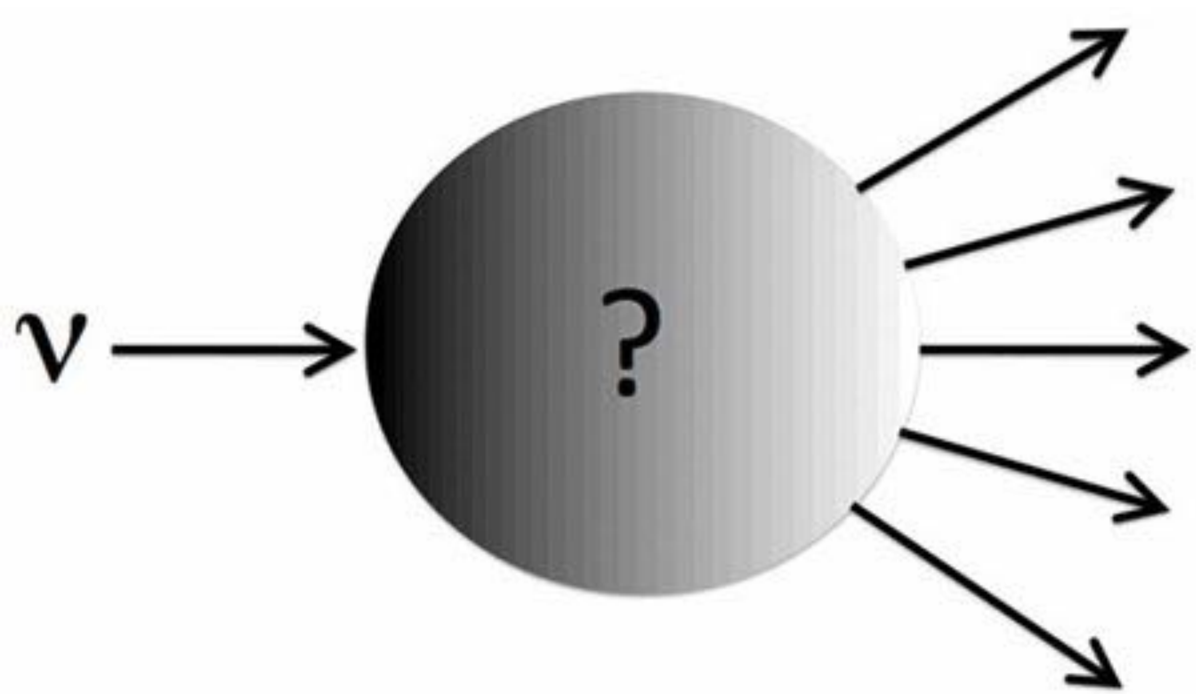
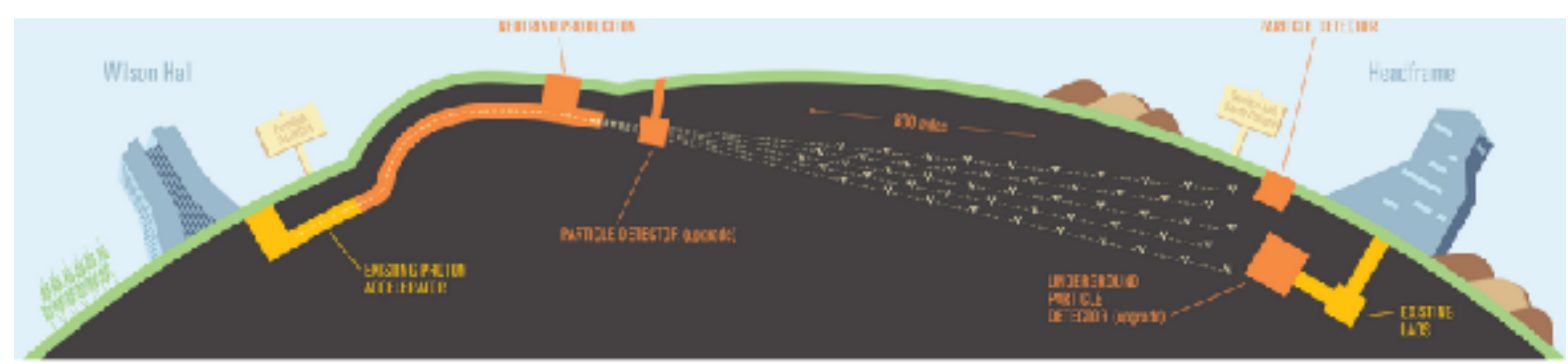
Neutrino-nucleus interactions





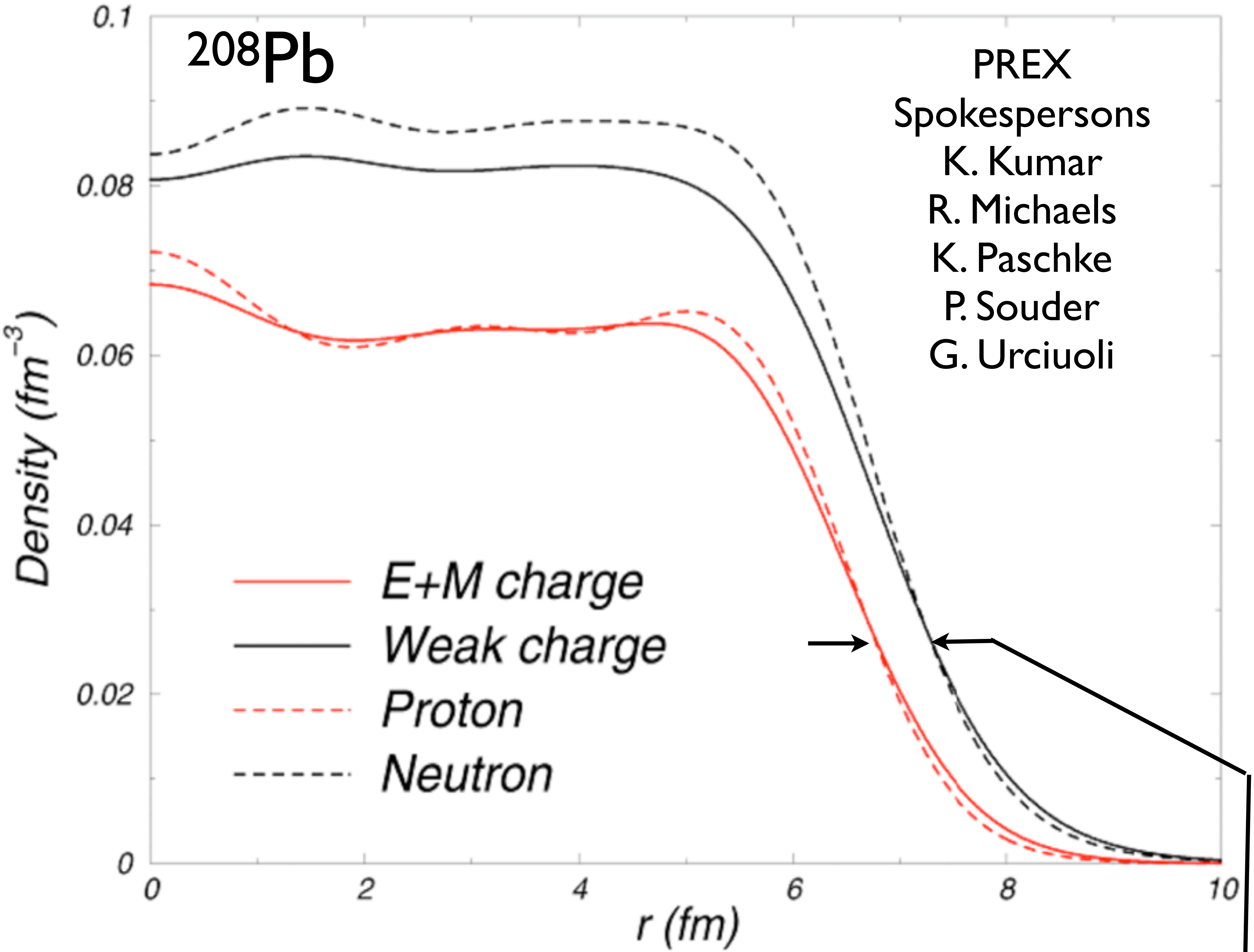
Chuck Horowitz, Indiana U., ECT*, Trento, Italy, Jul. 2018

Neutrino-nucleus Interactions

- Coherent elastic scattering
- Quasielastic scattering
- SN neutrino interactons

Neutrino-nucleus elastic

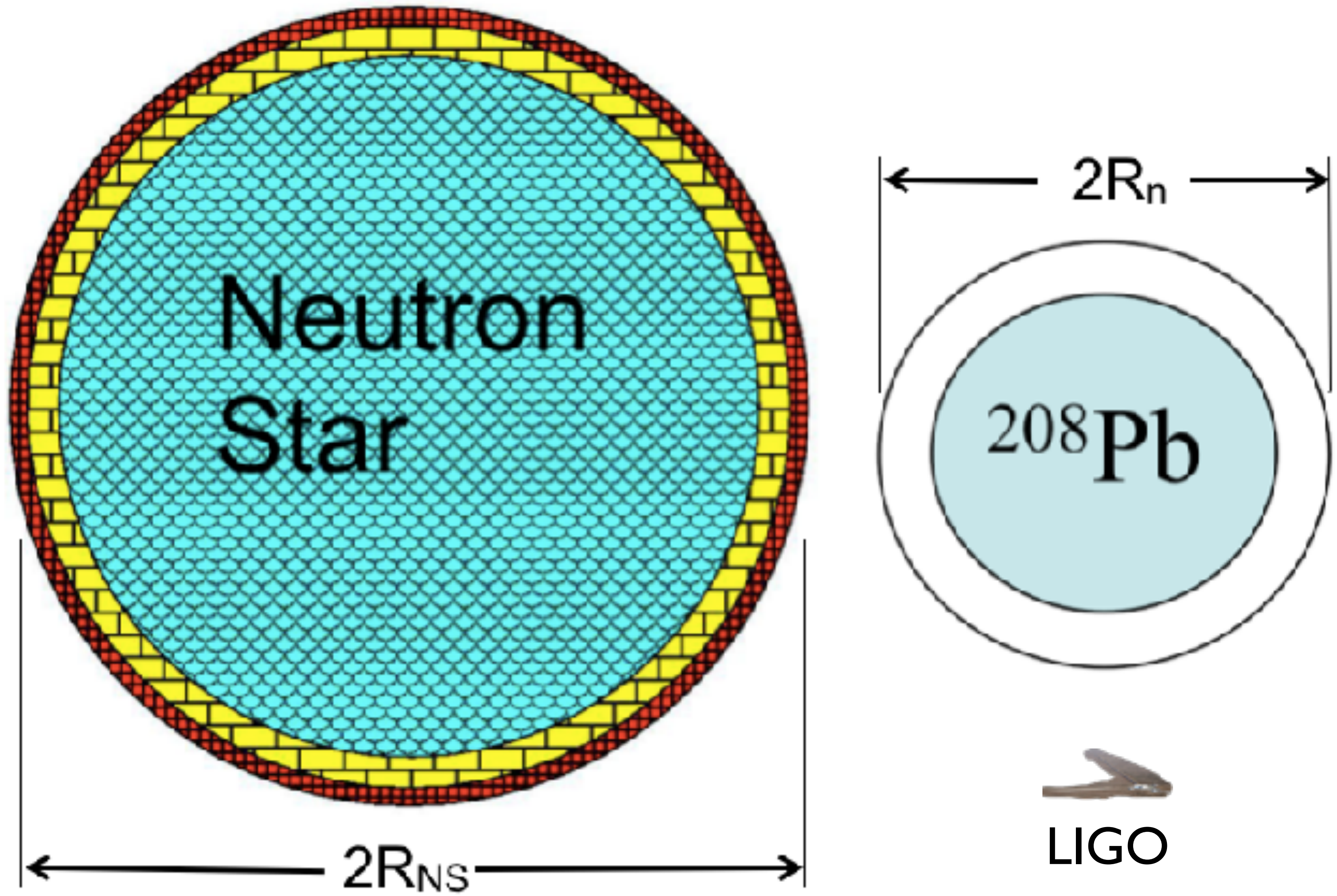
- Beautiful COHERENT experiment using ν from π decay at rest at Spallation Neutrino Source in Oak Ridge.
- Important future ν technology: very large, conceptually clean, cross section.
- Can measure neutron density in a nucleus because weak charge of proton $1\text{-}4\sin^2\Theta_W \sim 0.05$ is small, while weak charge of neutron -1 is large.
- Neutron density can also be determined with parity violating elastic electron scattering.



- PREX measures how much neutrons stick out past protons (neutron skin).

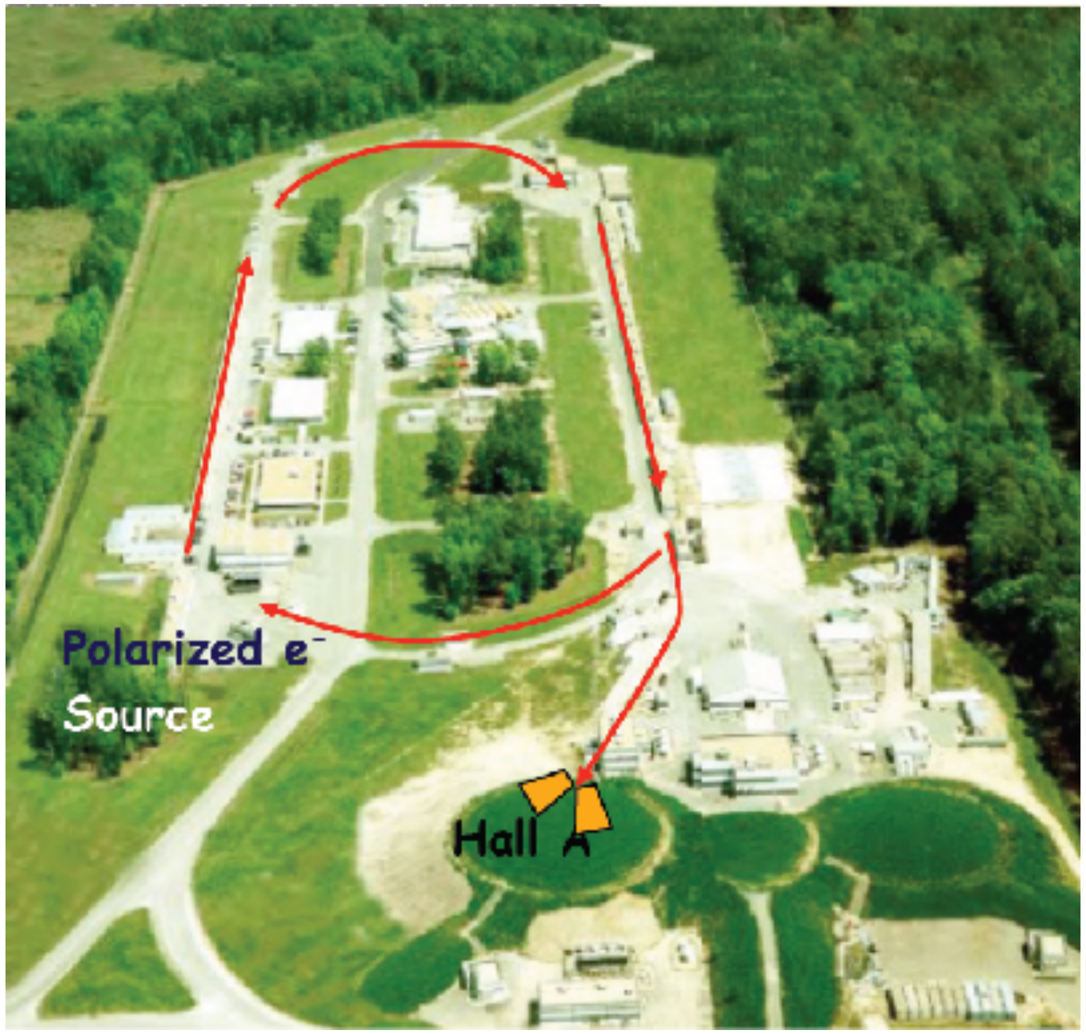
Radii of ^{208}Pb and Neutron Stars

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.



Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

PREX in Hall A Jefferson Lab



- **PREX**: ran in 2010. 1.05 GeV electrons elastically scattering at ~5 deg. from ^{208}Pb

  A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sym) ppm

- From A_{pv} I inferred neutron skin: $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm. [Determined R_n to 3%.]

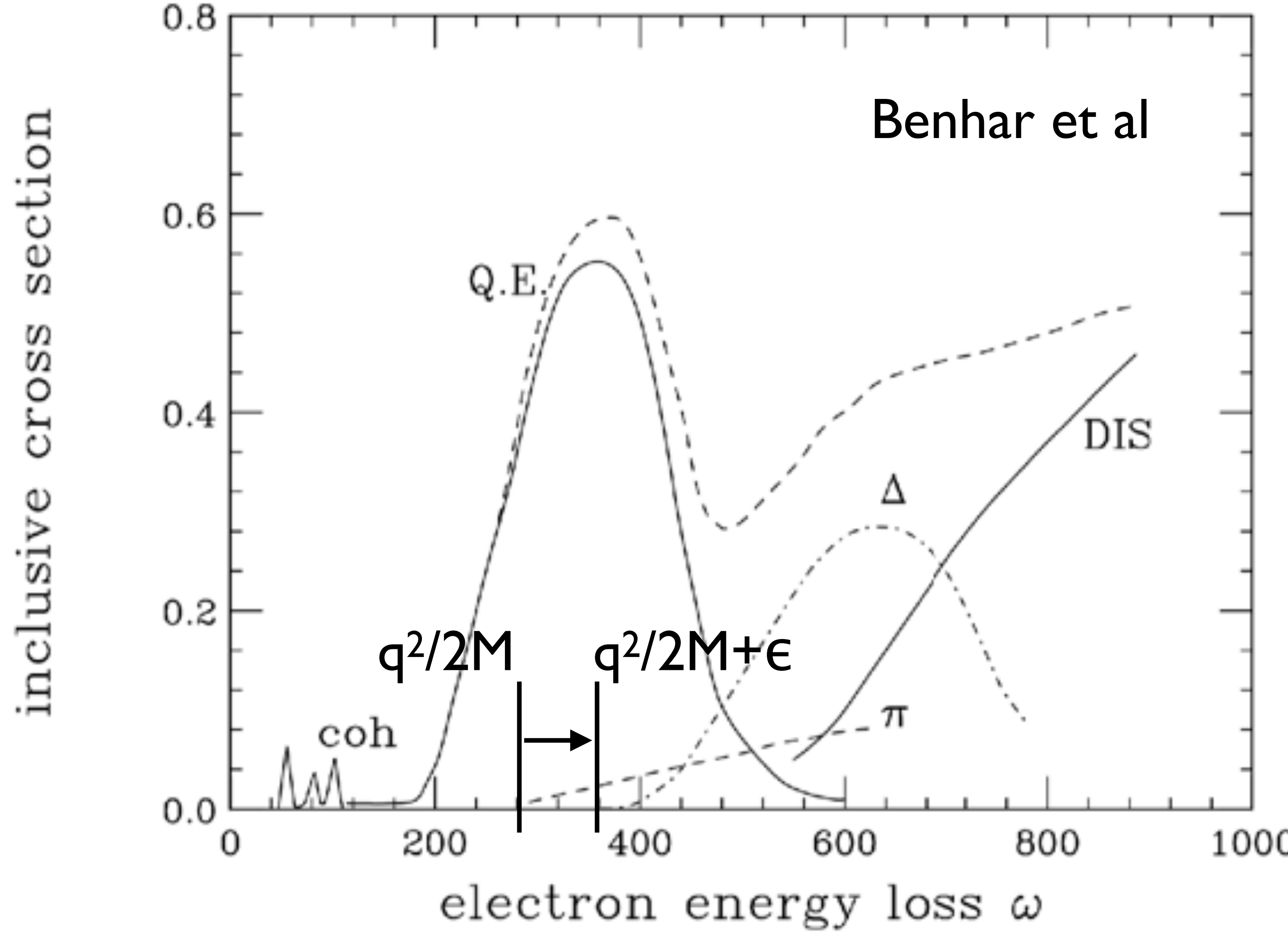
- Next runs scheduled for 2019

- **PREX-II**: ^{208}Pb with more statistics. Goal: R_n to ±0.06 fm (1%).

- **CREX**: Measure R_n of ^{48}Ca to ±0.02 fm (0.6%). Microscopic calculations feasible for light n rich ^{48}Ca to relate R_n to *three neutron forces*.

Quasielastic electron scattering

- Fermi gas parabola peaks at $q^2/2M+\epsilon$ (binding energy shift) and has width related to Fermi momentum.
- Origin of ϵ may appear different in finite nucleus vs local density approximation
- Finite nucleus: initial state nucleon is bound with energy $E_i = -\epsilon$ and momentum $p_i<k_F$.
- Final nucleon has momentum $p_f = p_i + q$ and energy $E_f=p_f^2/2M$.
- Electron E loss: $\omega=E_f-E_i$.



- Fermi gas parabola described by width k_F and binding energy shift ϵ.

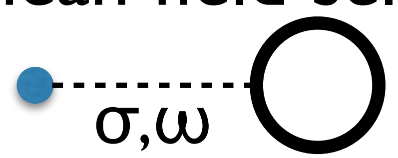
Local Density Approximation

- If ω is large, lepton only interacts with nucleon for very short time. Nucleon does not have time to leave nucleus before probe stops interacting.
- Model system as ~uniform nuclear matter with nucleons moving in mean fields or self-energy Σ.
- Relativistic Σ is a 4x4 Dirac matrix with large attractive scalar S and repulsive vector V components: $\Sigma(k)=S(k)+\gamma_0 V(k)$.
- Energy of plane wave with momentum k is $E(k)=[k^2+M^*(k)^2]^{1/2} + V(k)$
- Here the effective mass is $M^*(k)=M+S(k)$.
- $\omega=E(p_i+q)-E(p_i) \sim q^2/2M^*$ if S, V independent of k.
- Binding E shift: $\epsilon \sim q^2/2(1/M^* - 1/M)$ from $M^* < M$.

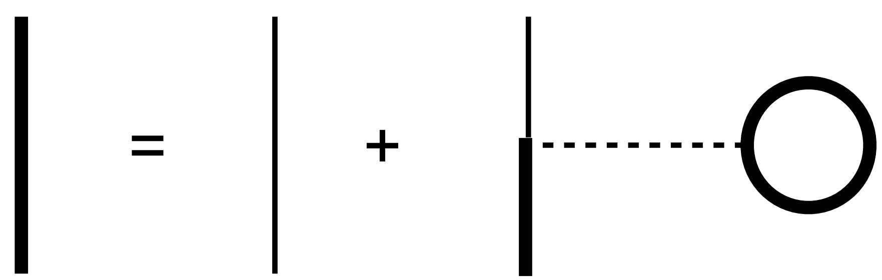
Momentum dependent Self-E

- Relativistic Brueckner calculations, that include short range correlations, find $S(k)$ and $V(k)$ each decrease with k for large k so that $M^*(k) \longrightarrow M$. This keeps ϵ from being overestimated as q increases.
- Current conservation: divergence of current related to time derivative of charge density.
- One body current operator with momentum dependent $\Sigma(k)$ will not in general conserve current.
- Need contributions from two-body or meson exchange currents (MEC) to conserve current.
- Chiral EFT, where it converges, provides framework for calculating consistent MEC.

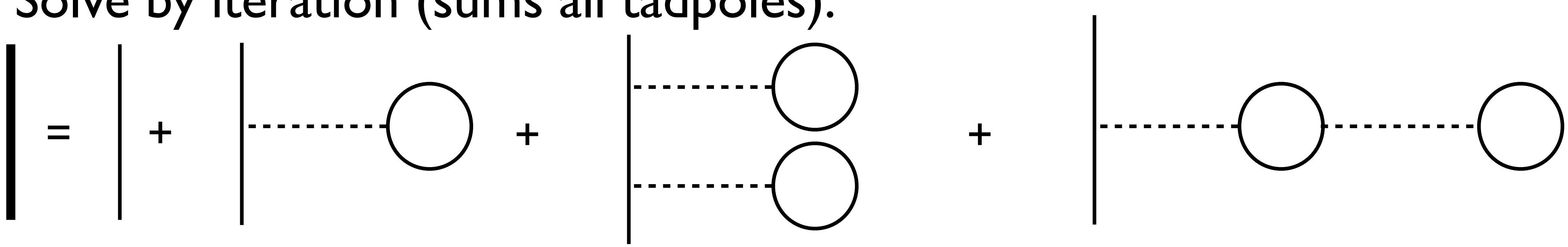
Linear Response and RPA

- Weak probe of strongly interacting system. Work to all orders in strong interactions, but only lowest order in weak int.
- Example: the linear response of a mean field ground state is given by the Random Phase Approximation (RPA). This is a coherent sum of all 1-particle 1-hole (1p-h) excitations.
- Relativistic mean field self-energy Σ from σ and ω meson exchange:
$\Sigma = S+\gamma_0 V =$ 

- Dyson's eq. for interacting nucleon propagator (heavy line)

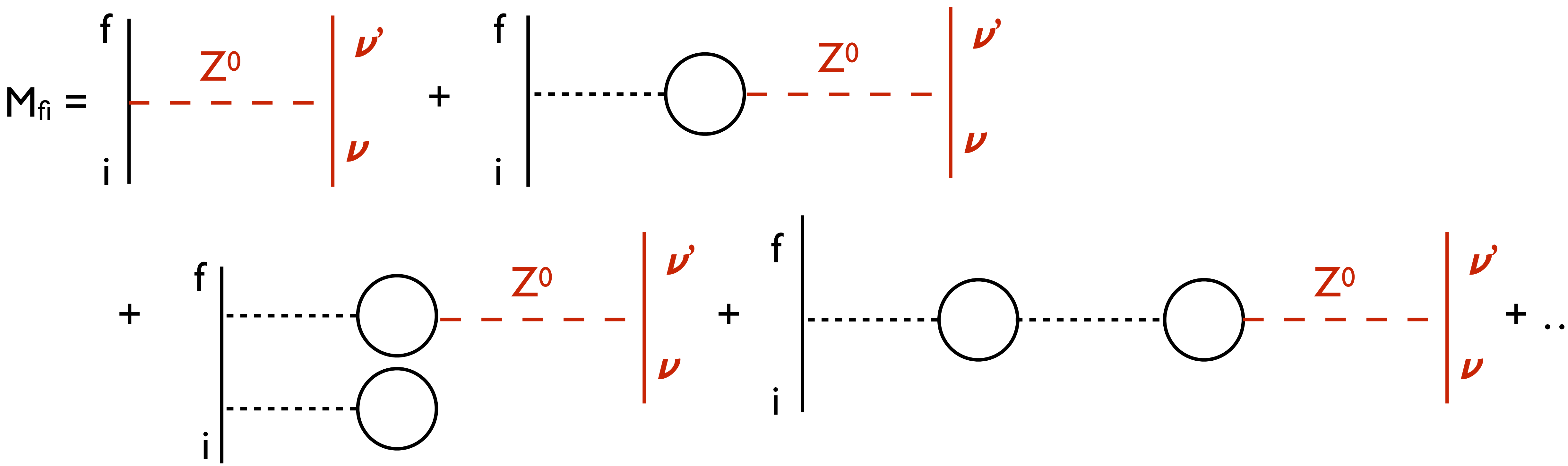


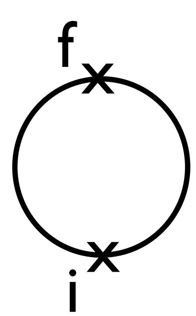
- Solve by iteration (sums all tadpoles):



$+ \ldots$

Linear response: attach ν once



- $|M_{fi}|^2 \sim$ 

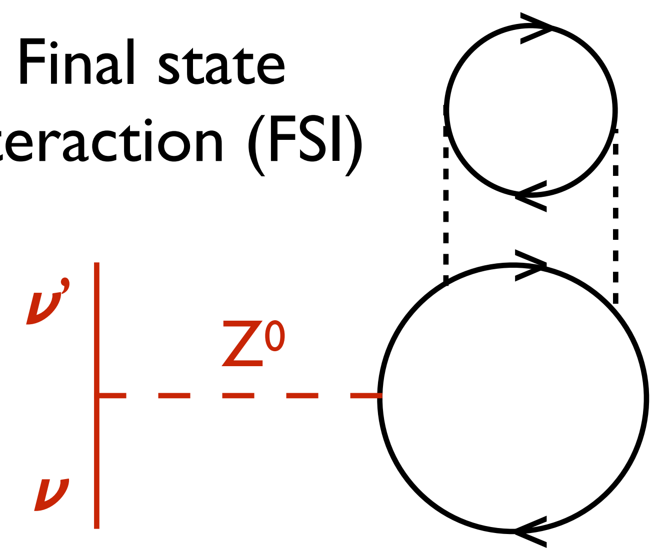
$= \text{Im}\,\mathbf{\Pi}(q,\omega)$

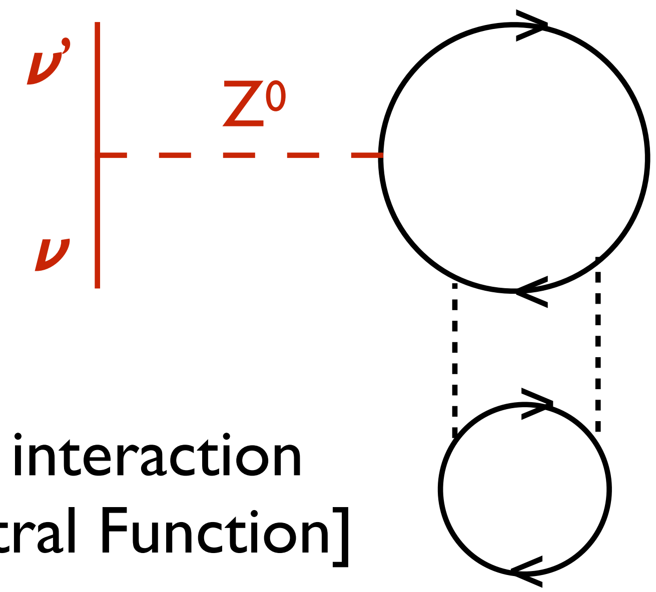
- RPA sums ring diagrams: $d^2\sigma/d\Omega dE \sim \text{Im}\,\mathbf{\Pi}/[1-D\mathbf{\Pi}]$.
  Here $D \sim g^2/(q^2-m^2)$ is a meson propagator (--------------).
- RPA at low q,ω can describe collective excitations such as giant resonances. At high q, RPA corrections small.

2 particle 2 hole excitations

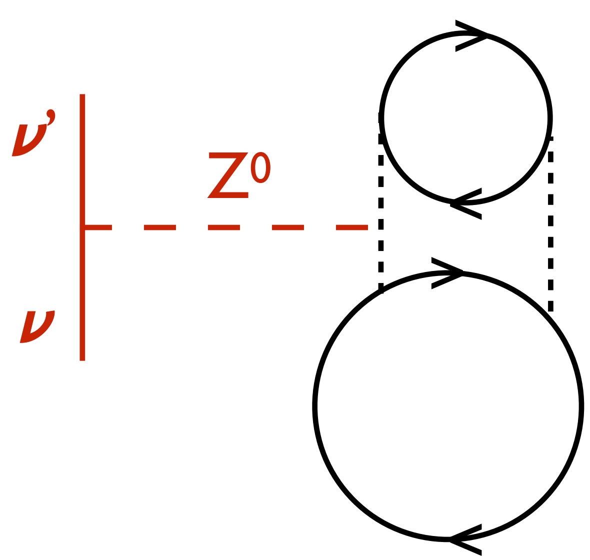
- First correction to RPA involves 2p-2h excitations. Arrow to left (<) is a hole (below Fermi surface) while arrow to right is a particle (>).

Final state interaction (FSI)





Initial state interaction (ISI) [in Spectral Function]



Meson exchange current (MEC)

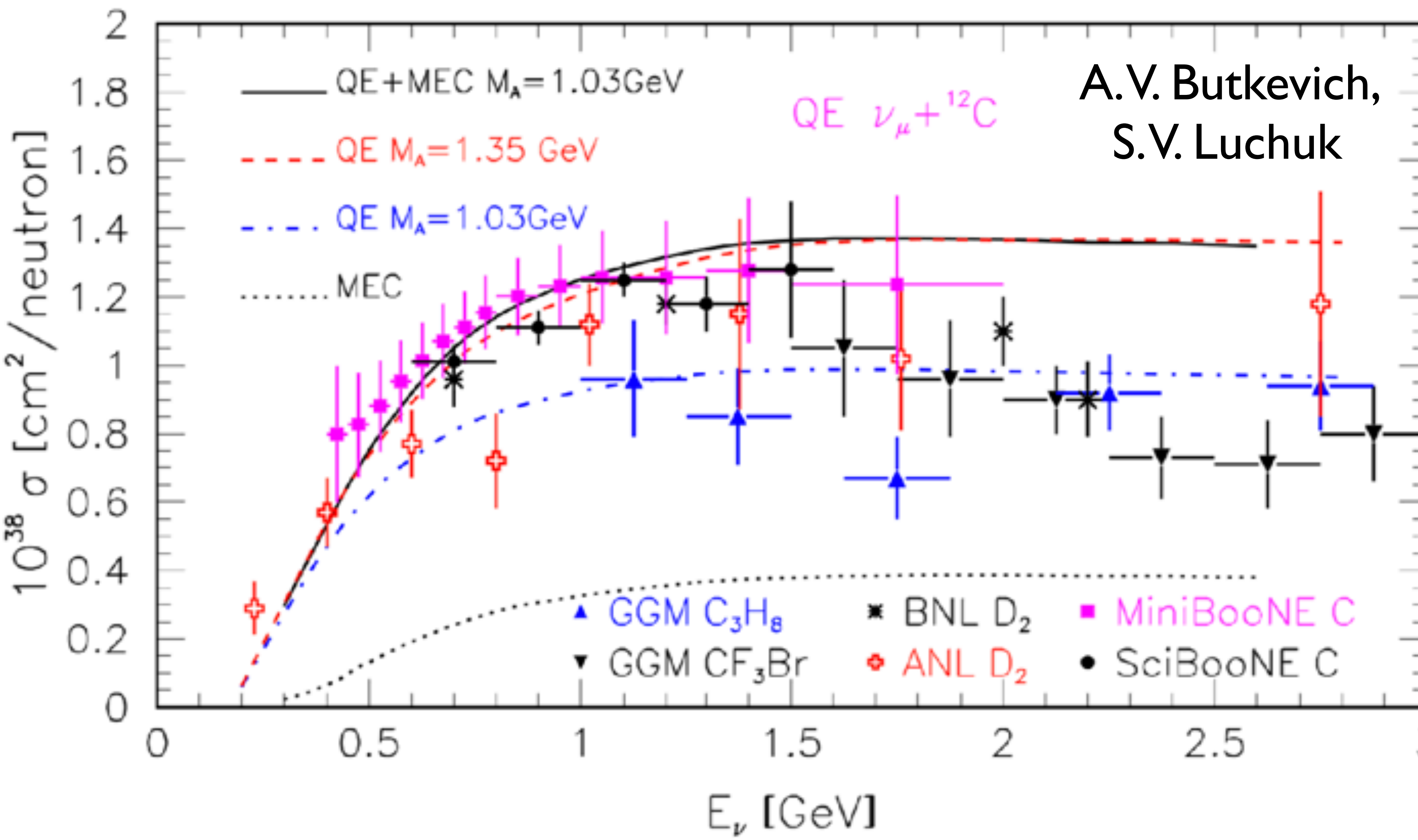
All 3 diagrams involve neutrino interacting with correlated nucleons.

Longitudinal/Transverse Responses in Electron Scattering

- Can separate cross section into longitudinal (from charges) and transverse (from currents) responses.

$$\frac{d^2\sigma}{d\Omega_{e'}\,dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4}\, R_L(|\mathbf{q}|,\omega) \;+\; \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega)\right]$$

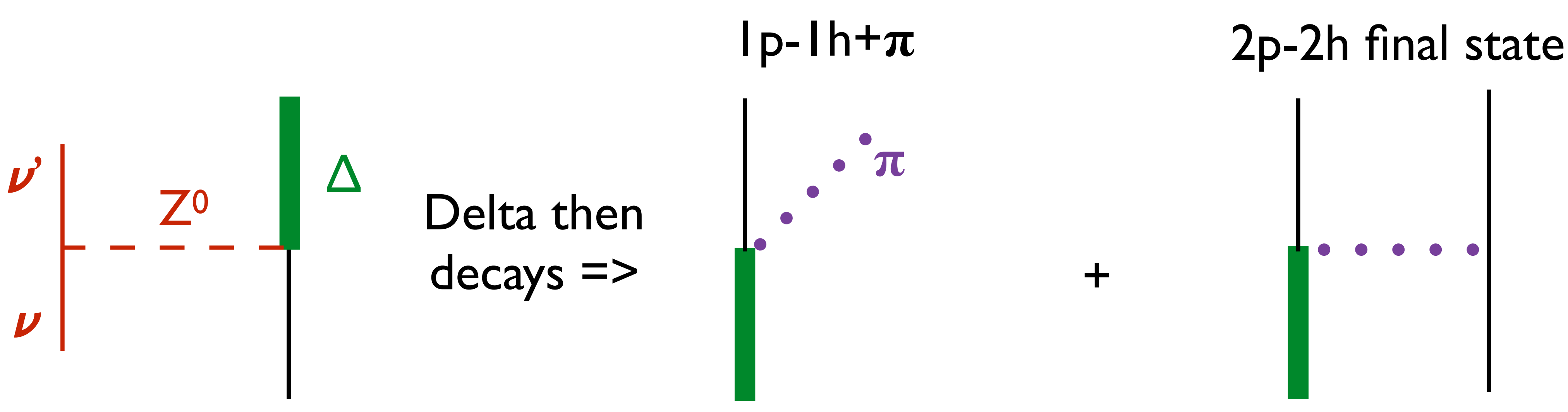
- Longitudinal should satisfy Coulomb sum rule (area ~ number of protons) and is reasonably well described by 1p-1h alone.
- Transverse response somewhat underestimated by just 1p-1h and appears to have noticeable contributions from 2p-2h including MEC.



- Total cross section for ν_μ - ^{12}C quasielastic scattering.
- Can explain Mini-BooNE data with (1) only 1p-1h but "big" M_A=1.35 GeV or (2) 1p-1h plus 2p-2h with "correct" M_A=1.03 GeV.
- Nucleon axial form factor: $G_A(q)=(1+q^2/M_A^2)^{-2}$.

Delta and pion production

- As ω increases can convert nucleon into a Δ (Δ-hole state).
- What is self-energy (mean field) for a Δ in the medium?
- Imaginary part of Σ gives total width for Δ to decay to π + 1p-1h and to 2p-2h.



Renormalization group and effective interactions

- Nuclear wave functions, at different momentum resolutions, can have differing amounts of short range correlations.
- At low momentum resolutions, can incorporate short range correlations into effective interactions.
- Density functional theories (DFT) describe low momentum observables such as binding E or ground state charge density with effective one body degrees of freedom determined from a density functional. Functional is very hard to calculate (because it includes complex effects from higher momentum scales). Often simply fit to data.
- May need higher resolution models of nuclear ground state to describe neutrino scattering at higher momentum transfers (q~1 GeV/c or more).

When does the ν scatter from quarks or from hadrons?

- At what kinematics q, ω does the ν scatter from an "individual" quark or from a "whole" hadron?
- Clearly low E neutrino scattering best described with hadrons while deep inelastic scattering (DIS) at large q^2 described with quarks.
- "Quark hadron duality": in-between there may be an overlap region that can be described either as a sum of hadron resonances or with quark degrees of freedom.
- Continuum with increasing resolution: nucleons + mean field, nucleons + short range correlations, nucleons+ excited baryons + mesons, quarks and gluons.

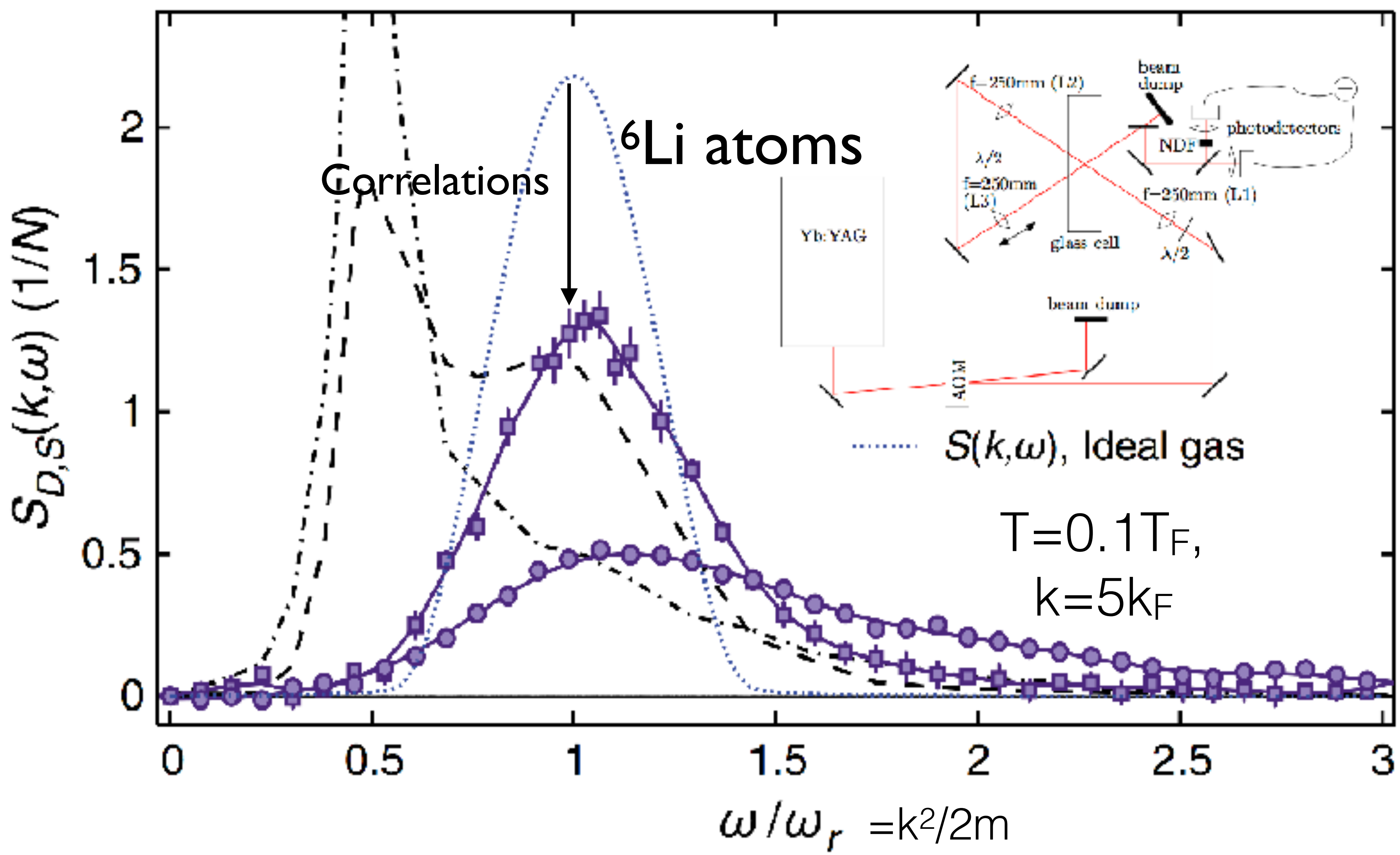
Quantum Computer

- 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.

Interacting neutron gas model

- Consider neutral current neutrino scattering from a strongly interacting neutron gas. Cross section $d^2\sigma/d\Omega dE \sim (1+\cos\Theta)S_V(q,\omega) + g_a^2(3-\cos\Theta)S_A(q,\omega) +/- g_a S_I(q,\omega)$
- Vector response: $S_V(q,\omega)=\int e^{i\omega t}\,dt\,\langle 0|\rho^*(q,t)\rho(q,0)|0\rangle$. Density is $\rho(q,t)=\Sigma_i \exp[iq\cdot x_i(t)]$. Can measure S_V with electron-nucleus scattering.
- Axial response: $S_A(q,\omega)=\int e^{i\omega t}\,dt\,\langle 0|\mathbf{S}^*(q,t)\cdot\mathbf{S}(q,0)|0\rangle$. Axial current —> spin current in non rel. limit. Spin density: $\mathbf{S}(q,t)=\Sigma_i\, \boldsymbol{\sigma}_i \exp[iq\cdot x_i(t)]$. Can measure S_A with cold atom simulations.
- Interference response: $S_I(q,\omega)$ is + for neutrinos and - for antineutrinos. It is O(E/M) and small for low neutrino energy E.

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 $S_V(k,\omega)$.

The future is extremely bright!

- 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-nucleus interactions

- PREX/ CREX: K. Kumar, P. Souder, R. Michaels, K. Paschke…
- Neutrino interactions in supernovae: Liliana Caballero, Achim Schwenk, Evan O'Connor…
- Graduate students: Zidu Lin (2018), Hao Lu (Astronomy), Jianchun Yin, Zack Vacanti. Also Matt Caplan (2017)

U.S. DEPARTMENT OF ENERGY | Office of Science

NUCLEI
Nuclear Computational Low-Energy Initiative

OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY