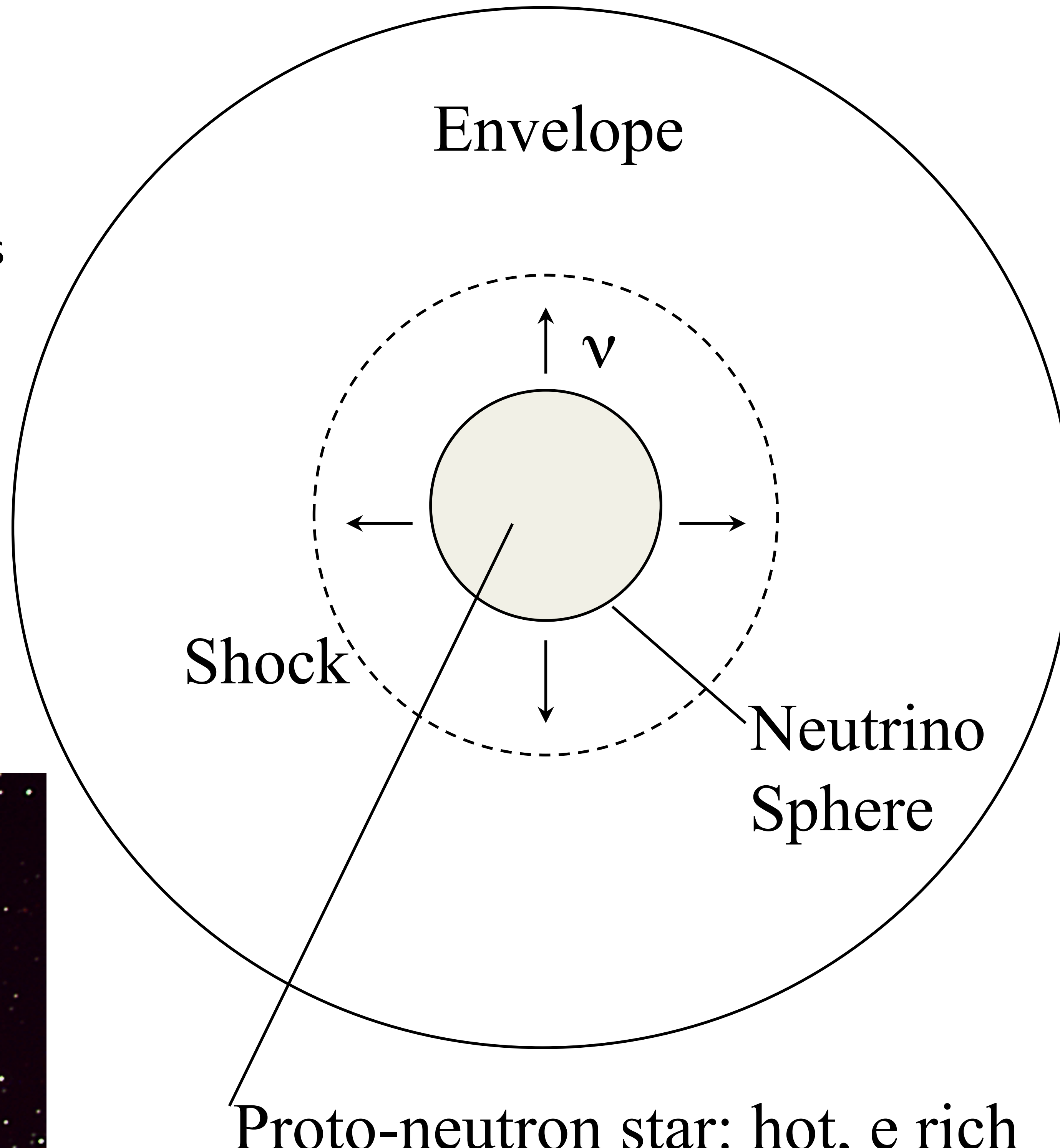
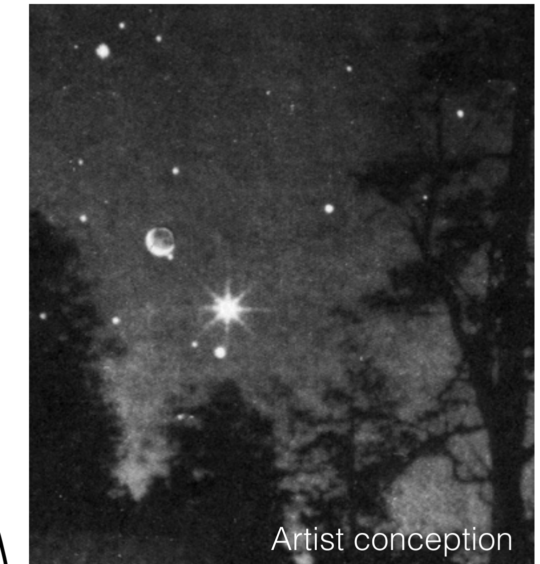
NS Born in Core Collapse Supernovae

Core of massive star collapses to form proto-neutron star. νs form neutron star energizes shock that ejects outer 90% of star.

