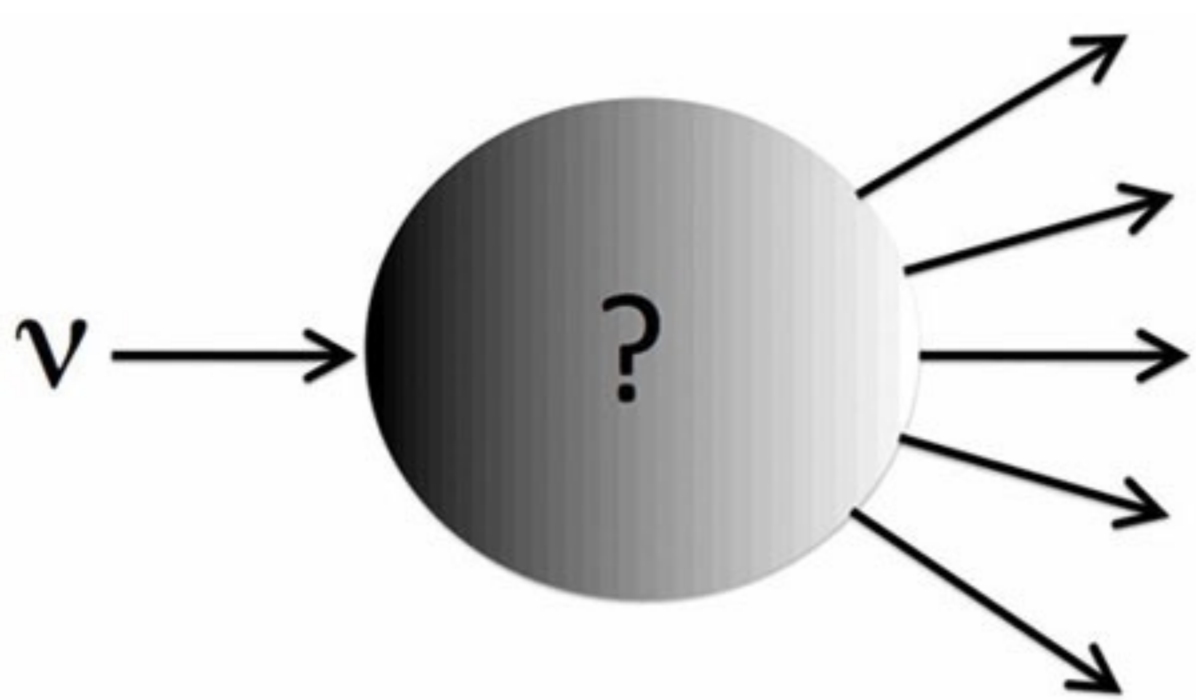
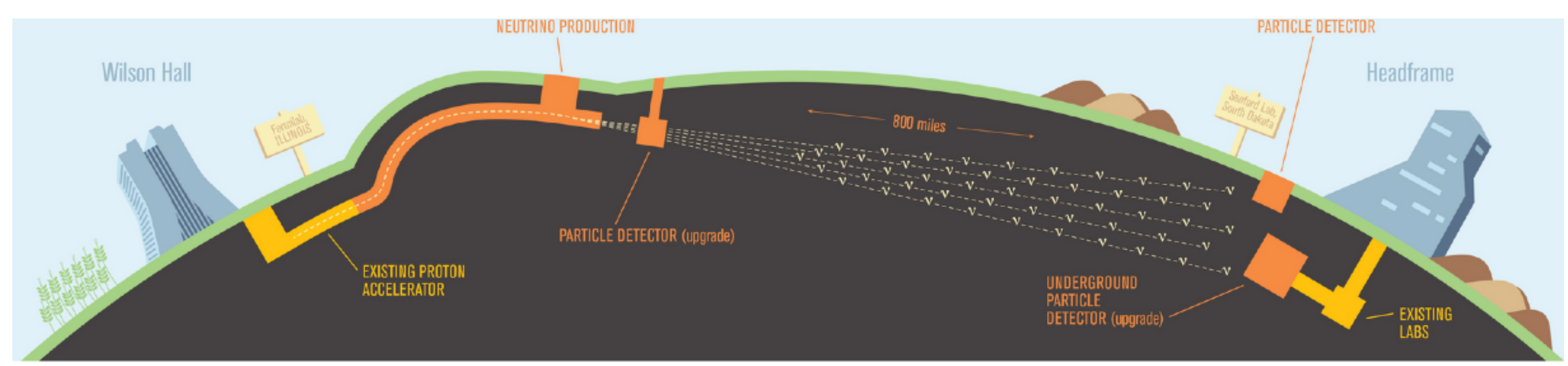
Neutrino interactions in SN and Nucleosynthesis



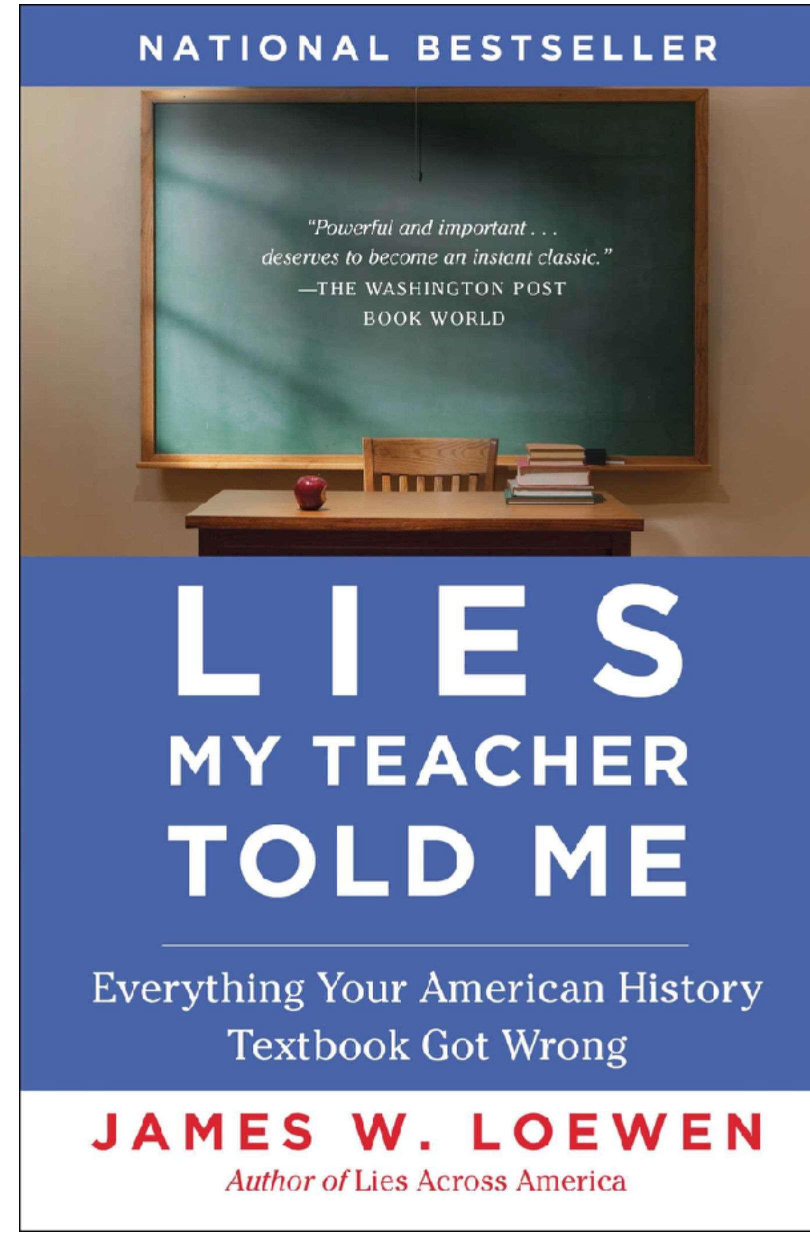


Chuck Horowitz, Indiana U., FRIB and GW170817, Jul. 2018

Blue Kilonova and Neutrinos

- GW170817 was too far away to detect neutrinos directly. Do we have indirect evidence of their effects during the merger?
- Is the observation of a blue kilonova at early times evidence of neutrinos changing the electron fraction of some component(s) of the ejecta?

Supernovae



According to many textbooks, supernovae are the site of the r-process. Why are the textbooks wrong?

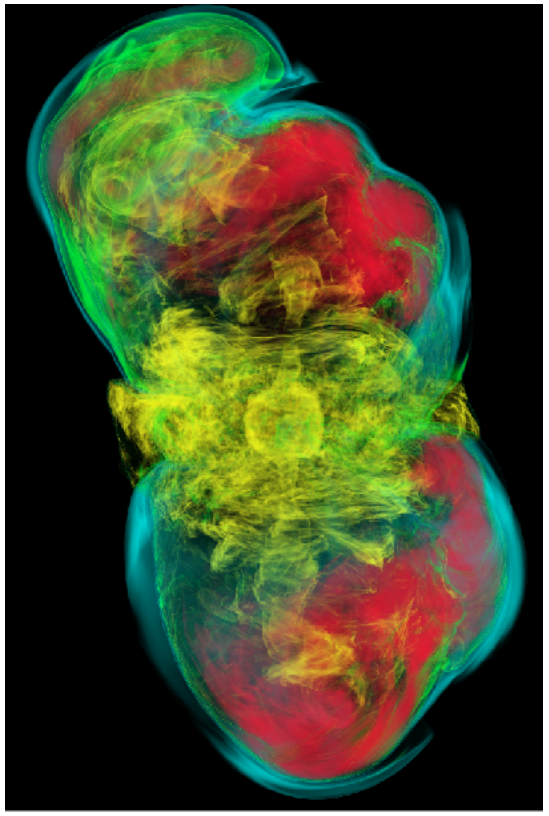
Wind is not neutron rich enough because of simple neutrino physics.

Neutrino Interactions in SN

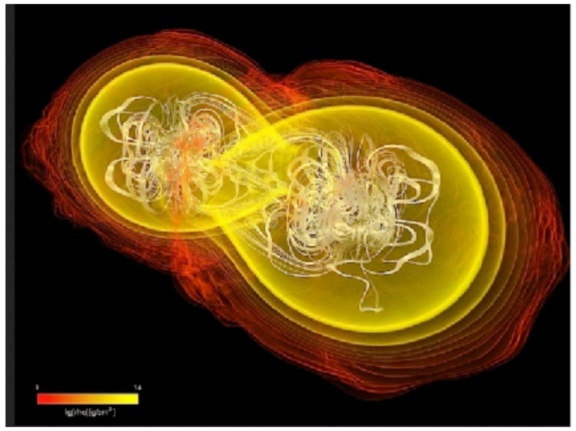
- Neutral current interactions and explosion mechanism
- Charged current interactions and nucleosynthesis
- SN neutrino detectors

Supernova vs merger neutrinos

- Very important to observe neutrinos from next galactic SN: for nucleosynthesis, for neutrino oscillations, and for other neutrino physics …
- And what we learn about SN neutrinos very likely will have important implications also for neutrinos from NS mergers. For example could observe unusual oscillations during a SN that may also be present in mergers.



SN simulation



NS merger simulation

Neutral current interactions

- Nucleon-nucleon spin correlations reduce neutral current interactions and this may impact SN explosion.

ν interactions in SN matter

ν_e + n —> p + e (Charged current capture rxn)
ν + N —> ***ν*** + N (Neutral current elastic scattering, important opacity source for mu and tau ***ν***)

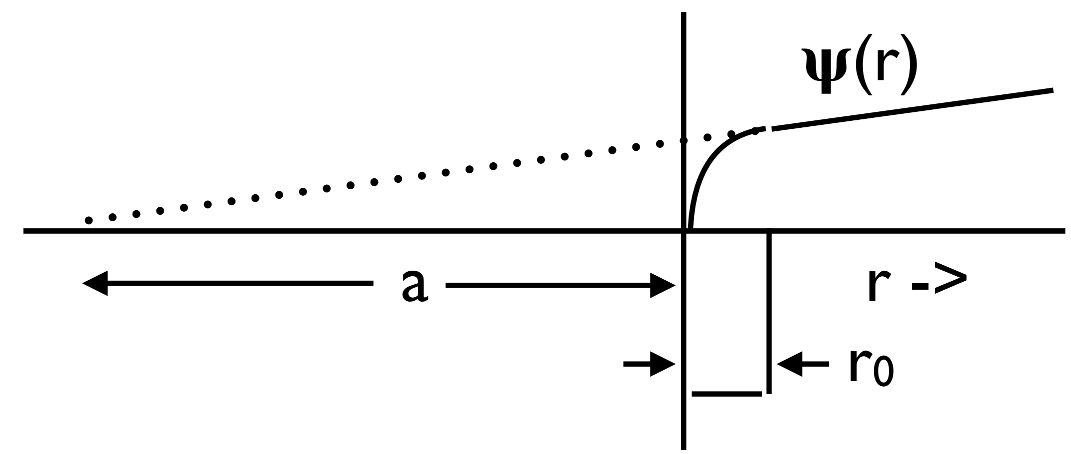
- Neutrino-nucleon neutral current cross section in SN is modified by axial or spin response S_A, and vector response S_V, of the medium.

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

- Responses S_A, S_V —> 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***, where $\boldsymbol{\nu}$ decouple, at ~ 1/100 of nuclear density.
- Here warm neutron rich matter is approximately a unitary gas.
- Unitary gas has large scattering length **a** and small effective range $\mathbf{r_0}$.
- Because of the large scattering length, correlations are important even at low densities.
- Two neutrons are correlated into spin zero $^1S_0$ state that reduces spin response S_A<1.

