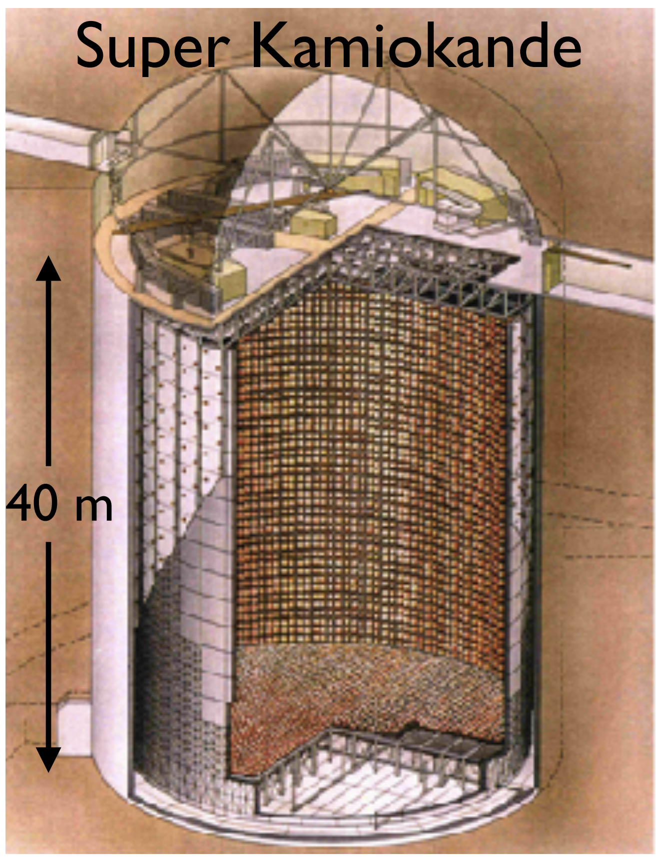
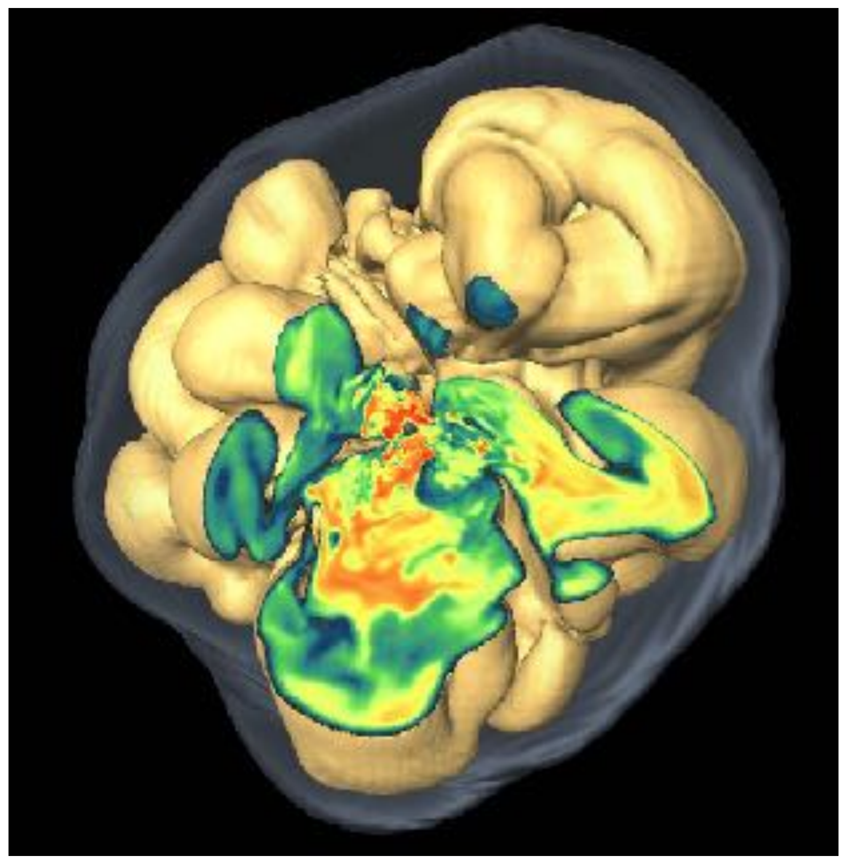
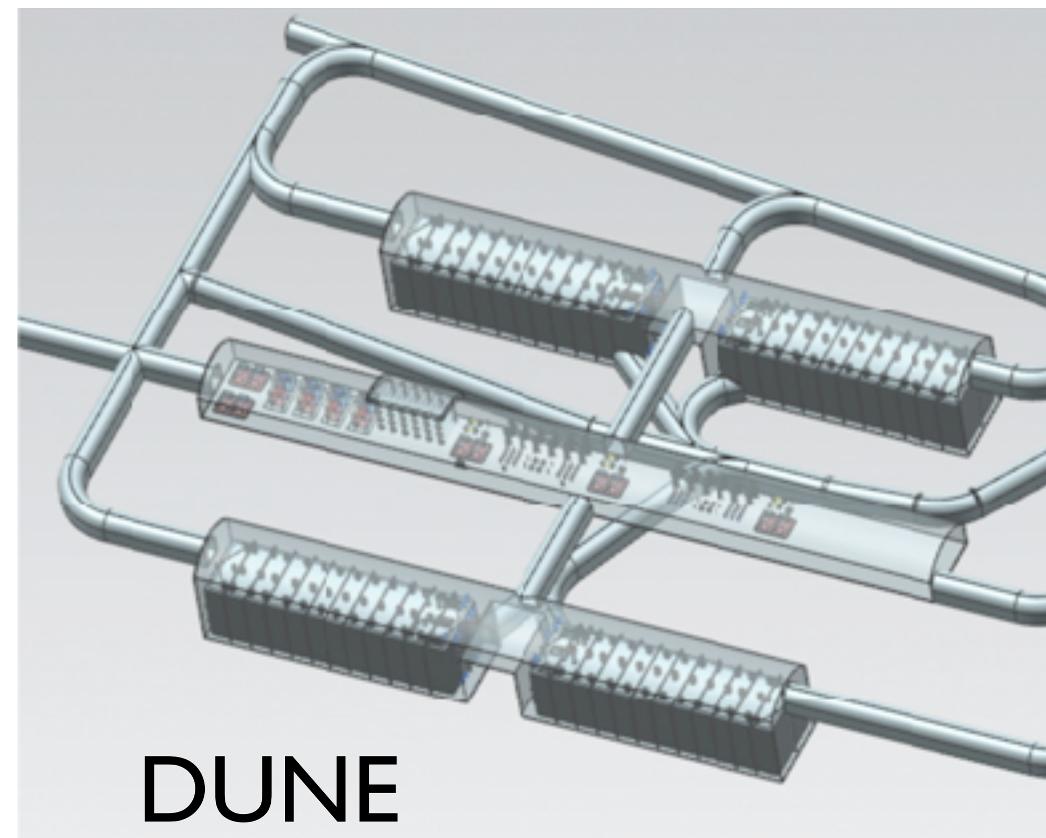
Microphysics for supernova simulations and neutrino signals







Chuck Horowitz, Indiana U., SN neutrinos, MITP, Mainz, Oct. 2017

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Selected examples of microphysics that may impact the neutrino signals from a galactic core collapse SN

1. Equation of state

2. Neutrino opacities

Equation of state (EOS)

- Is a large table with many different parts that extends over many decades in density ρ, temperature T, and proton fraction Y_p. EOS includes:

- **$P=P(\rho, T, Y_p)$** and other thermodynamic functions E, S, μ…

- **Composition $Y_i=Y_i(\rho,T,Y_p)$** for many species i [often p, n, ^{4}He, A]. Important for neutrino ν interactions.

- **EOS and ν opacities should be consistent.**

  - Attractive strong interactions at just below nuclear density lead to correlations between nucleons that enhance vector response S_V.

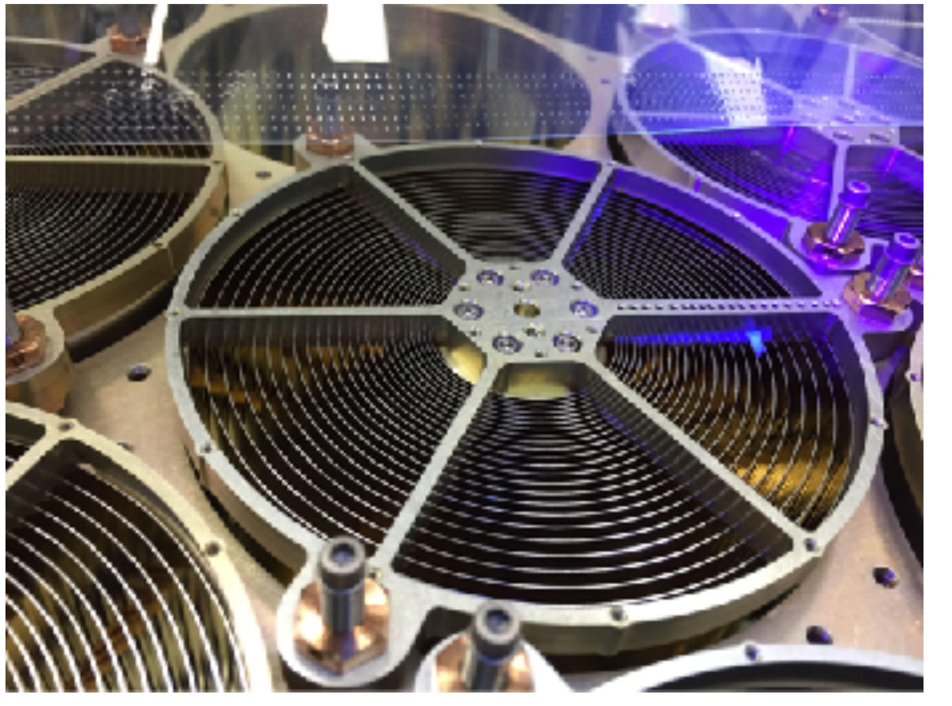
  - Effective mass M* in EOS gives density of states for ν opacities.