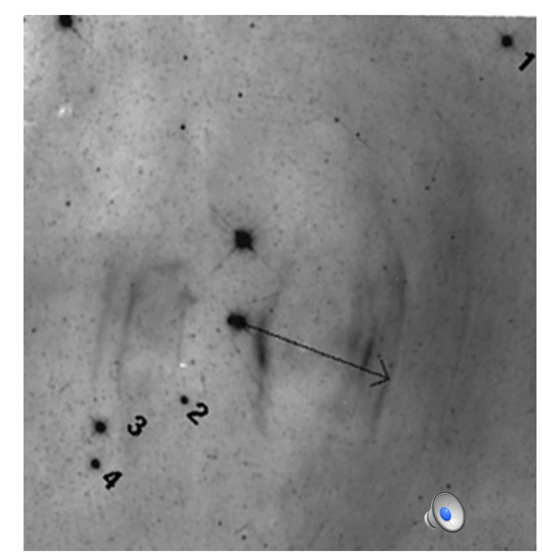




July 5, 1054

Crab nebula

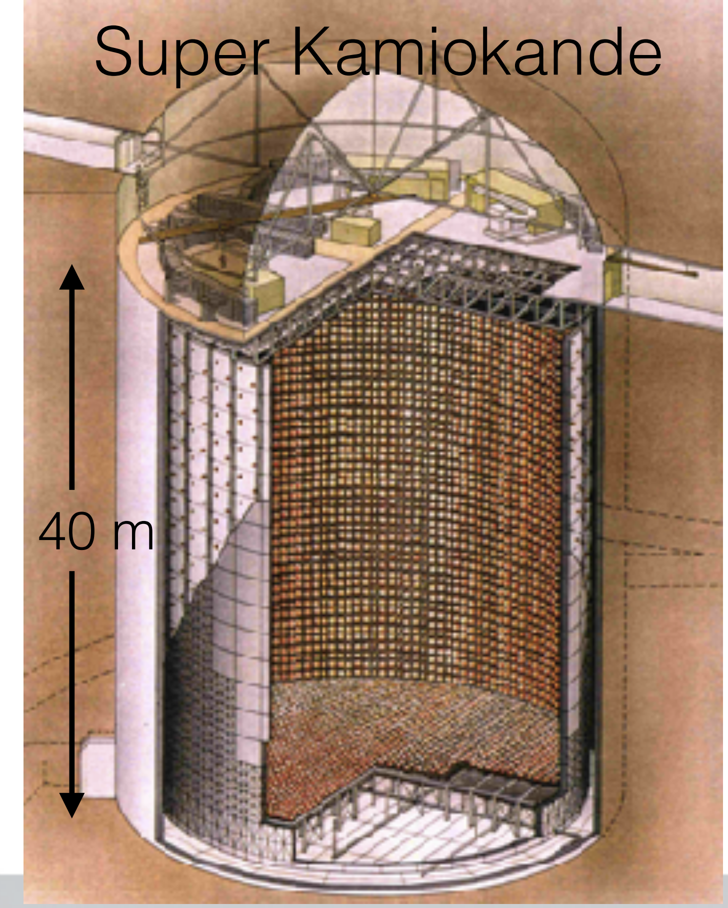
Crab Pulsar

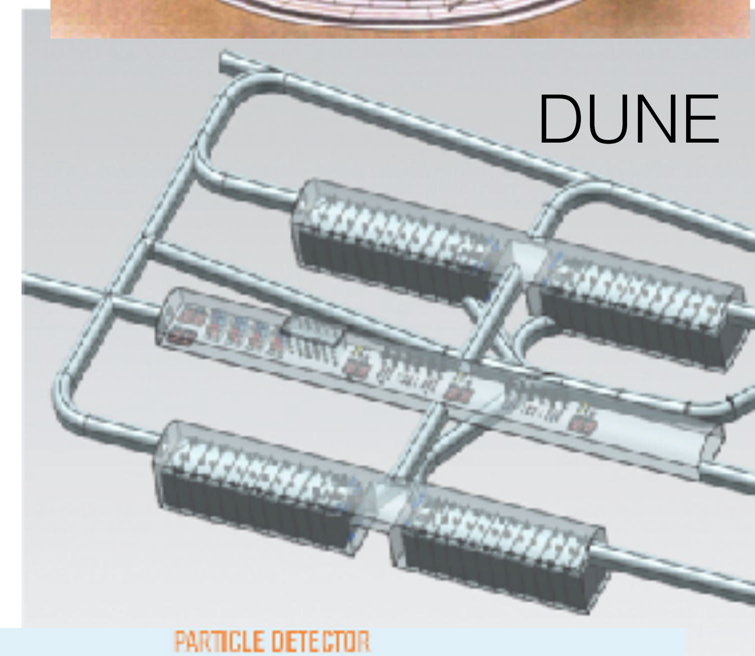


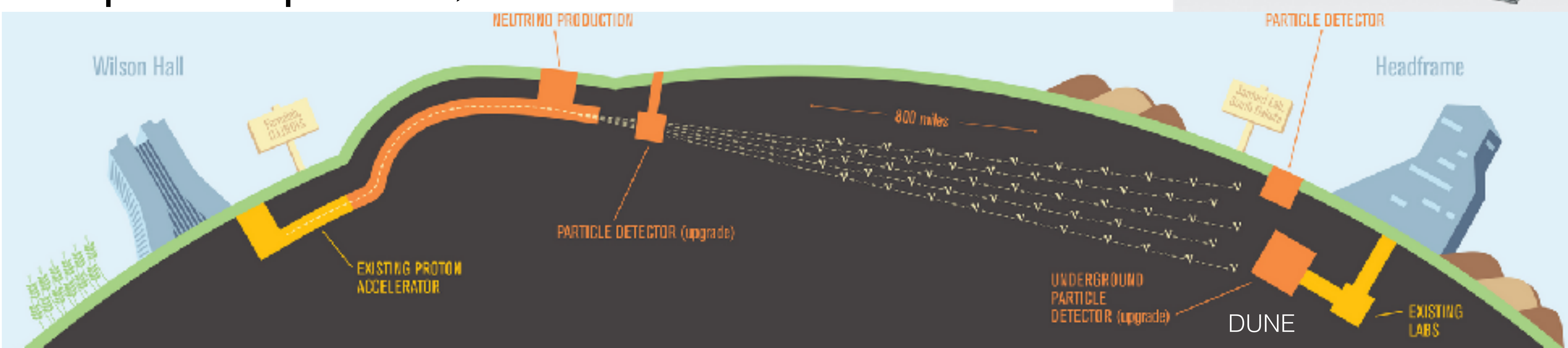
Hubble ST

Detecting Supernova Neutrinos

- SN radiate the gravitational binding energy of a neutron star, 0.2 $M_{sun}c^2$, as 10^{58} neutrinos in ~10 s
- Historic detection of ~20 neutrinos from SN1987A
- Expect several thousand events from next galactic SN in Super Kamiokande: 32 kilotons of H_2O + phototubes. Good antineutrino detector.
- Deep Underground Neutrino Experiment (DUNE) in South Dakota plans 40 kilotons of liquid Ar to study oscillations of Fermilab neutrinos. Good neutrino detector.
- Hyper Kamiokande is possible very large version of SuperK. Expect 100,000 events. Good for late times.

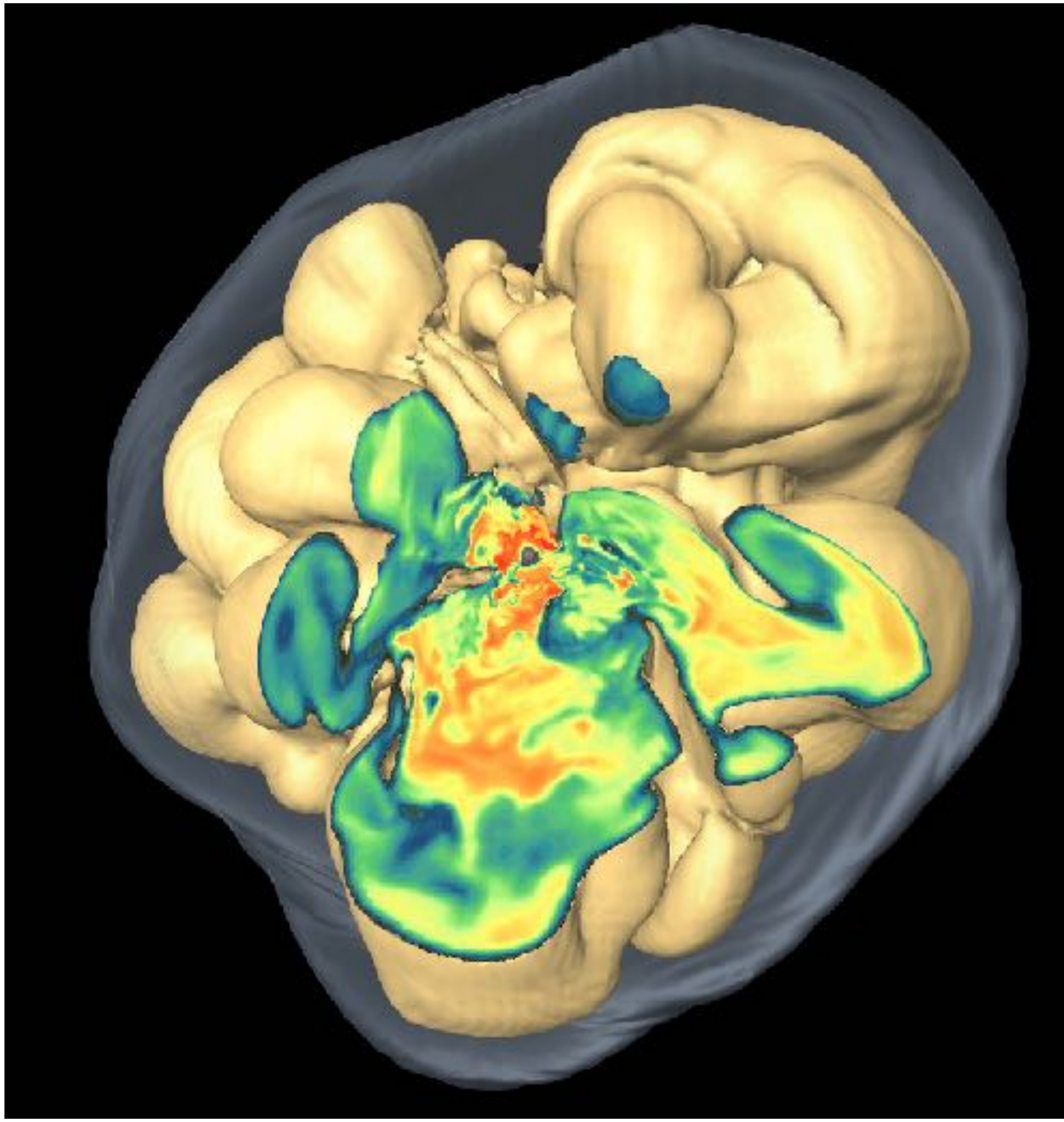






How do SN explode?

- Situation is not so clear.
- Many Two-dimensional simulations with realistic nu transport explode.
- Very costly 3D simulations may be less likely to explode than 2D.
- Possibilities: 1) asymmetries in pre-SN star may aid explosion, 2) resolution / accuracy of nu transport, 3) Equation of state, 4) **Neutrino interactions** — perhaps important corrections have been left out.



Some Important ν Interactions

ν + n —> p + e (Charged current capture rxn)

$\bar{\nu}$ + p —> n + e^+ (also inverse rxns)

Symmetry E important, Luke Roberts

ν + N —> ν + N (Neutral current elastic scattering, important opacity source for mu and tau ν)

ν + e —> ν + e (Important for energy loss)

ν + A —> ν + A (Large coherent cross section)

Today

- Garching group reduced νN by 10 to 20% (from large strange quark contribution to nucleon spin) and a failed 3D simulation exploded. We will explore reduction from NN correlations instead of strange quarks.

Neutrino-nucleon scattering

- Neutrino-nucleon neutral current elastic scattering in free space

$$\frac{d\sigma_0}{d\Omega}_{\nu N} = \frac{G_F^2 E_\nu^2}{4\pi^2}\left({C_{a,N}}^2(3-\cos\theta) + {C_{v,N}}^2(1+\cos\theta)\right)$$

- In a supernova, cross section is modified by axial or spin response S_A, and vector response S_V, of the medium.

$$\frac{1}{V}\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{16\pi^2}\left(g_a^2(3-\cos\theta)(n_n+n_p)S_A + (1+\cos\theta)n_n S_V\right)$$

- Responses S_A, S_V —> 1 in free space. Normally S_A dominates because of $3g_a^2$ factor.

Neutrinosphere as unitary gas

- Much of action in SN at *low densities* near neutrinosphere at $n \sim n_0/100$ (nuclear density n_0).

- Average distance between two neutrons near neutrinosphere is less than NN scattering length.