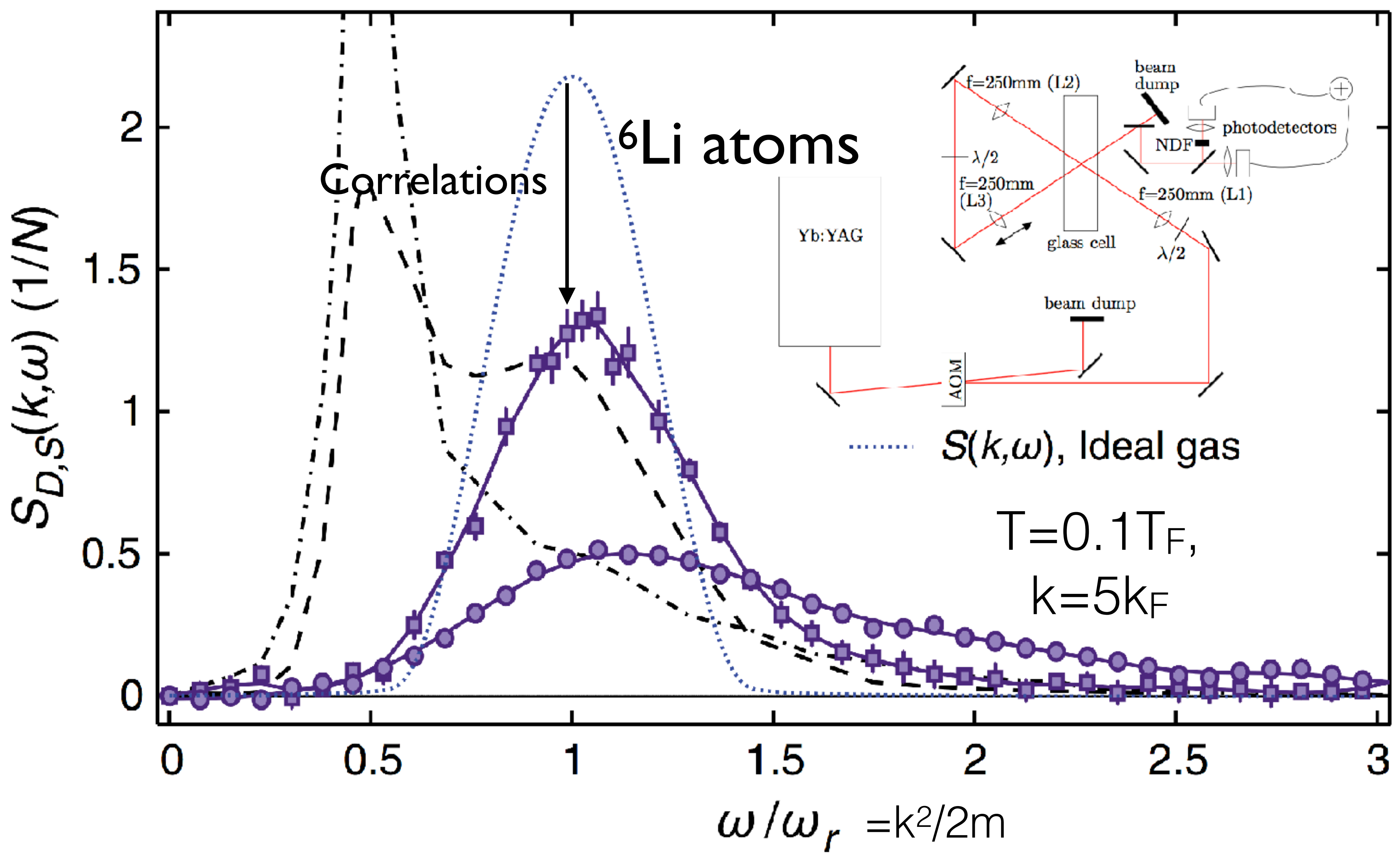


Neutron-neutron scattering wave function $\boldsymbol{\psi}$ at low energies. Intercept is large scattering length a=-19 fm. Actual range of potential is approx. effective range r_0<< a.

Quantum Computer

- Can one calculate neutrino-nucleus scattering on a quantum computer? Yes and no. QC can determine real time correlation (response) functions that are difficult on a CC. But QC does not solve sign problem to determine ground state.
- Can one "observe" neutrino-nucleus scattering with a quantum simulator? Yes.
- Tune interactions between laboratory cold atoms to simulate nucleon-nucleon interactions. Measure dynamical response functions of the cold atoms, with light scattering, that are necessary to predict neutrino-nucleus cross sections.

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



Dynamical response versus excitation energy ω. Free response is dotted. Spin or axial response $S_A(k,\omega)$ is solid line + squares, while dashed line is vector or density response $S_V(k,\omega)$.

Virial Expansion for Unitary Gas

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

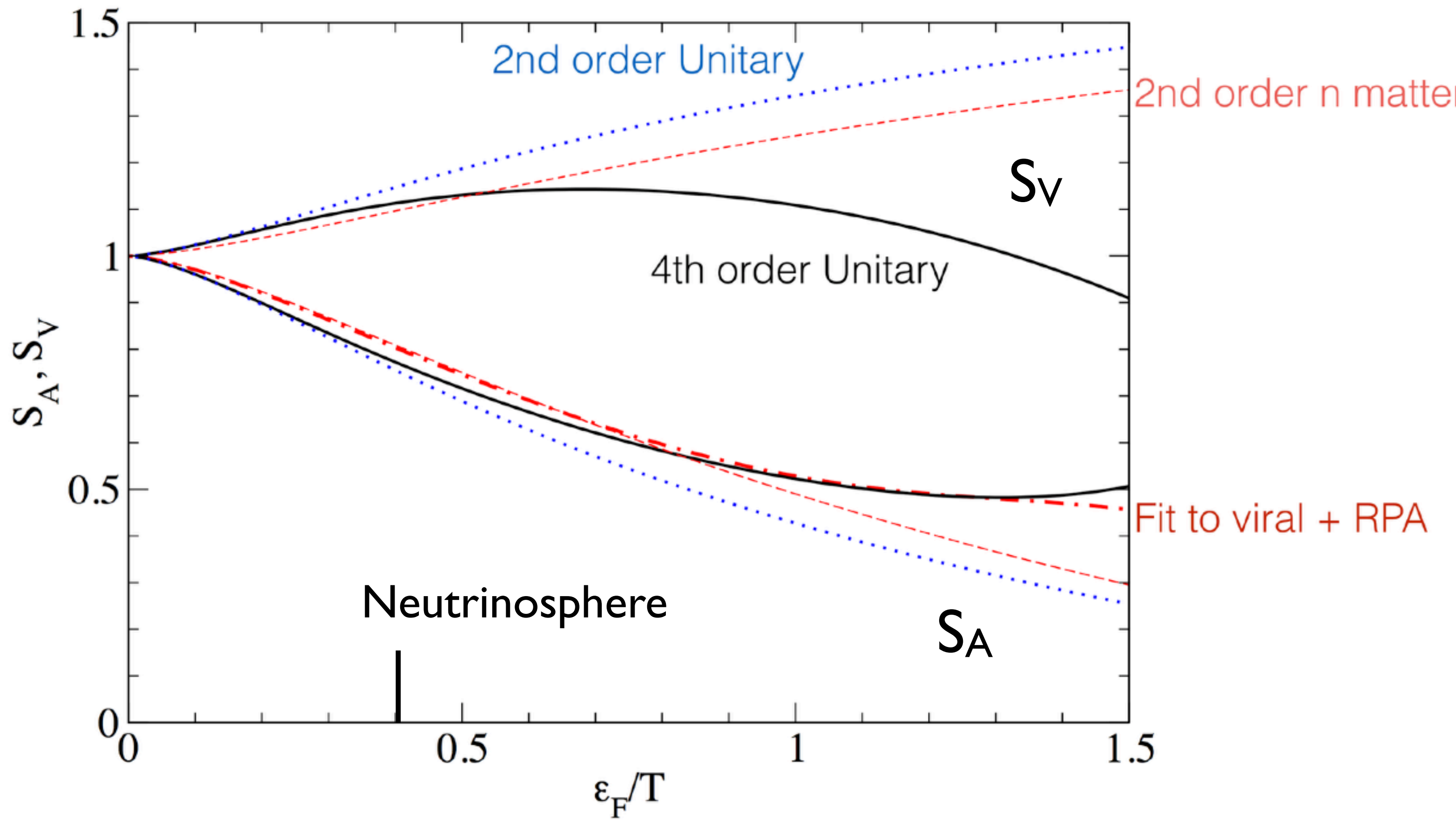
$$P = \frac{2T}{\lambda^3}\sum_{n=1}^{4} b_n z^n \qquad\qquad n = \frac{z}{T}\frac{dP}{dz}$$

