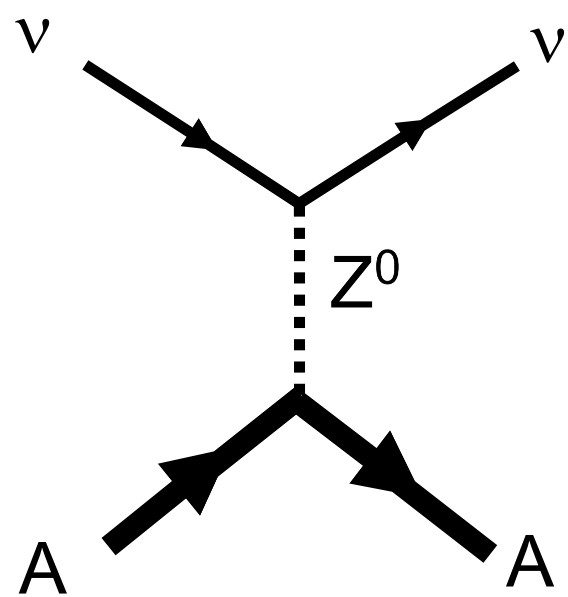
CEvNS Backgrounds
... focusing on the "friendly fire" variety

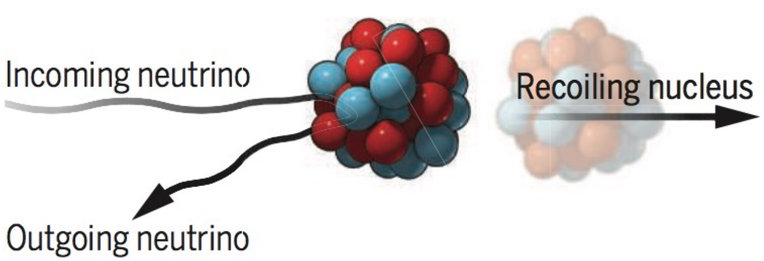
Kate Scholberg
Wondram workshop
June 24, 2021

Coherent elastic neutrino-nucleus scattering (CEvNS)

$\nu + A \rightarrow \nu + A$



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV



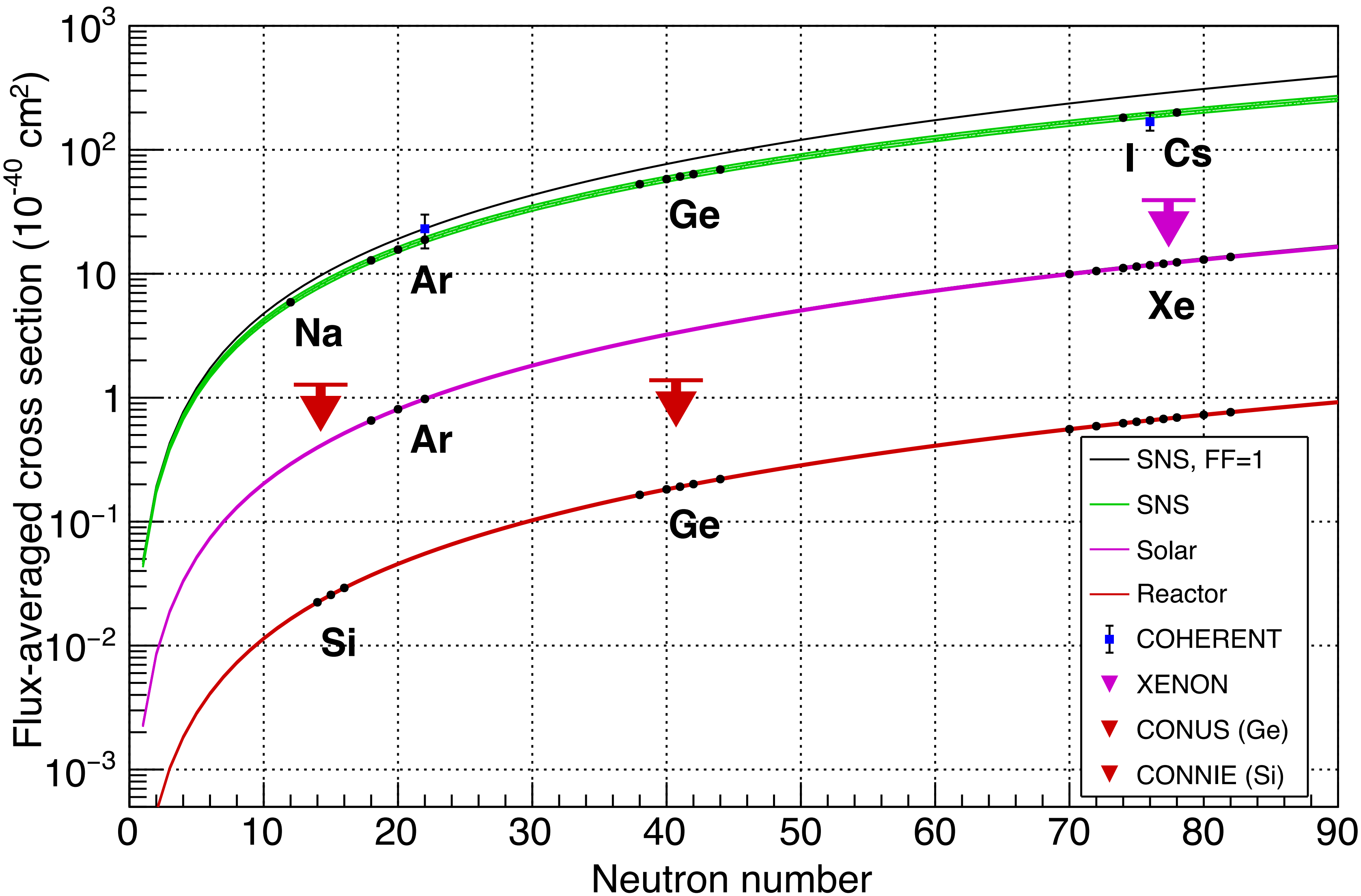
Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

A: no. of constituents

Image: J. Link *Science* Perspectives

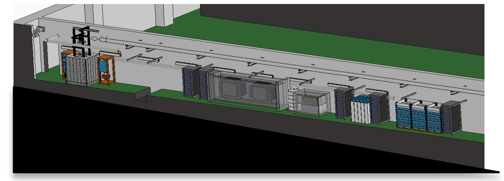
Status of CEvNS measurements

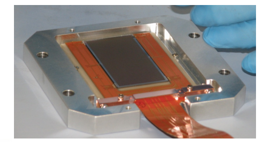


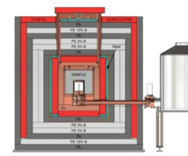
CEvNS Efforts Worldwide

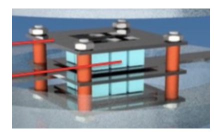
Experiment	Technology	Location	Source
COHERENT	CsI, Ar, Ge, NaI	USA	πDAR
CCM	Ar	USA	πDAR
CONNIE	Si CCDs	Brazil	Reactor
CONUS	HPGe	Germany	Reactor
MINER	Ge/Si cryogenic	USA	Reactor
NuCleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe	Reactor
νGEN	Ge PPC	Russia	Reactor
RED-100	LXe dual phase	Russia	Reactor
Ricochet	Ge, Zn bolometers	France	Reactor
TEXONO	p-PCGe	Taiwan	Reactors

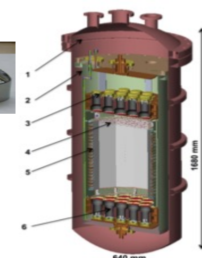
Reactors

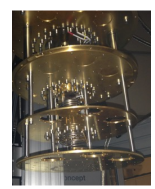


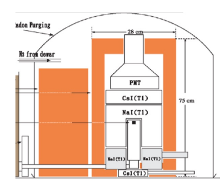












+ DM detectors, +directional detectors +more...
many novel low-background, low-threshold technologies

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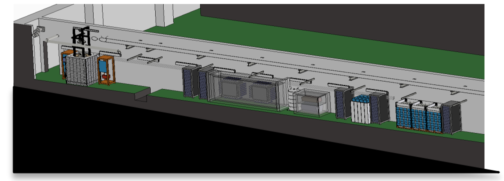
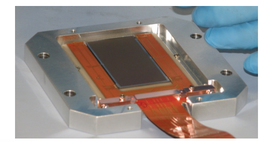
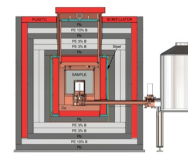
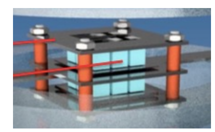
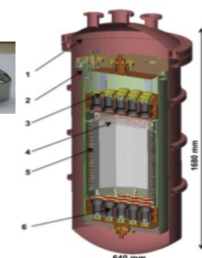
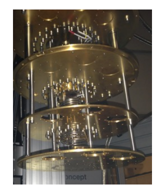
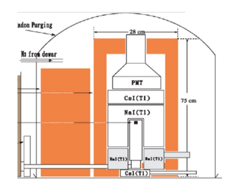
Reactors





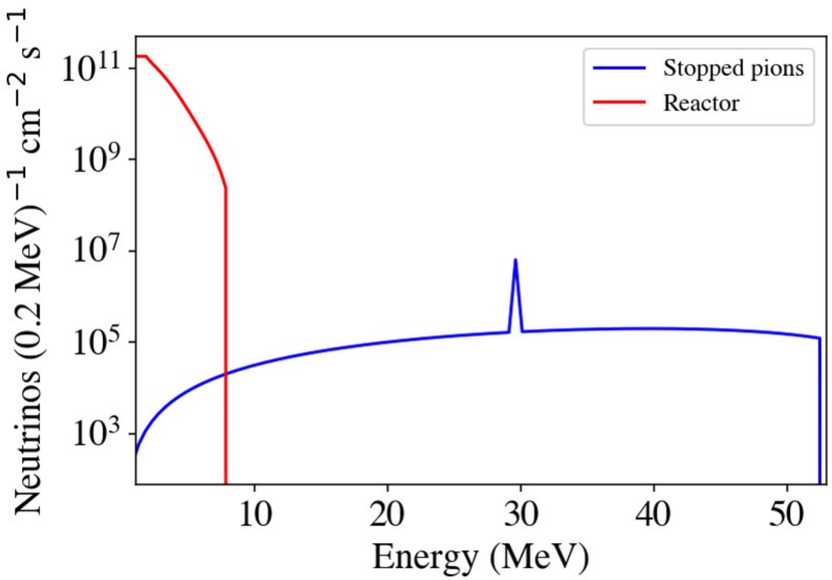




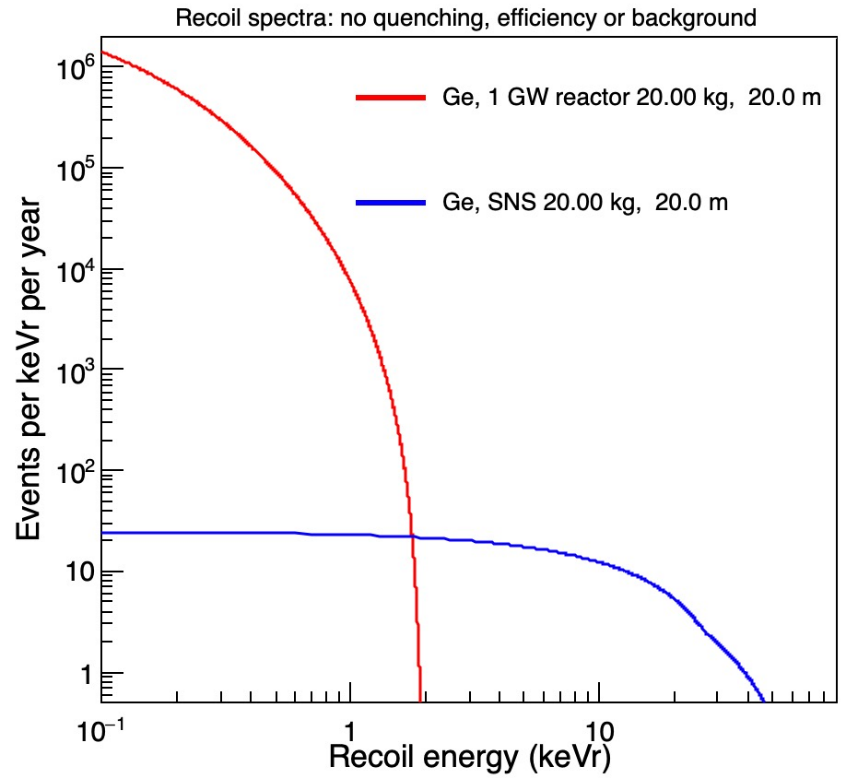
+ DM detectors, +directional detectors +more...
many novel low-background, low-threshold technologies

variety of materials

Reactors vs stopped-pion neutrinos for CEvNS

Fluxes





Reactor: huge flux
nuebar only
<~8 MeV
steady state → **bkgds hard**

Stopped pions:
lower flux
3 flavors (numu, nue, numubar)
up to ~50 MeV
can be pulsed

Reactor: higher rate
low energy recoils

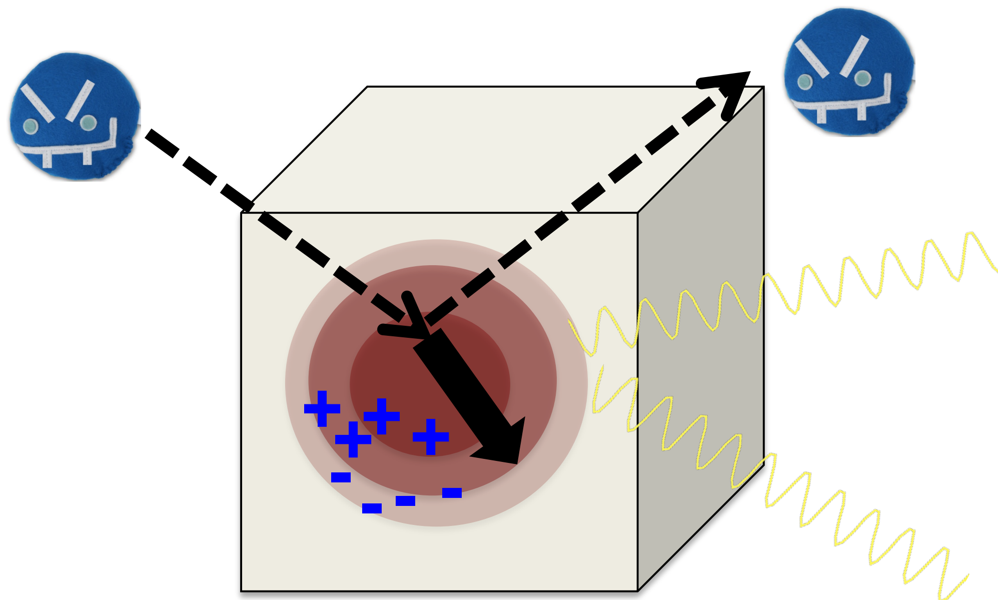
Stopped pions:
lower rate
higher energy recoils

Backgrounds

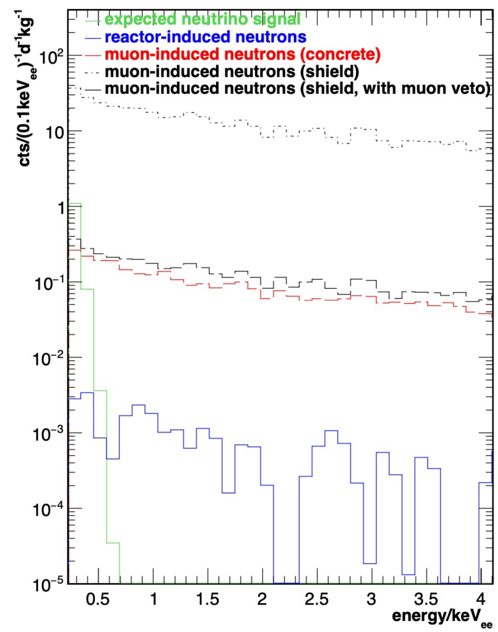
Usual suspects:

- cosmogenics
- ambient and intrinsic radioactivity
- detector-specific noise and dark rate

Neutrons are especially not friends*



CONUS arXiv:1903.09269



These are very detector/site/shielding-specific

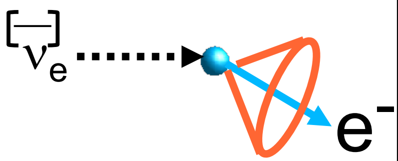
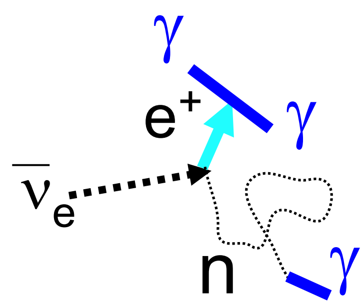
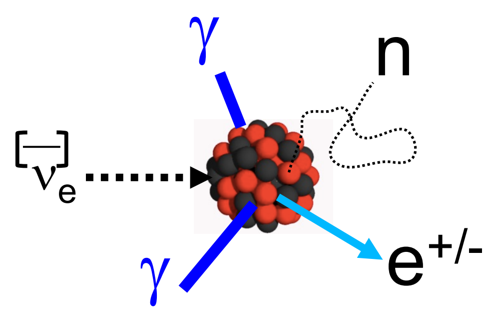
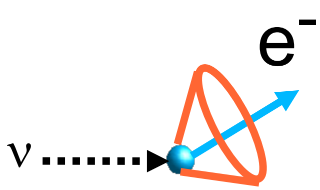
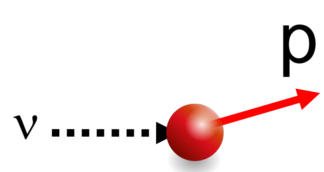
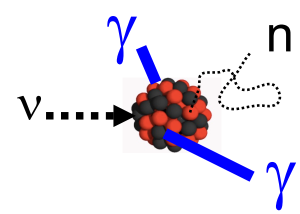
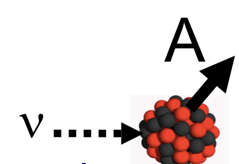
... nasty ones are *correlated with source.*

Here will focus on `friendly' **neutrino-induced bg**

... likely subdominant, but irreducible

*Thanks to Robert Cooper for the "mean neutron"

Neutrino interactions in the few-few 10's of MeV range

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \to \nu + A^*$  $\nu + A \to \nu + A$  Coherent elastic (CEvNS)

Neutrino interactions in the few-few 10's of MeV range

inelastics

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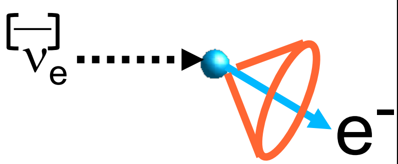
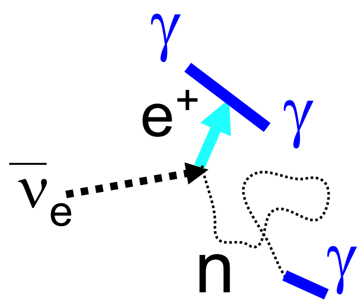
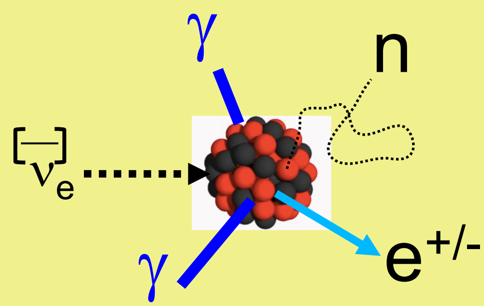
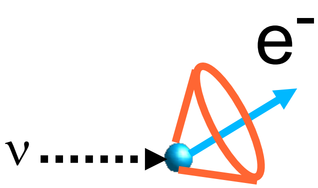
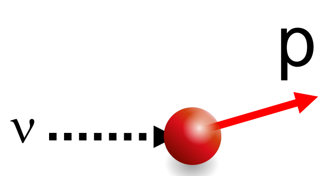
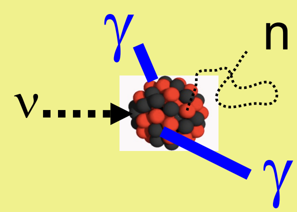
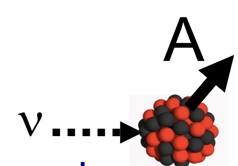
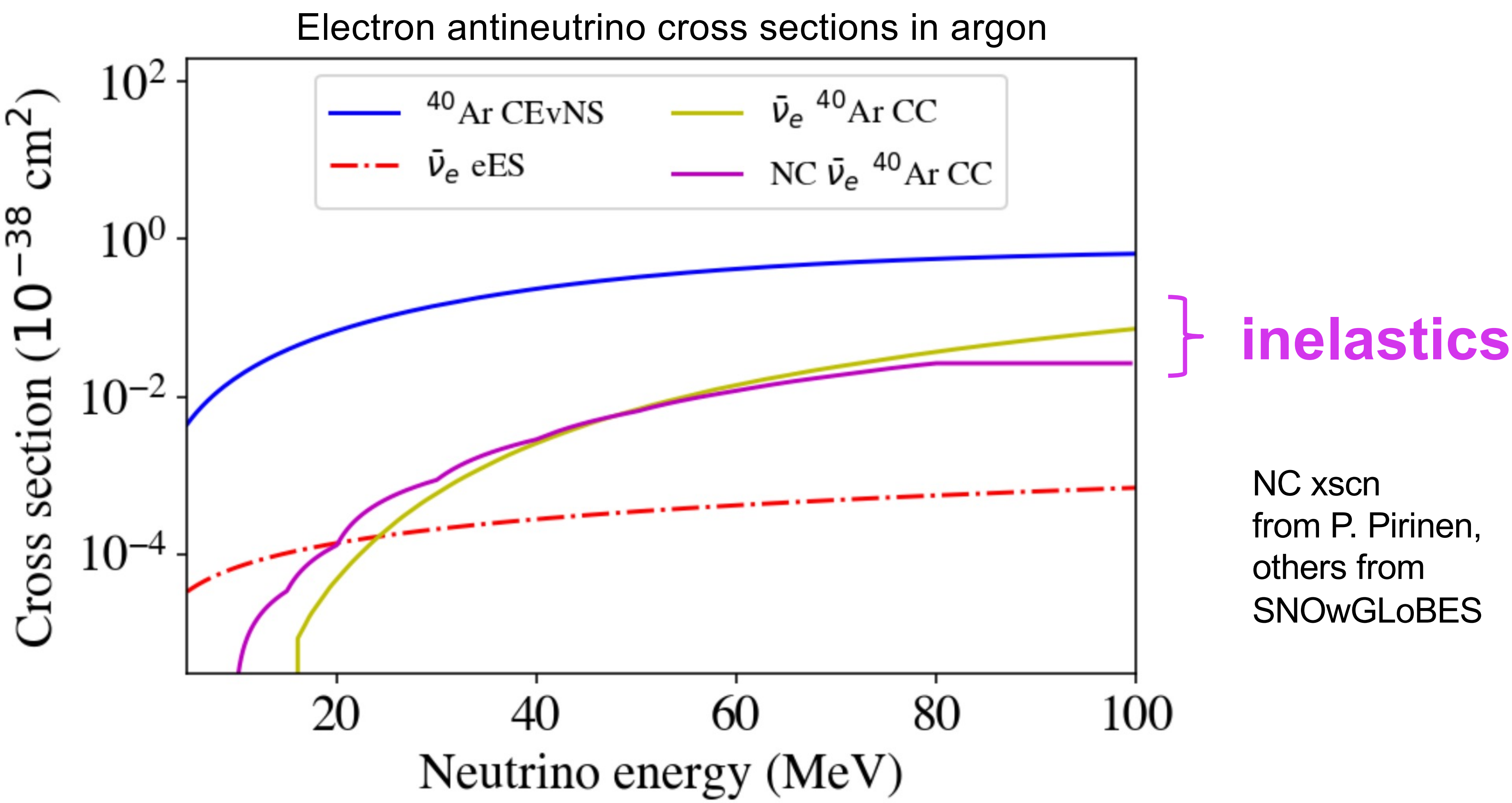
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

Example: argon*



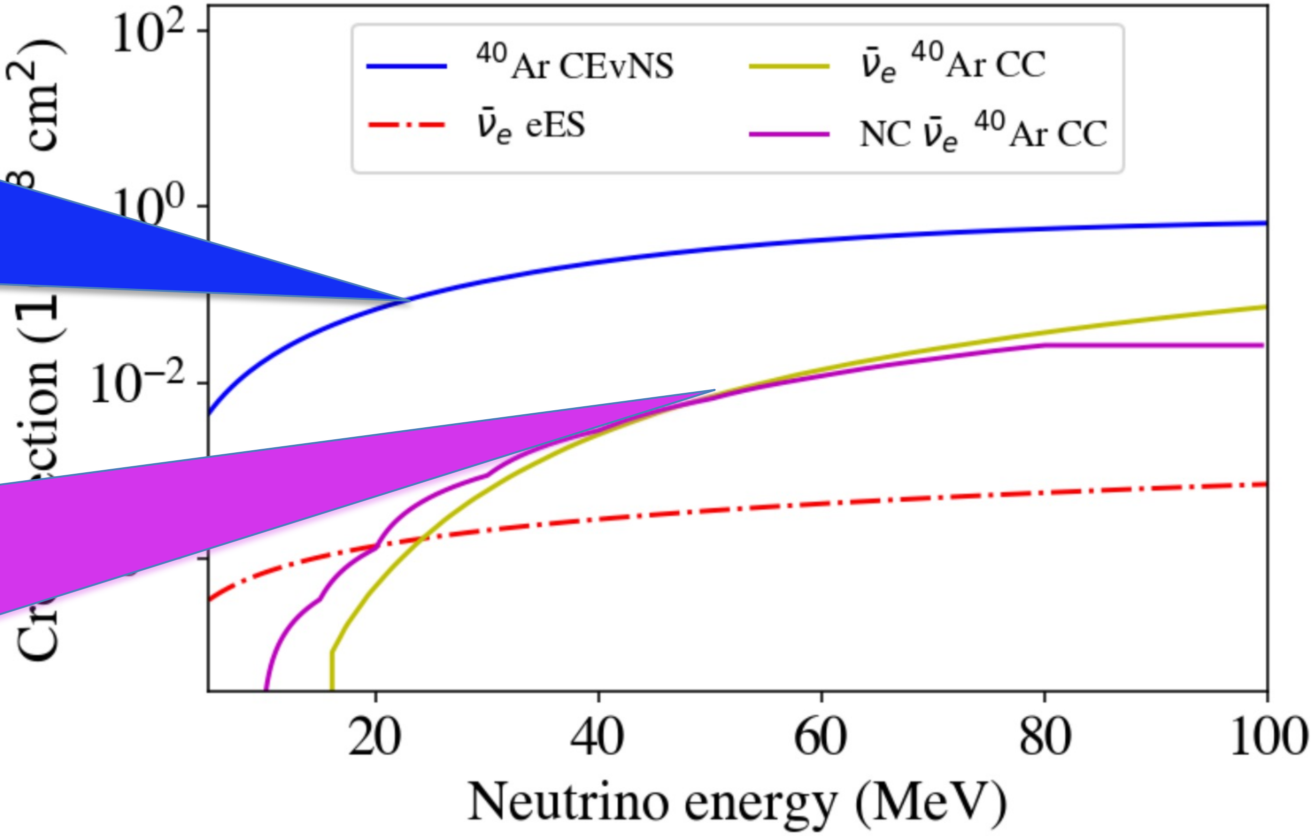
NC xscn
from P. Pirinen,
others from
SNOwGLoBES

*not actually the best example, since inelastic interactions
have high thresholds wrt reactor ν's

Example: argon

Lots of these...
but they are little

Few inelastics...
but they are big



For CEvNS with reactor neutrinos:

Inelastic neutrino interactions can be considered both a signal and a background.

If you just want lots of neutrino counts, doesn't matter

But you do want to know the inelastic contribution (event-by-event or statistically):

- for physics (BSM, nuclear physics)
- for determining neutrino absolute flux and spectrum for any application

Neutrino Induced Neutrons (NINs)

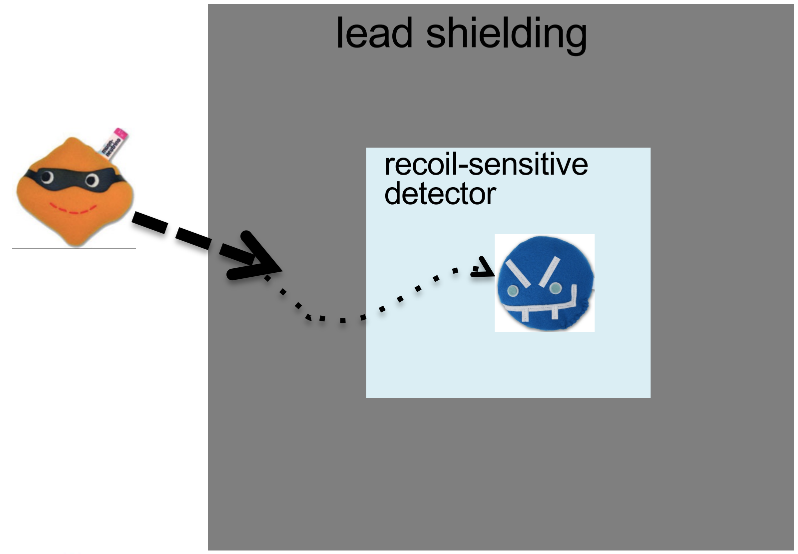
For example, in lead:

$$\nu_e + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Bi}^* + e^- \quad \text{CC}$$

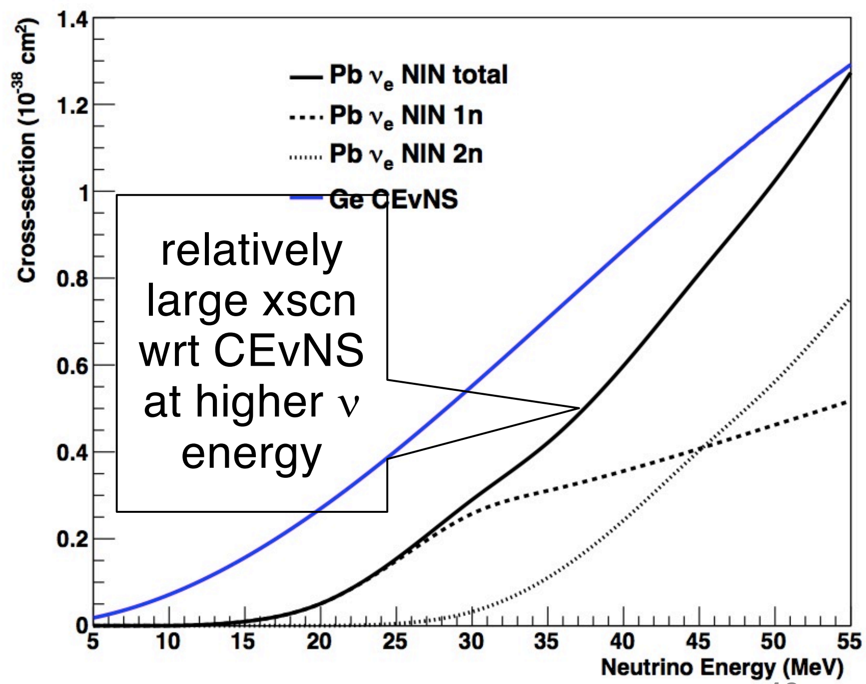
1n, 2n emission

$$\nu_x + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Pb}^* + \nu_x \quad \text{NC}$$

1n, 2n, γ emission



- reactor neutrinos are mostly below threshold for NINs in lead
- however there could be some materials which create NINs (poorly known xscns!)
- IBD in shielding (or untagged positrons) also make NINs!



Inelastics as backgrounds for CEvNS

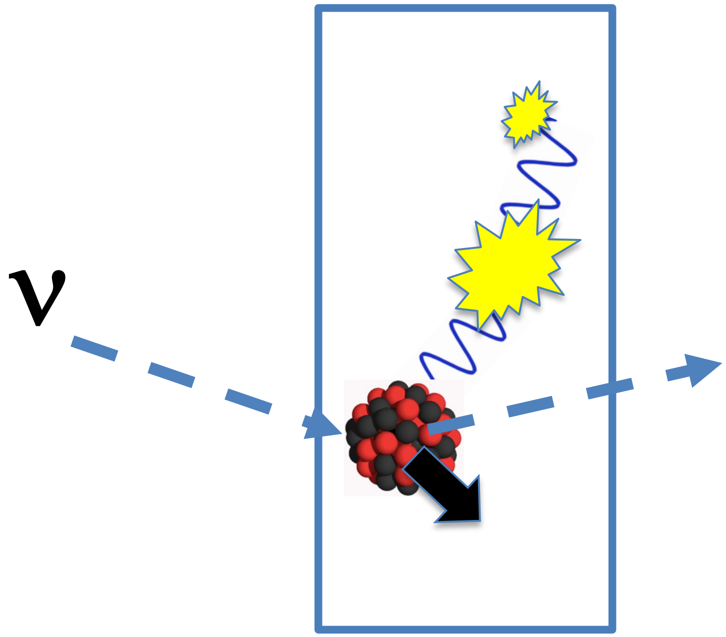
Charged-current:

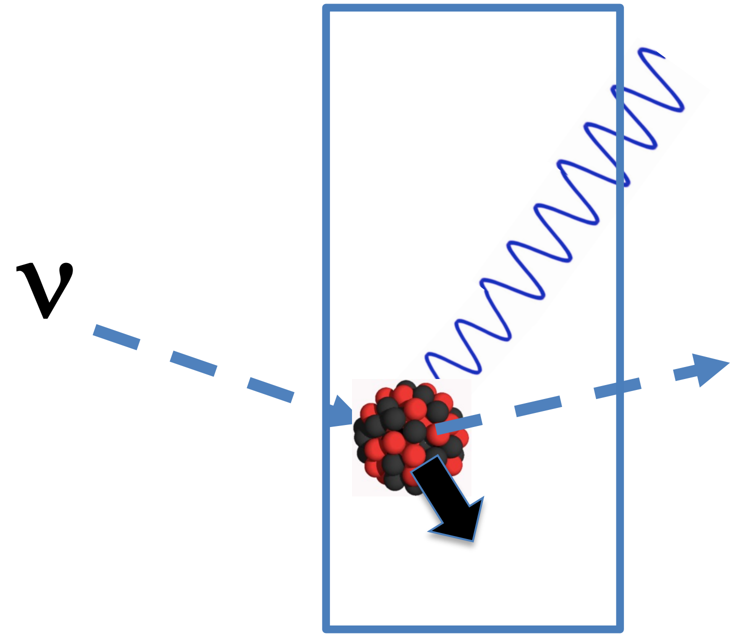
- Big old lepton (positron for nuebar) usually tags the interaction
- But: can have NINs or gammas in shielding

Neutral-current:

- Cross sections tend to be lower than CC
- However, interaction products are potentially harder to disentangle
  - NINs (nucleons)
  - De-excitation gammas (taggable)
  - Also: hit-and-run bg...(small detectors)

Neutral-current backgrounds for CEvNS





crash & flash:
~nothing in CEvNS ROI
(but could look for
the flash in
higher energy range,
as signal in itself)

crash & dash:
no gamma seen,
low-energy recoil
could fake CEvNS

What is known about inelastic neutrino-nucleus cross sections at low energy? very nucleus-specific!

- a few measurements at stopped-pion energy (not nuebar); only two (on ^{12}C) @10% level
- reactor neutrinos on deuterium
- not much else in the way of measurements

TABLE VII. Experimentally measured (flux-averaged) cross sections on various nuclei at low energies (1–300 MeV). Experimental data gathered from the LAMPF (Willis et al., 1980), KARMEN (Bodmann et al., 1991; Zeitnitz et al., 1994; Armbruster et al., 1998; Maschuw, 1998; Ruf, 2005), E225 (Krakauer et al., 1992), LSND (Athanassopoulos et al., 1997; Auerbach et al., 2001; Auerbach et al., 2002; Distel et al., 2003), GALLEX (Hampel et al., 1998), and SAGE (Abdurashitov et al., 1999; Abdurashitov et al., 2006) experiments. Stopped π/μ beams can access neutrino energies below 53 MeV, while decay-in-flight measurements can extend up to 300 MeV. The ^{51}Cr sources have several monoenergetic lines around 430 and 750 keV, while the ^{37}Ar source has its main monoenergetic emission at $E_\nu = 811$ keV. Selected comparisons to theoretical predictions, using different approaches are also listed. The theoretical predictions are not meant to be exhaustive.

Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	$^2H(\nu_e, e^-)pp$	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara, Kohyama, and Kubodera, 1990)
^{12}C	$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	Stopped π/μ	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)	9.4 [Multipole](Donnelly and Peccei, 1979)
		Stopped π/μ	E225	10.5 ± 1.0(stat) ± 1.0(sys)	9.2 [EPT] (Fukugita, Kohyama, and Kubodera, 1988).
		Stopped π/μ	LSND	8.9 ± 0.3(stat) ± 0.9(sys)	8.9 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	$^{12}C(\nu_e, e^-)^{12}N^*$	Stopped π/μ	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)	5.4–5.6 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
		Stopped π/μ	E225	3.6 ± 2.0(tot)	4.1 [Shell] (Hayes and Towner, 2000)
		Stopped π/μ	LSND	4.3 ± 0.4(stat) ± 0.6(sys)	
	$^{12}C(\nu_\mu, \nu_\mu)^{12}C^*$	Stopped π/μ	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)	2.8 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	$^{12}C(\nu, \nu)^{12}C^*$	Stopped π/μ	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)	10.5 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	$^{12}C(\nu_\mu, \mu^-)X$	Decay in flight	LSND	1060 ± 30(stat) ± 180(sys)	1750–1780 [CRPA] (Kolbe, Langanke, and Vogel, 1999) 1380 [Shell] (Hayes and Towner, 2000) 1115 [Green's Function] (Meucci, Giusti, and Pacati, 2004)
	$^{12}C(\nu_\mu, \mu^-)^{12}N_{g.s.}$	Decay in flight	LSND	56 ± 8(stat) ± 10(sys)	68–73 [CRPA] (Kolbe, Langanke, and Vogel, 1999) 56 [Shell] (Hayes and Towner, 2000)
^{56}Fe	$^{56}Fe(\nu_e, e^-)^{56}Co$	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe, Langanke, and Martínez-Pinedo, 1999)
^{71}Ga	$^{71}Ga(\nu_e, e^-)^{71}Ge$	^{51}Cr source	GALLEX, ave.	0.0054 ± 0.0009(tot)	0.0058 [Shell] (Haxton, 1998)
		^{51}Cr	SAGE	0.0055 ± 0.0007(tot)	
		^{37}Ar source	SAGE	0.0055 ± 0.0006(tot)	0.0070 [Shell] (Bahcall, 1997)
^{127}I	$^{127}I(\nu_e, e^-)^{127}Xe$	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210–310 [Quasiparticle] (Engel, Pittel, and Vogel, 1994)

What about theoretical predictions?

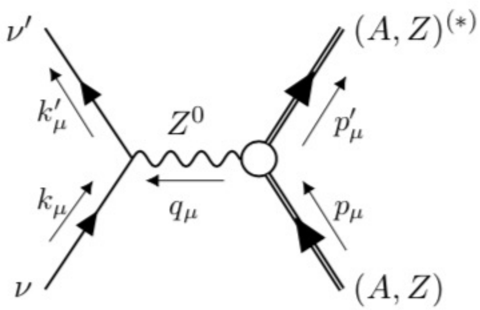
- Available calculations are not copious, but improving

Example:

Neutral-current neutrino-nucleus scattering off Xe isotopes

arXiv:1804.08995

P. Pirinen[1], J. Suhonen[1], and E. Ydrefors[2]



$$\frac{d^2\sigma}{d\Omega dE_{\rm ex}} = \frac{G_{\rm F}^2\,|\mathbf{k}'|\,E_{k'}}{\pi(2J_i+1)}\left(\sum_{J\geq 0}\sigma_{\rm CL}^J + \sum_{J\geq 1}\sigma_{\rm T}^J\right)$$

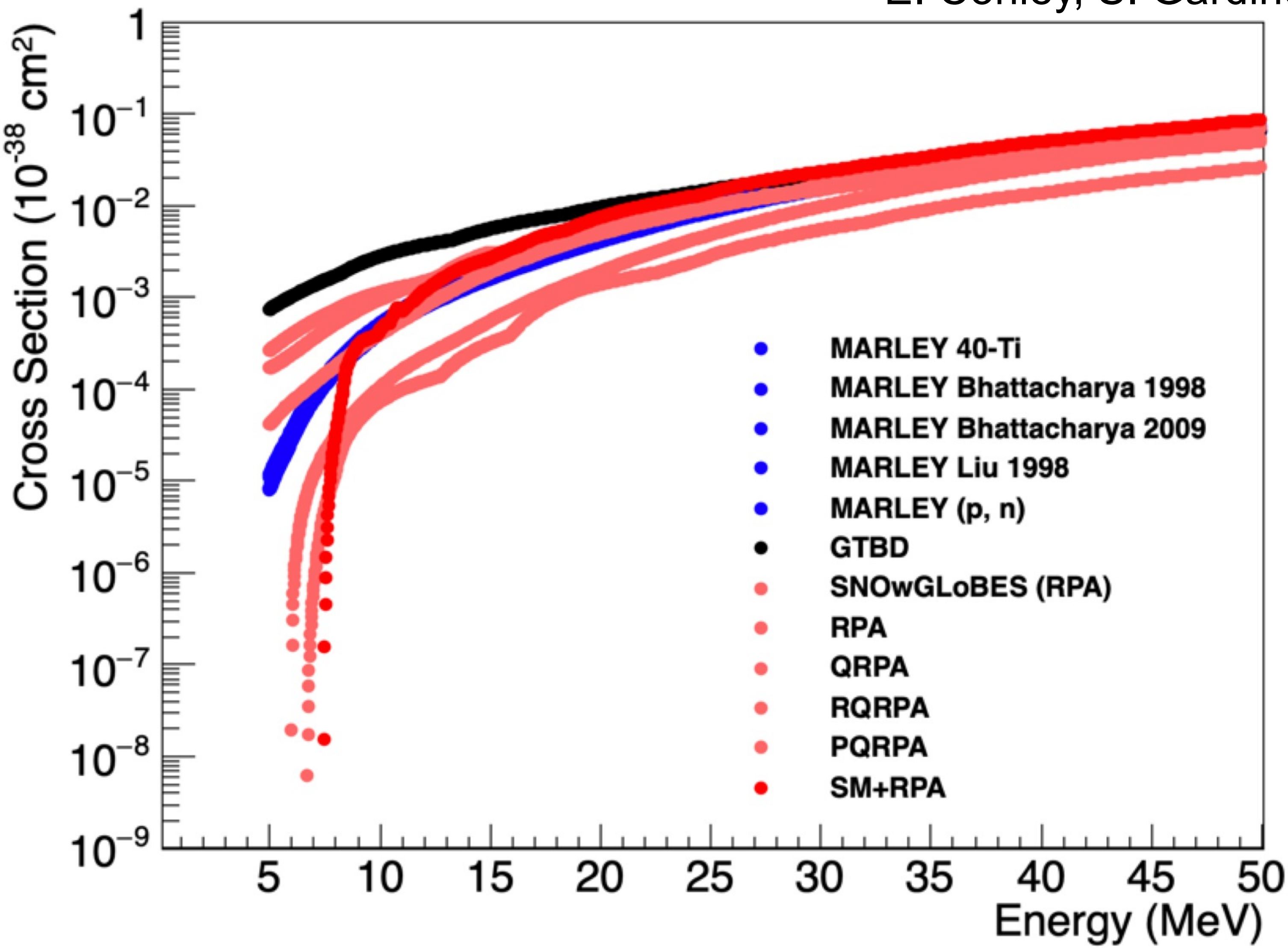
$$\sigma_{\rm CL}^J = (1+\cos\theta)\,|\langle J_f||\mathcal{M}_J(q)||J_i\rangle|^2 + (1+\cos\theta - 2b\sin^2\theta)\,|\langle J_f||\mathcal{L}_J(q)||J_i\rangle|^2 + qE_{\rm exc}(1+\cos\theta)\times 2{\rm Re}\,\{\langle J_f||\mathcal{M}_J(q)||J_i\rangle^*\langle J_f||\mathcal{L}_J(q)||J_i\rangle\}\,,$$

$$\sigma_{\rm T}^J = (1-\cos\theta + b\sin^2\theta)\left[|\langle J_f||\mathcal{T}_J^{\rm mag}(q)||J_i\rangle|^2 + |\langle J_f||\mathcal{T}_J^{\rm el}(q)\rangle|^2\right] \mp \frac{E_k+E_{k'}}{q}(1-\cos\theta)\times 2{\rm Re}\,\{\langle J_f||\mathcal{T}_J^{\rm mag}(q)||J_i\rangle\langle J_f||\mathcal{T}_J^{\rm el}||J_i\rangle\}\,,$$

- Development of MARLEY is promising

Example of variation in theory predictions at low energy

E. Conley, S. Gardiner



This is for ν_eCC, but gives an idea of (large) uncertainties for these kinds of calculations

What do we need?

- Direct measurements @ reactor energy,
  if possible

- More theory!
  (nuclear structure theorists, please help!)

- **Measurements to validate theory**
  - stopped-pion source may still help with this,
    even if energy range and flavors
    do not match reactor fluxes
  - other scattering (e.g. (p,n)) can also help

- Priority materials:
  Ge, Si, Ca, W, O, Pb, Xe, Na, I, Ar, Fe, Al, Zn, S, F
  [COHERENT: Ar, Ge, Na, I, Pb, Fe @SNS]

Summary

- Reactor CEvNS has high rate, but very low recoil energy
- Backgrounds are the primary difficulty
- Source-correlated neutrinos create non-CEvNS (inelastic) background
  - probably quite small at reactor energies **but large uncertainties**
- Both measurements and theory welcome