← 19 fm → nn scattering length

← 8.5 fm → Average distance between two neutrons at $n_0/100$

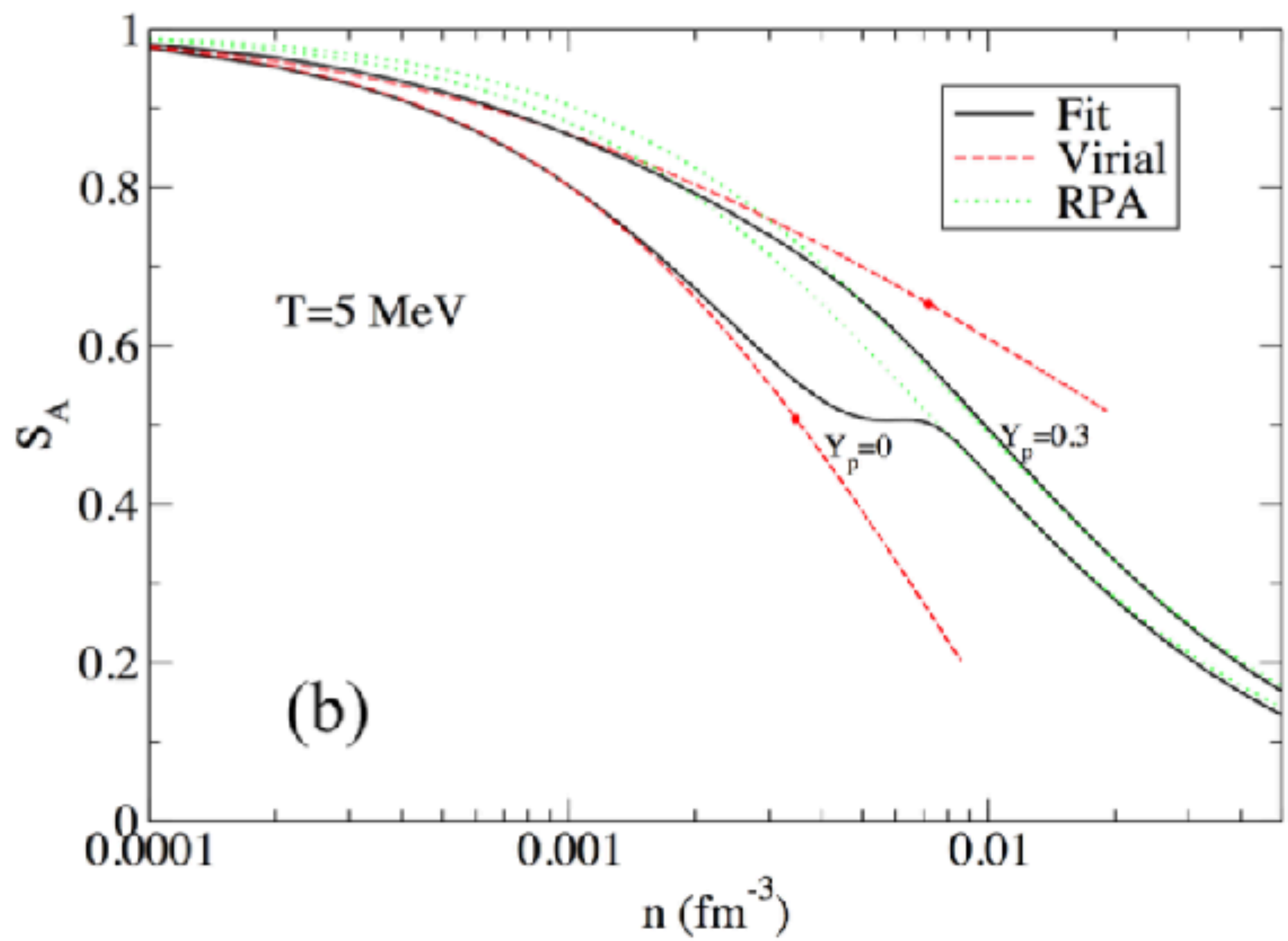
↔ 1.4 fm Range of NN force

- Because of the long scattering length one can have important correlations even at low densities.

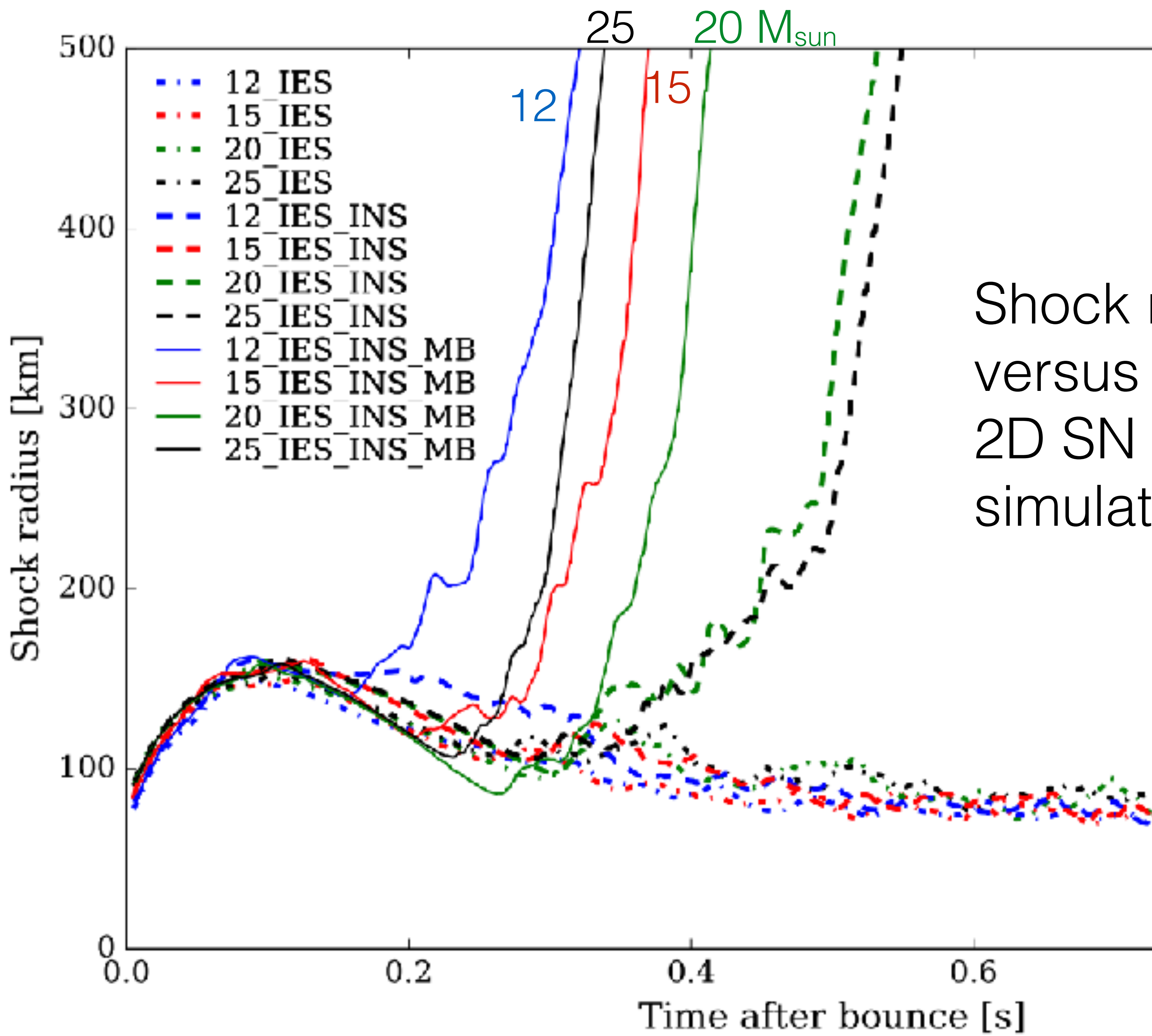
- Two neutrons are correlated into spin zero $^1S_0$ state that reduces spin response $S_A<1$.

Axial Response in Virial Expansion

- At low densities n and or high temperatures T one can expand equation of state in powers of the fugacity $z=e^{\mu/T}$ with μ the chemical potential.
- Generalize to partially spin polarized gas to determine long wavelength limit of axial response:
  $S_A \sim 1 + \lambda^3 n\, b_a$
  with b_a 2^{nd} viral coefficient for spin polarization gas.
- b_a is about -0.64 from observed nucleon-nucleon elastic scattering phase shifts.



In Phys. Rev. C **95** (2017) 025801 we provide a simple fit $S_A^f(n,T,Y_p)$, valid for all densities, that reproduces viral result at low densities and a common Random Phase Approximation model at high densities. Fit can easily be used in SN simulation.



Shock radius versus time for 2D SN simulations

- All 2-D SN simulations by Burrows et al [arXiv:1611.05859] with correlations (S_A<1) explode (solid lines) while 12 and 15 M_{sun} stars fail to explode, and 20, 25 M_{sun} explode later, without correlations (S_A=1).

Vector response S_V

- At higher densities (10^{13} to 10^{14} g/cm^3 instead of 10^{11} to 10^{12}) nucleons can cluster into nuclei or nuclear pasta.

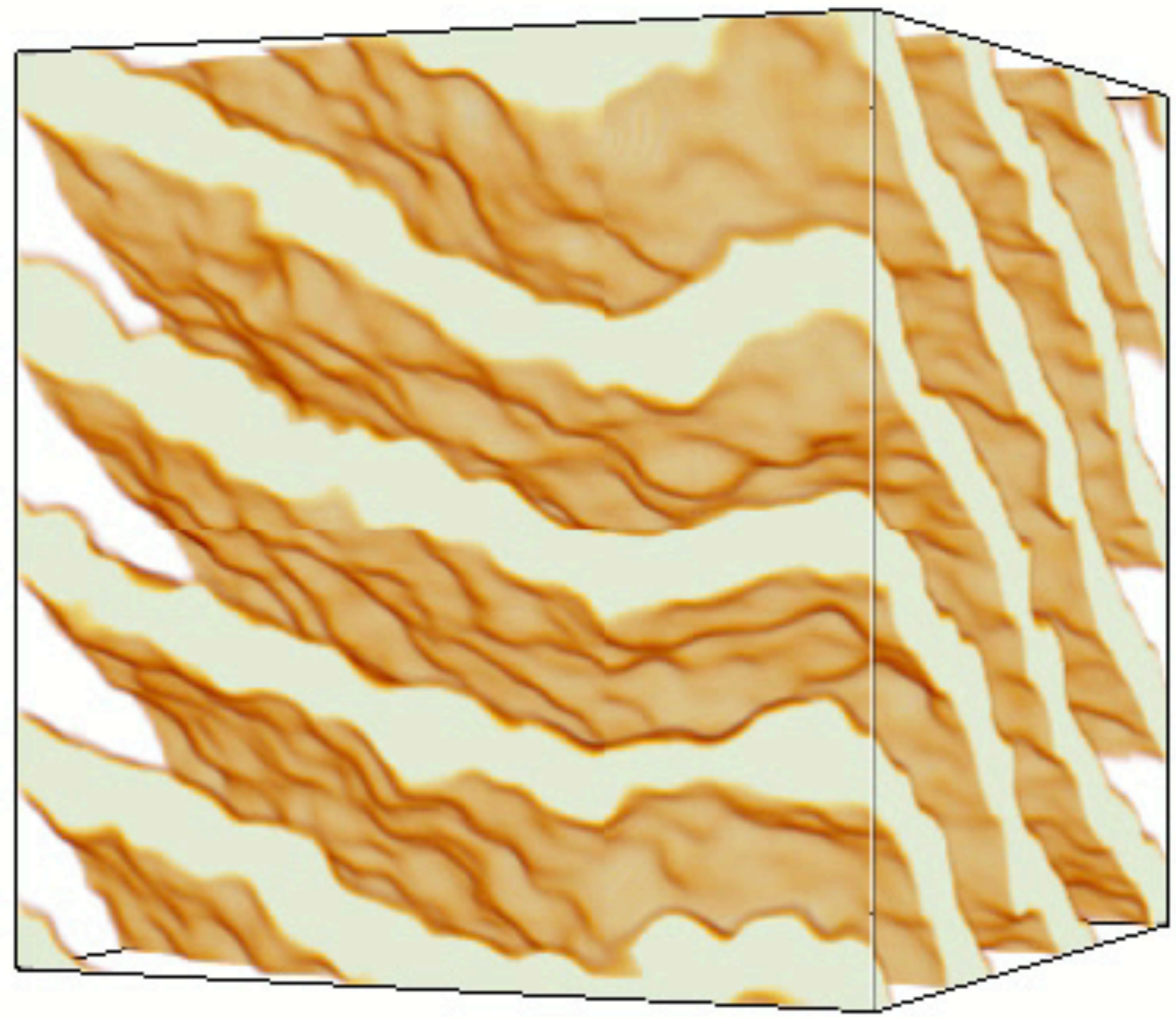
- Neutrinos can scatter coherently from theses clusters greatly increasing the vector response S_V.

- Neutrino interactions at these higher densities are important at later times > few s.

S_V and Nuclear Pasta

- Nuclear matter, at somewhat below ρ_0, forms complex shapes because of competition between short range nuclear attraction and long range Coulomb repulsion —> “Coulomb frustration”.
- Nuclear pasta expected in neutron stars at base of crust about 1 km below surface at $\sim 1/3\rho_0$.
- **Semiclassical MD model**: $v(r)=a\, e^{-r^2/\Lambda} + b_{ij}\, e^{-r^2/2\Lambda} + e_i e_j\, e^{-r/\lambda}/r$ Parameters of short range interaction fit to binding E and density of nuclear matter.

MD simulation with slowly increasing volume



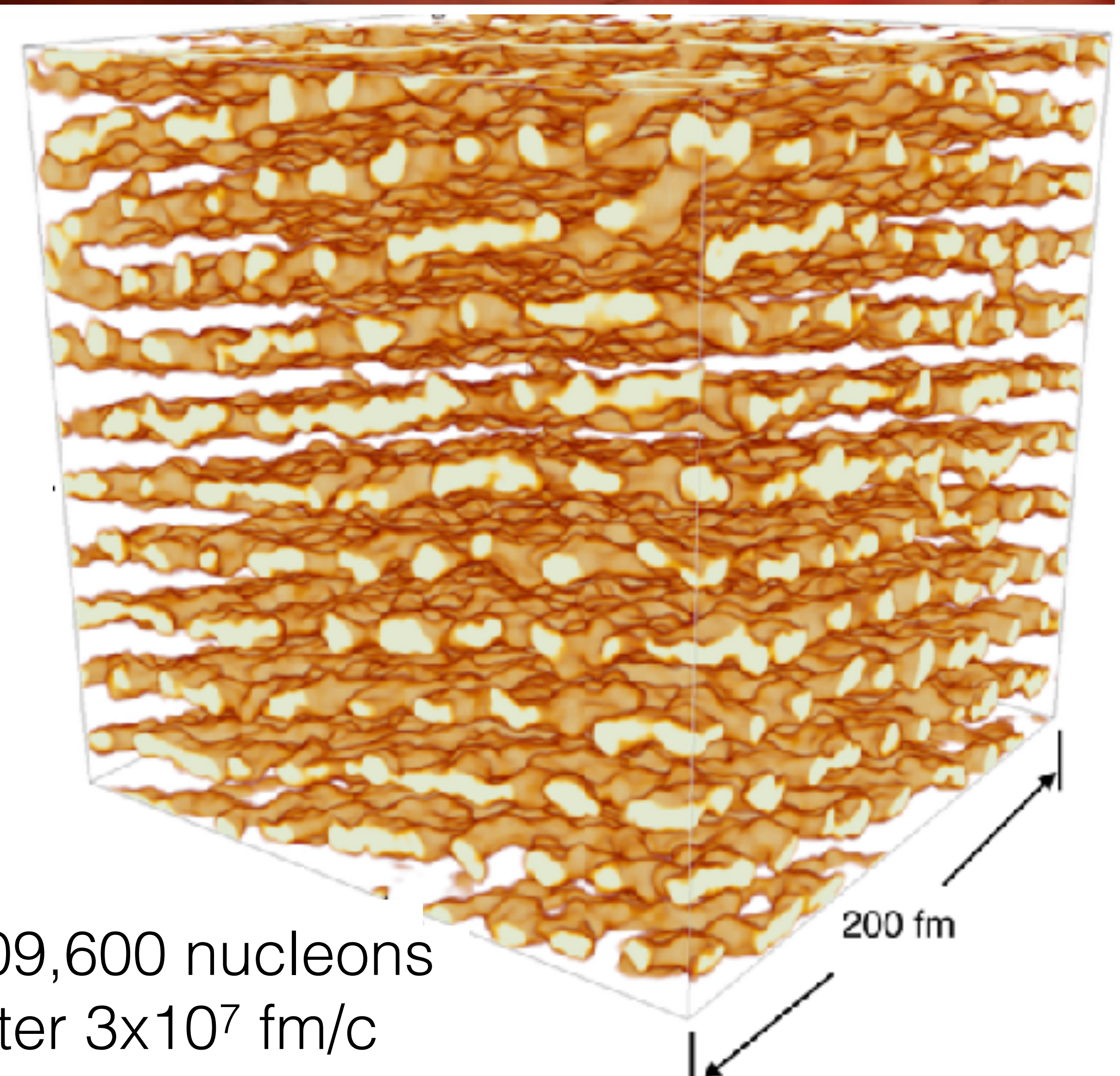
Andre Schneider

$n = 0.0585 \mathrm{fm}^{-3}$

51200 nucleons, T=1 MeV, Y_p=0.4

IUMD

- Indiana University Molecular Dynamics (IUMD) is a classical MD code (no collisions) that runs efficiently on many GPUs.
- Can run for many particles 10^6 +, or for long times 10^8 + fm/c. (It can take a long time to form and equilibrate complex pasta structures.)
- Written by Don Berry



409,600 nucleons after 3×10^7 fm/c

S_ν is Static Structure Factor

- The static structure factor adds coherently the amplitude for a neutrino to scatter from every neutron in the system.

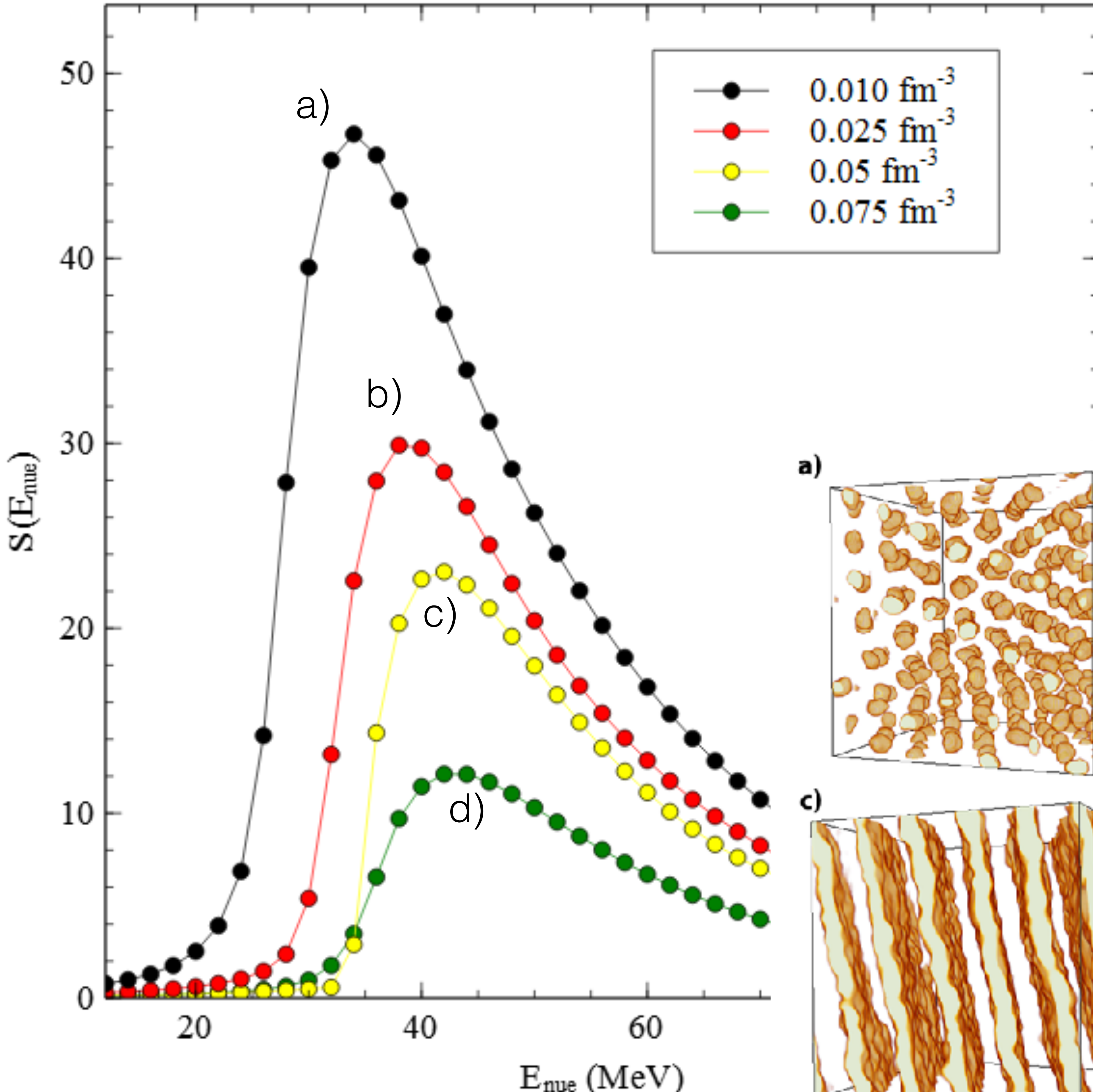
$$S_\nu(\boldsymbol{q}) = \langle \rho_n^*(\boldsymbol{q}, t)\rho_n(\boldsymbol{q}, t)\rangle_t$$

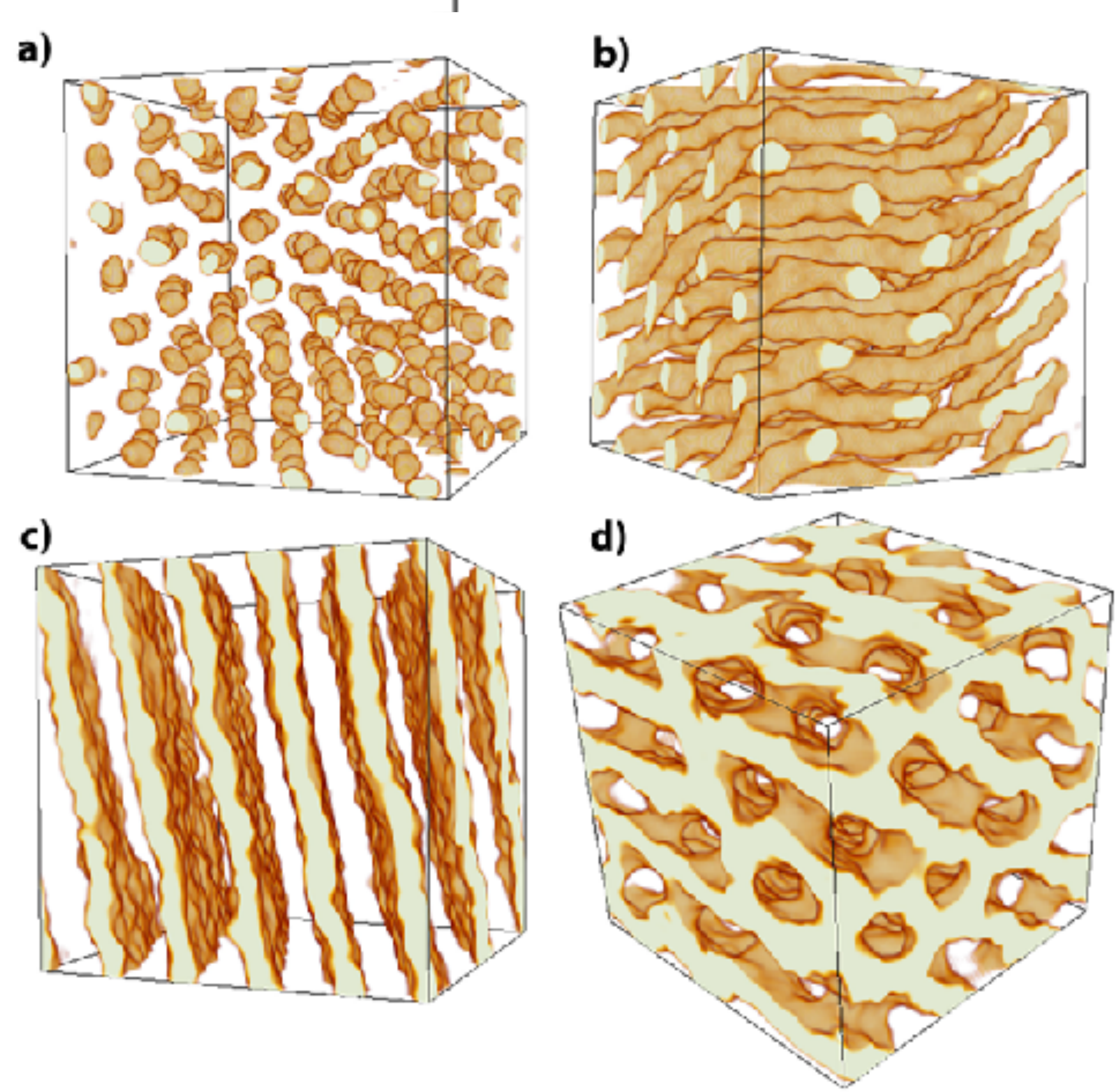
$$\rho_n(\boldsymbol{q}, t) = N^{-1/2} \sum_{j=1}^{N} e^{i\boldsymbol{q}\cdot\boldsymbol{r}_j(t)}$$

- Time average from trajectories in MD simulation.

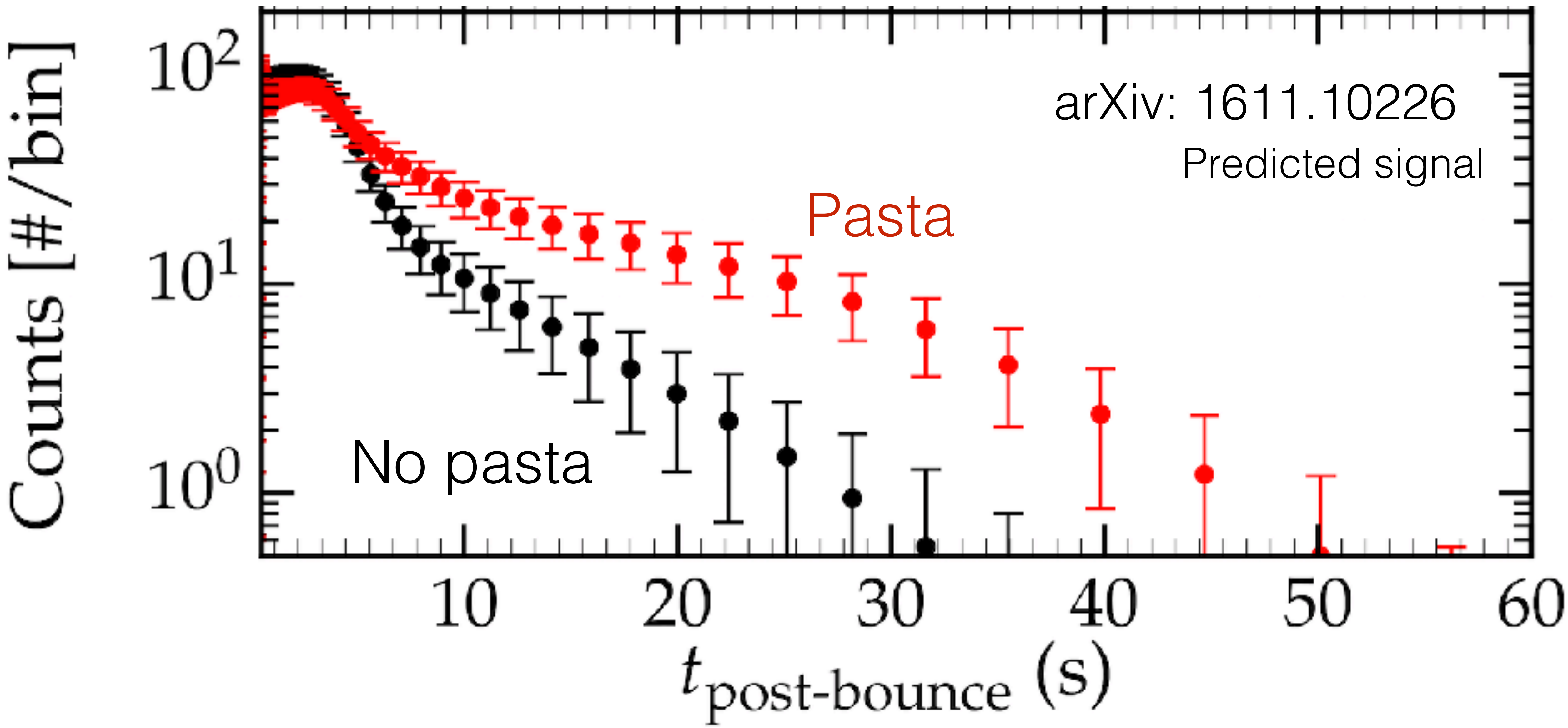
- Neutrino scattering cross sec. proportions to $S_\nu(q)$

arXiv: 1611.10226





SN signal at 10 kpc in Super-K



- Neutrino-pasta coherent scattering slows neutrino diffusion and leads to a dramatic increase in counts at late times (>10 sec after core collapse) compared to a simulation without pasta. Important to observe neutrinos for as long as possible, helped by large Hyper-K statistics.

S_V, S_A Responses of SN Matter

- Supernova dynamics and SN neutrino signals depend on spin S_A and density S_V responses of low density warm nuclear matter.
- Not a home work problem: we need the response in a periodic box.
- As entropy decreases: (1) gas of free nucleons, (2) unitary gas with important NN correlations, (3) nucleon gas with light clusters, (4) light + heavy clusters (nuclei) and or pasta, (5) uniform nuclear matter.
- Lets work together to use your transport model (tested against HI data) to calculate the neutrino response of SN matter in some or all of these regimes.

Recreating SN Conditions in Lab

- Transport models connect **Femtonovae** (HIC in lab) with **Supernovae** in heavens.
- Neutrinosphere temperatures: T ~5 MeV (5 to 10 MeV) [E of 20 SN1987A events]
- Densities: 1/100 to 1/10 nuclear density.
- Proton fraction Y_p: ~0.3 to 0.01. Measure n rich and p rich systems and extrapolate.
- Probe EOS, Sym. E, composition, density and spin responses… of SN matter.

Neutrino response in Supernova Matter from Transport Models

- Axial response of supernova matter: Liliana Caballero, Achim Schwenk, …
- MD simulations of nuclear pasta: **Matt Caplan, Zidu Lin**, Don Berry, Farrukh Fattoyev, Andre Schneider…
- Neutrino pasta scattering: Luke Roberts, Evan O’Connor, Tobias Fischer,W. Newton…

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