- Long wavelength response:

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

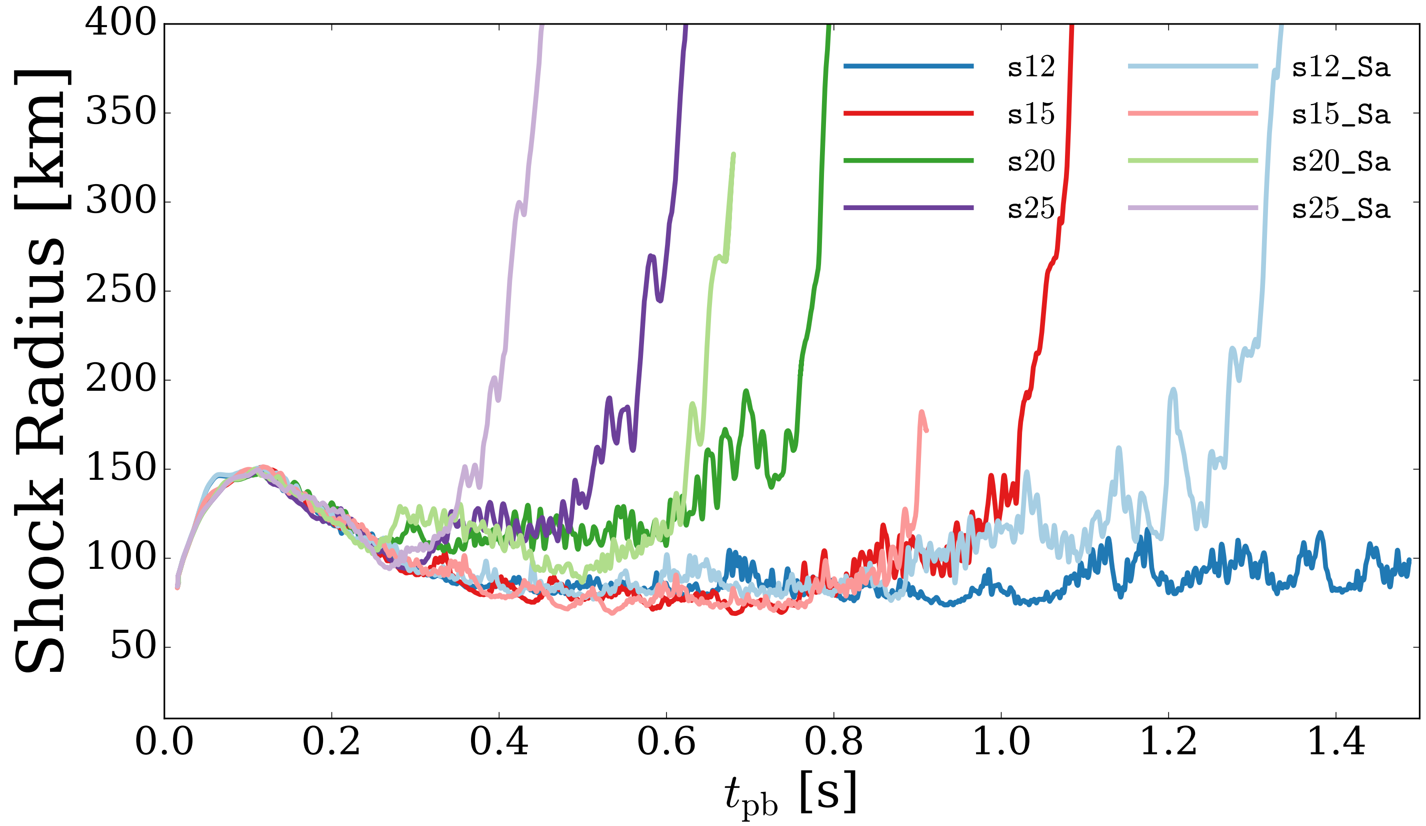
$$S_V(q \to 0) = \frac{1 + 4zb_2 + 9z^2 b_3 + 16z^3 b_4}{1 + 2zb_2 + 3z^2 b_3 + 4z^3 b_4}$$

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



Responses of unitary gas vs Fermi energy over temperature.
Calculated in the long wavelength limit using a 4th order viral expansion.
Phys. Rev. C **96**, 055804 (2017).

Radius of SN shock vs time



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.

