# Theory and Phenomenology of Coherent Elastic Neutrino Nucleus Scattering

Gail McLaughlin

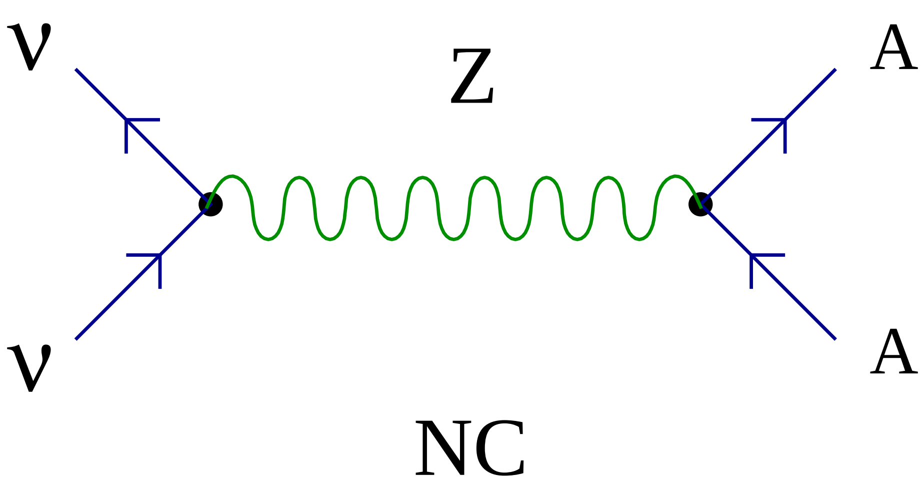
NC State

# Coherent Elastic Neutrino Nucleus Scattering ($CE\nu NS$)

- neutrino interacts with nucleus through neutral current
- can't see neutrino afterward, but could see small kick to nucleus

**Outline**

- introduction
- where $CE\nu NS$ is already in use
- future physics from $CE\nu NS$



# Basic cross section

Coherent elastic neutrino nucleus scattering cross section

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[ 2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2} \right] \frac{Q_W^2}{4} F^2(Q^2)$$

- $E$ : neutrino energy, $T$ : nuclear recoil
- $Q^2 = \frac{2E^2TM}{(E^2-ET)}$ : squared momentum transfer
- $Q_W = N - Z(1 - 4\sin^2\theta_W)$: weak charge
- F($Q^2$): form factor - largest uncertainty in cross section

Assumes a spin zero nucleus, no non-standard model interactions

# Making a theoretical prediction

Fold cross section (previous slide) with incoming neutrino spectrum (e.g. left figure) to find nuclear recoil spectrum (right figure)

## $\nu s$ from $\pi/\mu$ decay at rest

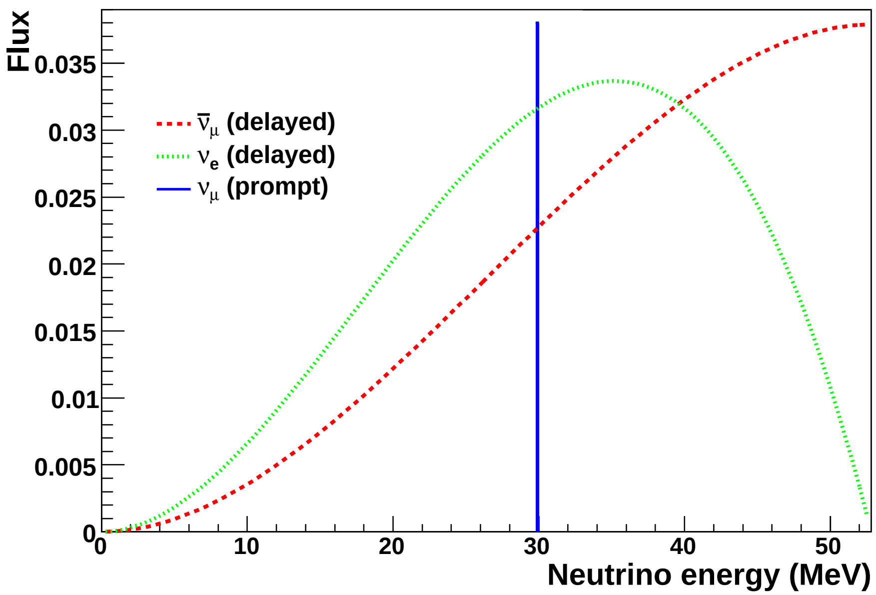



Fig. from Scholberg 2006

## Spectrum of nuclear recoils

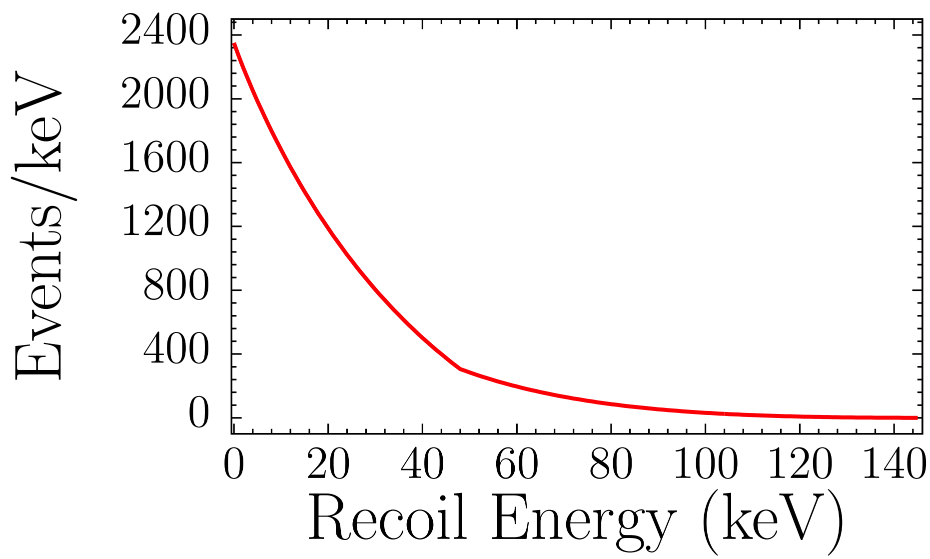



Fig. from Patton et al 2012

# Coherent Elastic Neutrino Nucleus Scattering (CE$\nu$NS) appears many places

A few of these

- Opacity source in supernova neutrinos
- Mechanism for detecting supernova neutrinos
- Means for studying active-sterile oscillations
- Background in dark matter detectors

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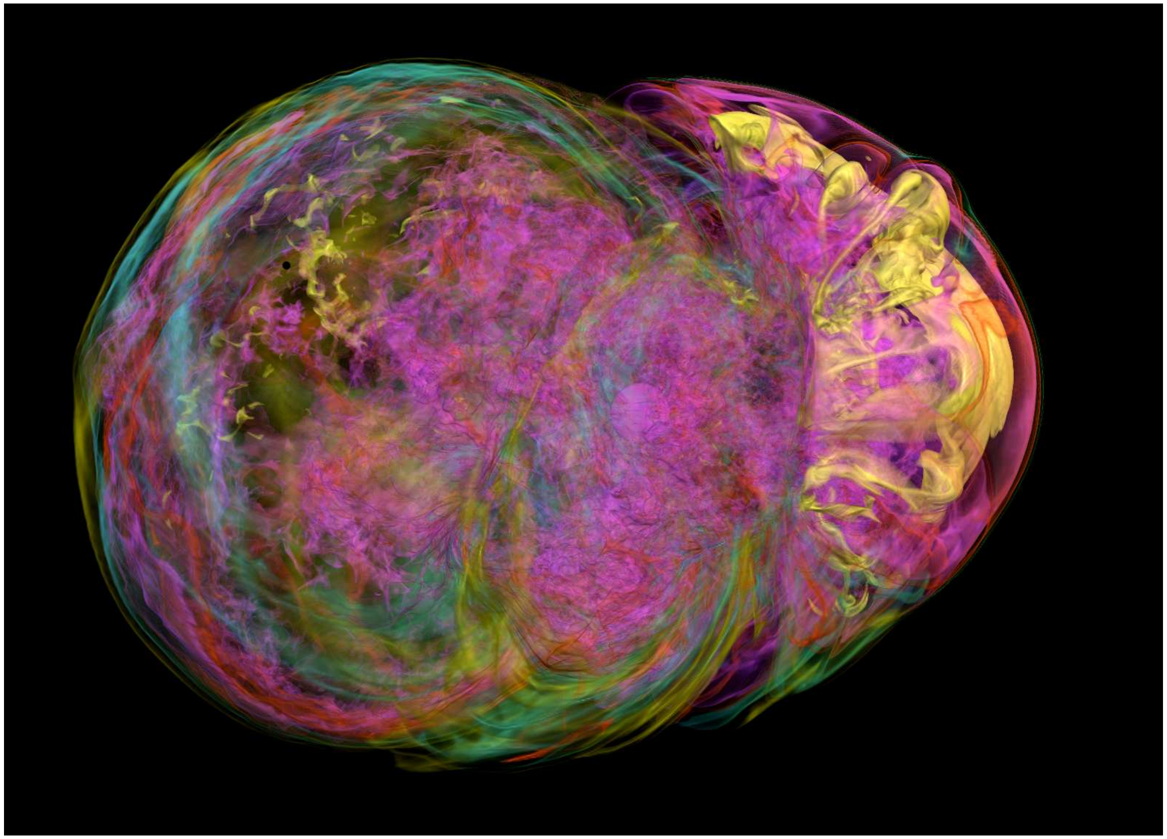
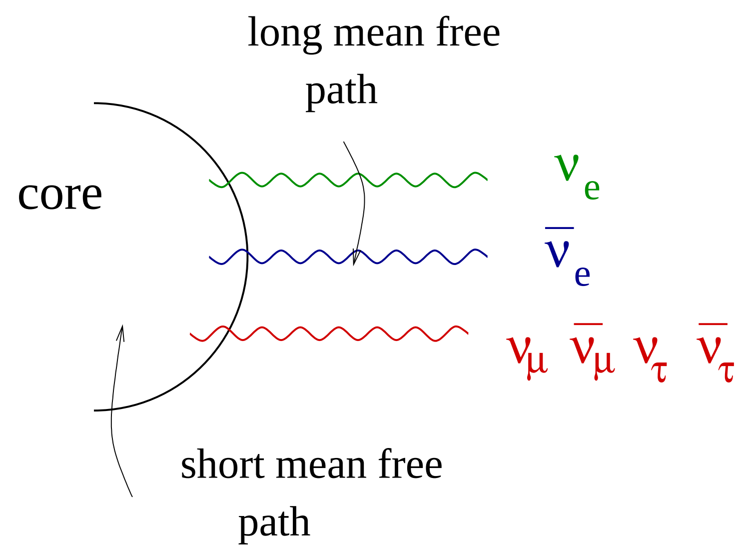
# Supernovae Neutrinos






Schematic picture of neutrino emission from proto-neutron star

Figure from J. Blondin

Neutrinos are emitted from deep in the center

# Coherent elastic neutrino nucleus scattering is an opacity source in supernova

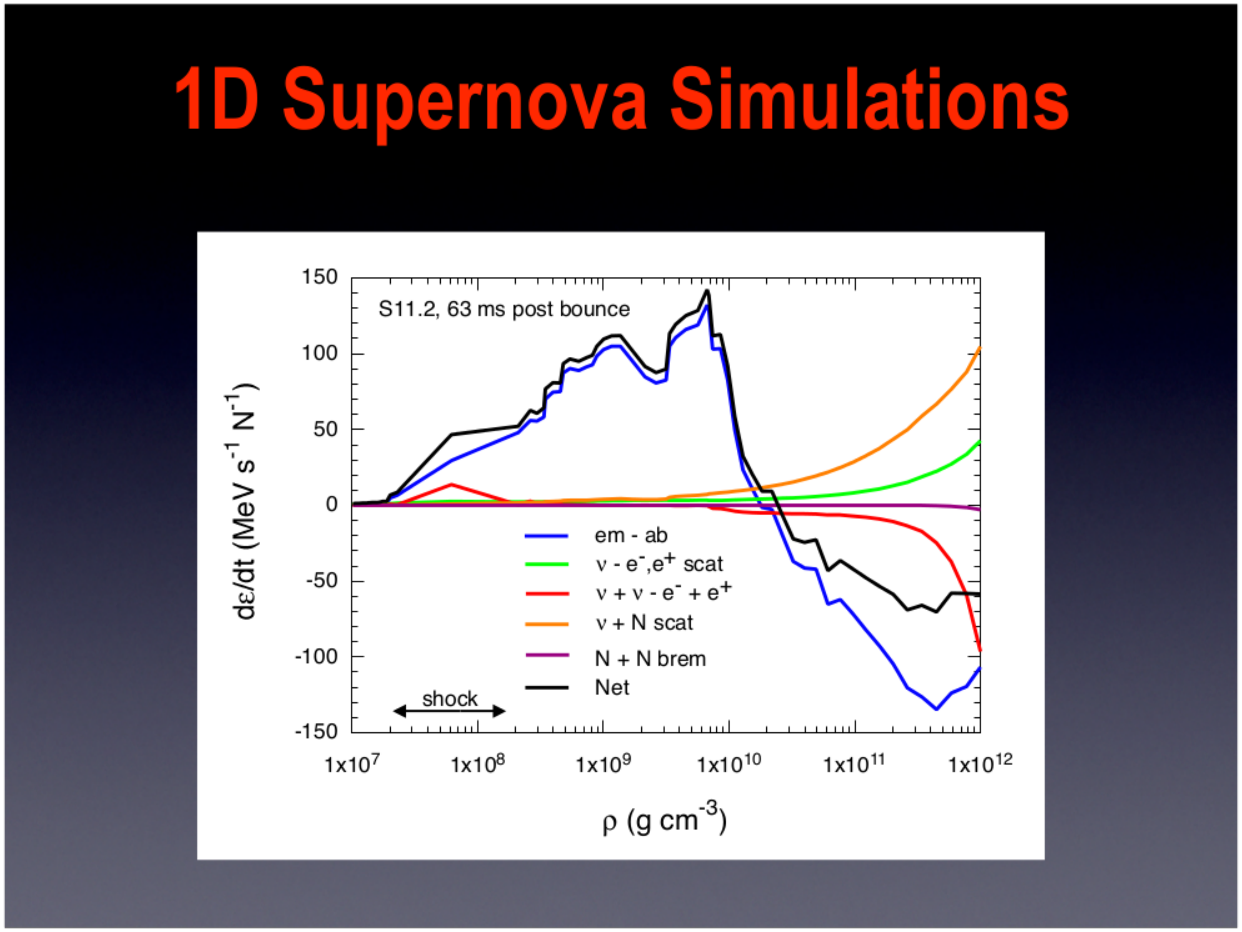



Figure from S. Bruenn

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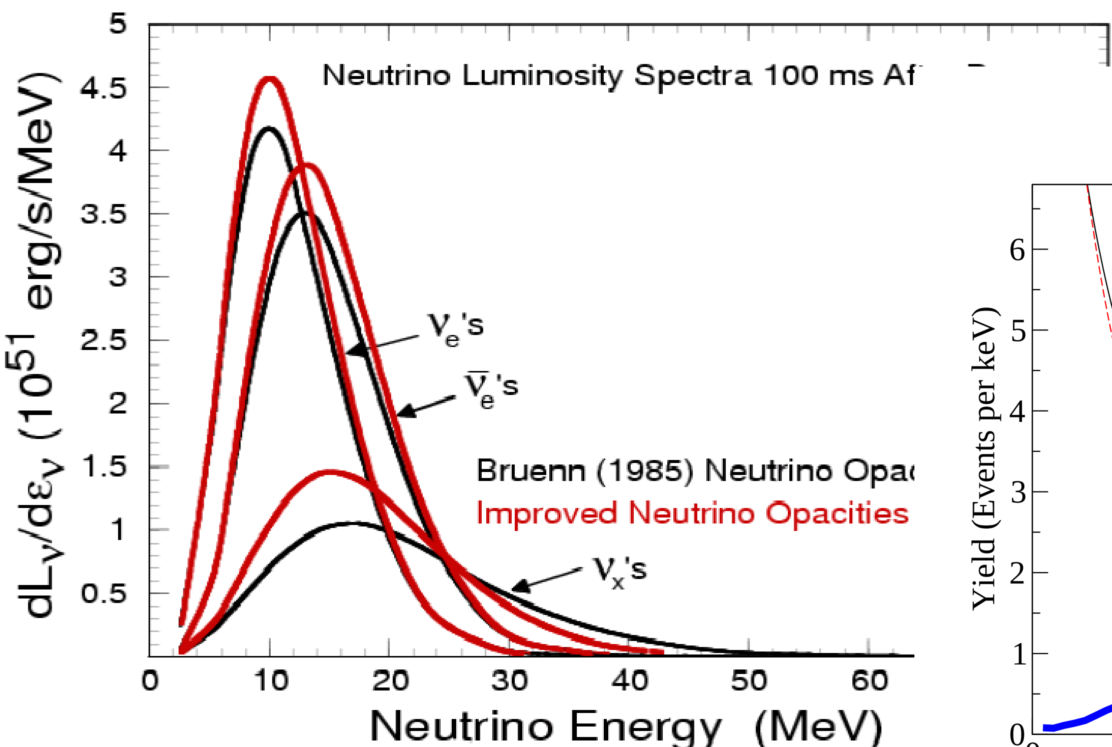
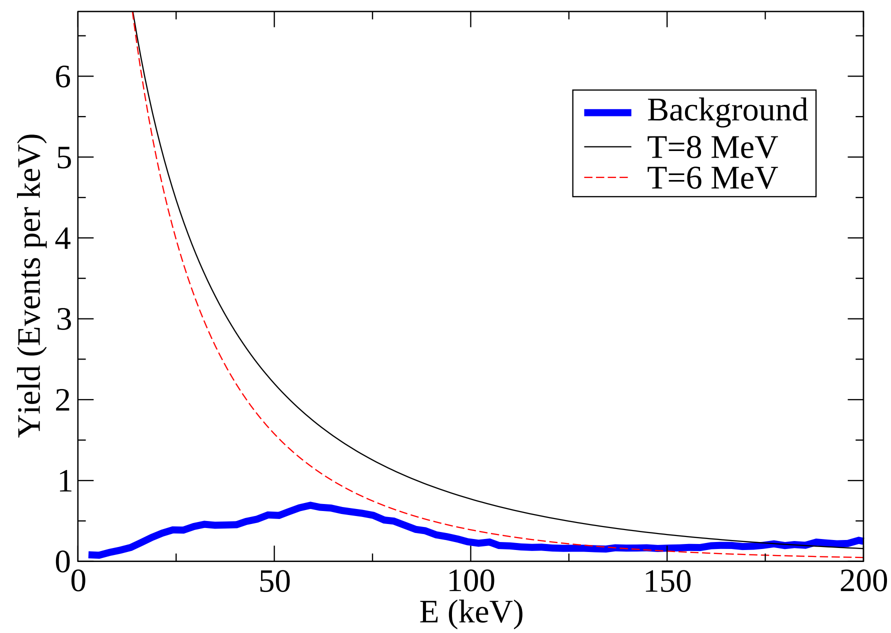
# Coherent Elastic Neutrino Nucleus Scattering (CE$\nu$NS) for detecting supernova neutrinos




spectra from ORNL group




Event rates in CLEAN detector, Horowitz et al 2003

# Coherent Elastic Neutrino Nucleus Scattering (CE$\nu$NS) appears many places

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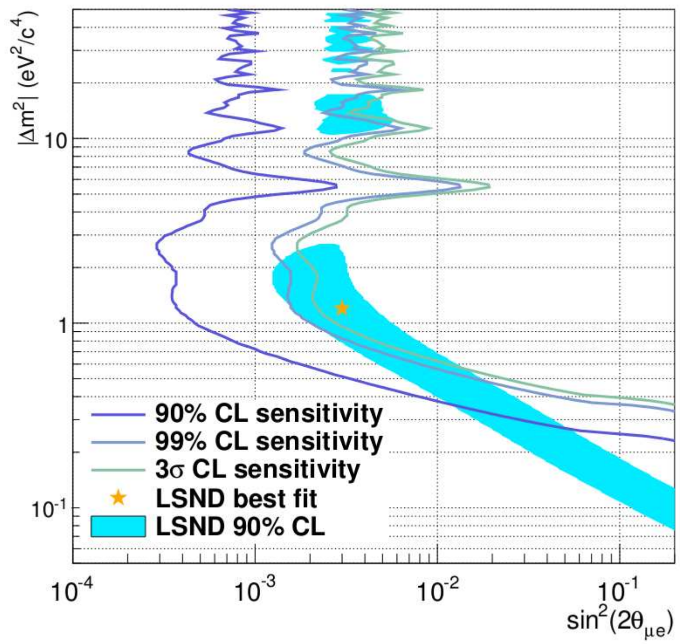
# CE$\nu$NS proposed as a mechanism for probing sterile neutrino oscillations

( Anderson et al 2012, Formaggio et al 2012)

Since CE$\nu$NS measures only neutral current it is insensitive to active flavor transformation, ideal for studying active sterile transformation

Example: sensitivity to sterile oscillations using Ar at Dae$\delta$alus




Anderson et al 2012

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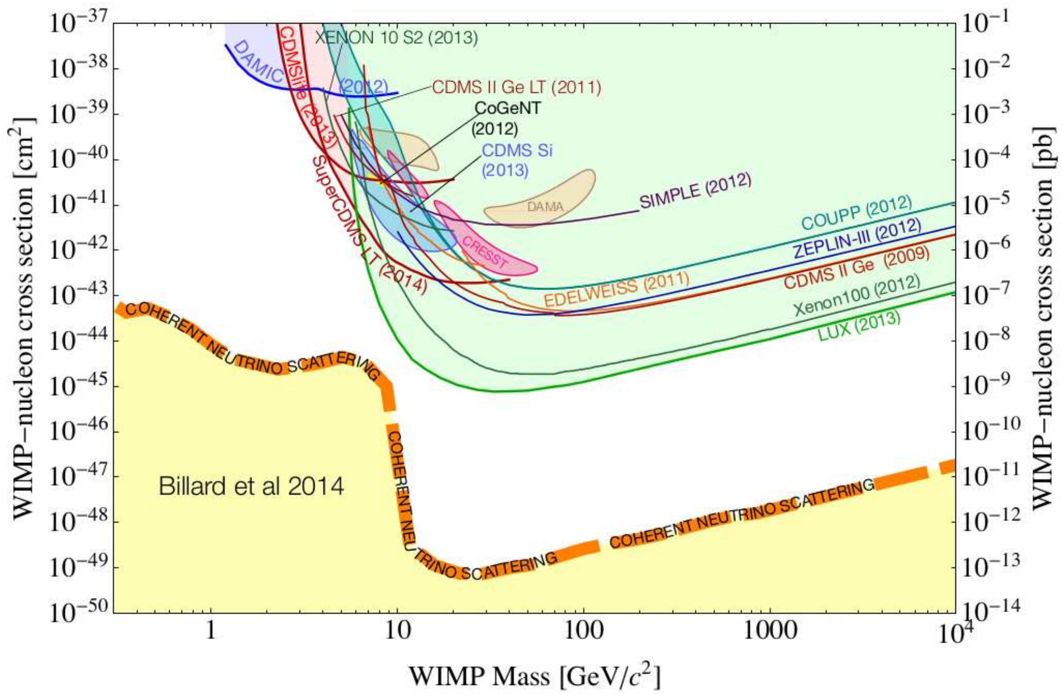
# CE$\nu$NS background is a limit on future dark matter sensitivity

discussed in Snowmass Summary: WIMP Dark Matter Direct Detection

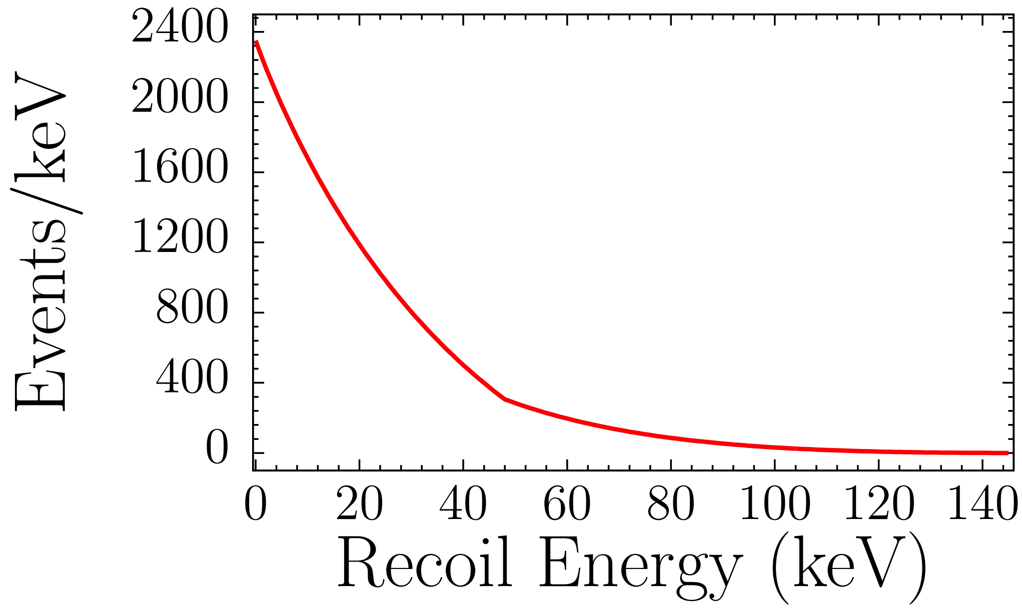


Even though we are counting on this process, it has never been detected!

Why not? Large cross section but need to see the small recoil of the nucleus

# Beyond First Detection of CE$\nu$NS

- nonstandard $\nu$ interactions
- form factor



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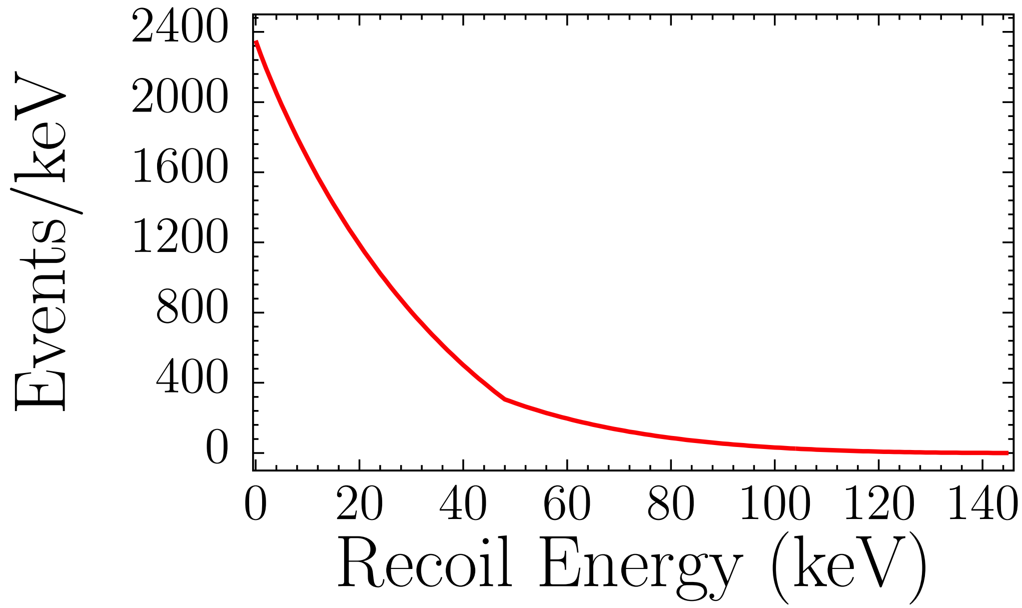


# Nonstandard interactions

Some nonstandard interactions are currently poorly constrained. Examples are vector couplings for electron neutrinos with up and down quarks, $\epsilon_{ee}^{uV}$ and $\epsilon_{ee}^{dV}$, although there are other couplings that contribute as well. To define the NSI, use eq from Barranco et al 2006,

$$\mathcal{L}_{\nu Hadron}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} \left[\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta\right] * \left(\varepsilon_{\alpha\beta}^{qL}\left[\bar{q}\gamma_\mu(1-\gamma^5)q\right] + \varepsilon_{\alpha\beta}^{qR}\left[\bar{q}\gamma_\mu(1+\gamma^5)q\right]\right) \quad (1)$$

The vector couplings are the only ones relevant for spin zero nuclei $\varepsilon_{\alpha\beta}^{qV} = \varepsilon_{\alpha\beta}^{qL} + \varepsilon_{\alpha\beta}^{qR}$.

Limits are $-1.0 < \epsilon_{ee}^{uV} < 0.6$ and $-0.5 < \epsilon_{ee}^{dV} < 1.2$

# Nonstandard interactions

Continue considering example $\epsilon_{ee}^{uV}$ and $\epsilon_{ee}^{dV}$. The zero order effect on CE$\nu$NS is to change the standard model weak charge to an effective weak charge.

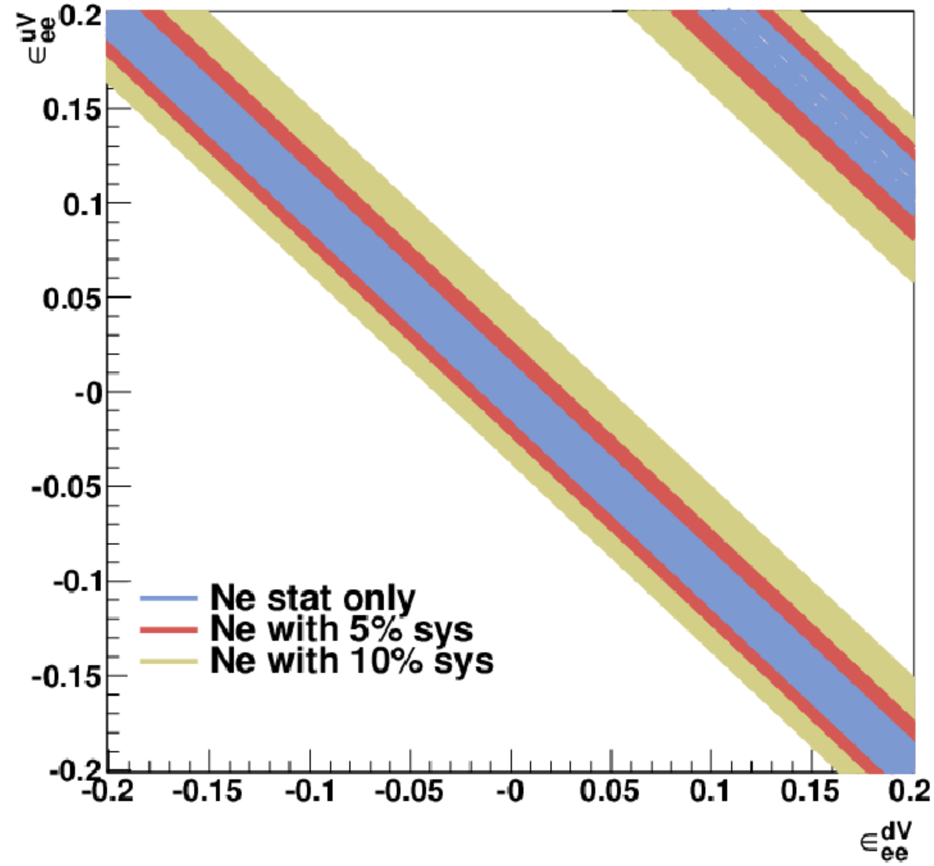
$$Q_W = N(1 - 2\epsilon_{ee}^{uV} - 4\epsilon_{ee}^{dV}) + Z(1 - 4\sin^2\theta_W + 4\epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})$$

Recall:

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

# Nonstandard interactions

Changing the size of $Q_W$ effectively changes overall magnitude of recoil curve. Shows limits which could be achieved after 100 kg/yr at SNS.

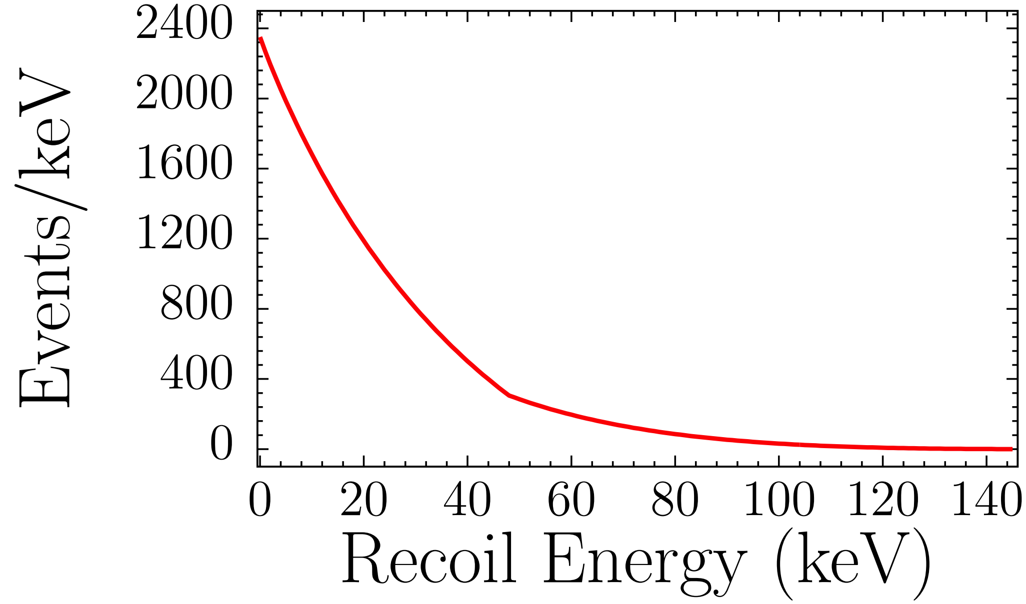



Scholberg 2006

Additional non-standard interactions such as the flavor changing neutral currents can be probed. Also, first order effect in changing relative contributions of neutron and proton form factor.

# Beyond First Detection of CE$\nu$NS

- nonstandard $\nu$ interactions
- form factor

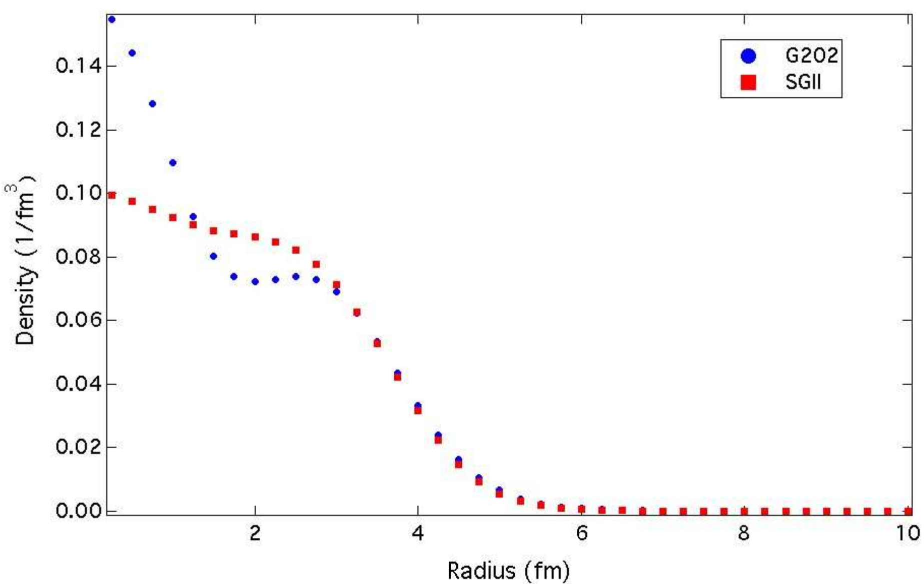


# Form factor

## Understanding the structure of the nucleus

Form factor, $F(Q^2)$ is the Fourier transform of the density distributions of protons and neutrons in the nucleus.

$$F(Q^2) = \frac{1}{Q_W} \int \left[\rho_n(r) - (1 - 4\sin^2\theta_W)\rho_p(r)\right] \frac{\sin(Qr)}{Qr} r^2 dr$$




density distributions

$$\langle R^2 \rangle^{1/2}_{SGII} = 3.405 \text{ fm}$$
$$\langle R^2 \rangle^{1/2}_{G202} = 3.454 \text{ fm}$$

# Form factor

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- Proton form factor term is suppressed by $1 - 4\sin^2(\theta_W)$
- Neutron form factor is not suppressed

CE$\nu$NS can be used to determine the form factor Amanik et al 2009

# Form factor

$$F(Q^2) = \frac{1}{Q_W} \int \left[\rho_n(r) - (1 - 4\sin^2\theta_W)\rho_p(r)\right] \frac{\sin(Qr)}{Qr} r^2 dr$$

- Proton form factor can be measured by electromagnetic probes.
- Neutron form factor is less well known:
- Neutron scattering - many measurements - requires theory to go from cross section to form factor
- Parity violating electron scattering - PREX at Jlab Pb at one $Q^2$, extract $A_{PV} \sim 0.65 \times 10^{-6}$ then determine neutron radius, now also CREX at Jlab on Ca

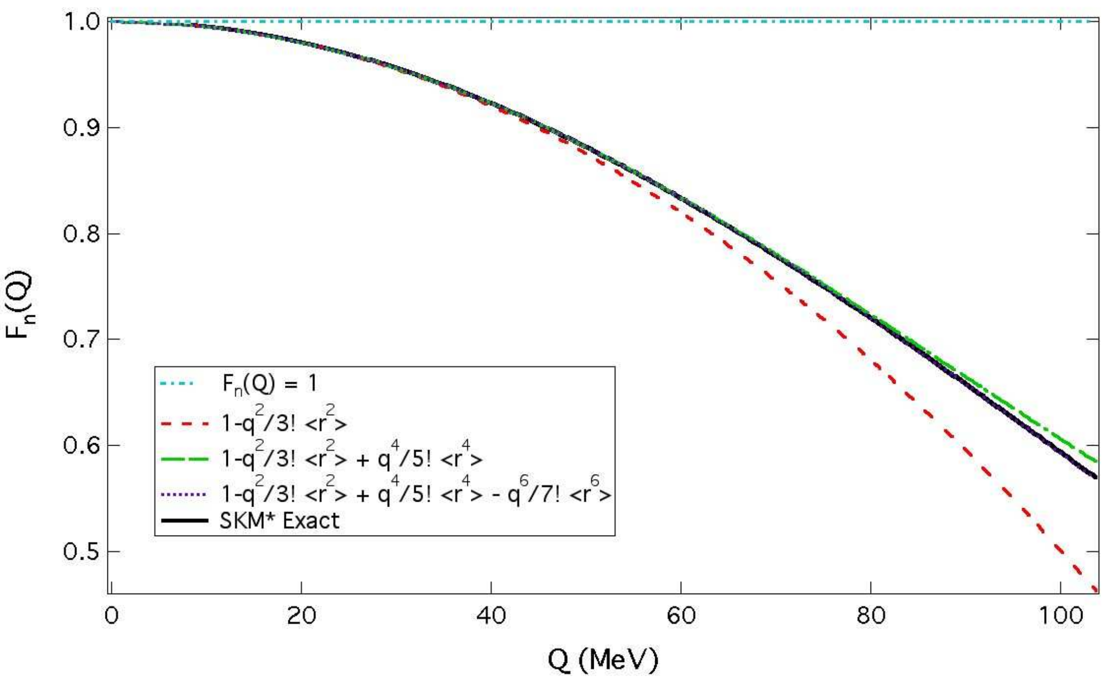
C$\nu$NS recoil curve can be fit: neutron radius and higher moments

# Nuclear-Neutron form factor from CE$\nu$NS

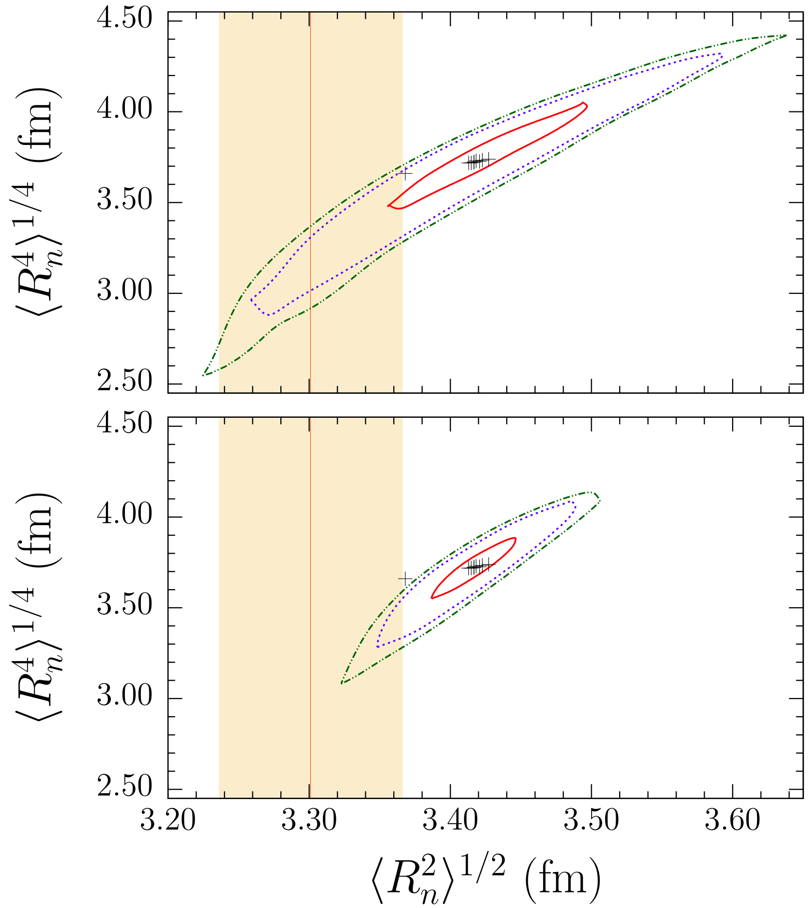
Taylor expand the $\sin(Qr)$ form factor:

$$F_n(Q^2) = \frac{1}{Q_W}\int \rho_n(r)\frac{\sin(Qr)}{Qr}r^2dr \approx \frac{N}{Q_W}(1 - \frac{Q^2}{3!}\langle R_n^2\rangle + \frac{Q^4}{5!}\langle R_n^4\rangle - ...)$$

Moments of the density distribution, $\langle R_n^2\rangle$, $\langle R_n^4\rangle$ characterize the form factor. Patton et al 2012, 2013



# Liquid argon scenario

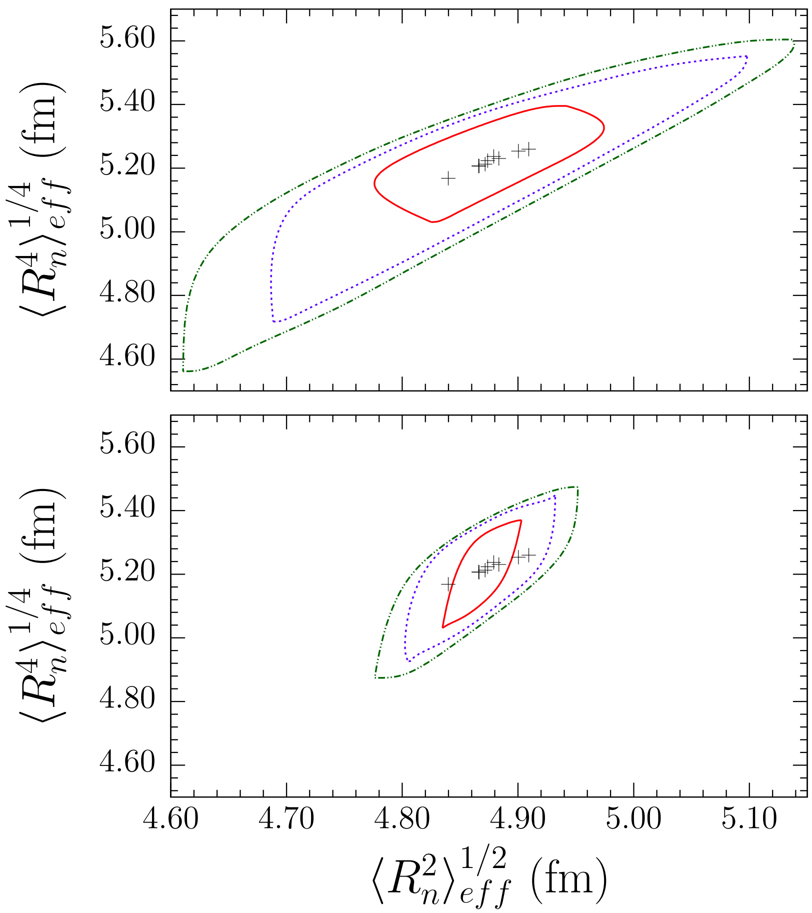



3.5 tonnes argon 16m from SNS, 18m from Dae$\delta$alus, 30m from ESS for one year. Shows 40%, 91% and 97% confidence contours. Crosses are theory predictions.

Fig. from Patton et al 2012

Band is measurement from neutron scattering. Top plot: normalization of neutrino flux not known, bottom plot normalization of neutrino flux known.

# Xenon is more constraining




300 kg Xenon 16m from SNS, 18m from Dae$\delta$alus, 30m from ESS for one year. Shows 40%, 91% and 97% confidence contours. Crosses are theory predictions.

fig. from Patton et al 2012

Top plot: normalization of neutrino flux not known, bottom plot normalization of neutrino flux known.

## Beyond NSIs and the form factor

- Nonstandard $\nu$ interactions
- Form factor
- $\sin^2\theta_W$
- $\nu$ magnetic moment

$$Q_W = N + Z(1 - 4\sin^2\theta_W)$$

# Beyond NSIs and the form factor

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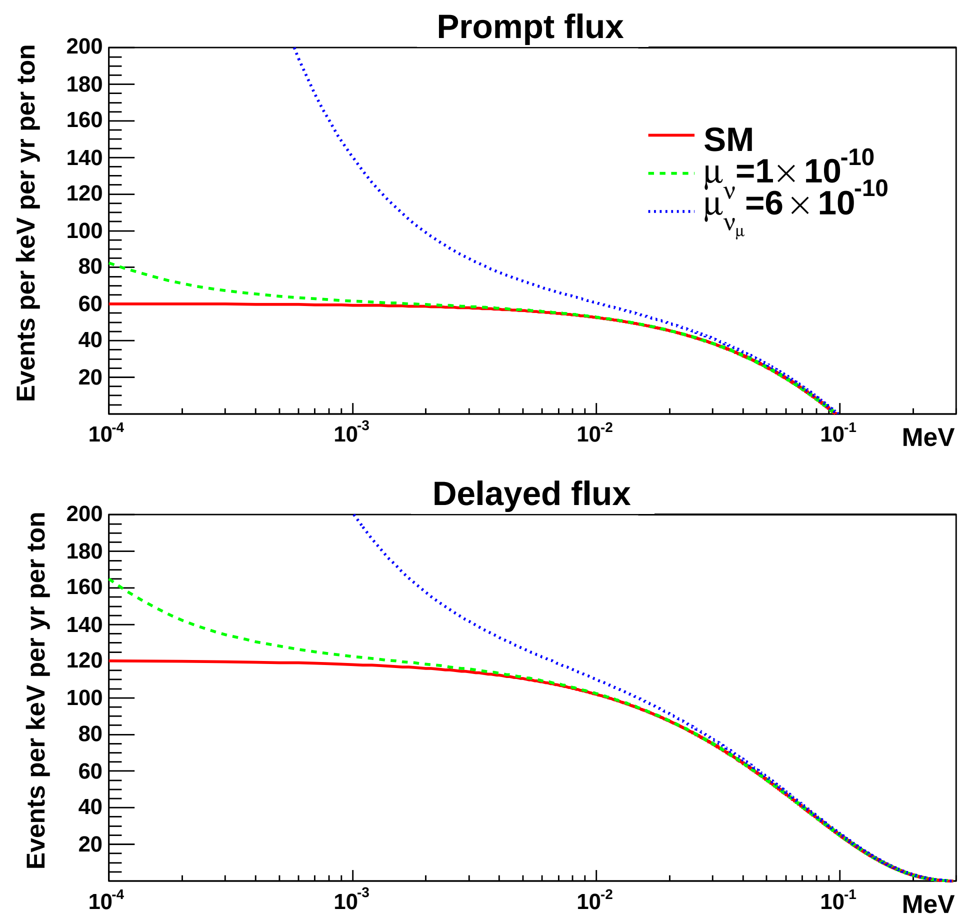


fig from Scholberg 2006

Look for excess events at low recoil energy using neutrinos from stopped $\pi/\mu$

# Summary

- Coherent elastic neutrino nucleus scattering is not yet detected, but in many communities such as supernova simulation, supernova detection, active-sterile oscillations, dark matter detection it is assume to exist as predicted by standard model
- Going beyond a first detection...
  - non-standard interactions
  - form factor
- and beyond these...
  - Weinberg angle
  - neutrino magnetic moment
- overall, a rich physics opportunity from the theory point of view