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The X_{17}

Neutron skin

Conclusions

Exploring light Z' -bosons and neutron skin with Coherent Elastic neutrino Nucleus Scattering at the ESS

Johan Rathsman (Lund University)

Based partially on arXiv:2509.15128 and arXiv:2603.15246 with:
Joakim Cederkäll, Yaşar Hiçyılmaz, Else Lytken, Stefano Moretti

15th Nordic Meeting on Nuclear Physics, Visby, May 5-8, 2026



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Outline:

Coherent elastic neutrino nucleus scattering

The X_{17} - example of a light Z'

Neutron skin effect

Conclusions



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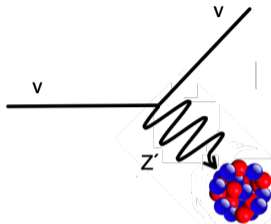
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Conclusions

Coherent Elastic neutrino Nucleus Scattering (CE ν NS)

- Coherent elastic scattering off the whole nucleus
- $[N - (1 - 4 \sin^2 \theta_W)Z]^2$ enhancement in SM cross-section (N neutrons, Z protons)
- Tabletop detector possible – $\mathcal{O}(10)$ kg
- High sensitivity also to BSM physics - such as the X_{17}
- Also sensitive to neutron skin effect - important for neutron stars
- Nuclear recoil energies down to ~ 1 keV
- Requires extremely low threshold to be sensitive
- Current lowest threshold corresponds to 5 electron-hole pairs in Germanium





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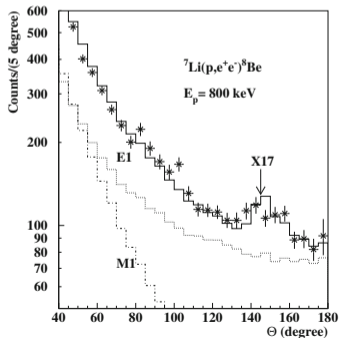
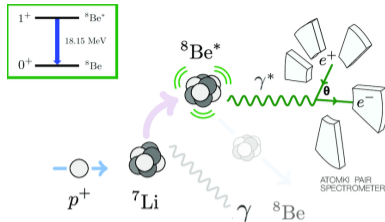
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Evidence for the X_{17} – a fifth force

- finding a fifth force would be a major breakthrough in our understanding of the universe
- $p \ ^7\text{Li} \rightarrow \ ^8\text{Be}^* \rightarrow \ ^8\text{Be} \ e^+ e^-$,
 $p \ ^3\text{H} \rightarrow \ ^4\text{He}^* \rightarrow \ ^4\text{He} \ e^+ e^-$ and
 $p \ ^{11}\text{B} \rightarrow \ ^{12}\text{C}^* \rightarrow \ ^{12}\text{C} \ e^+ e^-$
 data from the Atomki experiment could be explained by a light Z' with a mass of 17 MeV - the X_{17}
- supporting evidence from PADME experiment in $e^+ e^- \rightarrow Z' \rightarrow e^+ e^-$
- such a state could be found (or ruled out) in CE ν NS@ESS





Cross-section for $CE\nu NS$ with light Z'

Dominated by vector coupling of nucleus (axial vector coupling \propto nucleus spin)

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$$\frac{d\sigma^{\nu e/\mu N}}{dy} = \frac{[N - (1 - 4 \sin^2 \theta_W)Z]^2 [F_V(y)]^2}{4\pi m_\mu^2} \left(1 - \frac{y}{x^2}\right) \times \left(\frac{G_F m_\mu^2}{\sqrt{2}} - \frac{C_{\text{eff}}^{\nu e/\mu}}{y + m_{Z'}^2/m_\mu^2}\right)^2$$

where $G_F m_\mu^2/\sqrt{2} = 9.3 \times 10^{-8}$ and

$$x = \frac{2E_\nu}{m_\mu}, 0 < x < 1$$

$$y = E_{\text{nr}}/E_{\text{nr}}^{\text{max}}, 0 < y < 1, E_{\text{nr}}^{\text{max}} = m_\mu^2/(2M)$$

$$C_{\text{eff}}^{\nu e/\mu} = C_V^{\nu e/\mu} \frac{NC_V^n + ZC_V^p}{N - (1 - 4 \sin^2 \theta_W)Z}$$