Charged current interactions

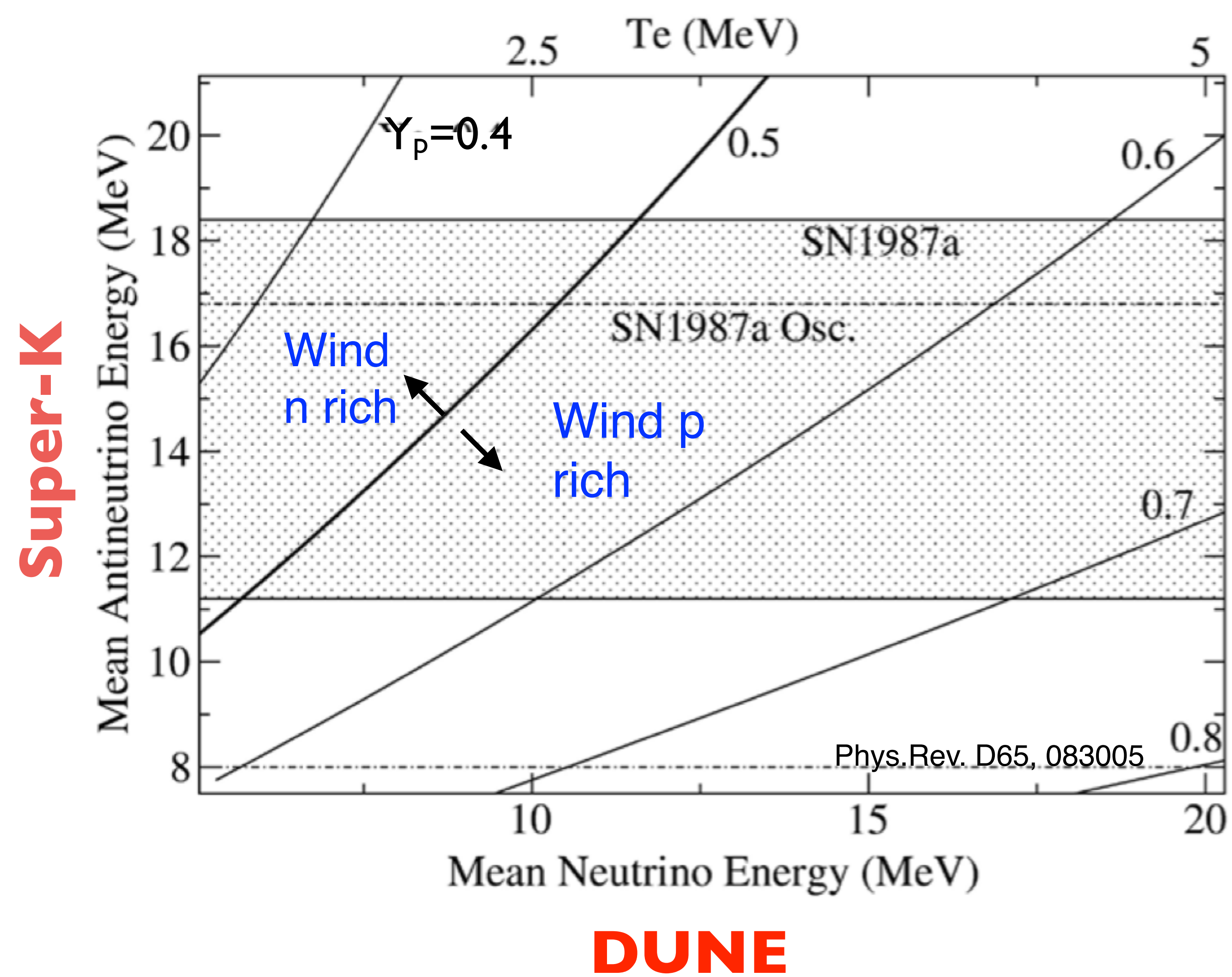
- Neutrinos destroy neutrons, anti-neutrinos make neutrons.
- Corrections to charged current interactions can change Y_e and nucleosynthesis.

SN neutrinos and r-process nucleosynthesis

- Possible site of r-process is the neutrino driven wind in a SN.
- Ratio of neutrons to protons in wind set by capture rates that depend on neutrino and anti-neutrino energies.

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

- Composition of wind depends on anti-neutrino energy (Y-axis) and neutrino energy (X-axis).
- **SN simulations find wind is not n rich enough for r-process!**



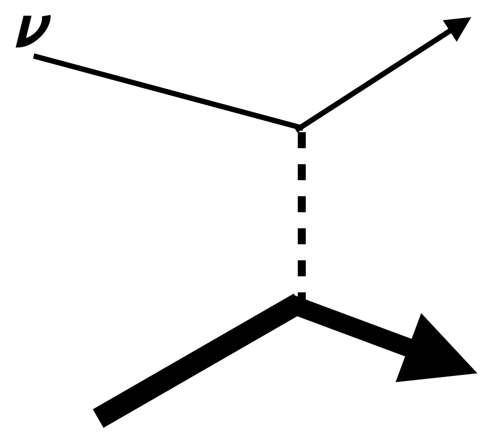
- Important to observe in detail both neutrinos and antineutrinos from next galactic SN!

Binding energy shift

- Converting a neutron in the medium to a proton releases the symmetry energy (energy of pure neutron matter minus energy of symmetric nuclear matter). ν+n->p+e
- This increases the neutrino, and reduces the antineutrino, absorption cross section. Effect is surprisingly large at low (near neutrino-sphere) densities because of the large scattering length.
- Binding E shift is difference in neutron and proton chemical potentials compared to free chemical potentials and can be calculated model independently from viral expansion.

Weak magnetism

- If nucleons don’t recoil then neutrino and anti-neutrino cross sections are equal.
- First recoil correction is of order the neutrino energy over the nucleon mass E_{nu}/M. It has a large coefficient a from weak magnetism. This increases neutrino and decreases anti-neutrino cross sections.
- Weak magnetism increases Y_e (by ~10%??) and can convert a slightly n rich wind to slightly proton rich.



Nucleon

$\sigma \sim G_F^2 E^2 [1 +/- aE/M]$

Neutrino oscillations

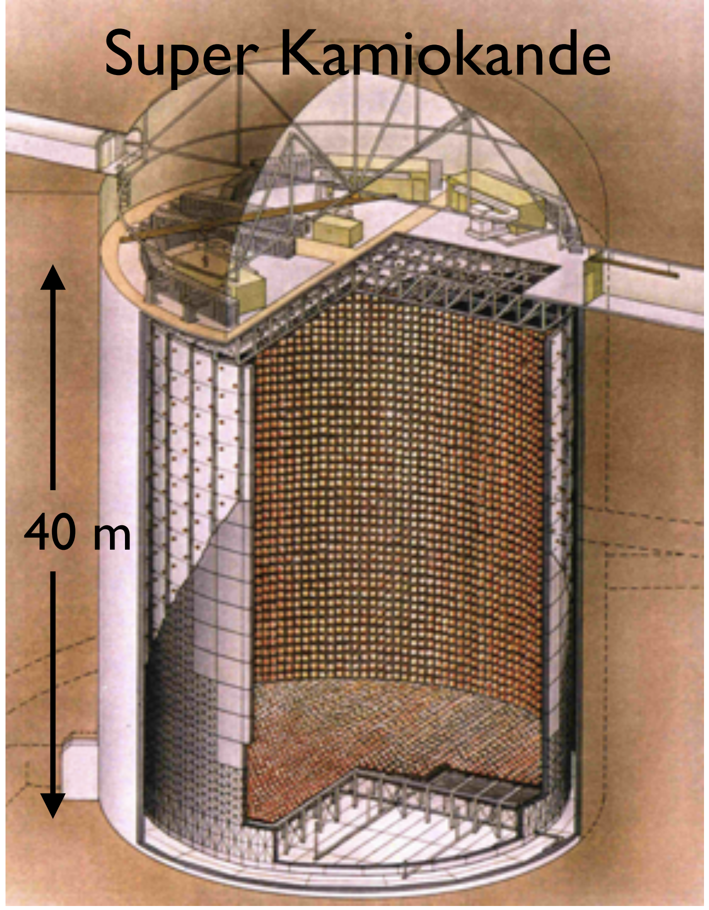
- Vacuum
- MSW (neutrinos seeing flavor dependent mean fields from electron and nucleon backgrounds)
- Nonlinear (neutrinos seeing mean fields from other neutrinos)
- Full oscillations are complicated, sensitive to new physics, and uncertain.
- Can impact Ye and nucleosynthesis.
- Observations of neutrinos and antineutrinos from next galactic supernova very important!

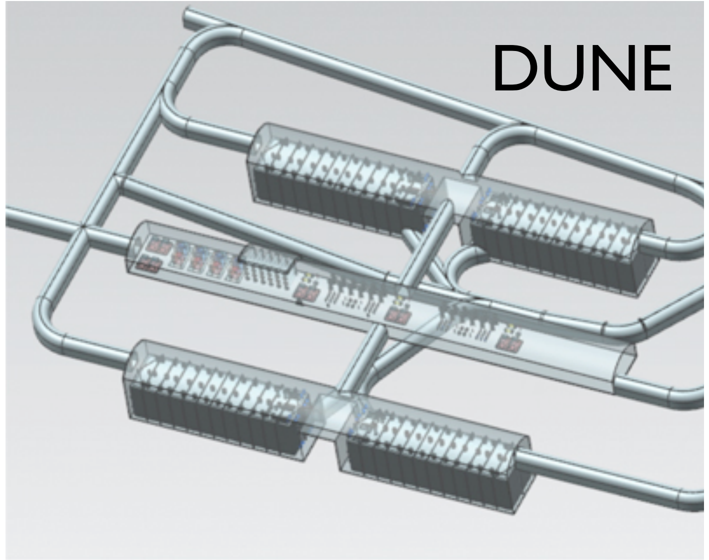
Supernova Neutrino Detectors

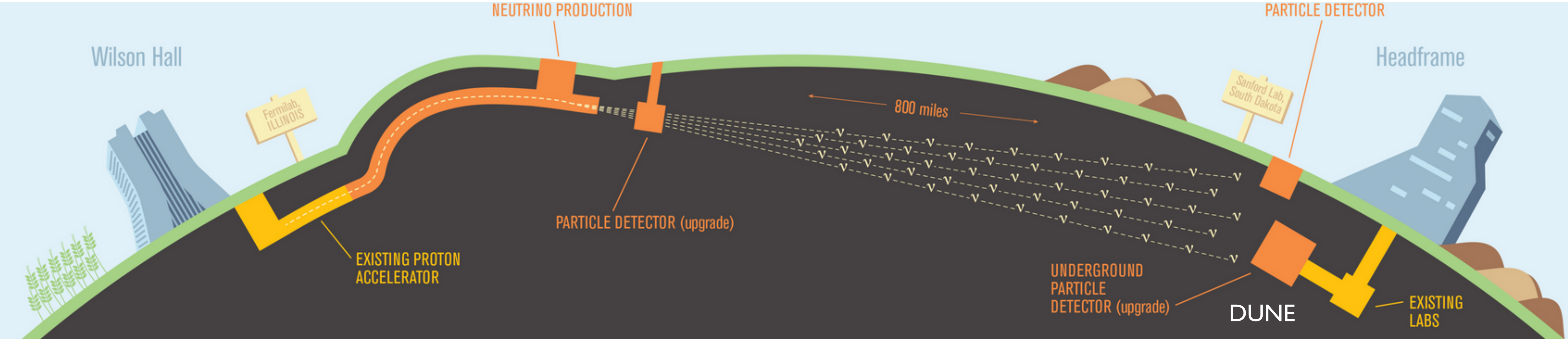
- Will provide a fundamental data set for nucleosynthesis from next galactic SN.
- Important meeting ground between nuclear physics, high energy physics, and astrophysics.

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.**
- DUNE's day job: measure differences between oscillations of neutrinos and antineutrinos.







SN neutrino detectors

- Detecting neutrinos from next galactic SN is very important for neutrino oscillations (nonlinear + matter effects very rich), nonstandard neutrino interactions, new particle searches, … also astrophysics: explosion mechanism, nucleosynthesis, neutron star / black hole formation …

- Measure **individual** anti-ν_e, ν_e, and ν_x fluxes and spectra.

- Have good anti-ν_e detector: SK (~10,000 events), Hyper-K even more.

- Need good ν_e detector (DUNE). Calibrate DUNE for SN by measuring charge current Ar cross section for πDAR ν at SNS. Neutrinos destroy neutrons. Anti-nu make neutrons. Important to accurately measure energy differences between anti-nu and nu.

- Need good neutral current detector (ν-nucleus coherent ??).

Detecting SN via ν-Nucleus elastic

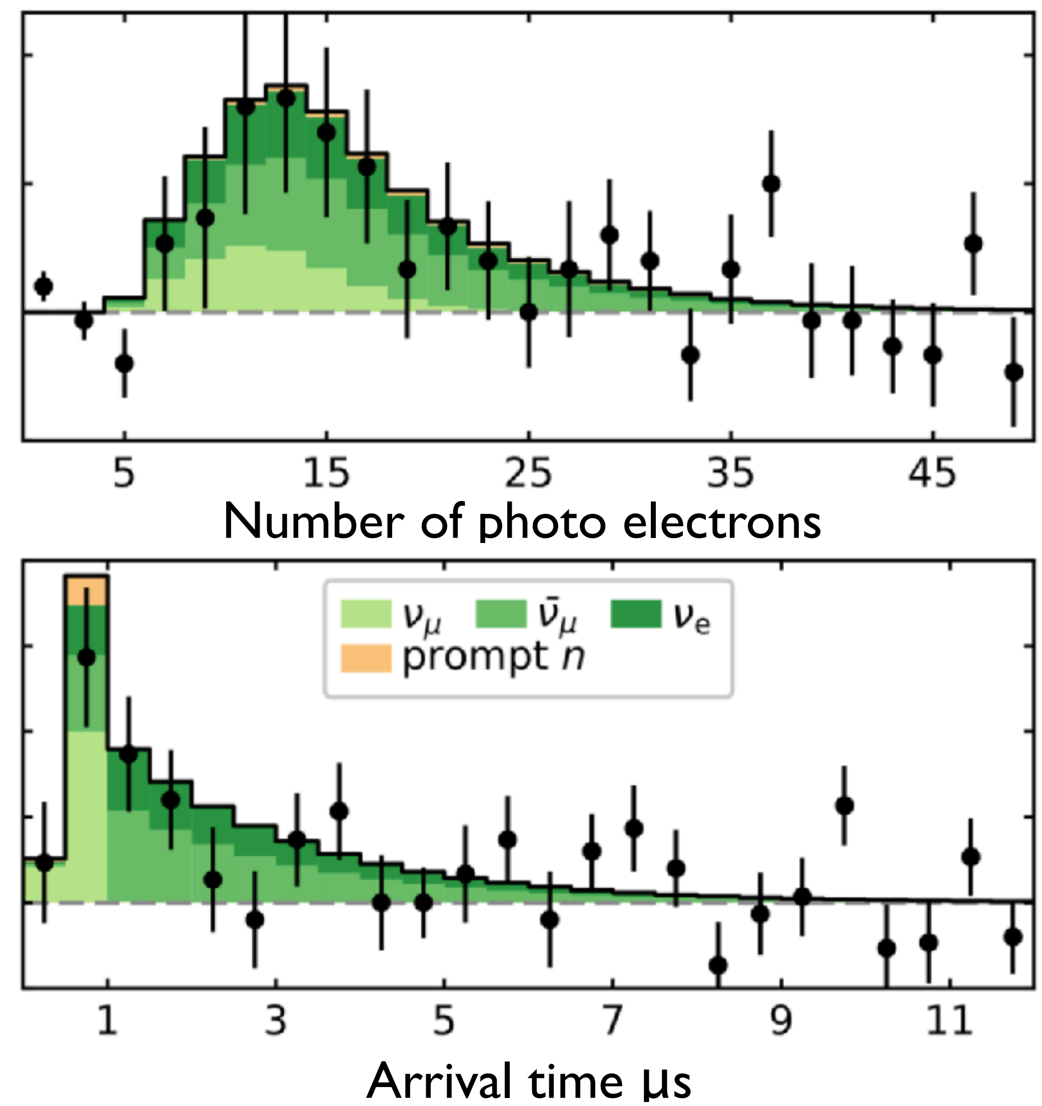
- Ton scale dark matter detectors now sensitive to SN via ν-nucleus elastic scattering, if low threshold to see ~5 keV nuclear recoils.

  —CJH+D. McKinsey

- Very large coherent cross section $\sim N^2$. Sensitive to all six flavors of ν and anti-ν. All nucleons contribute (not just H gives factor of ~10) —> ***Large yield of tens of events per ton*** (for SN at 10 kpc). Compared to 100s of events per ***kiloton*** for Super-K.

- ν-Nucleus elastic scattering was just observed for first time with beautiful COHERENT experiment at Spallation Neutron Source in TN.

Observation of ν-nucleus elastic scattering from CsI at SNS



D. Akimov et al, Science, Aug. 3

Neutron star merger summer school

- The next generation of really good young scientists, working in nuclear physics, astrophysics, astronomy, and related areas, participated in a neutron star merger summer school, May 16-18, 2018 at FRIB.

Neutrino interactions in SN and nucleosynthesis

- Neutrino interactions in supernovae: Liliana Caballero, Achim Schwenk, Evan O'Connor, Sean Couch…
- Graduate students: Zidu Lin (2018), Jianchun Yin, and Zack Vacanti.

U.S. DEPARTMENT OF ENERGY | Office of Science

NUCLEI
Nuclear Computational Low-Energy Initiative

OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY