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Exploiting electron parity violation

From Standard Model tests to dark matter detection predictions

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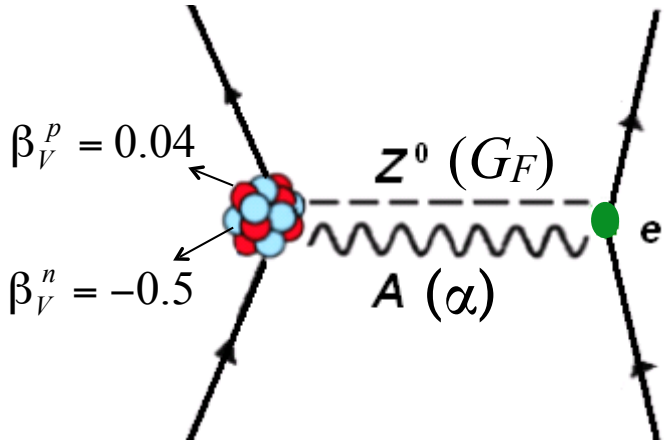
Summary

- Electroweak interactions
- Parity-violating electron scattering
- Coherent neutrino scattering
- Connection between parity-violating electron scattering and coherent neutrino scattering
- WIMP direct detection

Electroweak interactions

Electron scattering



Electromagnetic + Weak neutral

$$\left[\bar{f}\, q^f \gamma^\mu\, f\right] A_\mu$$

Vector

$$\alpha = \frac{g_\gamma^2}{4\pi}$$

~10^{-2}

$$\left[\bar{f}\left(c_V^f\, \gamma^\mu - c_A^f\, \gamma^\mu \gamma^5\right) f\right] Z_\mu^0$$

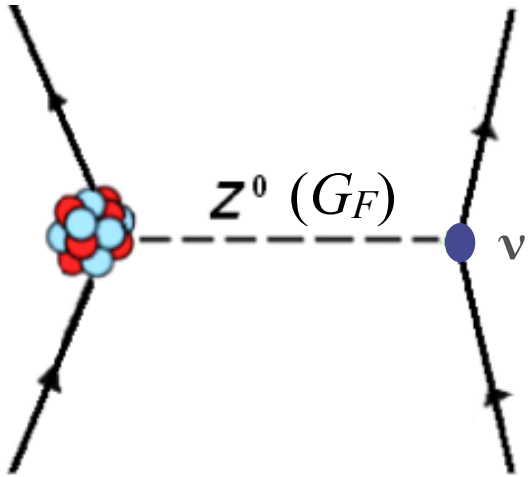
Axial - Vector

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{m_W}\right)^2$$

~10^{-5} GeV^{-2}

Currents ---------- Couplings

Neutrino scattering



Weak neutral

$$\left[\bar{f}\left(c_V^f\, \gamma^\mu - c_A^f\, \gamma^\mu \gamma^5\right) f\right] Z_\mu^0$$

Axial - Vector

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{m_W}\right)^2$$

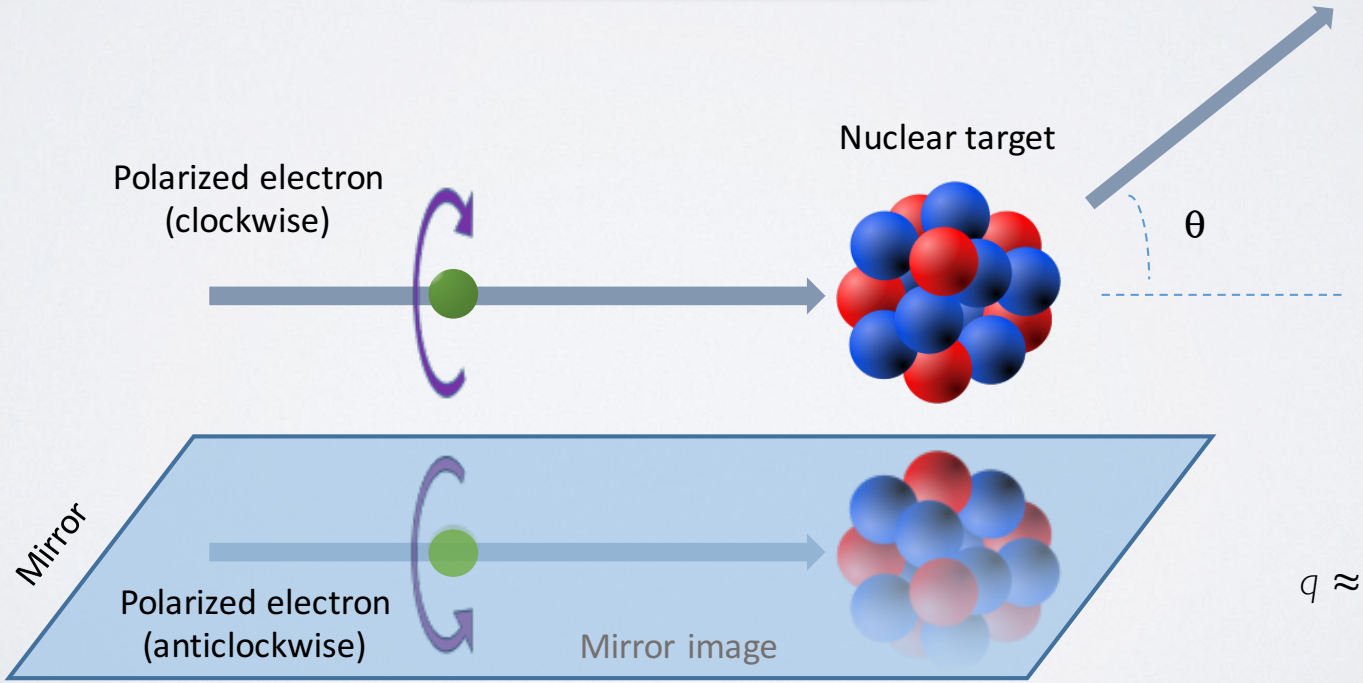
~10^{-5} GeV^{-2}

Parity-violating electron scattering

Definition

Parity-violating (helicity) asymmetry:

$$\mathcal{A} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$



$q \approx 2\,E\,\sin(\theta/2)$

Parity-violating electron scattering

Definition

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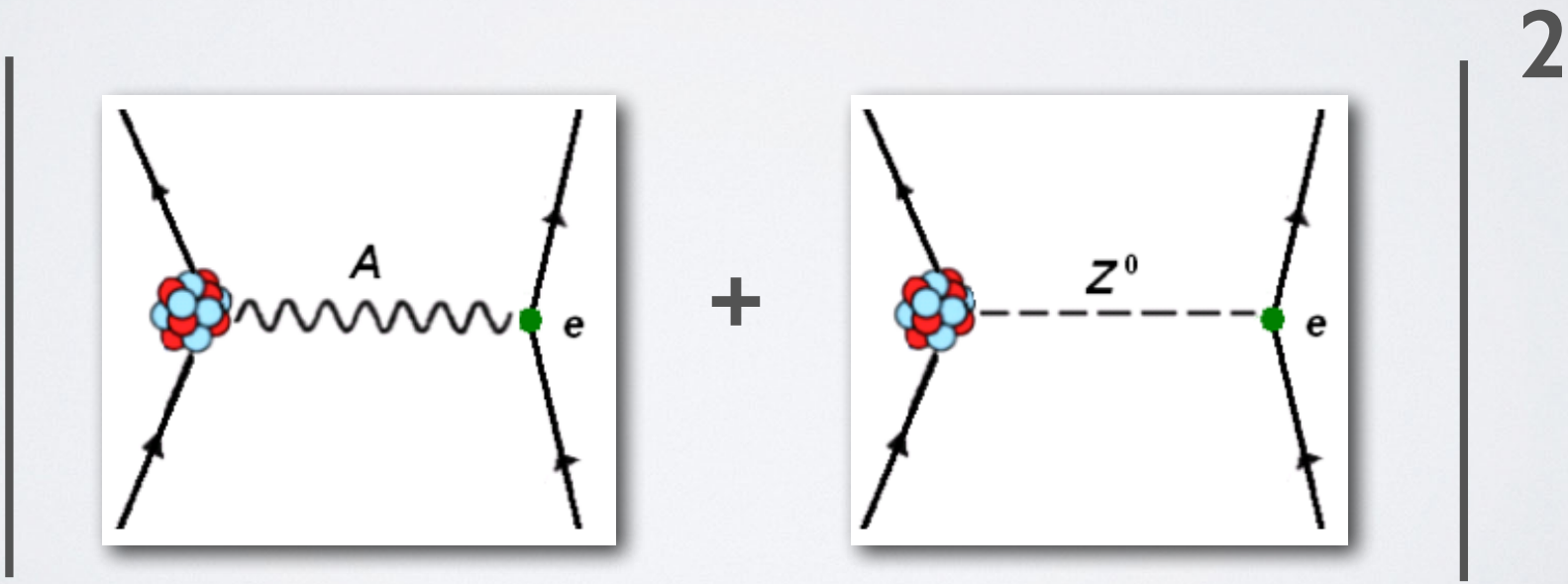
$$\mathcal{A} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$



Parity-violating electron scattering

Definition

Parity-violating (helicity) asymmetry:

$$\mathcal{A} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

Within plane wave Born approximation and for isospin-0 (N = Z), spin-0 targets, the 'reference asymmetry' is:

$$\mathcal{A} = \mathcal{A}^{\mathrm{ref}} \equiv -\frac{G_F}{\sqrt{2}\pi\,\alpha}\,|Q^2|\,a_A^e\,\sin^2\theta_W$$

$\sim 10^{-6}$

Assumptions
- Only one photon and one Z^0 are exchanged.
- Electron wave functions are not distorted by the target charge.
- Target state is spin-0, isospin-0 (non isospin mixing).

Parity-violating electron scattering

Definition

Parity-violating (helicity) asymmetry:

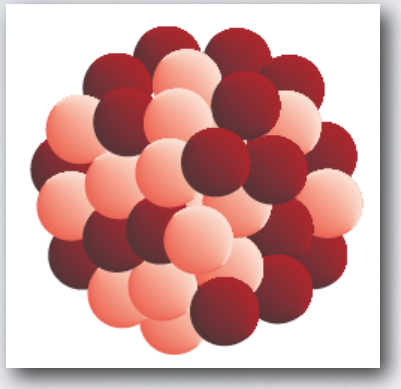
$$\mathcal{A} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

For N $\neq$ Z nuclei:

$$\mathcal{A} \approx -\frac{G_F}{\sqrt{2}\,2\pi\,\alpha}\,|Q^2|\,a_A^e\,\beta_V^n\,\frac{N}{Z}\,\frac{F_n}{F_p}$$

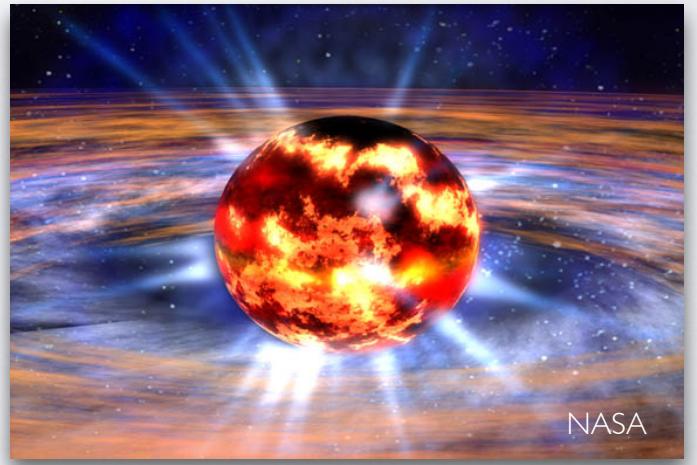
Parity-violating electron scattering

Applications



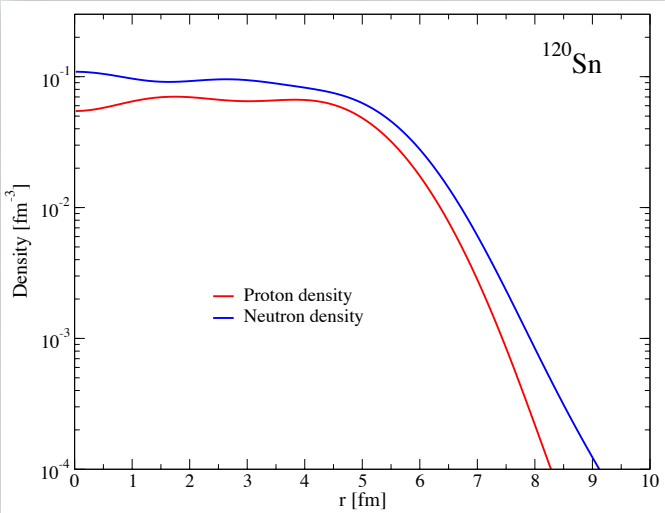
- Determination of the neutron radius and neutron skin of heavy nuclei (PREX, CREX experiments), isospin mixing, neutron-rich matter equation of state, …

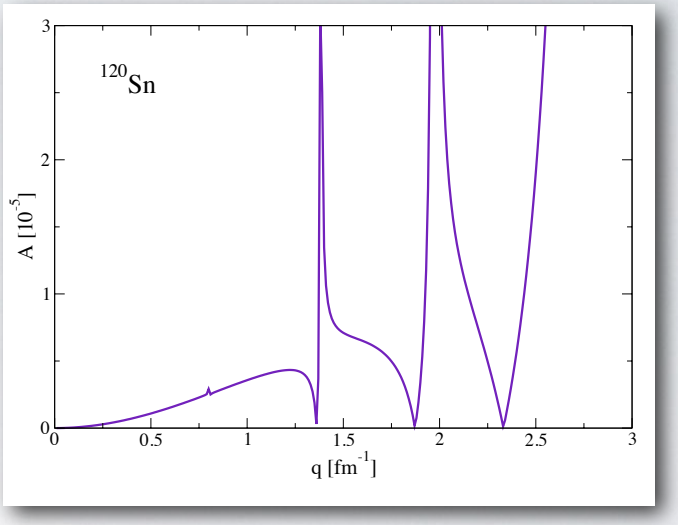
- Extrapolation to properties of neutron stars: radius, transition density, size of crust, …



Parity-violating electron scattering

Applications

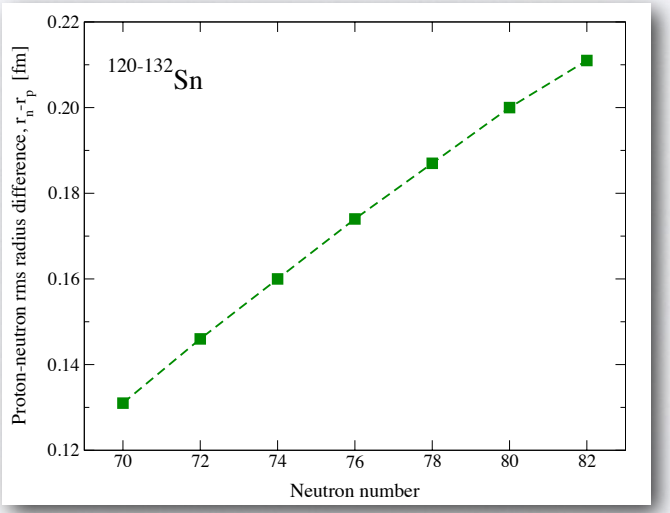




Nucleon densities ⟷ (Form factors) ⟷ PV asymmetry

Neutron skin thickness

$r_n - r_p$

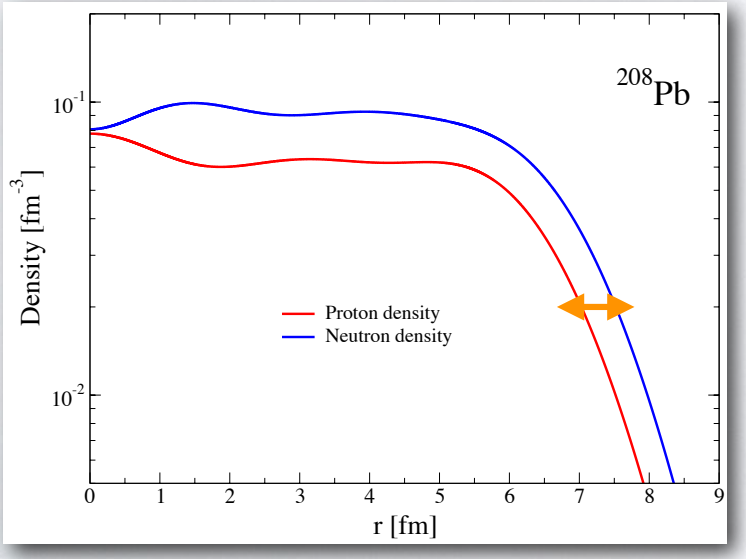


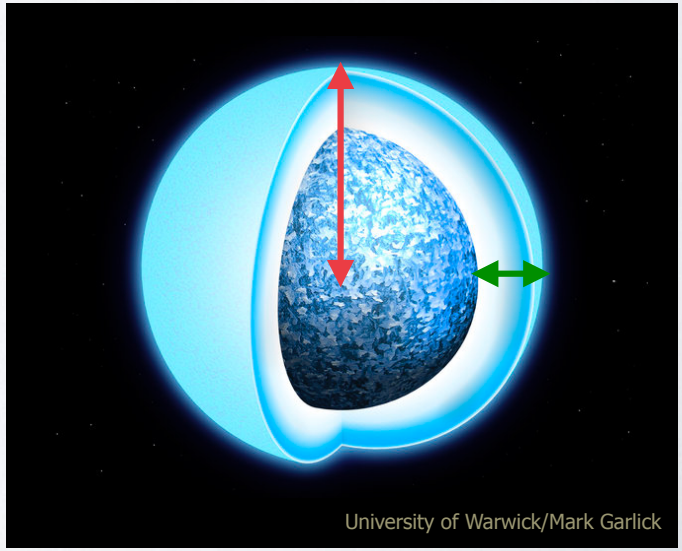
Parity-violating electron scattering

Applications

Possible relationship between nuclear structure and neutron star structure through the equation of state of neutron-rich matter:

- The larger the **neutron skin thickness** of nuclei, the larger the **radius** of neutron stars.
- The larger the **neutron skin thickness** of nuclei, the smaller the **crust thickness** of neutron stars.





Parity-violating electron scattering

Applications

- Accurate evaluation of the weak mixing angle, the size and momentum-dependence of higher-order electroweak radiative corrections, …

Related to the current interest in low-energy, high-luminosity polarized electron beams for high precision parity-violating experiments: MESA@Mainz, FEL@JLab, Cβ@Cornell.

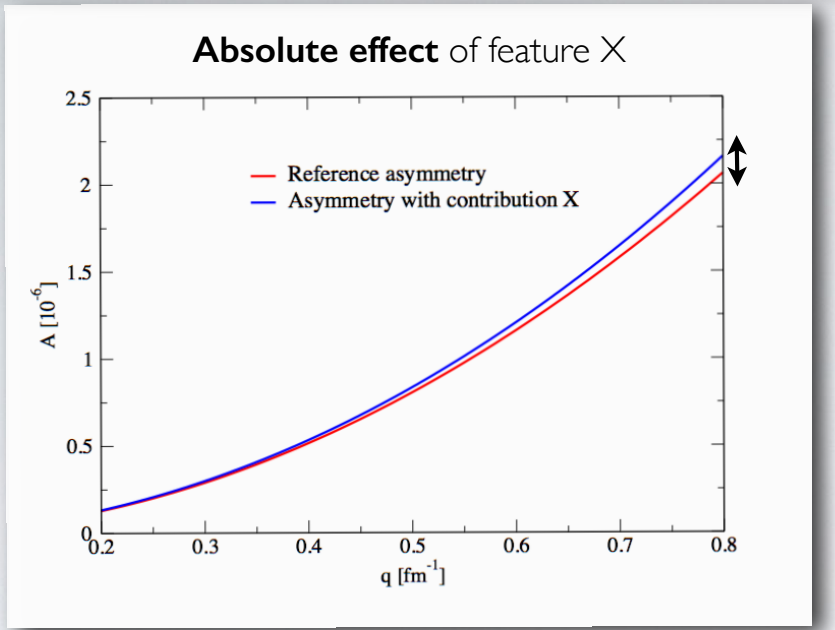
Accurate theoretical knowledge is required of the size and uncertainty of the nuclear and nucleon structure effects involved.

Parity-violating electron scattering

Analysis

- Computation of nuclear and nucleon structure effects on the parity-violating observables in electron scattering. Focus on a carbon 12 target (spin 0, N = Z).
- Estimation of the theoretical uncertainties related to the previous calculations.
- Search for the optimal kinematic conditions to achieve the required theoretical and statistical uncertainties.

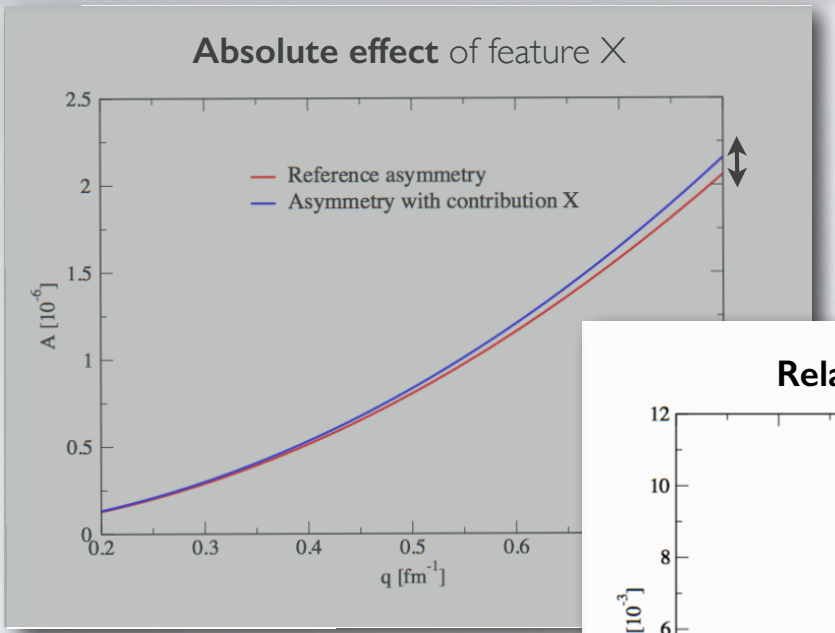
Parity-violating electron scattering

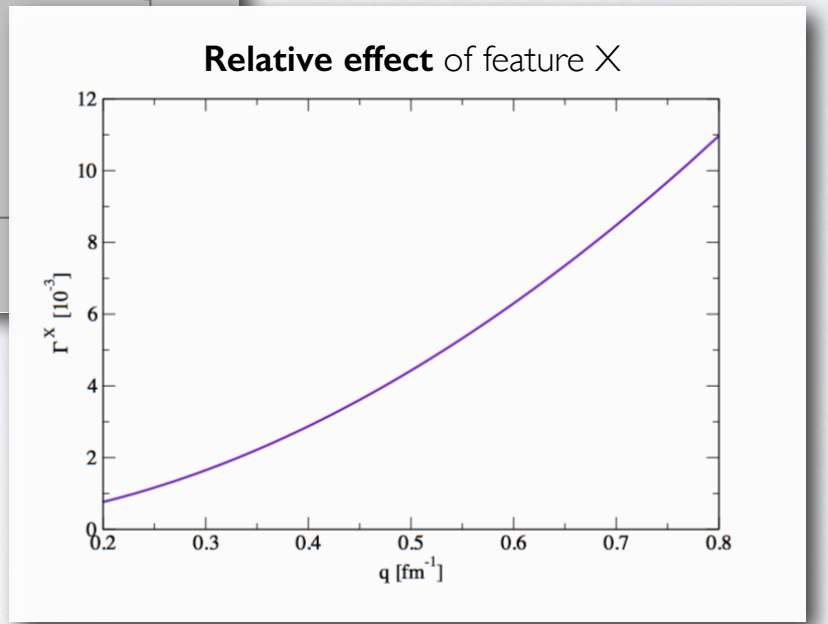


Analysis

Parity-violating electron scattering

Analysis

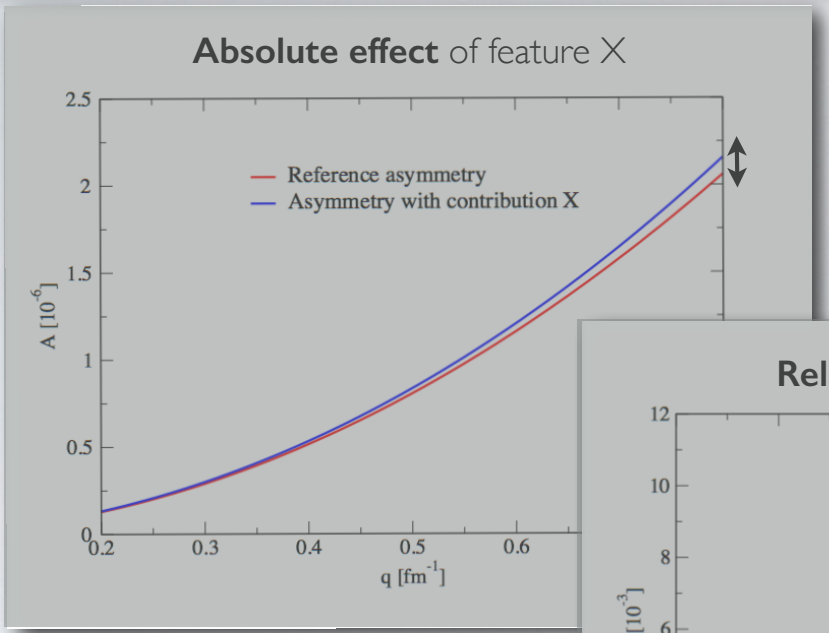


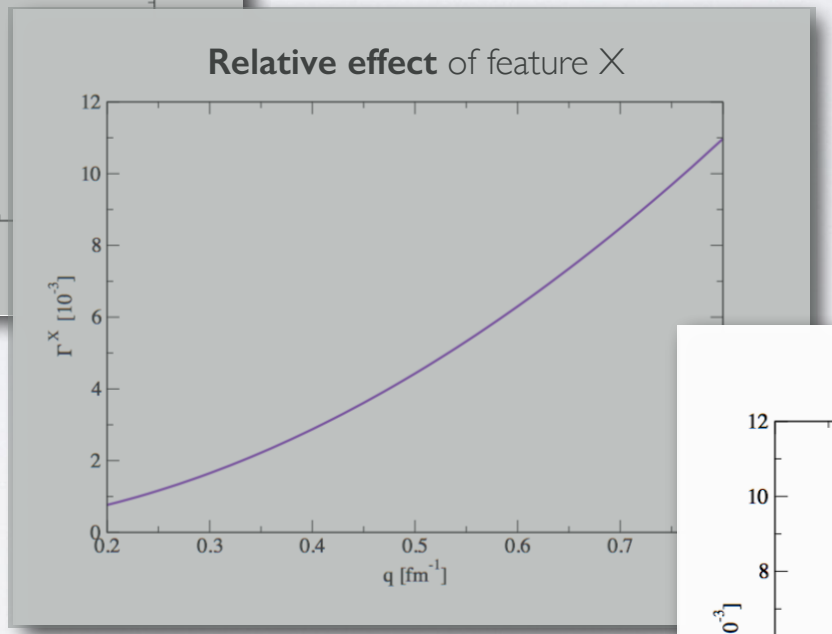


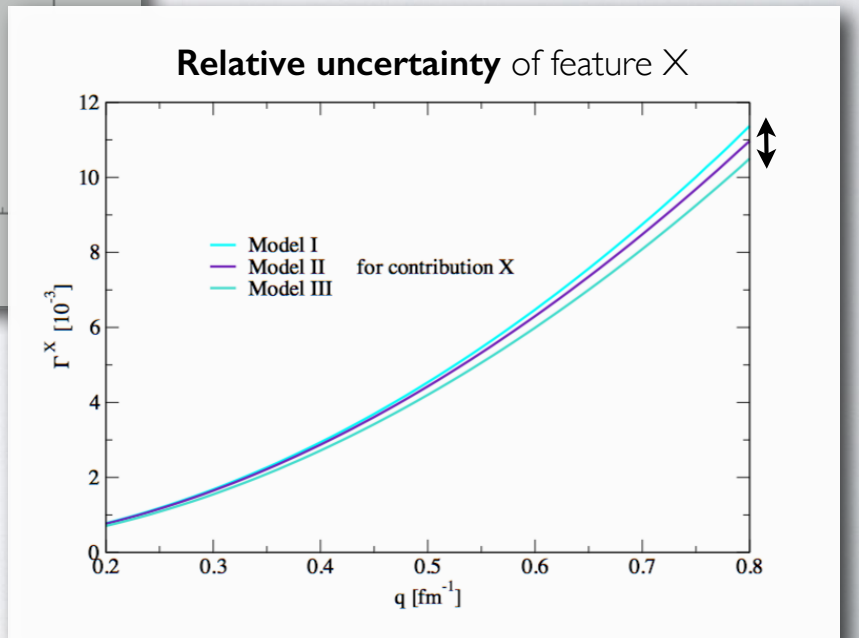
$$\Gamma^X = \frac{A^X - A^{\mathrm{ref}}}{A^{\mathrm{ref}}}$$

Parity-violating electron scattering

Analysis







$$\Gamma^X = \frac{A^X - A^{\mathrm{ref}}}{A^{\mathrm{ref}}}$$

$$\Delta\Gamma^X = \Gamma^{X_a} - \Gamma^{X_b} = \frac{A^{X_a} - A^{X_b}}{A^0} = \frac{\Delta A^X}{A^0}$$

Parity-violating electron scattering

Analysis

- Distortion of the electron wave function due to the Coulomb field created by the nuclear charge distribution: from plane-wave (PW) to distorted-wave (DW) calculations.
- Isospin mixing in the nucleus due to the Coulomb interaction acting differently on protons and neutrons.
- Strangeness content of the nucleons modifying the isoscalar (but not the isovector) nuclear responses.
- Meson exchange currents among the nucleons affecting differently the isoscalar and the isovector nuclear responses.
- Inelastic transitions to excited nuclear states differing significantly from the ground state (e.g. different nominal isospin).

Parity-violating electron scattering

Analysis

Summary of sizes and uncertainties

(150 MeV incident electron energy, 25º - 45º scattering angle range)

Contribution to PV asymmetry	Relative size	Relative uncertainty
Coulomb distortion of projectile wave function	3 %	0.01 %
Nuclear isospin mixing (electromagnetic origin)	0.4 %	0.05 %
Nucleon strangeness content (mainly electric)	0 - 1 %	1%
Meson exchange currents	< 0.1 %	< 0.1 %
Inelastic contributions	< 0.1 %	--

Coherent neutrino scattering

Definition

- Weak neutral current process, neutrino in and neutrino out: only nuclear recoil can be detected.
- The target nucleus remains in its ground state (elastic scattering).
- The cross section is roughly proportional to A^2.
- Larger when the wavelength corresponding to the momentum transfer is similar to the nuclear size ($q \lesssim 70$ MeV for ^{12}C).
- It is the only elastic contribution for even-even nuclear targets, and usually dominant for other targets.

$$\left(\frac{d\sigma}{d\Omega}\right)^{ref}_{(\nu,\nu)} = \frac{G_F^2}{2\pi^2}\left[(a_A^\nu)^2 + (a_V^\nu)^2\right]\varepsilon_\nu'^2\cos^2(\theta_\nu/2)\, f_{rec}^{-1} A^2 \sin^4\theta_W$$

(ERL, $q \to 0$)

Coherent neutrino scattering

Applications

- Determination of electroweak constants at low momentum transfer as well as higher-order corrections.
- Testing the universality of the weak interaction for charged and neutral leptons.
- Analysis of structure details of the target (*e.g.* axial structure).
- Astrophysical processes (*e.g.* stellar core collapse, supernova neutrinos).
- Extension to direct detection of certain types of dark matter particles.

Parity violating electron and coherent neutrino scatterings

- Relationship between coherent electron-nucleus and coherent neutrino-nucleus cross-sections in PWBA:

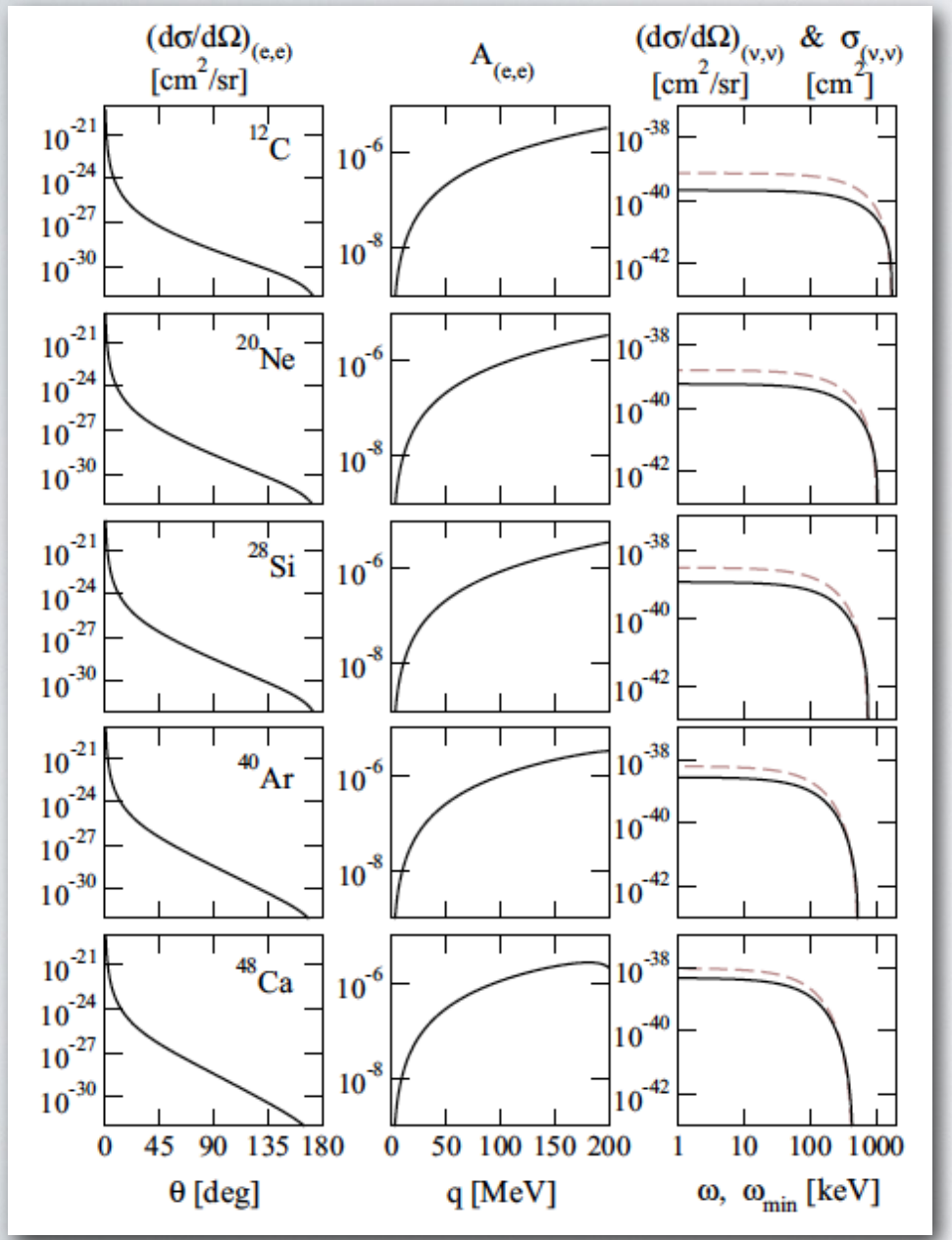
$$\left(\frac{d\sigma}{d\Omega}\right)_{(\nu,\nu)} = \mathcal{A}^2_{(e,e)}\left(\frac{d\sigma}{d\Omega}\right)_{(e,e)}$$

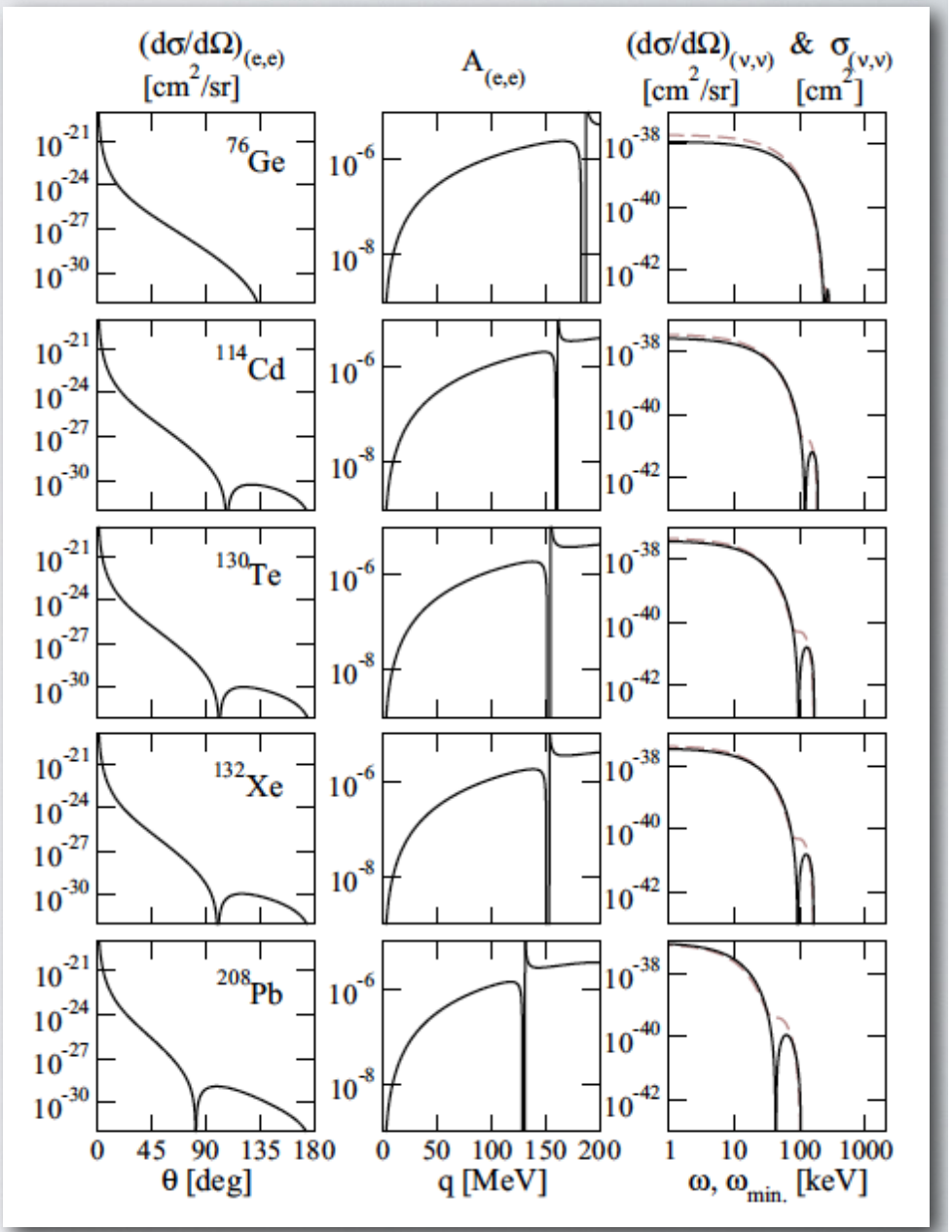
Deviations from this prediction
- Coulomb distortion.
- Effect of higher order corrections.
- Non-SM couplings of neutrinos to Z^0.

- Relationship between their relative uncertainties:

$$\mathcal{E}_{\left(\frac{d\sigma}{d\Omega}\right)_{(\nu,\nu)}} \approx 2\,\mathcal{E}_{\mathcal{A}_{(e,e)}}$$

Parity violating electron and coherent neutrino scatterings





WI(M)P direct detection

WI(M)Ps: Weak interacting (massive) particles

- Weak-like interactions (like neutrinos): the current has vector and axial components.
- May have much heavier masses than Standard Model neutrinos.
- Examples: supersymmetric particles (neutralinos), **sterile neutrinos**.

Flavor eigenstates

Mass eigenstates

$$|\nu_a\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_b\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

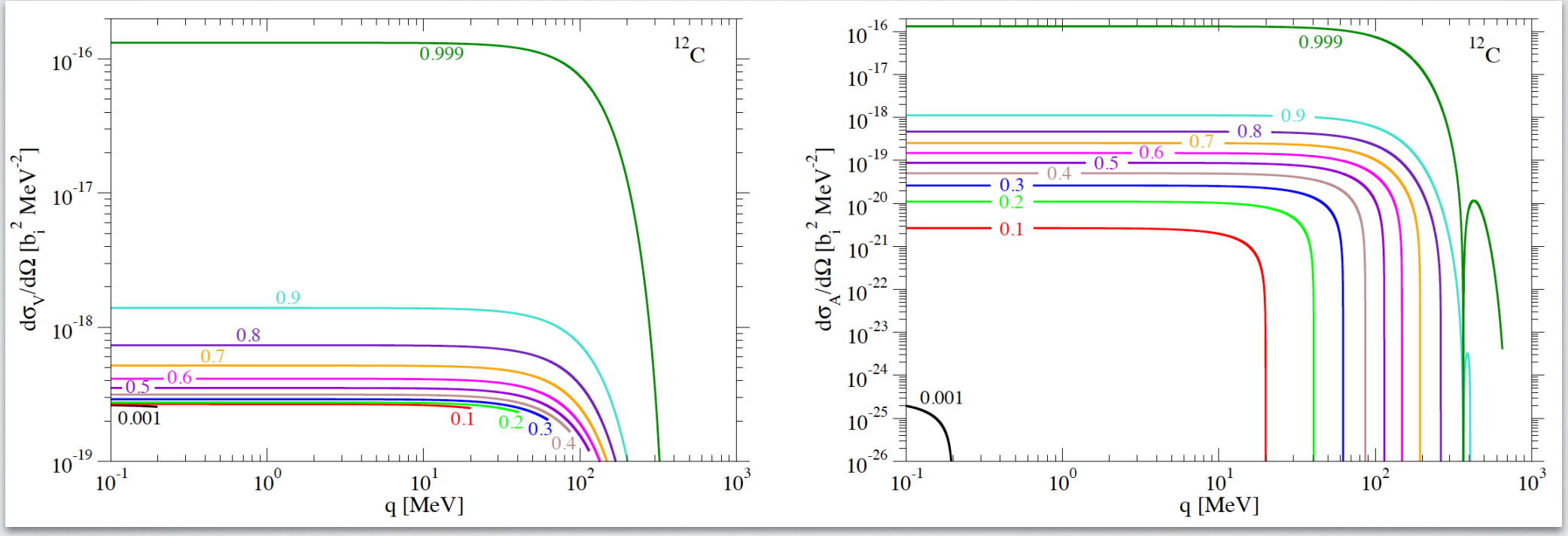
$$|\nu_1\rangle\,,\ |\nu_2\rangle\,,\ |\nu_3\rangle\,,\ |\nu_4\rangle$$

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix},\ \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix},\ \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix},\ \begin{pmatrix}\nu_s\\ -\end{pmatrix}$$

Standard Model | ?

WI(M)P direct detection

WIMP - ^{12}C elastic scattering differential cross sections as a function of momentum transfer q (proportional to nuclear recoil energy), for several WIMP velocities **β** and WIMP mass 100 MeV.



Vector component

Axial component

Conclusions

Parity violation in electron scattering

- Nuclear structure: radius, neutron skin, isospin mixing
  - Nuclear matter equation of state, neutron star radius and structure
- Nucleon structure: form factors, strangeness content
- Standard Model tests and parameters
- Neutrino-nucleus coherent scattering
  - WI(M)P direct detection

References:

PRC 89 (2014) 015501, JPG 42 (2015) 034006, NPA 828 (2009) 306, JPG 37 (2010) 064019, PRC 92 (2015) 055504, NPB 866 (2013) 177 , AIPCP 1541 (2013) 167, arXiv:1603.05932v1