  - Spin dependent interactions in EOS important for axial response S_A, but poorly constrained (Skyrme forces can have ferromagnetic phases)

EOS and Neutron Star radii

- **Two very different radii**: Neutron star radius $\mathbf{R_{NS}}$ and Proto-neutron star $\mathbf{R_{PNS}}$

- R_{NS}: radius of cold, beta equilibrated NS.
  - Is irrelevant for SN dynamics during first second because star is hot and lepton rich.
  - R_{NS} determines binding E of NS and total E radiated in ν. $\mathbf{E_{total} \sim 0.6\ GM^2/R_{NS}}$
  - R_{NS} determined by P of cold EOS at ~ $2\rho_0$.
  - Presently R_{NS}=10 to 14 km. Optimistic: assume by next galactic SN that R_{NS} known to 10% from X-rays (NICER) or Gravitational Waves (GW).



Neutron star interior composition explorer (NICER), aims to determine R_{NS} from curvature of space implied by X-ray light curve. Launched to space station June 3, 2017.

Total E in Neutrinos

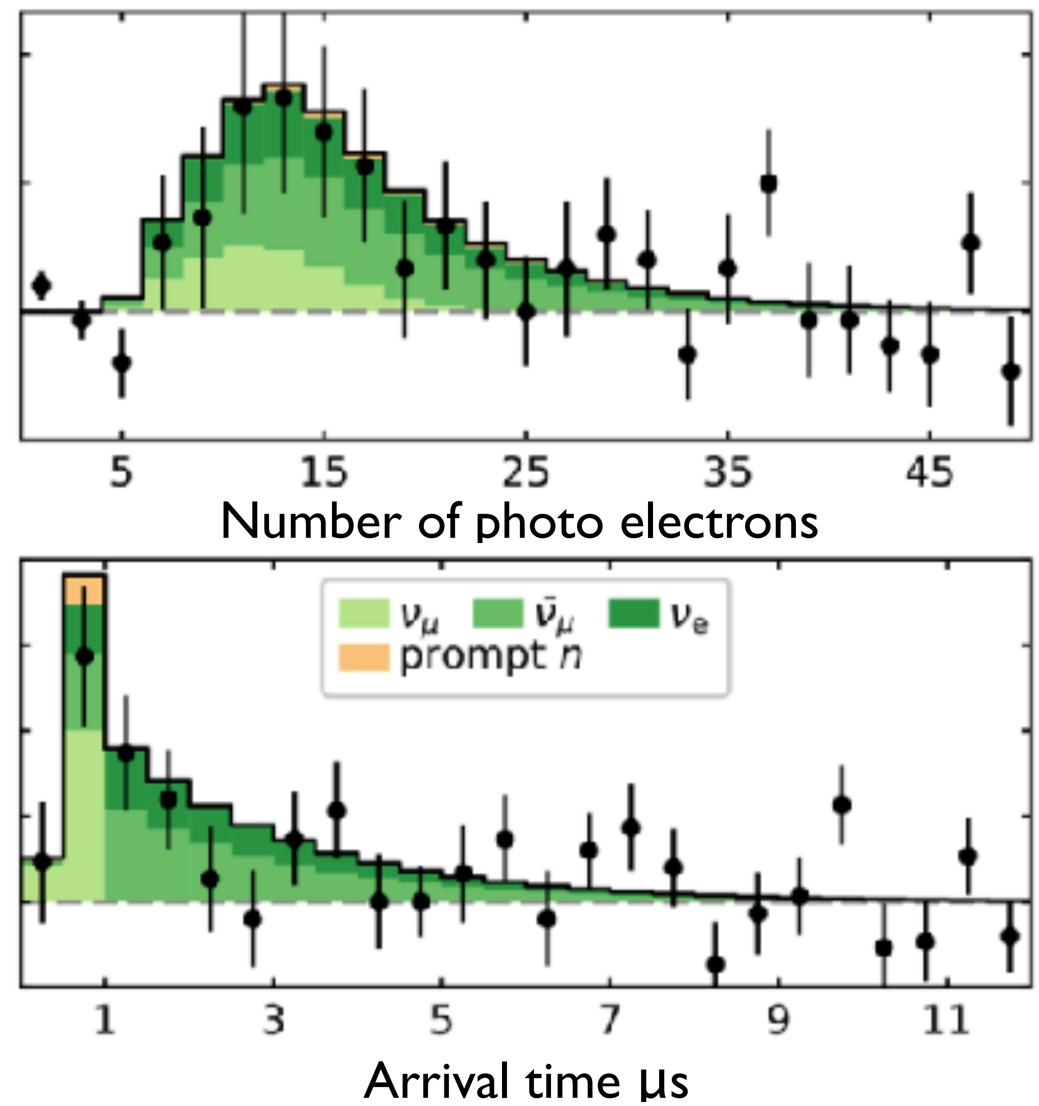
- Constrains distance to SN, mass of new NS, cooling by new particles such as axions, sterile neutrinos …

- Can we measure E_{tot} to 10%? Or better?

- Option 1: Individual flavors. Measure anti-ν_e very well in Super-K…, measure ν_e well in DUNE. Constrain ν_x via theory or indirect observations such as $^{16}O(\nu,\nu'\gamma)$. Good statistics, but some systematic errors.

- Option 2: flavor independent neutral current detector. ν-nucleus elastic scattering in dark matter detectors has very ***large yield of tens of events per ton*** (for SN at 10 kpc). Clean systematics, independent of (active) ν oscillations, but may have limited statistics.

Observation of ν-nucleus elastic scattering from CsI at SNS



D. Akimov et al, Science, Aug. 3

Proto-neutron star radius R_{PNS}

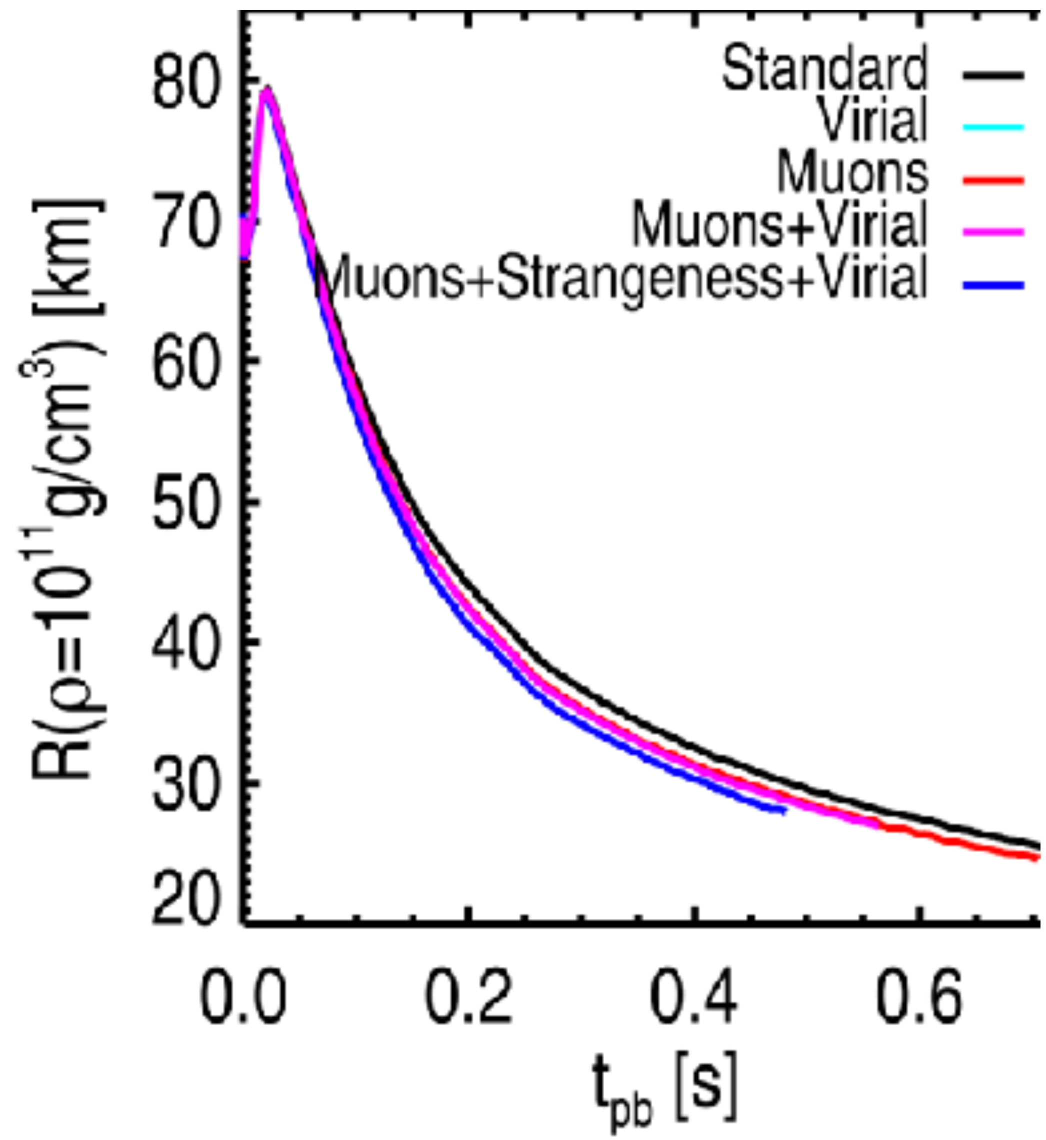
- R_{PNS} = radius of neutrinosphere around warm, lepton rich, proto-NS, and is very important for SN dynamics.

- Depends on thermal/ degeneracy pressure of leptons. Not so sensitive to strong interactions at high density.

- Smaller R_{PNS} gives deeper gravitational well so that accretion powers larger ν luminosities, to re-energize shock.

- Faster transport of heat, lepton #, out of star can lead to faster contraction of R_{PNS}.

- Also converting some electrons to muons reduces lepton pressure and R_{PNS}.



R_{PNS} vs time after core bounce in 2D SN simulations by Bolig et al, arXiv:1706.04630

SN Quantum Numbers

	Precollapse	SN	Neutron Star
# nu radiated		**10^{58}**	
Baryon #	10^{57}	10^{57}	**10^{57}**
Electron #	10^{57}	—>	**10^{56}**
Muon #	0	—>	**10^{55}**
Tau #	0	**10^{54}**	0
Strangeness	0	—>	?

- **Deleptonization**: During SN electron # of 10^{57} is radiated.
- **Muonization**: During SN muon # of **minus** 10^{55} is radiated.
- **Tau #**: Produce equal numbers of nu-tau, anti-nu-tau. However anti-nu_tau leave faster because of weak magnetism leaving star nu-tau rich [PLB **443** (1998) 58].

Macroscopic next generation matter and the changing of the generations

- A SN contains astronomical numbers of 2nd and third generation particles. It may be uniquely sensitive to new flavor physics.

- Example: muon to electron conversion: $\mu + A \longrightarrow e + A$ could increase the role of muons.

Neutrino Opacities

ν interactions in SN matter

$\nu_e + n \longrightarrow p + e$ (Charged current capture rxn)
$\nu + N \longrightarrow \nu + N$ (Neutral current elastic scattering, important opacity source for mu and tau ν)

- Neutrino-nucleon neutral current cross section in SN 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, $S_V \longrightarrow 1$ in free space. Normally S_A dominates because of $3g_a^2$ factor.

Neutrinosphere as unitary gas

- Much of the action in SN at *low densities* near neutrinosphere at n ~ $n_0/100$ (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

- Unitary gas is a system with near infinite scattering length and near zero effective range. Neutrinosphere is close to a unitary gas.

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

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

Can the spin response of a unitary gas help a supernova to explode?

- Well posed question.

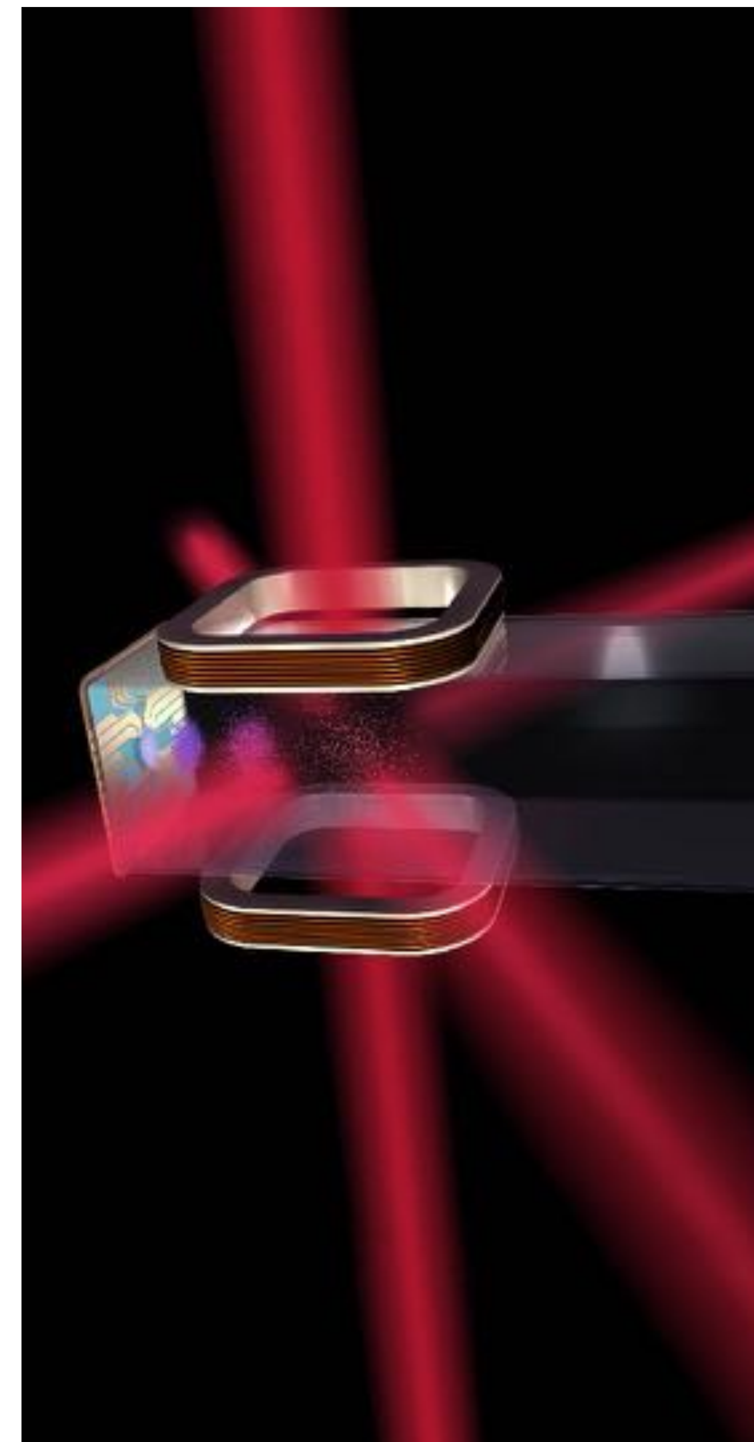
- Helpful to think of neutrinos interacting with a unitary gas as a special reference system for nuclear matter. Better to model neutrinosphere region as a unitary gas instead of a free (Fermi) gas as is often done.

- Many theoretical results for a unitary gas and many **experimental results** for cold atoms.

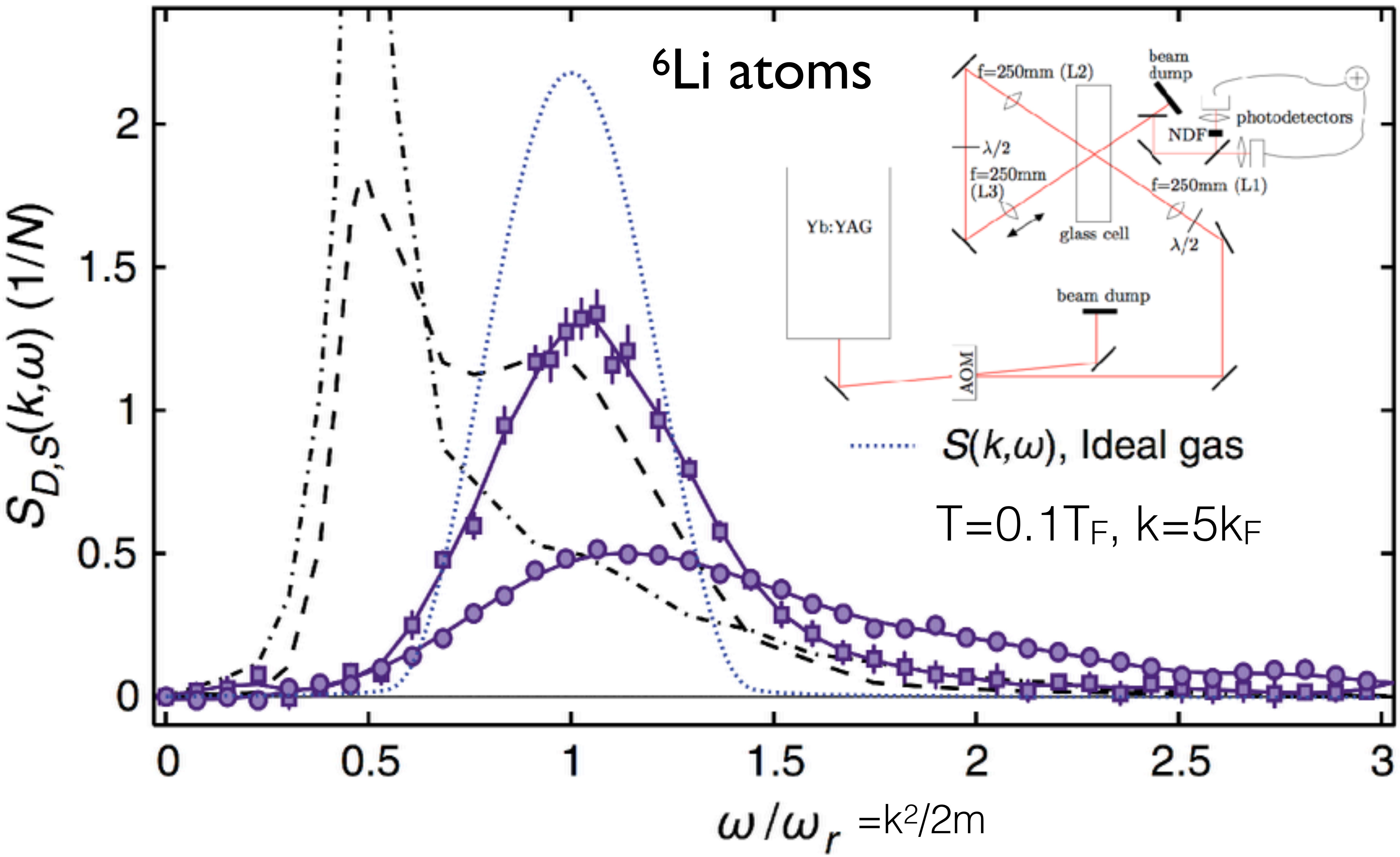
- Spin response <1 reduces scattering opacity.

- Effect may be important even at low $\sim 10^{12}$ g/cm^3 densities because of the large scattering length.

- Probably helps 2D (and 3D?) simulations explode perhaps somewhat earlier???



Dynamic Spin Response of a Strongly Interacting Fermi Gas
[S. Hoinka, PRL **109**, 050403]



$S_A(k,w)$ is solid line and squares, while dashed line is $S_V(k,w)$.
Static structure factors: $S_V(k) = \int dw S_V(k,w)$, $S_A(k) = \int dw S_A(k,w)$

Virial Expansion for Unitary Gas

- In high T and or low density limit, expand P in powers of fugacity z=Exp[chemical pot/T]

$$P = \frac{2T}{\lambda^3}\sum_{n=1}^{4} b_n z^n \qquad\qquad n = \frac{z}{T}\frac{dP}{dz}$$

- Long wavelength response:

$$S_V(q \to 0) = T/(\partial P/\partial n)_T = z(\partial n/\partial z)/n,$$

$$S_V(q \to 0) = \frac{1 + 4zb_2 + 9z^2 b_3 + 16z^3 b_4}{1 + 2zb_2 + 3z^2 b_3 + 4z^3 b_4}$$

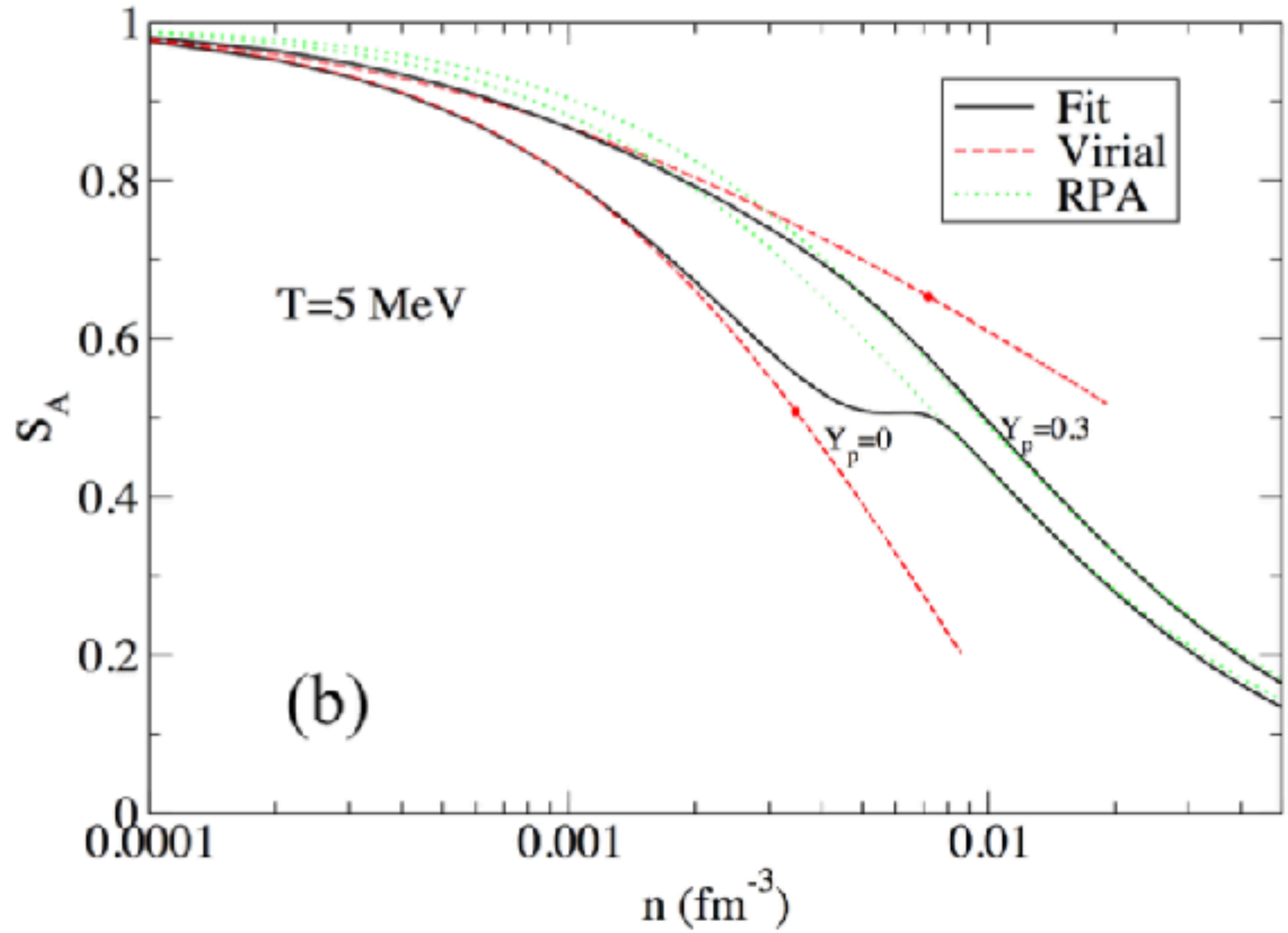
- Axial response: $S_A(q \to 0) = \dfrac{2z}{n}\dfrac{\partial}{\partial(z_1 - z_2)}(n_1 - n_2)\Big|_{z_1 = z_2}$

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.