C_V^f vector coupling to Z'



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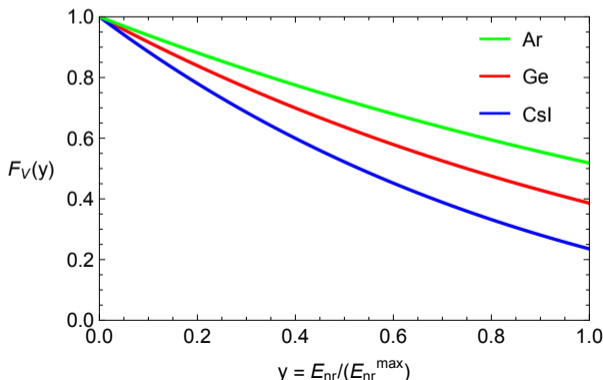
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Klein Nystrand nuclear form factor

$F_{V,Z}(y)$ and $F_{V,N}(y)$ nuclear form factors for protons and neutrons

$$F_{V,Z}(Q^2) = F_{V,N}(Q^2) = \frac{3}{(QR_A)^3} [\sin(QR_A) - QR_A \cos(QR_A)] \frac{1}{1 + a^2 Q^2}$$

$Q^2 = 2ME_{nr} = ym_\mu^2$, $R_A = 1.2A^{1/3}$ fm, and $a = 0.7$ fm.





Neutrino Sources

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Spallation sources

- pulsed proton beam producing neutrons and π^+
- π^+ stopped in target before decay, $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$
- $\tau_{\pi^+} = 26\text{ns}$, $\tau_\mu = 2200\text{ns}$

Nuclear reactors

- continues flux of anti-neutrinos $\bar{\nu}_e$ from fission products

Nuclear recoil spectrum by integrating over neutrino energy

$$\frac{dN_r}{dy} = \frac{m_{\text{det}} N_A}{M_A} \int_{\sqrt{y}}^1 \frac{d\sigma^{\nu N}}{dy} \frac{d\Phi_\nu}{dx} dx$$

kinematics gives $x > \sqrt{y}$ (head-on collision) or $E_\nu > \sqrt{E_{\text{nr}} M/2}$



Neutrino flux from $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$ decay at rest

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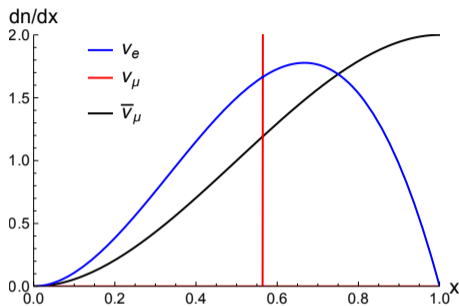
Conclusions

$$\frac{d\Phi_{\nu_e}}{dx} = \frac{rN_{\text{POT}}}{4\pi L^2} 12x^2(1-x)$$

$$\frac{d\Phi_{\bar{\nu}_\mu}}{dx} = \frac{rN_{\text{POT}}}{4\pi L^2} 2x^2(3-2x)$$

$$\frac{d\Phi_{\nu_\mu}}{dx} = \frac{rN_{\text{POT}}}{4\pi L^2} \delta(x-x_0)$$

- $x = \frac{2E_\nu}{m_\mu}$, $0 < x < 1$
- r nr of π^+ per proton
 $r = 0.08(0.3) @ 0.8(5) \text{ MW}$
- N_{POT} nr of protons on target
- L distance



$$x_0 = \frac{m_{\pi^+}^2 - m_\mu^2}{m_\mu m_{\pi^+}} \approx 0.564$$

$$m_\mu = 105.6 \text{ MeV} \Rightarrow E_\nu^{\text{max}} = 52.8 \text{ MeV}$$



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Neutrino flux from reactors

$$\frac{d\Phi_{\bar{\nu}_e}}{dx} = \frac{\Phi t_{\text{exp}}}{N_{\bar{\nu}_e}} \left[x e^{a_2 + b_2 x + c_2 x^2} + e^{a_1 + b_1 x + c_1 x^2 + d_1 x^3 + e_1 x^4 + f_1 x^5} \right]$$

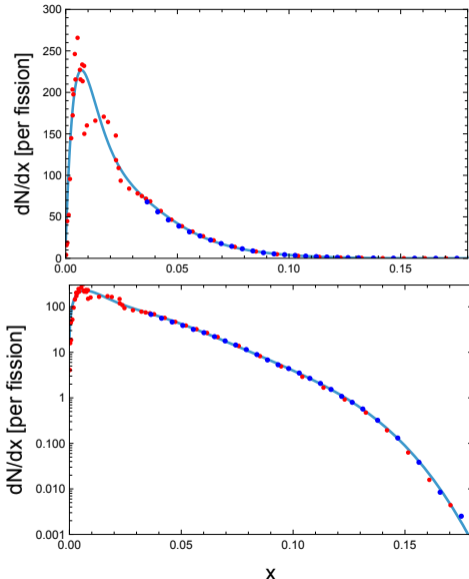
Fitted to data from DayaBay (blue) and calculation by Kopeikin (red), $N_{\bar{\nu}_e} = 6.8$

Total fluxes for experiments

- $\Phi_{\text{Dresden-II}} = 4.8 \times 10^{13} \text{ cm}^2/\text{s}$
- $\Phi_{\text{CONUS+}} = 1.5 \times 10^{13} \text{ cm}^2/\text{s}$

Much lower energy than π^+ -DAR

$\Rightarrow (\text{Much lower})^2$ nuclear recoil energy





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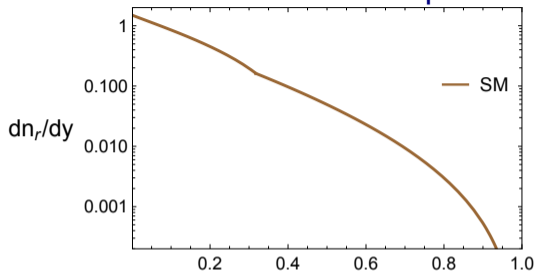
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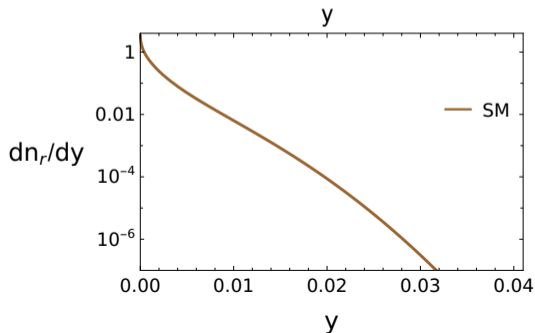
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Theoretical nuclear recoil spectra



$$\frac{dn_r}{dy} = \int_{\sqrt{y}}^1 \frac{d\sigma^{\nu N}}{dy} \frac{d\Phi_\nu}{dx} dx$$

π^+ DAR



reactors



Quenching factor for Germanium

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Ionisation energy smaller than nuclear recoil energy

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$$y_{\text{ion}} = Q(y)y$$

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Described by the Lindhard model

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Conclusions

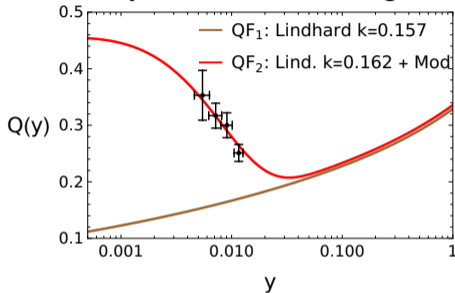
$$Q_{\text{Lind}}(y) = \frac{kg(y)}{1 + kg(y)}$$

$$g(y) = 3(C_Z y)^{0.15} + 0.7(C_Z y)^{0.60} + C_Z y$$

$$C_Z = E_{\text{nr}}^{\text{max}} \times 11.5 / Z^{7/3}$$

$$E_{\text{nr}}^{\text{max}} = 82.5 \text{ keV for Ge}$$

uncertainty at small recoil energies



$$QF_1 = Q_{\text{Lind}}(k = 0.157),$$

$$QF_2 = Q_{\text{Lind}}(k = 0.162) + Q_{\text{Mod}}$$

with $Q_{\text{Mod}}(y) = 0.36 \exp(-120y)$
 detector threshold $\Leftrightarrow y \gtrsim 0.01$



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Detector resolution

Finite detector resolution gives smearing

$$\frac{dN_r}{dy_{\text{rec}}} = \int_{y_{\text{min}}}^1 \frac{2}{1 + \text{Erf}\left(\frac{Q(y)y}{\sqrt{2}\sigma}\right)} \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(y_{\text{rec}} - Q(y)y)^2}{2\sigma^2}\right] \frac{dN_r}{dy} dy$$

minimal fractional recoil energy $y_{\text{min}} = 0.00034$

$\sigma = \sigma_E / E_{\text{nr}}^{\text{max}}$ is a dimensionless width with

$$\sigma_E^2 = \sigma_n^2 + E_{\text{ion}}\eta F,$$

where $\eta = 2.96 \text{ eV}_{\text{ee}}$, the Fano factor $F = 0.11$ and σ_n is the intrinsic resolution of the detector

$$\begin{aligned}\sigma_n^{\text{Dresden-II}} &= 68.5 \text{ eV}_{\text{ee}}, \\ \sigma_n^{\text{CONUS+}} &= 20.0 \text{ eV}_{\text{ee}}.\end{aligned}$$

Also thresholds: $E_{\text{rec}}^{\text{min,Dresden-II}} = 200 \text{ eV}_{\text{ee}}$ and $E_{\text{rec}}^{\text{min,CONUS+}} = 160 \text{ eV}_{\text{ee}}$



Detected recoil spectra for reactors compared to SM

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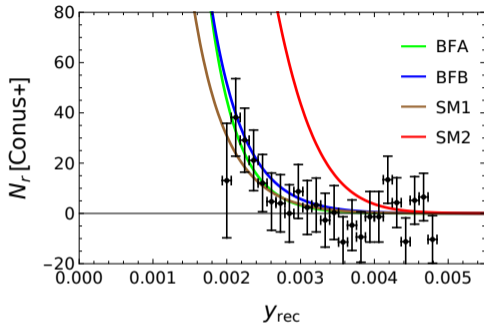
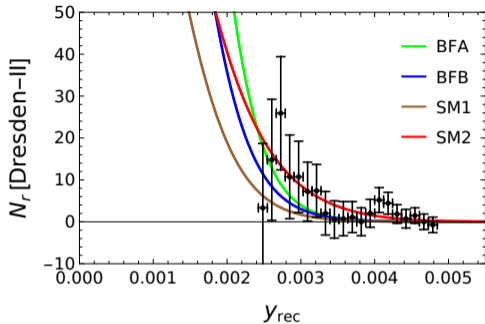
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not possible to construct quenching factor that describes both data sets

Y. Li, G. Herrera and P. Huber, JHEP **11** (2025), 022

use QF_1 since overall in better agreement with data

adding a X_{17} (BFA and BFA) able to describe both datasets



Statistical analysis of data

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$$\chi^2 = \sum_i \left(\frac{(1 + \rho)x_i - \mu_i}{\sigma_i} \right)^2 + \left(\frac{\rho}{\sigma_{\text{sys}}} \right)^2,$$

x_i model predictions for number of events

μ_i number of observed events

σ_i corresponding errors

ρ overall scale factor, determined from minimising χ^2

σ_{sys} overall systematic uncertainty, use $\sigma_{\text{sys}} = 0.17$ (CONUS+)



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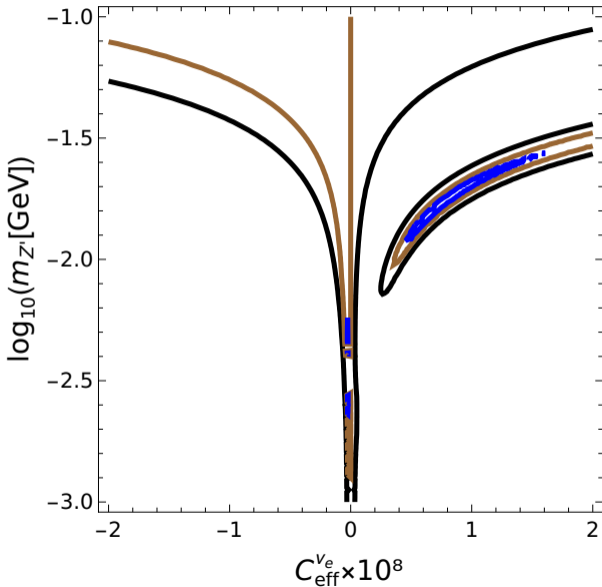
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χ^2 contours for arbitrary mass Z'



Brown = SM

Black = SM+6

Blue = SM-2

Preferred region:

$$m_{Z'} \approx [13, 25] \text{ MeV and}$$

$$C_{\text{eff}}^{\nu_e} \approx [0.5, 1.5] \cdot 10^{-8}$$

$C_{\text{eff}}^{\nu_e}$ positive \Leftrightarrow negative
interference with SM



χ^2 curve for X_{17}

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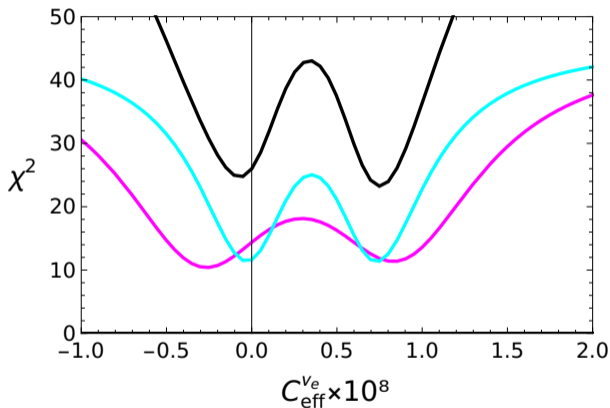
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magenta = Dresden-II

cyan = CONUS+

combined=black

Preferred values:

BFA: $C_{\text{eff}}^{\nu_e} \approx 0.8 \times 10^{-8}$

BFB: $C_{\text{eff}}^{\nu_e} \approx -0.2 \times 10^{-8}$



Adding in Ar, Ge and CsI data from COHERENT

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Approximate nuclear dependence of effective charges

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$$C_{\text{eff}}^{\nu e/\mu} = C_V^{\nu e/\mu} \frac{NC_V^n + ZC_V^p}{N - (1 - 4 \sin^2 \theta_W)Z}$$

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by average of effect on C_V^n and C_V^p

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$$C_{\text{eff}}^{\nu e/\mu}(\text{Ar}) = 1.020 C_{\text{eff}}^{\nu e/\mu}(\text{Ge})$$

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$$C_{\text{eff}}^{\nu e/\mu}(\text{CsI}) = 0.953 C_{\text{eff}}^{\nu e/\mu}(\text{Ge}),$$

Conclusions

Systematic scale uncertainties:

$$\sigma_{\text{sys}}^{\text{Ar}} = 0.13 \text{ (Argon),}$$

$$\sigma_{\text{sys}}^{\text{CsI}} = 0.12 \text{ (Caesium Iodine),}$$

$$\sigma_{\text{sys}}^{\text{Ge}} = 0.103 \text{ (Germanium).}$$



χ^2 contours for X_{17}

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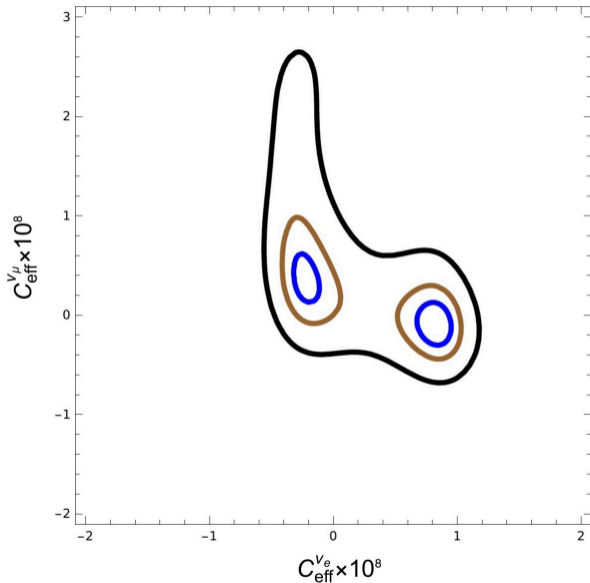
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Conclusions



Brown = SM

Black = SM+6

Blue = SM-2

Two distinct best fit regions

BFA: $C_{\text{eff}}^{\nu_e} = 0.8 \times 10^{-8}$,
 $C_{\text{eff}}^{\nu_\mu} = -0.1 \times 10^{-8}$

BFB: $C_{\text{eff}}^{\nu_e} = -0.2 \times 10^{-8}$,
 $C_{\text{eff}}^{\nu_\mu} = 0.3 \times 10^{-8}$



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Prospects at ESS

- ESS to start running in autumn 2026
- Initially with proton beam energy 840 MeV and 800 kW power
- Designed for 2 GeV and 5 MW



Two scenarios:

- LowFar: 840 MeV, 800 kW for 1 year at 25 meters from spallation target
- HighNear: 2 GeV, 5 MW for 5 years at 15 meters from spallation target

Main systematic uncertainties:

- neutron background, assuming 50 cm plastic shielding
- neutrino flux uncertainty, assuming 10% for LowFar and 2% for HighNear
- quenching factor uncertainty

Assume detector threshold $200 eV_{ee}$ and resolution $\sigma_n = 68.5 eV_{ee}$



Prospects at ESS, cont'd

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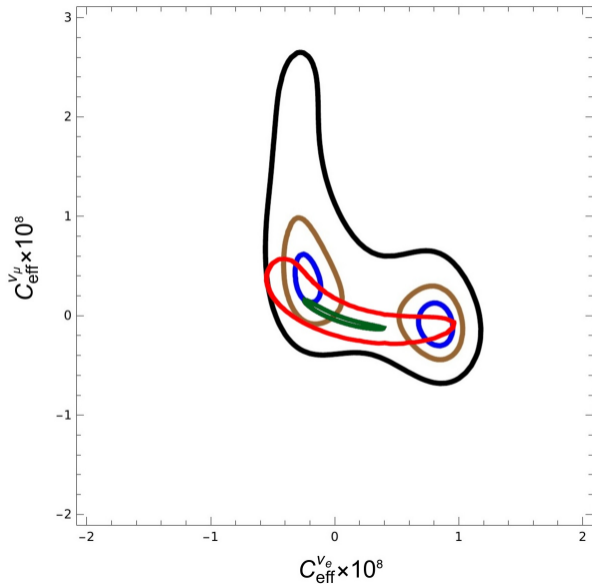
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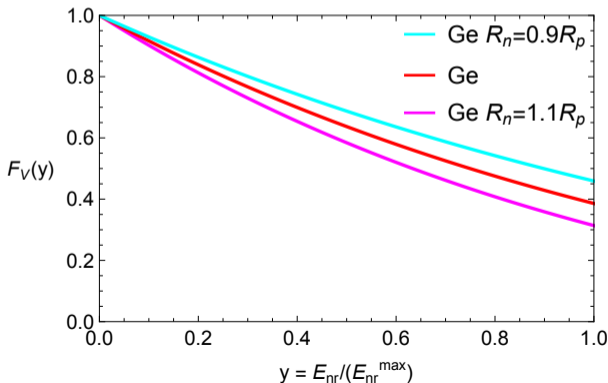
95% CL sensitivities
black: current
red: 1 year at 0.8 MW
green: 5 year at 5 MW



Neutron Skin

- Important for understanding dynamics of neutron stars
- Neutrinos direct probe of distribution of neutrons in nuclei
- Difference in radius of neutron and proton distributions,
 $R_n \neq R_p = 1.2A^{1/3}$ fm

Effects on the KN form factor (assuming only scattering from neutrons)





Recoil spectra

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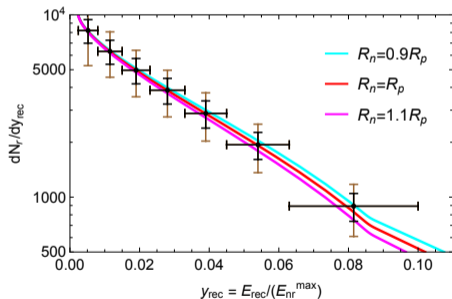
The X $_{17}$

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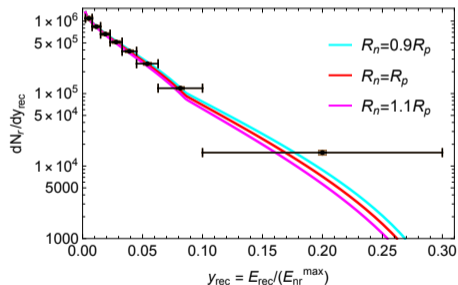
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Predictions for different neutron radii compared to expected experimental data:

- black error bars: statistical uncertainties
- brown error bars: statistical uncertainties + estimated systematics



LowFar - 1 year @ 840 MeV



HighNear - 5 years @ 2 GeV



Ratios of recoil spectra

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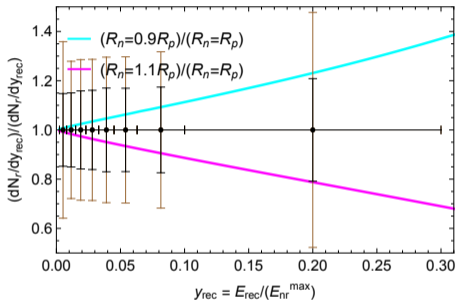
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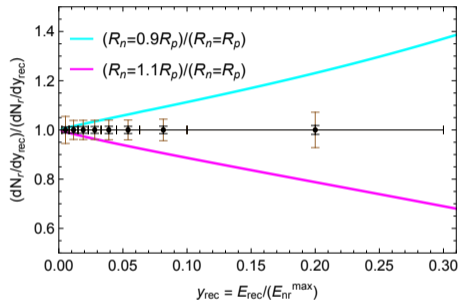
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LowFar - 1 year @ 840 MeV



HighNear - 5 years @ 2 GeV



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Conclusions and outlook

CE ν NS at reactors and spallation sources and X_{17} :

- can search for light Z' such as the X_{17}
- fit to available data prefers an X_{17} compared to the SM, requires flavour non-universality
- minimal model with Z' as the X_{17} can describe all available CE ν NS data

Neutron skin:

- high statistics needed (ESS)
- possible to reach 3-4% uncertainty on R_n/R_p
- need for more precise theory predictions?

Experimental challenges for CE ν NS

- quenching factor at low nuclear recoil energies ($E_{\text{rec}} \approx 200 \text{ eV}_{\text{ee}}$)
- neutron background at spallation sources
- need to measure absolute neutrino flux (uncertainty on r)



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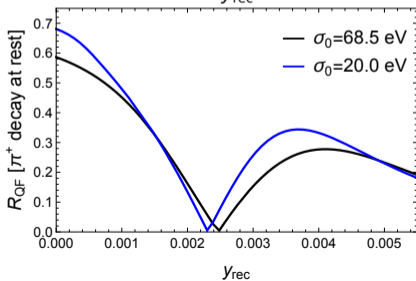
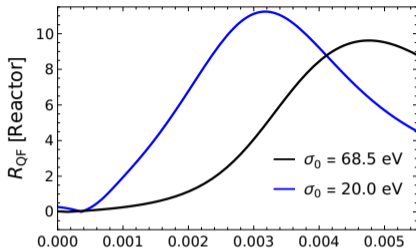
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Backup – quenching factor uncertainty



$$R_{\text{QF}} = \left| \frac{\left. \frac{dN_r}{dy_{\text{rec}}} \right|_{\text{QF2}} - \left. \frac{dN_r}{dy_{\text{rec}}} \right|_{\text{QF1}}}{\left. \frac{dN_r}{dy_{\text{rec}}} \right|_{\text{QF1}}} \right|$$