# Supernova Neutrinos and Nuclear Physics

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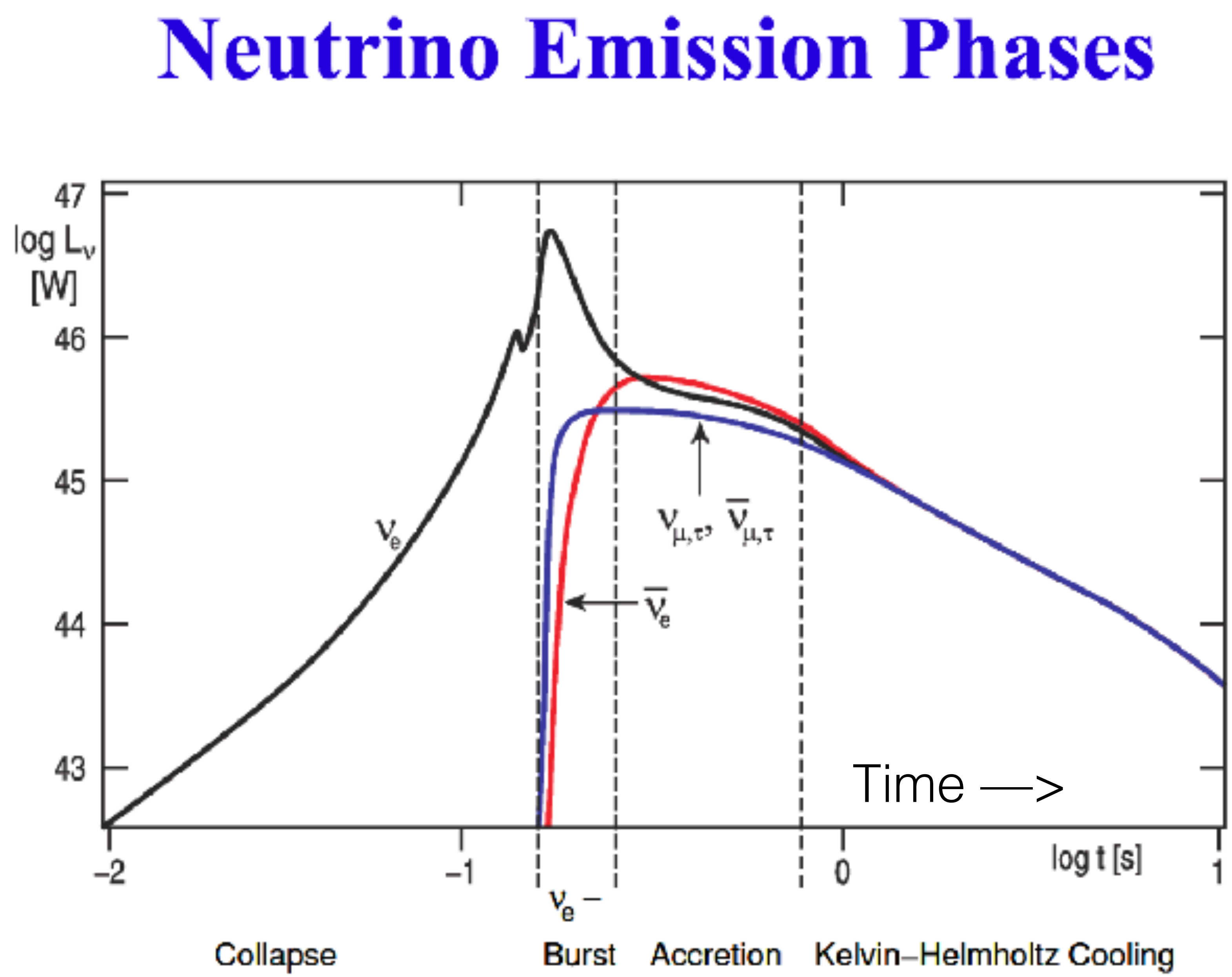
# Important SN neutrino features

- The **neutronization** burst involves both fundamental astrophysics and fundamental neutrino physics (osc of “clean” $\nu_e$ source…).
- Features related to **explosion mechanism**: accretion rate, progenitor structure and shells, SASI oscillations, ratio of $\nu_e$ from accretion to $\nu_x$ from diffusion…
- Features related to observations of **gravitational waves**.
- Features related to **nucleosynthesis** including $\nu_e$ vs anti-$\nu_e$.
- Features in the **late time** neutrino signal for as long as possible.
- Observation of the possible collapse to a **black hole**.



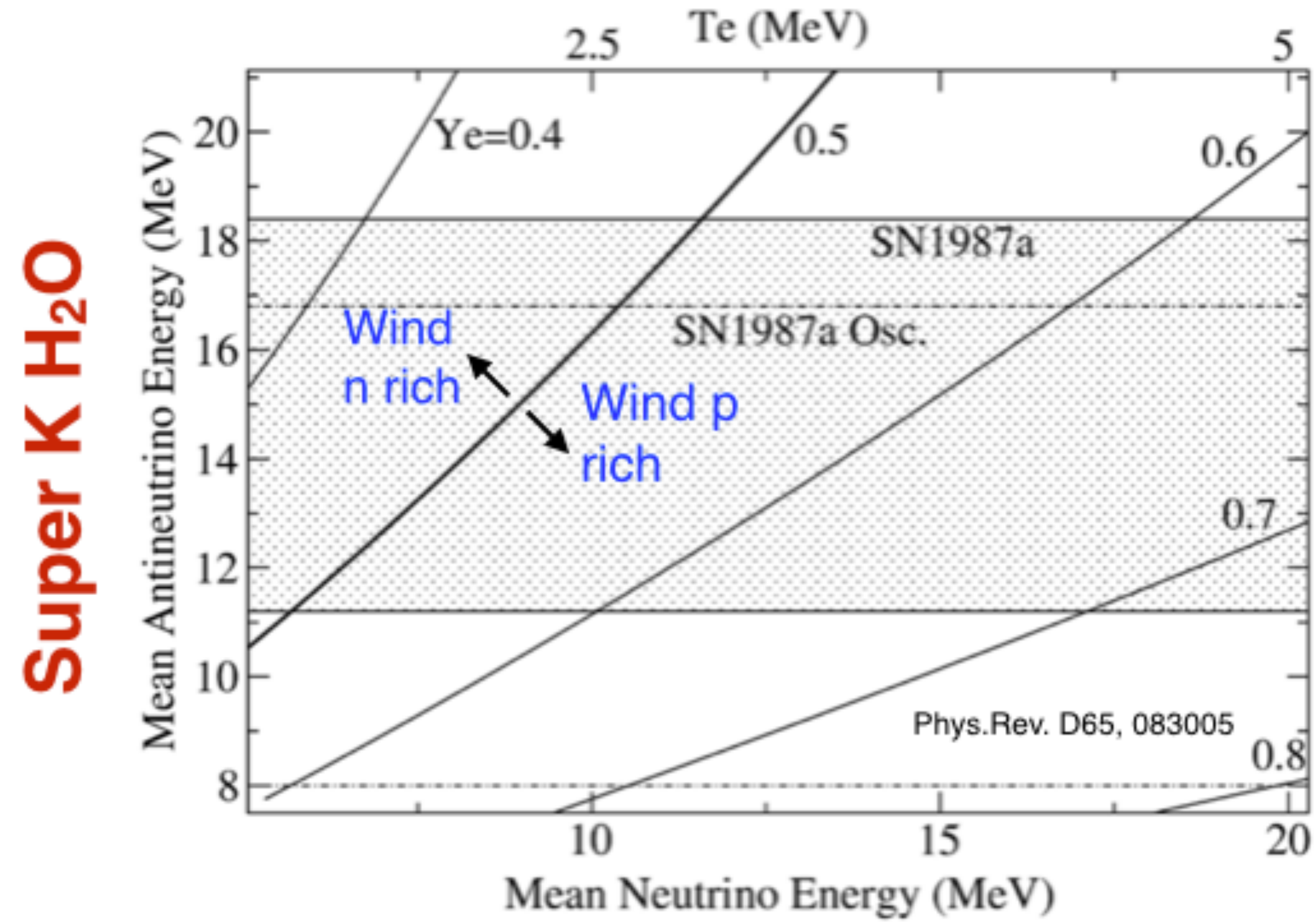

Thomas Janka

# SN neutrinos and r-process nucleosynthesis

- Half of heavy elements (including gold) are believed made in the rapid neutron capture process. Seed nuclei captures many n and decay.
- Important possible site for the r-process is the neutrino driven wind in core collapse supernovae.
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino / anti-neutrino energies.

$$\nu_e + n \rightarrow p + e$$

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




**DUNE liquid Ar**

Important to measure energy of both anti-nu (SK) and neutrinos (liquid argon DUNE). Should measure Ar cross section to interpret DUNE results.

**Present SN simulations find too few neutrons for heaviest r-process elements. But winds likely important nucleosynthesis site for some elements —> more n-rich wind heavier elements synthesized.**

# SuperNova Advanced Readiness Exercise (SNARE)

- SNARE is a drill that will help us to prepare, both theoretically and experimentally, for next galactic SN.

- Theoretical neutrino, gravitational wave, and E+M signals are generated for a supernova scenario.

- These signals will then be analyzed by each E+M, GW and neutrino detector. What will each detector "see"? What can we conclude? What important detectors or theory are we missing? — **Kate Scholberg (Duke)**

- Good way to highlight extraordinary capabilities of Hyper-K

# 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 (unlikely), 4) **Neutrino interactions** — perhaps important corrections have been left out.

# Some Important $\nu$ Interactions

**$\nu$ + n —> p + e (Charged current capture rxn)**

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

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

$\nu$ + e —> $\nu$ + e (Important for energy loss)

$\nu$ + A —> $\nu$ + A (Large coherent cross section)

- Garching group reduced $\nu$N 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 long scattering length can have important correlations even at low densities.

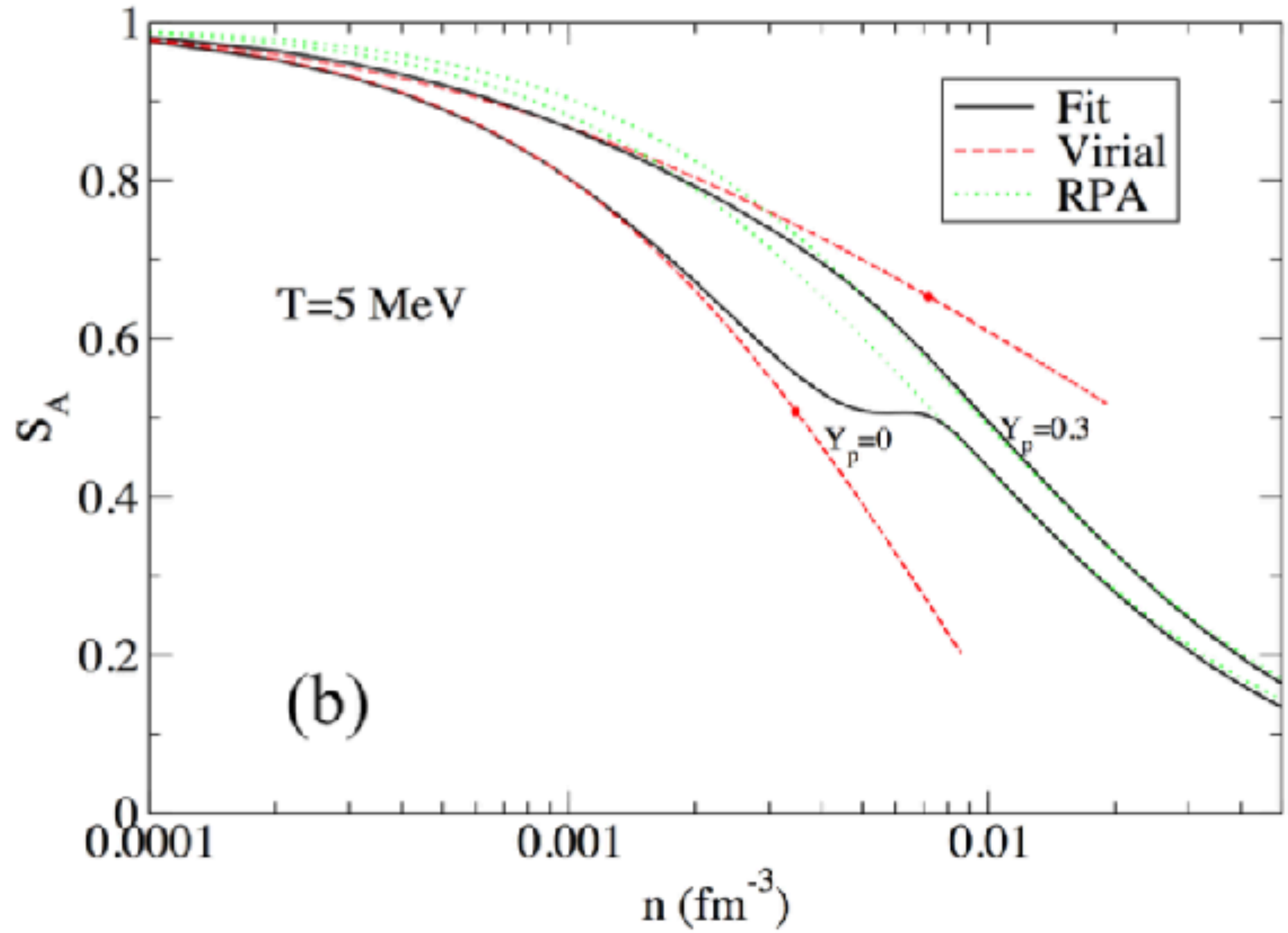
- Two neutrons are correlated into spin zero $^1S_0$ state that reduces spin response $S_A<1$.

# Axial Response in Virial Expansion

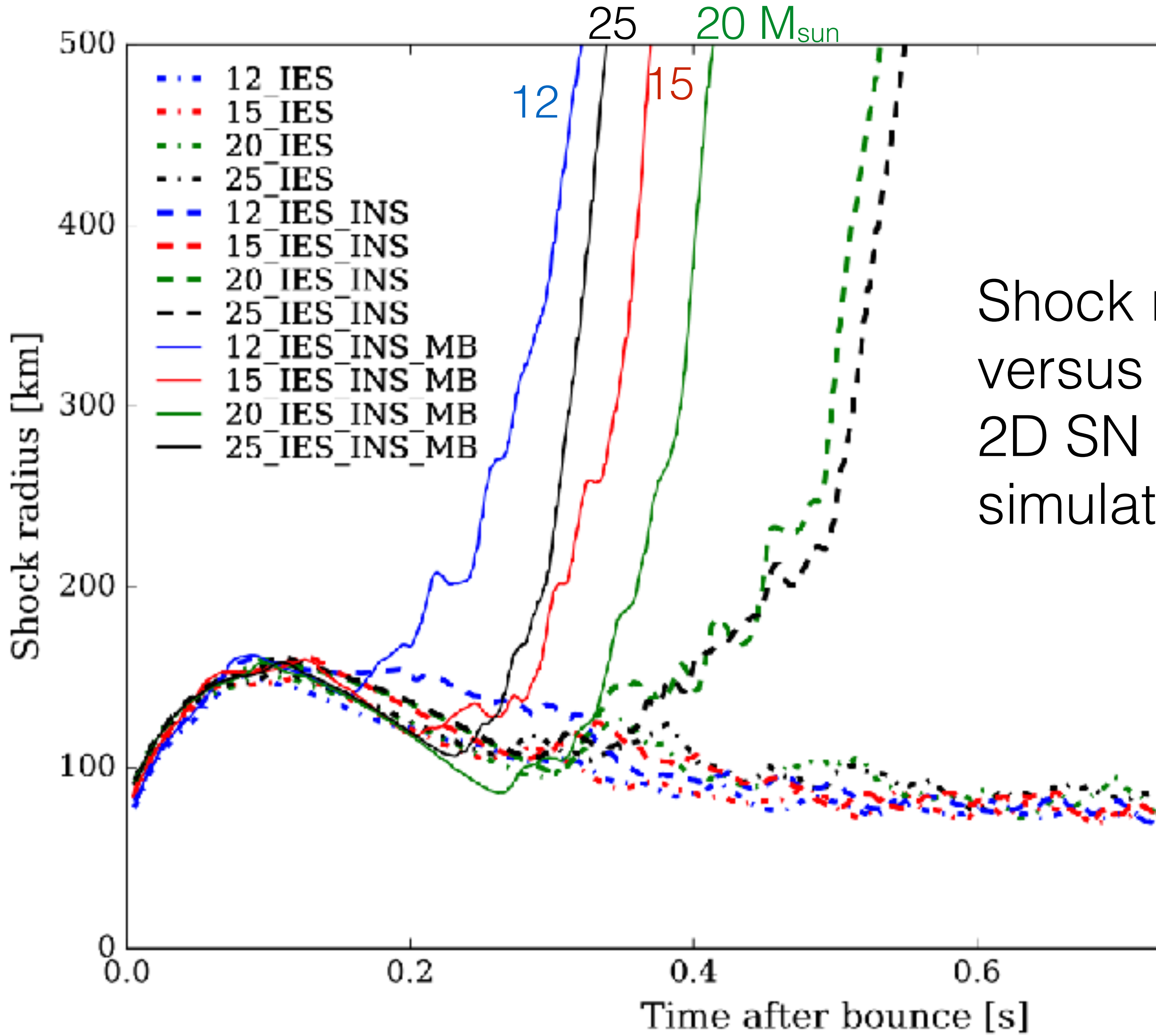
- At low densities $n$ and or high temperatures $T$ one can expand equation of state in powers of the fugacity $z=e^{\mu/T}$ with $\mu$ the chemical potential.

- 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.



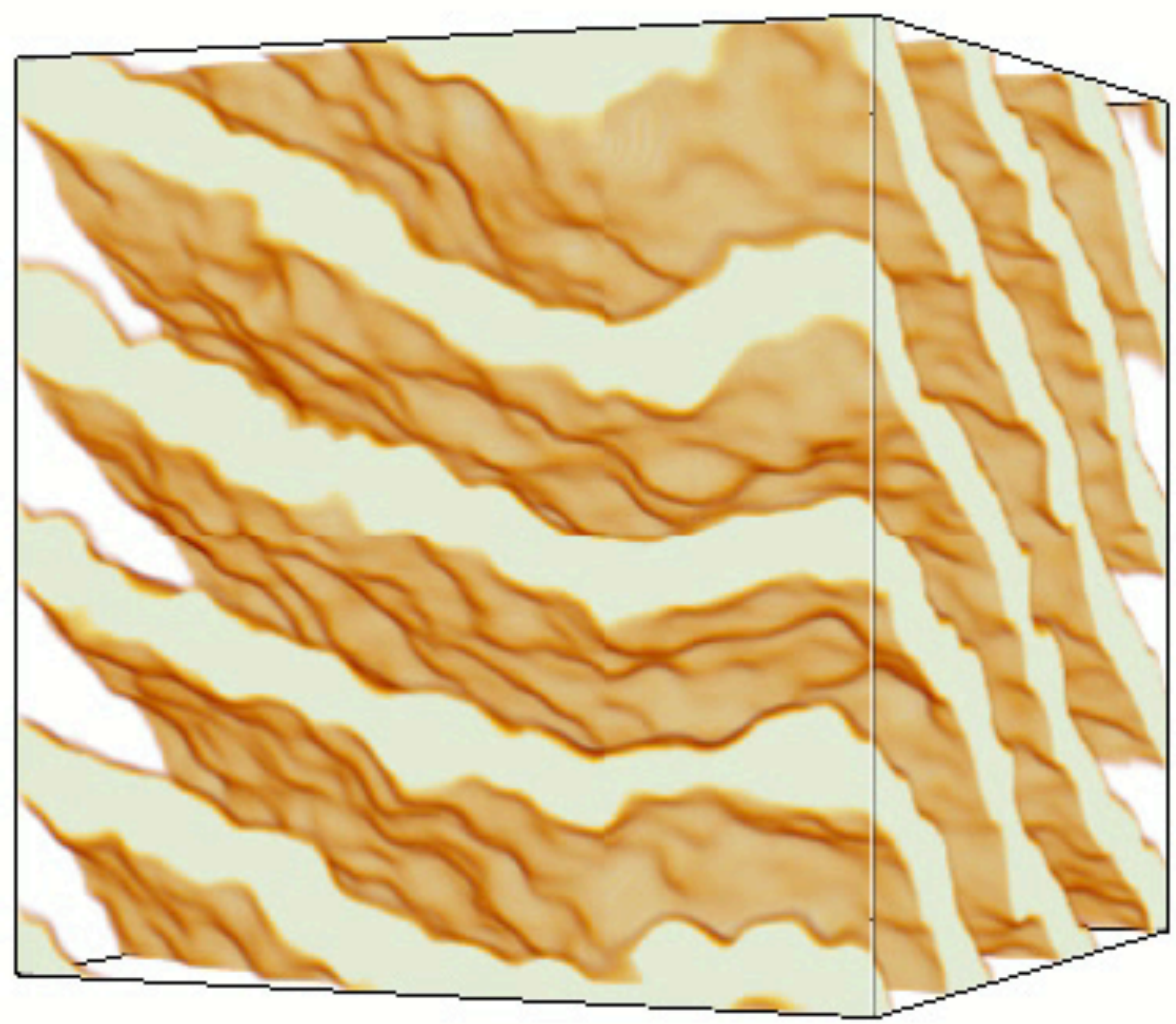

Shock radius versus time for 2D SN simulations

- 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).

# $S_V$ and Nuclear Pasta

- Nuclear matter, at somewhat below $\rho_0$, 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

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

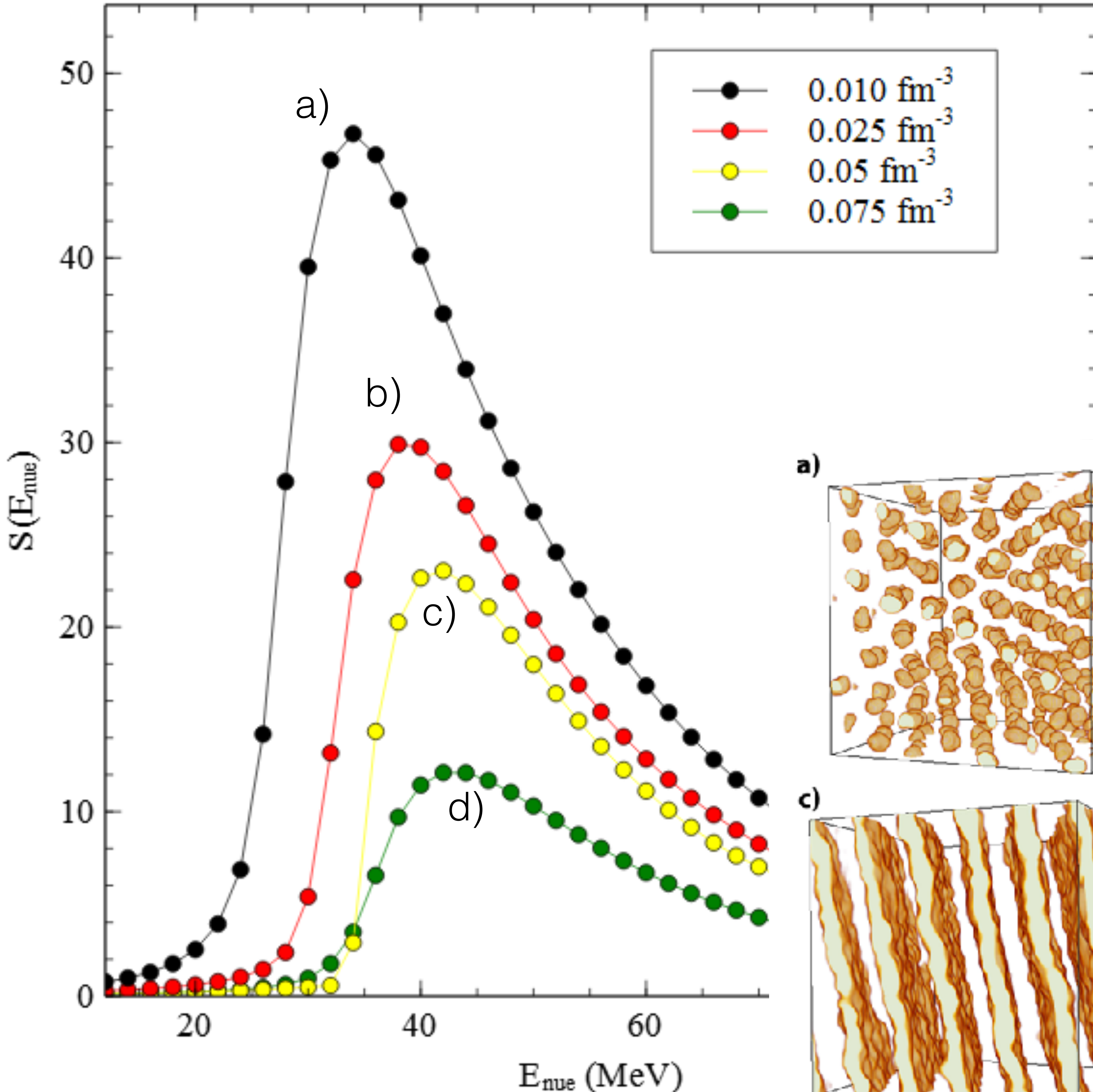
51200 nucleons, T=1 MeV, $Y_p$=0.4

# Neutrino-pasta diffraction

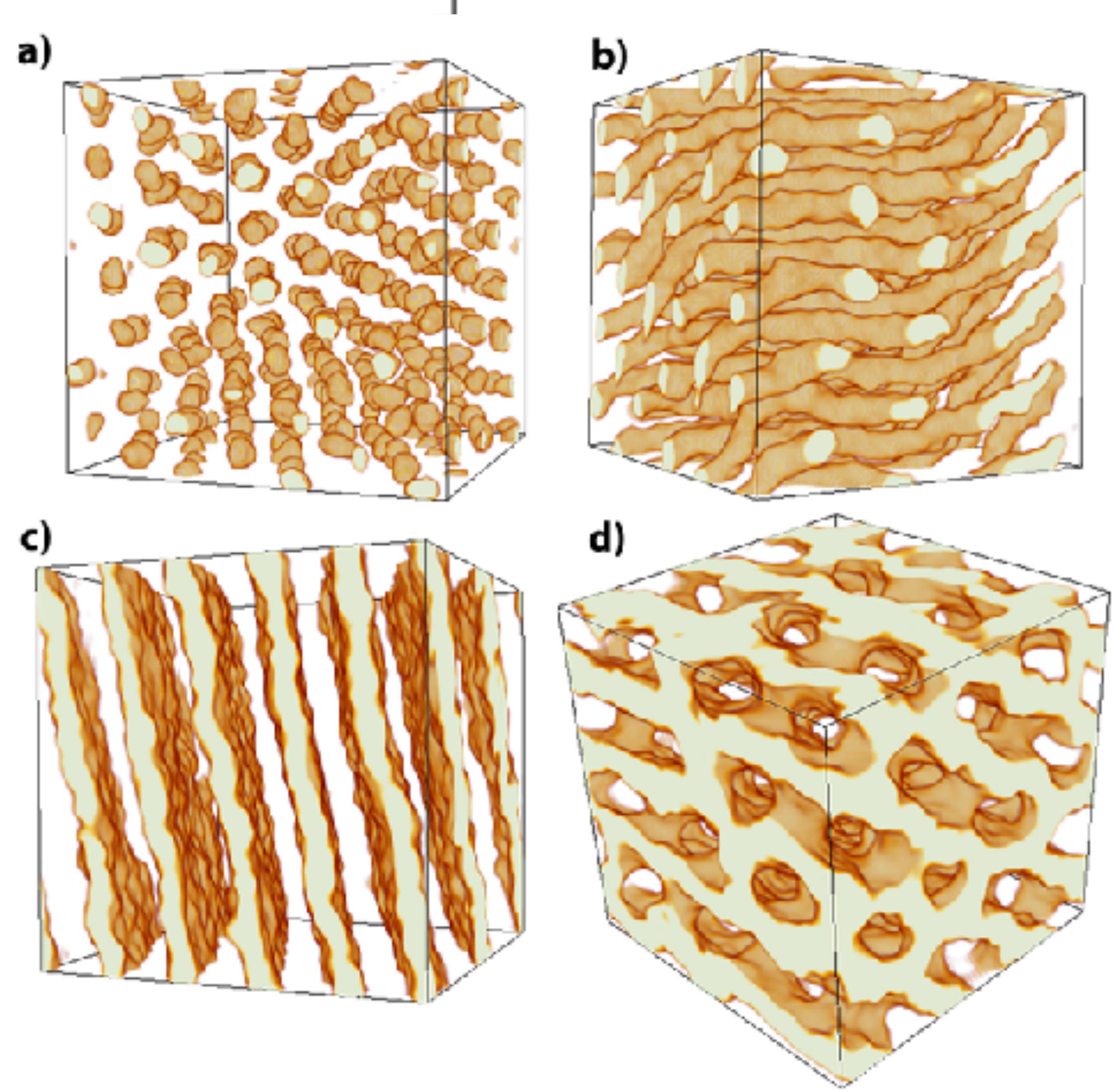


- Diffraction experiment needs source (SN), sample (Pasta), and detector (Hyper-K is ideal because of large statistics).

- Replace photons with neutrinos, and replace the Advanced Photon Source (~$10^{15}$ photons/s) with a core collapse Supernova (~$10^{57}$ neutrinos/s).

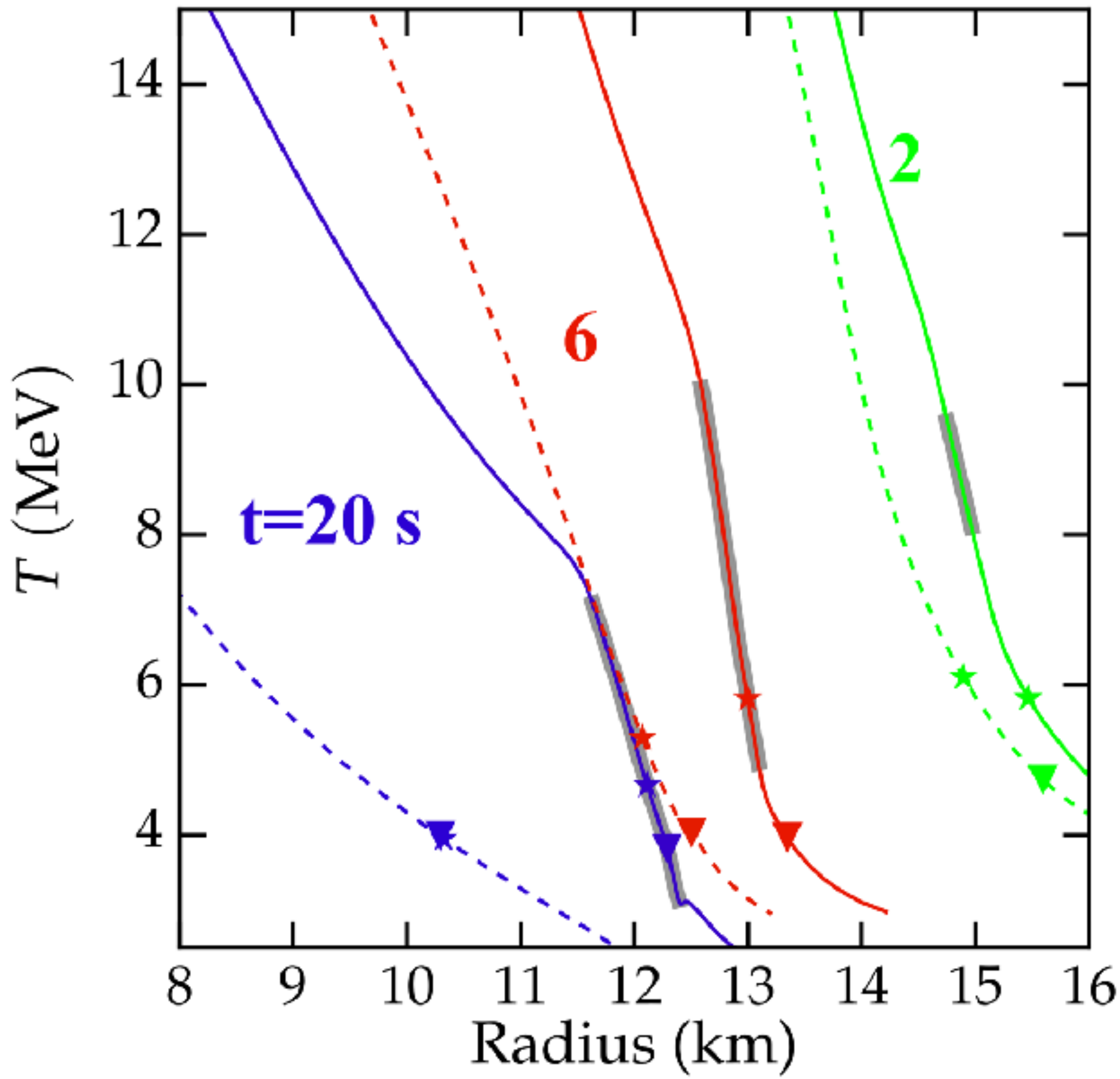



arXiv: 1611.10226

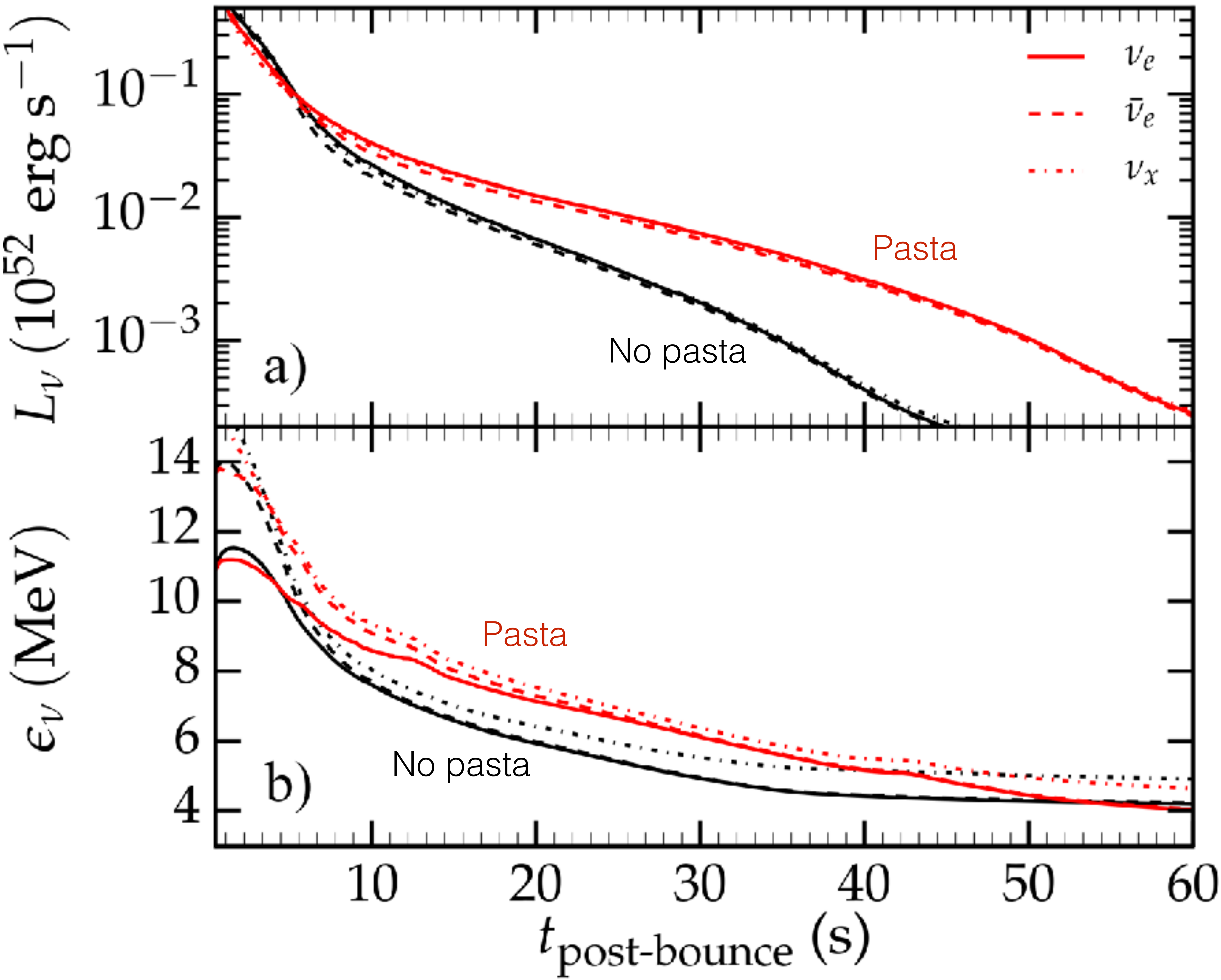


# Temperature profile of proto-neutron star

arXiv: 1611.10226

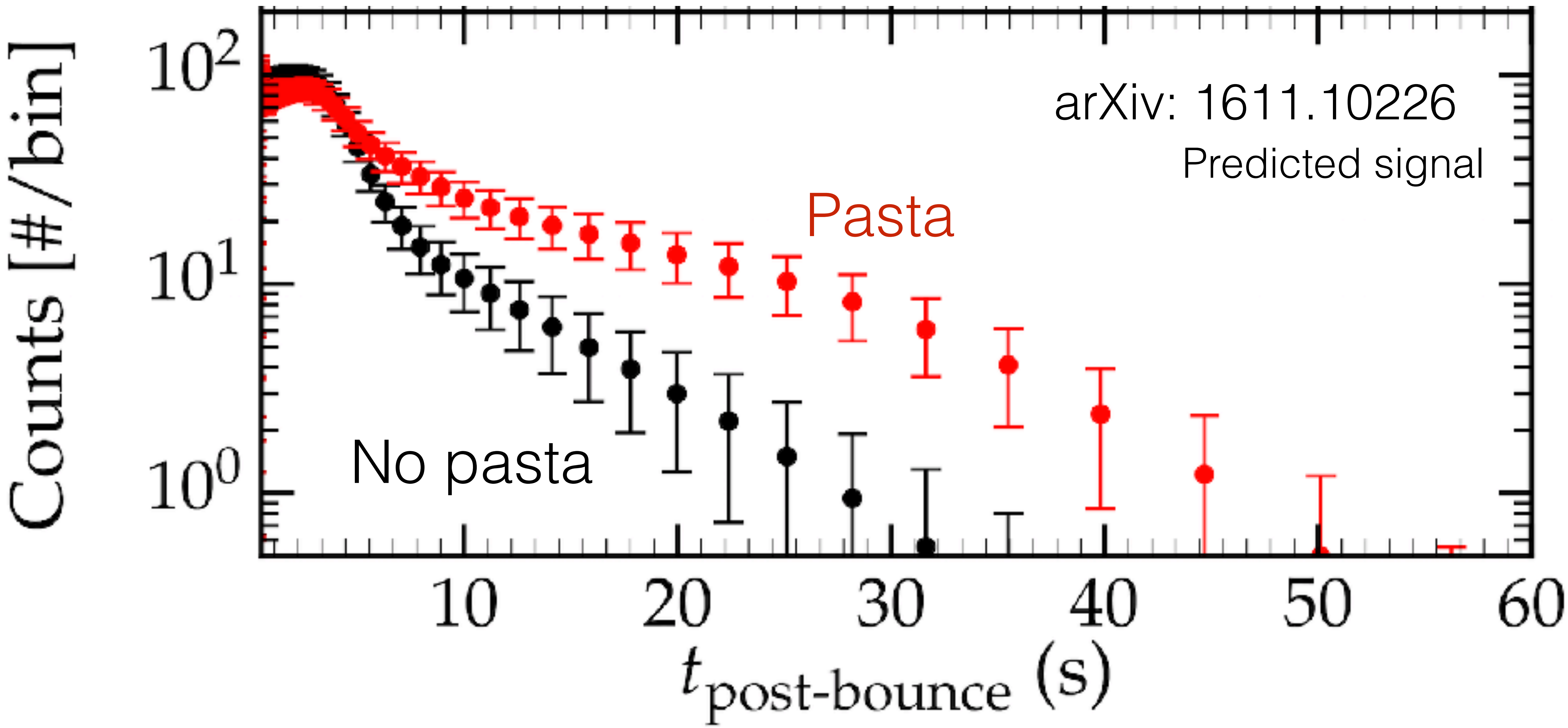



Solid lines include pasta and dashed lines neglect pasta, for indicated times after core bounce. Pasta present in shaded regions.



$L_\nu$ ($10^{52}$ erg s$^{-1}$)
$10^{-1}$
$10^{-2}$
$10^{-3}$
$\nu_e$
$\bar{\nu}_e$
$\nu_x$
Pasta
No pasta
a)
$\epsilon_\nu$ (MeV)
14
12
10
8
6
4
Pasta
No pasta
b)
10
20
30
40
50
60
$t_{\text{post-bounce}}$ (s)

# 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.

# Supernova Neutrinos and Nuclear Physics

- 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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