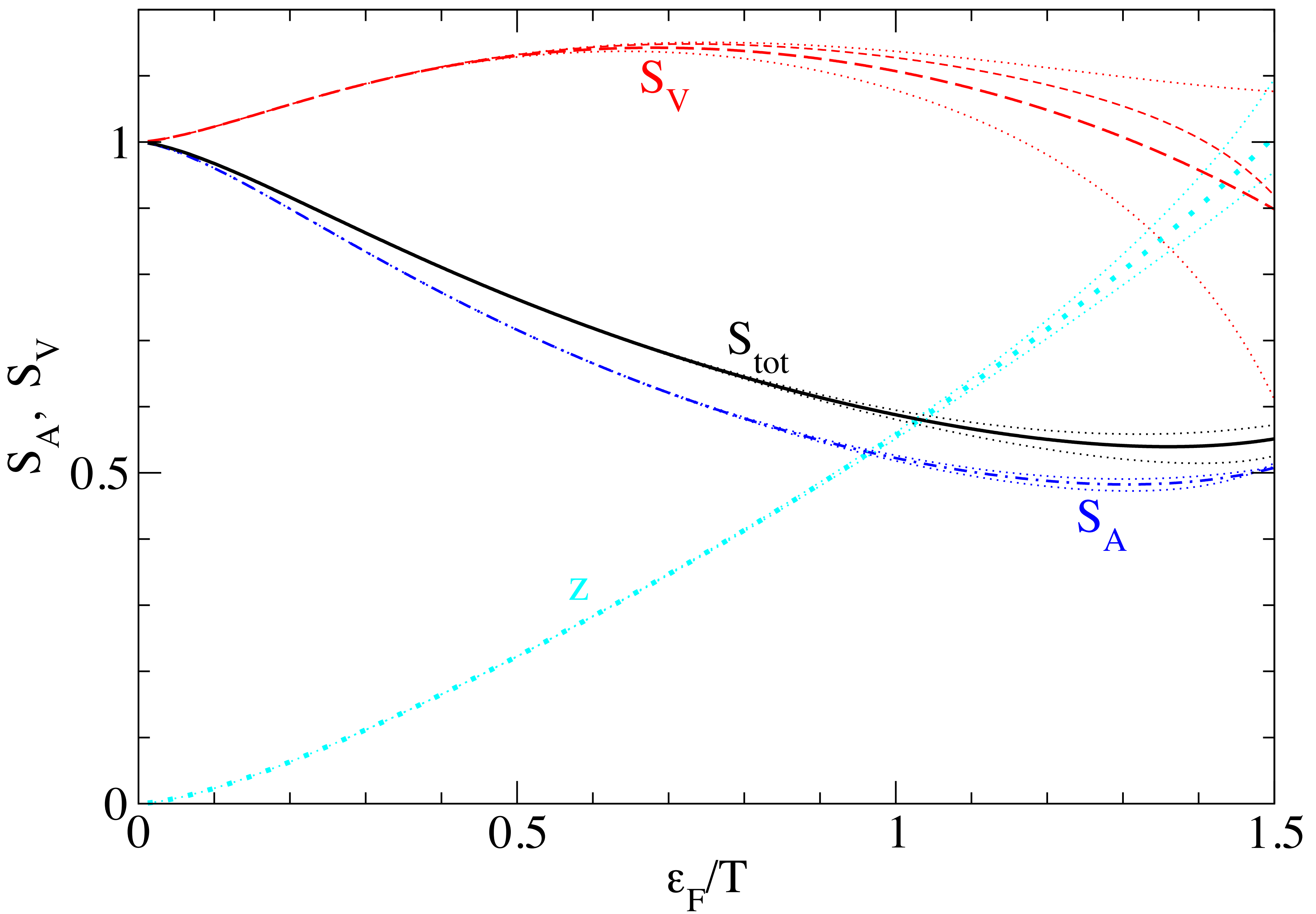
- Generalize to partially spin polarized gas to determine long wavelength limit of axial response:
  $S_A \sim 1 + \lambda^3 n\, b_a$
  with b_a 2nd viral coefficient for spin polarization gas.

- b_a is about -0.64 from observed nucleon-nucleon elastic scattering phase shifts.



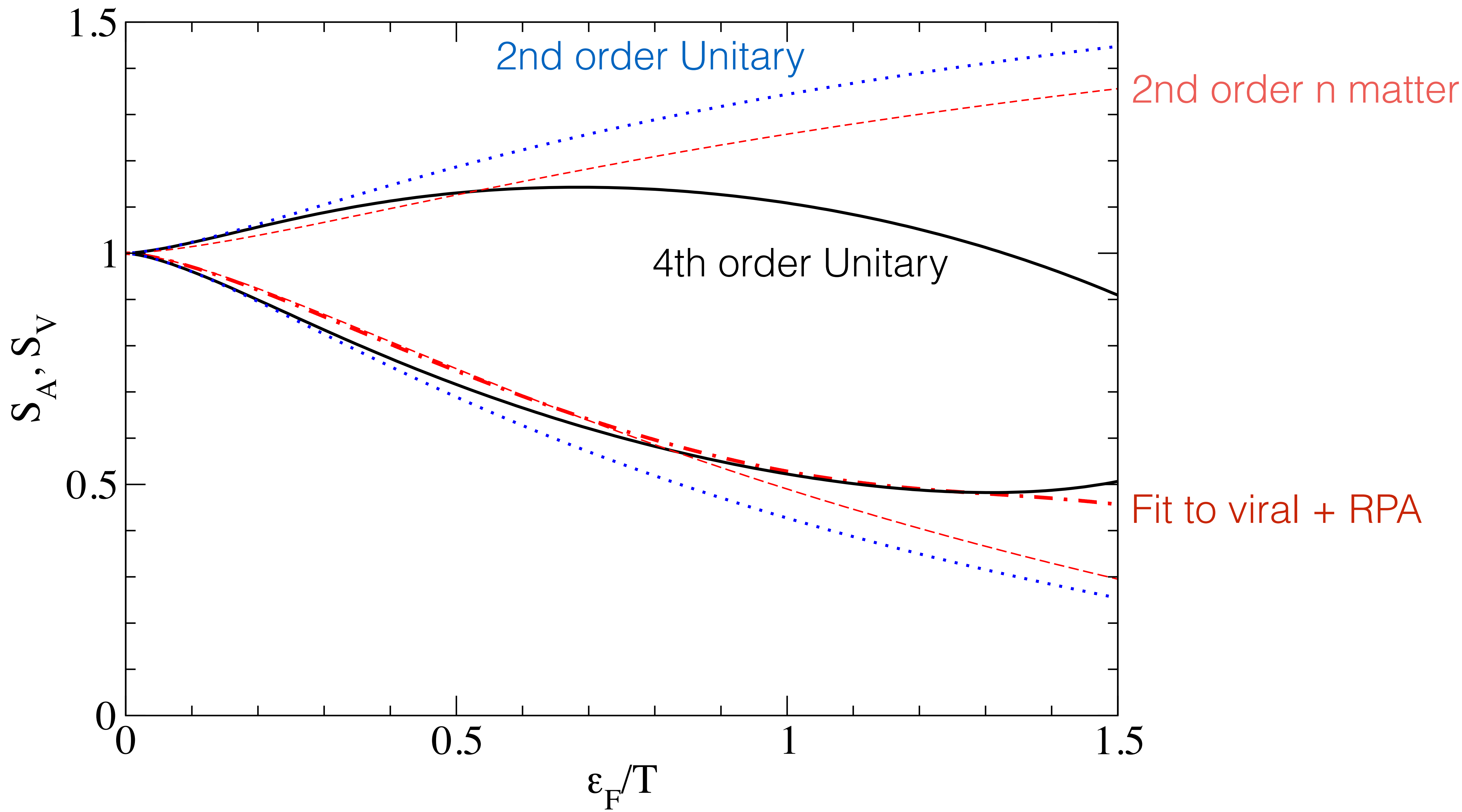
In Phys. Rev. C **95** (2017) 025801 we provide a simple fit $S_A^f(n,T,Y_p)$, valid for all densities, that reproduces viral result at low densities and a common Random Phase Approximation model at high densities. Fit can easily be used in SN simulation.

4th order Unitary results

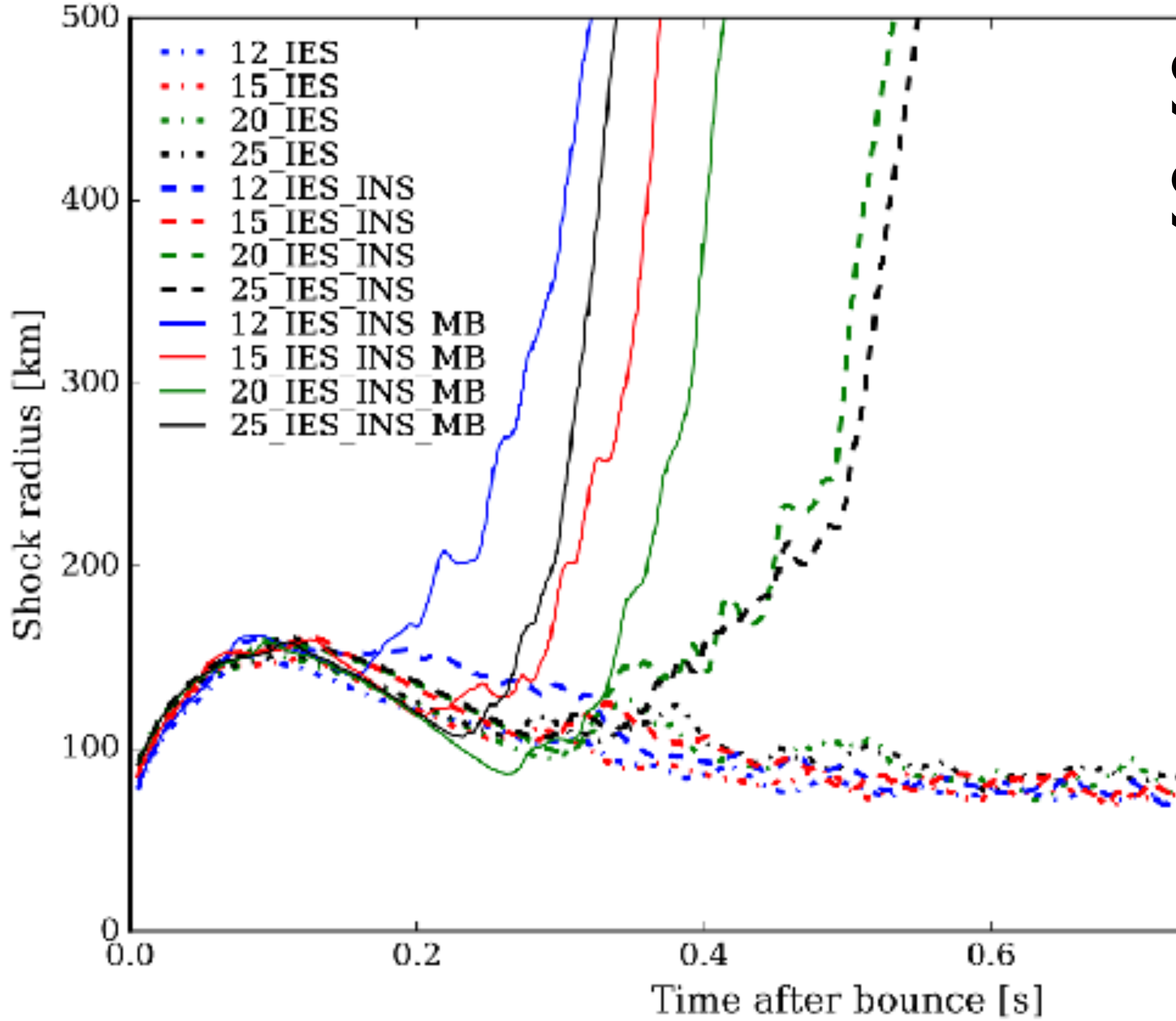


Unitary gas response

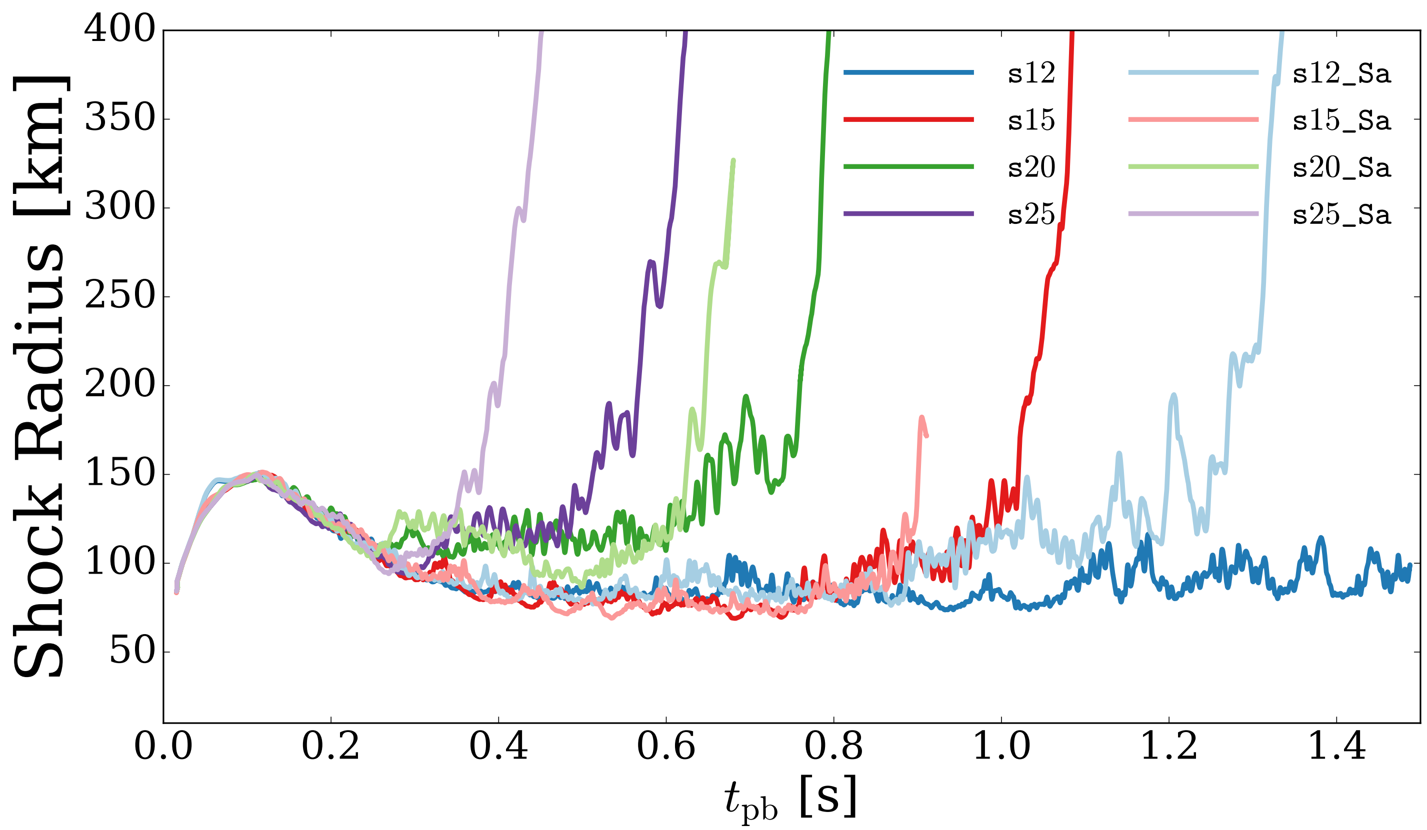
arXiv:1708.01788



Shock radius vs time for 2D SN simulations

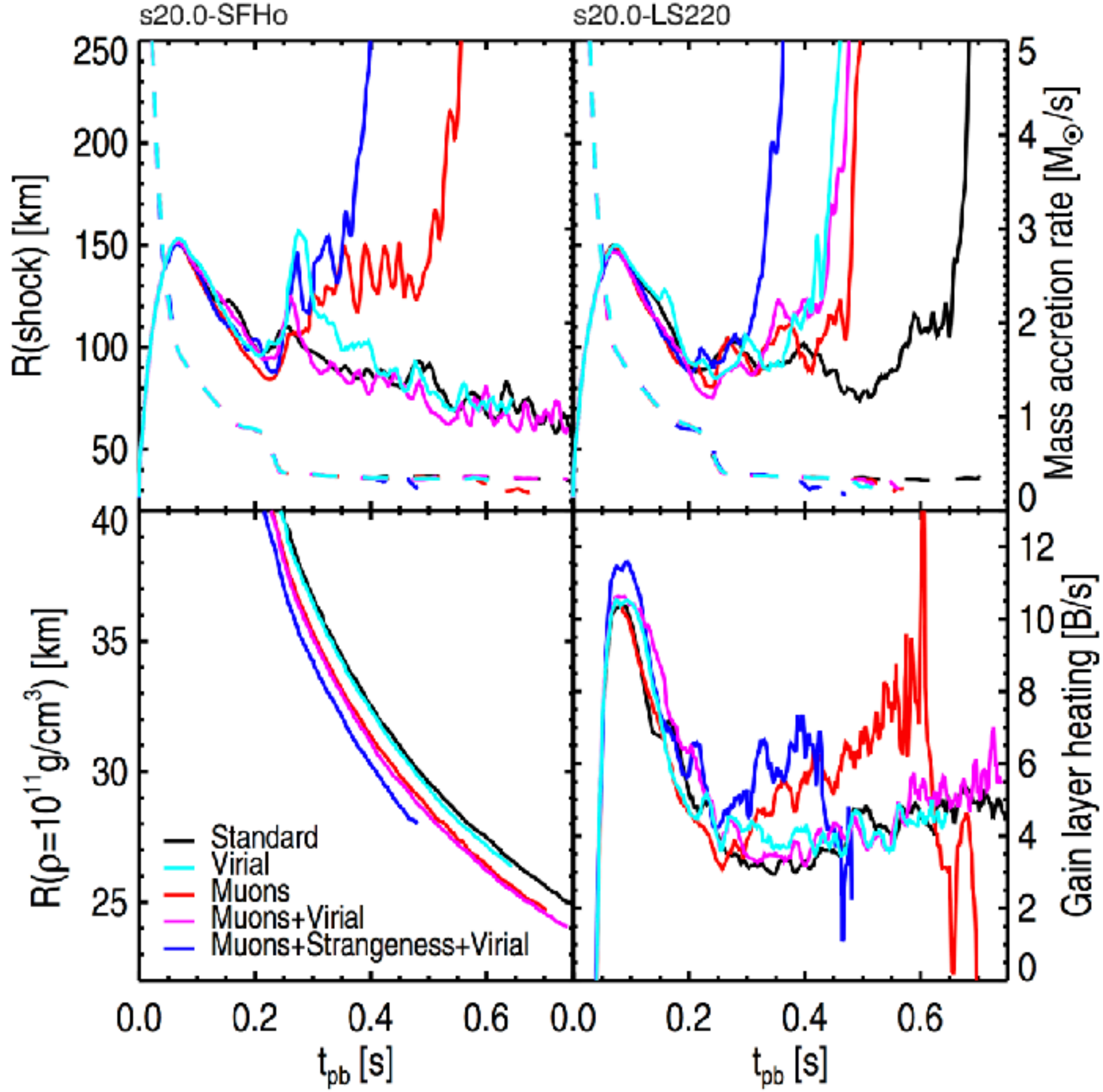


All 2-D SN simulations by Burrows [arXiv:1611.05859] with correlations (S_A<1) explode (solid lines) while 12 and 15 M_{sun} stars fail to explode, and 20, 25 M_{sun} explode later, without correlations (S_A=1).



Preliminary 2D SN simulations by Evan O'Connor and Sean Couch for 12 to 25 M_{sun} stars explode earlier (lighter color) if correlations (S_A<1) included.

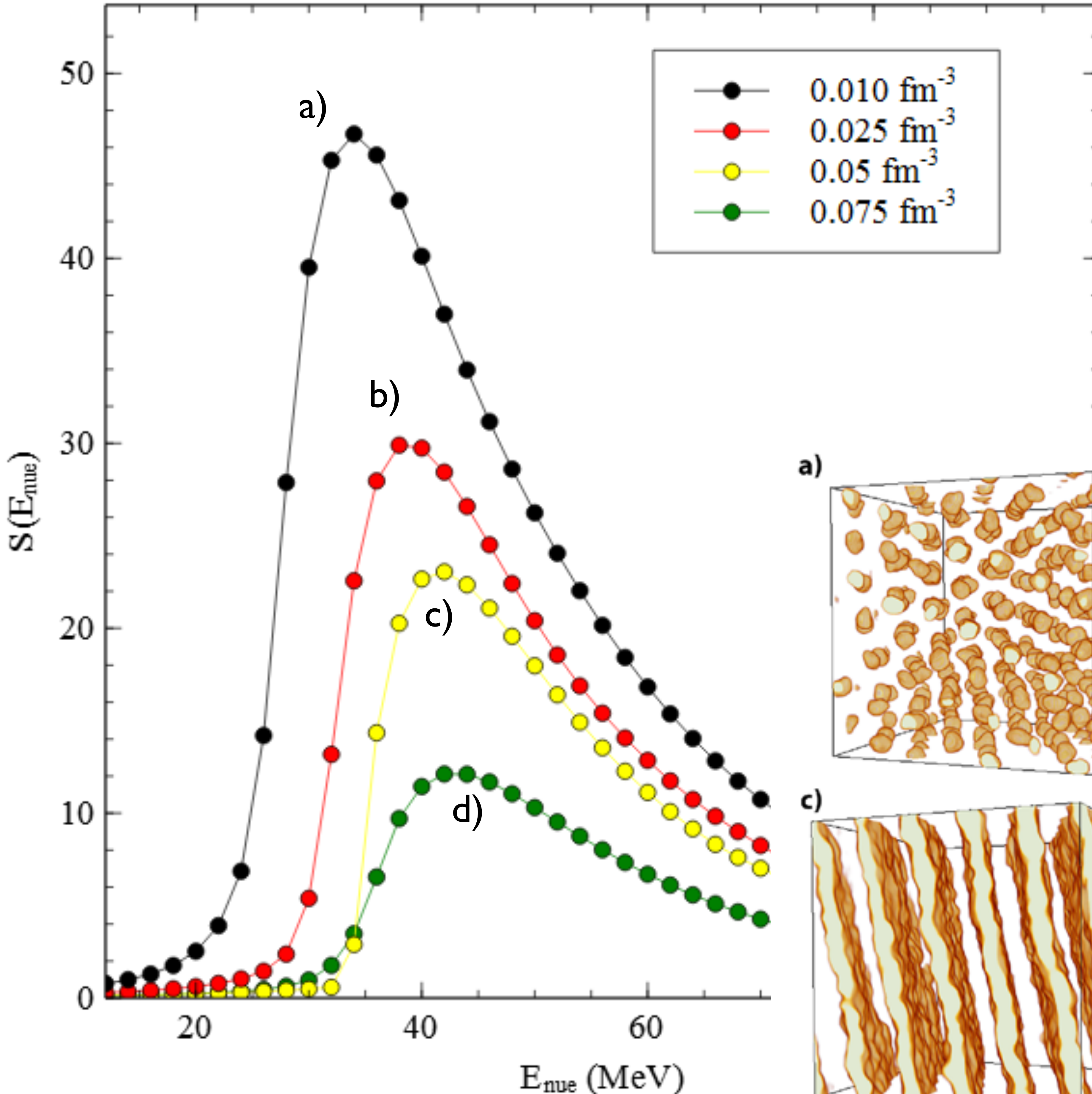
Sensitivity of SN dynamics motivates better treatments of neutrino interactions in SN matter.

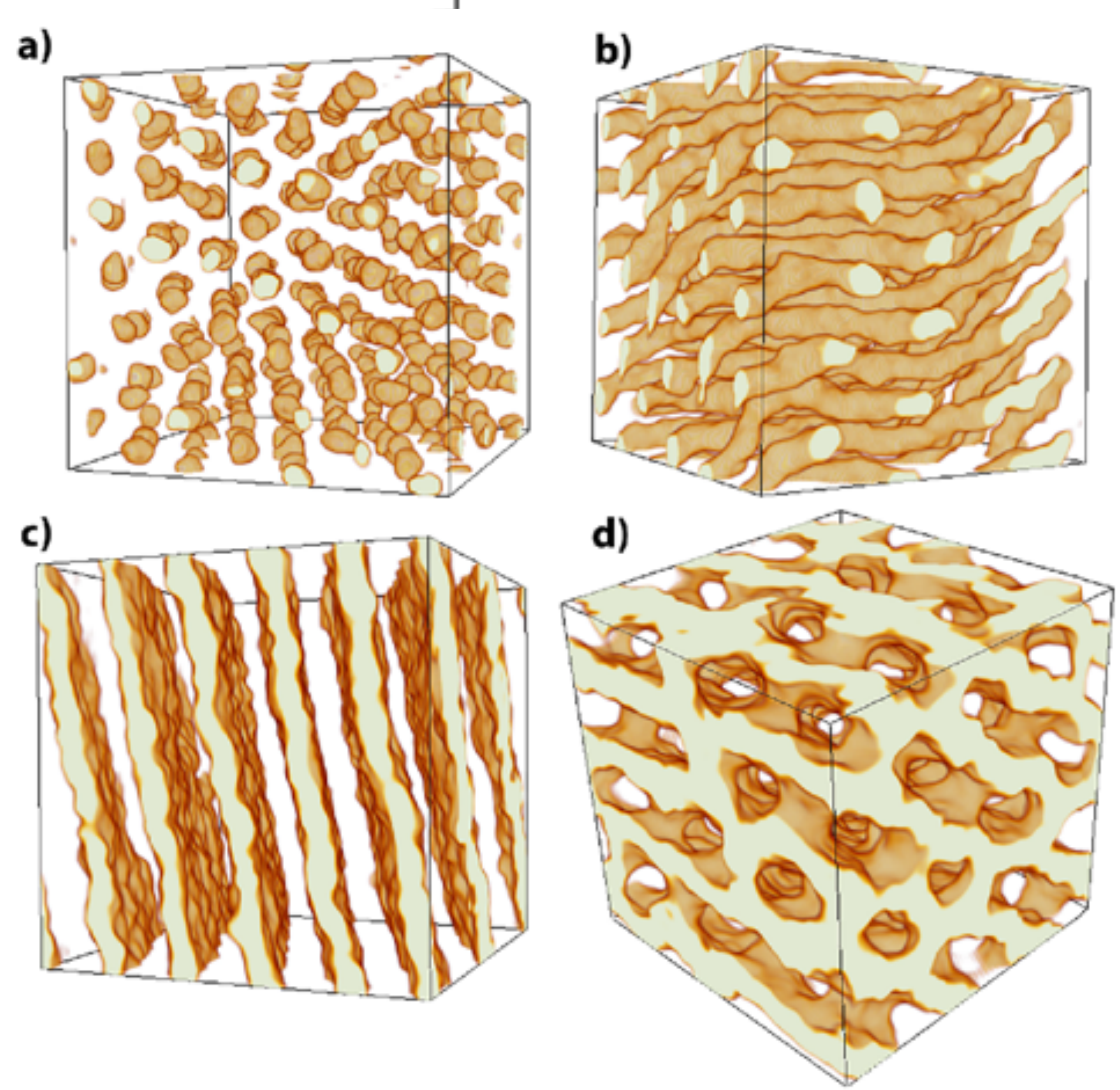


Bolig et al, arXiv:1706.04630

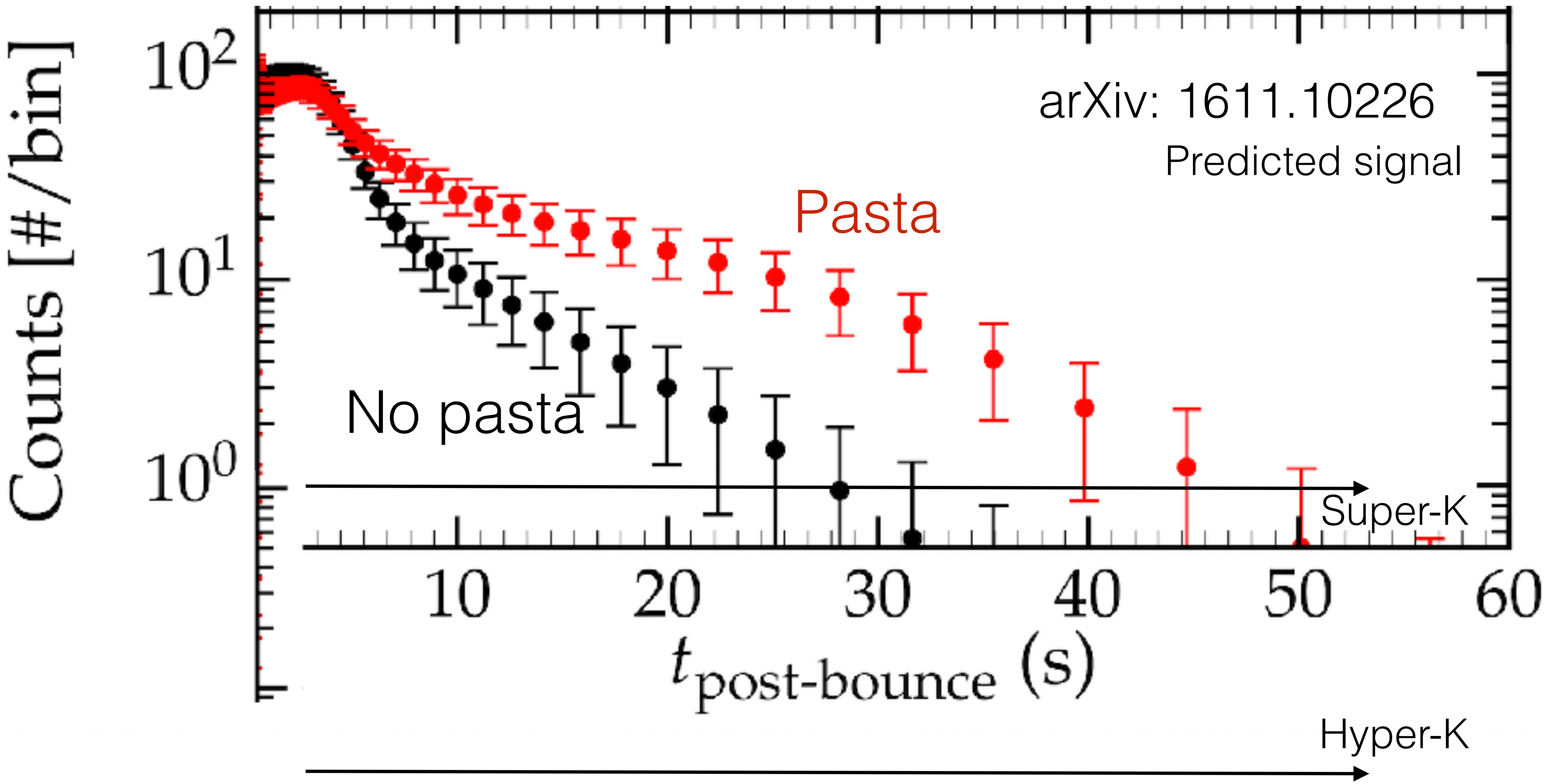
Vector response S_V and coherent neutrino-pasta scattering

arXiv: 1611.10226





SN signal at 10 kpc in Super-K



- Neutrino-pasta coherent scattering slows neutrino diffusion and leads to a significant 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.

Neutrino-nucleon elastic scattering

- Multi-D SN simulations sensitive to ~ 10% changes in ν-nucleon neutral current cross sections.

- Spin correlations between nucleons, from interactions with large scattering lengths, reduce neutral current opacities even at low neutrinosphere densities.

- These correlations can be calculated accurately with model independent virial expansions.

Neutrino-proton elastic scattering experiment at the SNS?

- Can one measure ν-p elastic scattering cross sections to ~10% in lab with (~ 30 MeV) neutrinos from pion decay at rest?

- This cross section is important for SN simulations.

- Constrain strange quark contributions to nucleon spin.

- Constrain nonstandard neutrino interactions that could impact SN dynamics.

- Note ν-p primarily involves axial currents and may provide complementary constraints to ν-A elastic scattering which probes vector currents.

SN neutrinos and r-process nucleosynthesis

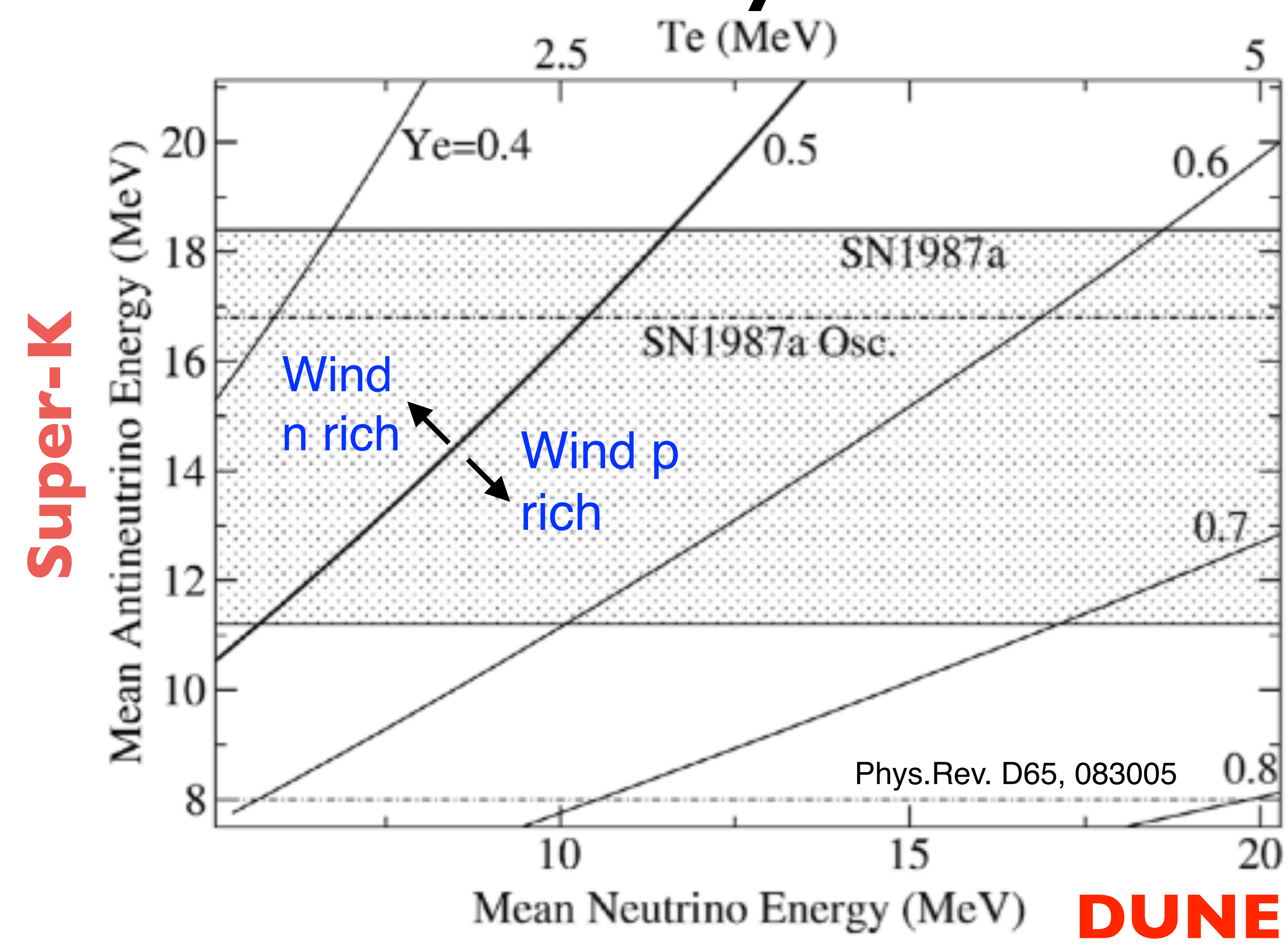
- Possible site of r-process (makes Au, Pt, U,…) is the neutrino driven wind in SN.

- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino and anti-neutrino energies.

$$\nu_e + n \rightarrow p + e \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

- Measure difference in average energy of **antineutrinos** and **neutrinos**. If large, wind will be neutron rich. If it is small, wind will be proton rich and likely a problem for r-process.

- Composition (Y_e) of wind depends on anti-neutrino energy (Y-axis) [results from ~20 SN1987A events shown] and energy of neutrinos (X-axis). Energy of neutrinos, not yet measured, depends on properties of n rich gas (nu-sphere).



SN simulations find too few neutrons for main or 3rd peak (Au, actinides) r-process. SN likely make lighter r-process nuclei.

Learn about impact of neutrinos on nucleosynthesis from a galactic SN. Neutrinos may be important in other r-process sites.

Microphysics for supernova simulations and neutrino signals

- Neutrino interactions in supernovae: **Zidu Lin**, Liliana Caballero, Achim Schwenk, Luke Roberts, Evan O'Connor, Tobias Fischer, W. Newton …
- Muons: R. Bollig, H.-T. Janka, A. Lohs, G. Martınez-Pinedo, and T. Melson

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