MITP, 27/06/2017 Blackboard talk & projected slides (EF)

Mainz Institute for Theoretical Physics

Isotope shift constraints on NP models
- light bosons coupling to e and n -

* 1704.05068 Method of isotope shifts for $y_e y_n$ (m_ϕ)

Berengut, Budker, Delaunay, Flambaum, Frugiuele, EF, Grojean, Harnik, Ozeri, Perez, Soreq

11 authors:
- 2 experimentalists, 9 theorists
- 4 atomic, 7 particle (mainly)
- 4 countries
- 8 institutes
- 5 present in the talk

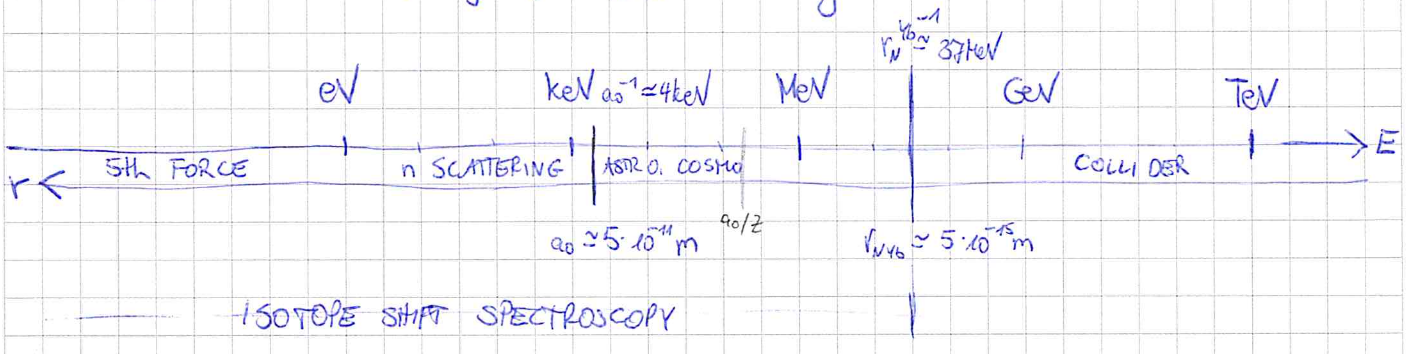
* 1602.04822 (v2) Generalisation of method and application to BSM models

Frugiuele, EF, Perez, Schlaffer

I Introduction

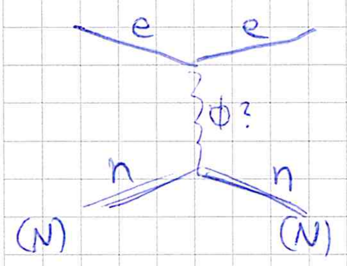
"The TeV scale: a threshold to NP ②" [MITP '17]

↪ NP can also be light → search broadly



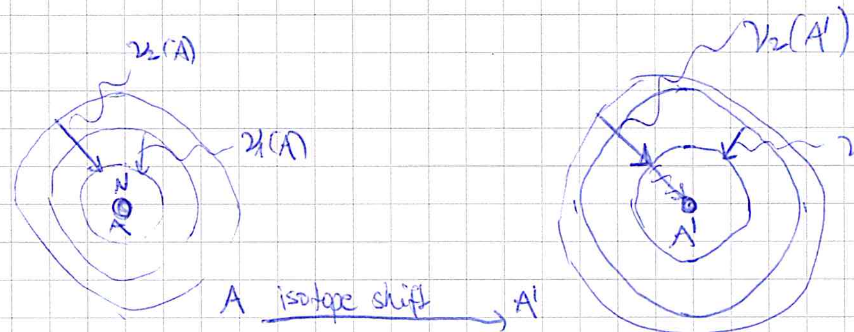
precision: narrow optical clock ⟷ energy

rel. 10^{-18} precision



- new scalar vector coupling to e, n changes energy levels
- but absolute frequencies difficult to measure precisely enough
  ↑ also theory less precise

$\Rightarrow$ difference: isotope shift



II King Linearity

$$\nu_i^{AA'} = \nu_i^{A} - \nu_i^{A'} = \underbrace{K_i\, \mu_{AA'}}_{\text{MS}} + \underbrace{F_i}_{\text{electronic}}\, \underbrace{\delta\langle r^2\rangle_{AA'}}_{\text{FS, nuclear}} + \dots$$

LO factorisation

- 2 transitions $\Rightarrow$ replace uncertain $\delta\langle r^2\rangle_{AA'}$

$\Rightarrow$ King relation $\quad m\nu_2^{AA'} = K_{21} + F_{21}\, m\nu_1^{AA'}$

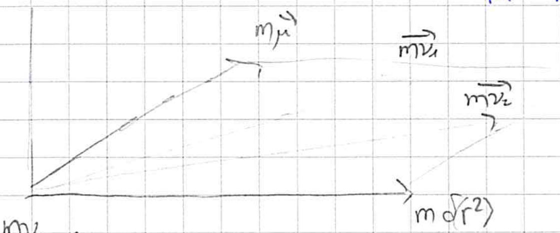
$m\nu_2^{AA'} = \nu_2^{AA'}/\mu^{AA'}$, $\quad \mu^{AA'} = \frac{1}{m_A} - \frac{1}{m_{A'}}$ reduced mass

$K_{21} = K_2 - F_{21} K_1$, $\quad F_{21} = F_2/F_1$

- 3 isotope pairs $\Rightarrow$ vectors of measured frequency shifts:

$$\overrightarrow{m\nu_i} = (m\nu_i^{AA_1}, m\nu_i^{AA_2}, m\nu_i^{AA_3})$$

$$= K_i\, \overrightarrow{m\mu} + F_i\, \overrightarrow{m\delta\langle r^2\rangle_A}$$

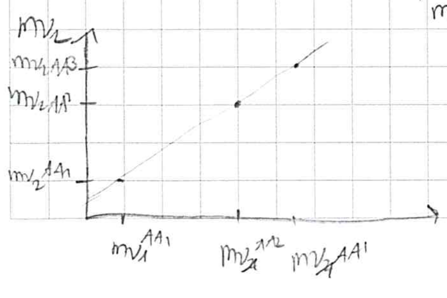


- if measured data lies in plane spanned by FS, MS

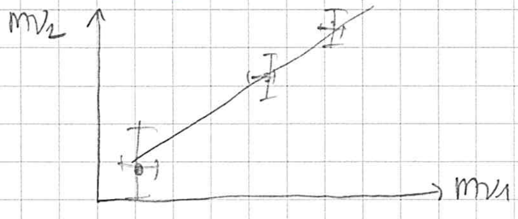
$\Rightarrow$ pairs $(m\nu_1^{AA'}, m\nu_2^{AA'})$ on straight line

$\Rightarrow$ King linearity (data-driven test of LO fact.)

$\Leftrightarrow$ $NL = (\overrightarrow{m\nu_1} \times \overrightarrow{m\nu_2}) \cdot \overrightarrow{m\mu} = 0$



- in reality: linear within 2D-error bars



- current data set: Ca^+ with $\sigma_\nu \simeq 100$ kHz

III NP contribution to NL

$$\vec{m\nu_i} = K_i \vec{m_\mu} + F_i \vec{m\delta\langle r^2\rangle} + y_e y_n X_i \vec{h}$$

$y_e y_n$ ↑ NP coupling; X_i ↑ NP electronic; $\vec{h}$ ← NP isotope dependence — also factorized!

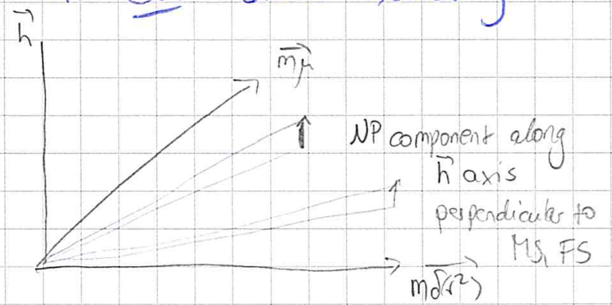
mod. King relation

$$\Rightarrow \vec{m\nu_2} = K_{21}\vec{m_\mu} + F_{21}\vec{m\nu_1} + y_e y_n \vec{h}\,(X_2 - X_1 F_{21})$$

$\Rightarrow$ NP can break linearity: $NL_{NP} = [\vec{m_\mu} \times (X_2 \vec{m\nu_1} - X_1 \vec{m\nu_2})] \cdot \vec{h}$

↑ $\vec{m\nu_2} = F_{21}\vec{m\nu_1} + \text{const}\,\vec{m_\mu}$, $\vec{m_\mu} \times \vec{m_\mu} = 0$

$$= [\vec{m_\mu} \times (X_2 - F_{21}X_1)\,\vec{m\nu_1}] \cdot \vec{h}$$



$\Rightarrow NP_{NL}$ vanishes if

(i) $\frac{X_2}{X_1} = \frac{F_2}{F_1}$ $\hat{=}$ case of heavy NP: $X_i \propto F_i$ short-range

$\Rightarrow$ NP indistinguishable from FS ↯ is not applicable

(ii) $\vec{h} \parallel \vec{m_\mu}$ or $\vec{h} \parallel \vec{m\delta\langle r^2\rangle}$ $\Rightarrow$ NP reabsorbed in K_{21} or F_{21}

general: if $\vec{h} \parallel$ lin. comb. of $\vec{m\nu_1}, \vec{m\nu_2}, \vec{m_\mu}$

- nuclear dependence: consider linear $h_{AA'} = (A-A')/\mu_{AA'}$ $\neq$ AA' amu
- electronic dependence: $V_{NP}(m_\phi, r) = \frac{y_e y_n}{4\pi r}(A-Z)\, e^{-m_\phi r}$ (Yukawa)

→ massless limit: $m_\phi \ll (1+n_e)/a_0$ $\Rightarrow V_{NP} \sim \frac{1}{r}$ (Coulomb)

→ heavy limit: $m_\phi \gtrsim r_N^{-1}$; $\frac{\delta(r)}{(m_\phi r)^2} \Rightarrow X_2 - F_{21}X_1 \to 0$ (dilution!)

coefficient $X_i = \frac{4\pi}{A-Z} \frac{d\,\varepsilon_{ab}}{d(y_e y_n)}\Big|_{y_e y_n = 0} \overset{\text{perturb.}}{\simeq} 4\pi \int d^3r\, \frac{e^{-m_\phi r}}{r} \left(|\psi_b(r)|^2 - |\psi_a(r)|^2 \right)$ for $i: a \to b$

CAVEAT

- if NL observed ⇒ no unambiguous sign of NP ! but 1 or several systems ?
- also SM can induce NL (at higher order) [analogy LHC: NP or N^nLO QCD?]
  - higher-order: FS, near-level mixing
  - nucl. polarizability
  - many-body effects
- strategy: NP ≤ observed NL (conservative)
- if NL_{SM} precisely calculated: $|NP| \leq |\text{observed NL} - \text{calculated SM NL}|$

  ⇝ more theory input needed

Setting bounds

- solve system of equations for 2 transitions, 3 isotope pairs

  $$\overrightarrow{m\delta\nu_2}^{th} = K_{21}\,\vec{m\mu} + F_{21}\,\overrightarrow{m\delta\nu_1}^{exp} + y_e y_n X_{21}\,\vec{h} \stackrel{!}{=} \overrightarrow{m\delta\nu_2}^{exp}$$

  each vector: 3 entries → 3 equations

  $K_{21}, F_{21}, X_{21}, y_e y_n$ ⇒ 4 electronic / NP unknowns

  ↓ calculate X_{21}

  ⇒ solve for 3 unknowns $K_{21}, F_{21}, y_e y_n$

$$y_e y_n = \frac{(\vec{m\nu_1} \times \vec{m\nu_2})\cdot\vec{m\mu}}{(\vec{m\mu}\times(X_2\,\vec{m\nu_1} - X_1\,\vec{m\nu_2}))\cdot\vec{h}}$$

- non-minimal input (> 2 transitions or > 3 pairs) → overconstrained

⇒ perform fit including 2D errors, χ^2, marginalize over $\vec{K}, \vec{F}$ ⇒ $y_e y_n$ interval

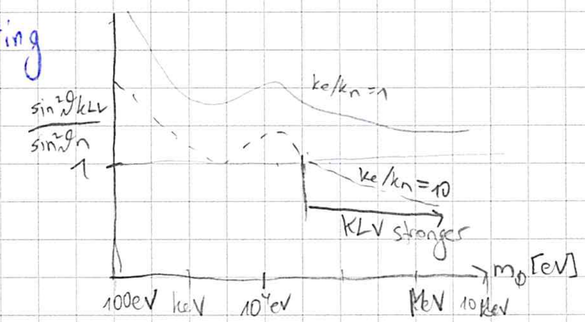
↪ available: 3 transitions Ca^+, 4 isotope pairs Kb

IV Models

1) Z'_{B-L} : $(B-L)(n) = 1$, $(B-L)(e) = -1$ $\Rightarrow$ not suppressed

2) Higgs portal: mixing $\vartheta_{h\phi}$ for n, e
- n scattering stronger bound
- if y_e more strongly enhanced than y_n (e.g. leptonic H portal, Giudice-Lebedev)

$\Rightarrow$ KLV can become stronger than n scattering



3) Chameleon: ϕ Scalar, m_ϕ increases with density ρ

$V_{eff}(\phi) = V(\phi) \mp \phi\rho/M$, (M scale)

$\delta H\big|_n = -\frac{m_e m_N}{4\pi r M^2} \overset{Yb^+ 1Hz}{\Rightarrow} M \gtrsim 500\,\text{TeV}$ in $m_\phi = 0$ (better than existing H, He)

4) $^8Be^*(1^+) \to {}^8Be(0^+)e^+e^-$, 6.8σ anomaly, $m_\phi = 17\,\text{MeV}$? real?

↳ Yb^+ 1Hz will probe y_e-y_n region required to explain excess

V Summary

- novel method to constrain light ($0 \leq m_\phi \lesssim \mathcal{O}(10)$ MeV) bosons, $y_e y_n$
- linearity measure: data driven
- possibility to include more data points in fit
- exp. prospect: 100 kHz → 1 Hz, Ca^+, Sr/Sr^+, Yb^+, Dy, Ba^+, more isotopes e.g. $^{46}Ca^+$
- theory input needed: SM NL, BSM electronic coefficients
- if NL observed ⇒ complementary approaches like Rydberg
- interesting BSM model applications

Isotope shifts as probes of New Physics models

Elina Fuchs
Weizmann Institute

Constraining BSM interactions via isotope shifts [1704.05068]
Julian Berengut, Dimitry Budker, Cédric Delaunay, Victor Flambaum, Claudia Frugiuele, EF, Christophe Grojean, Roni Harnik, Roee Ozeri, Gilad Perez and Yotam Soreq

Application to BSM models [1602.04822], to appear in PRD
Claudia Frugiuele, EF, Gilad Perez and Matthias Schlaffer

Mainz MITP Workshop
June 27, 2017

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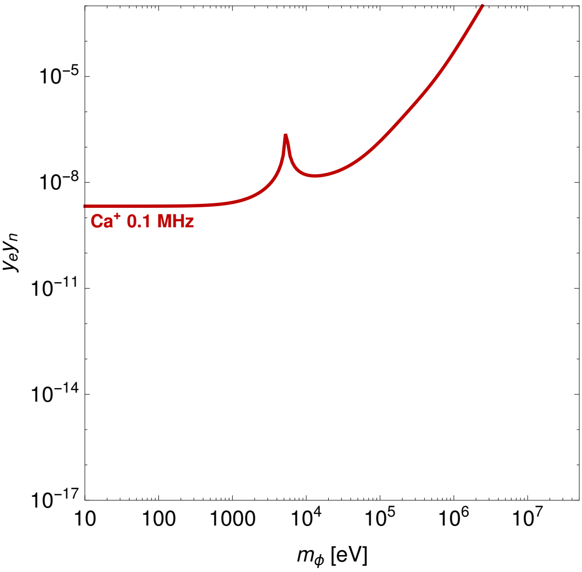
Constraints on $y_e y_n$



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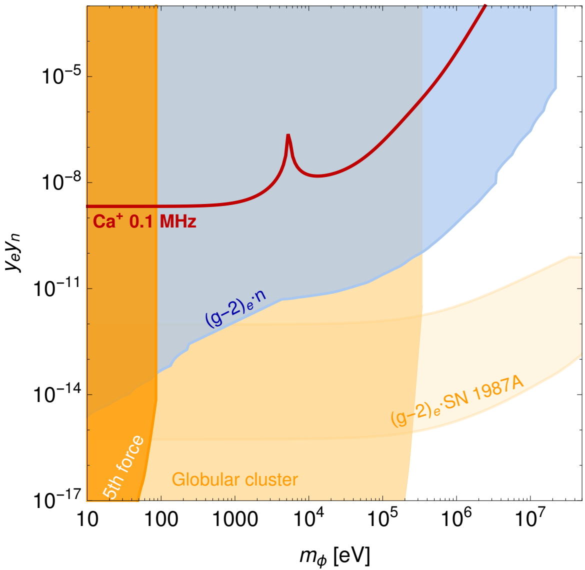

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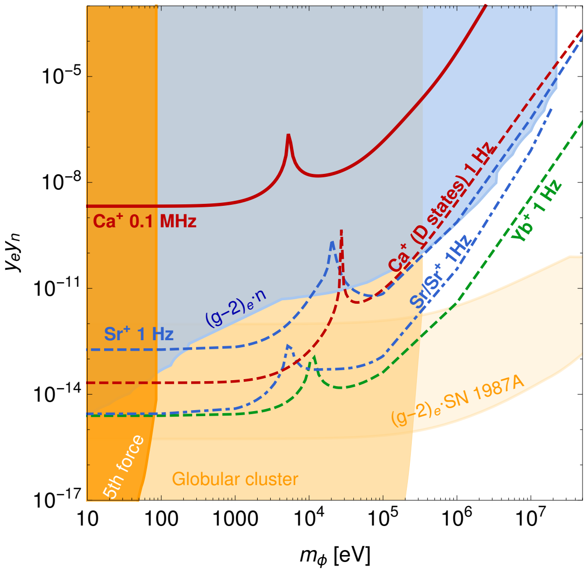

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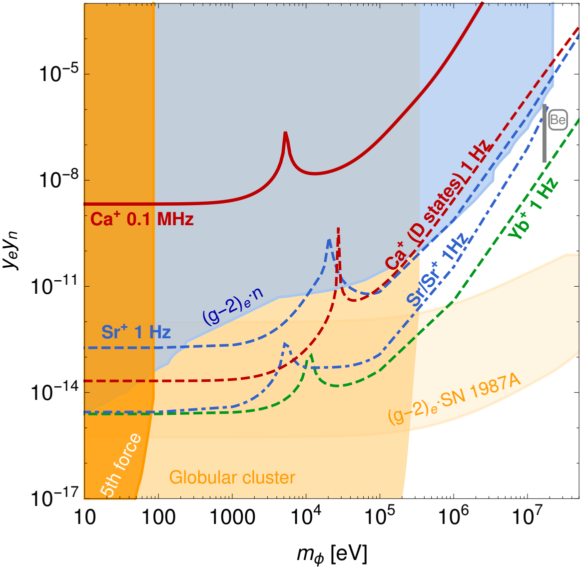
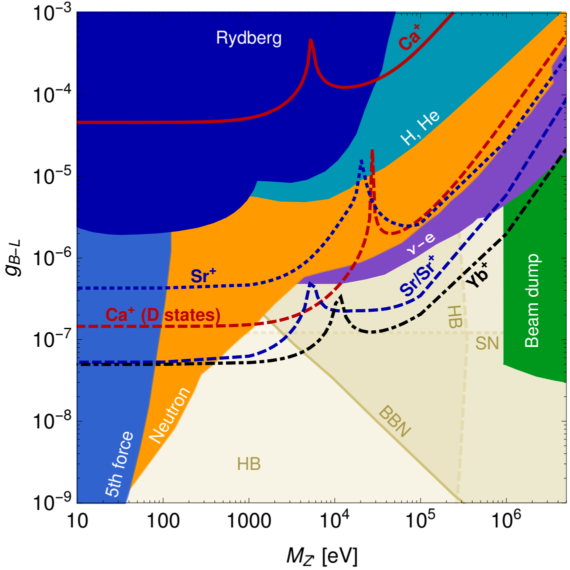
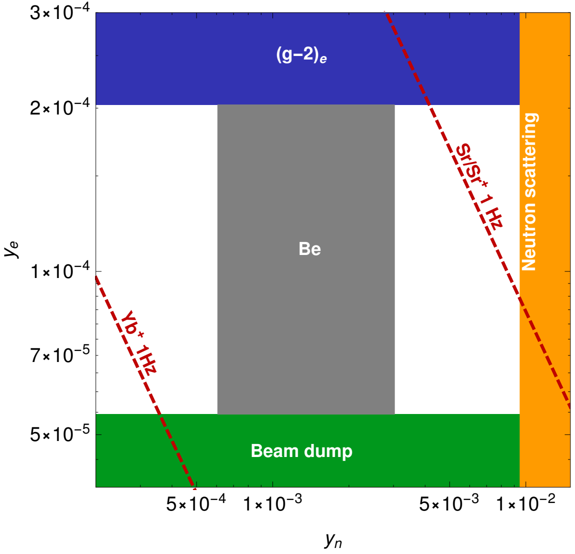


Constraining a Z' of $U(1)_{B-L}$



^{8}Be (17 MeV) anomaly



^{8}Be measurement:

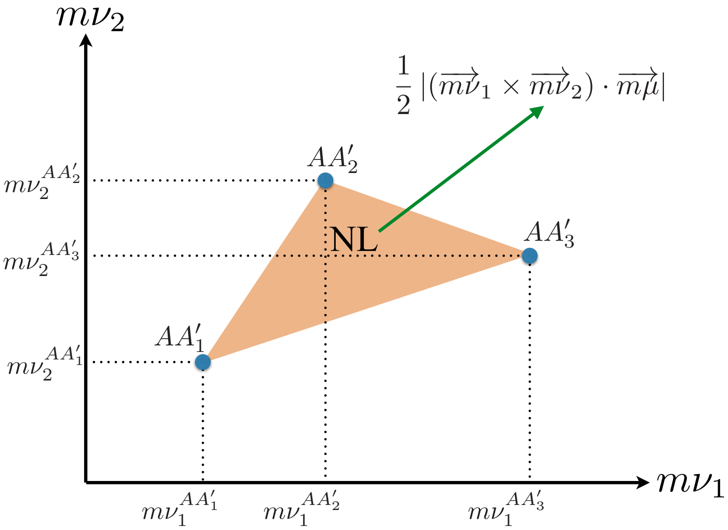
Krasznahorkay et al '15

Protophobic interpretation:

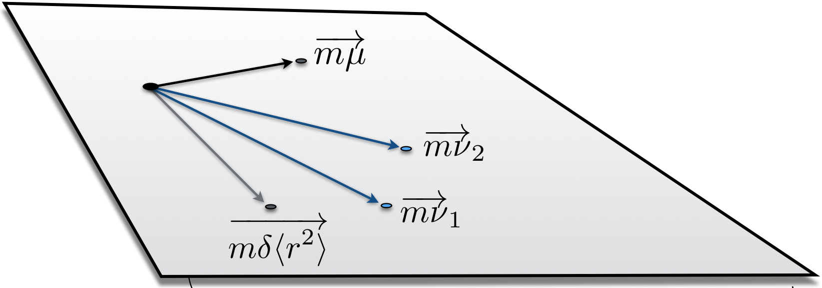
Feng et al '16 '16

APPENDIX

Nonlinearity volume or area

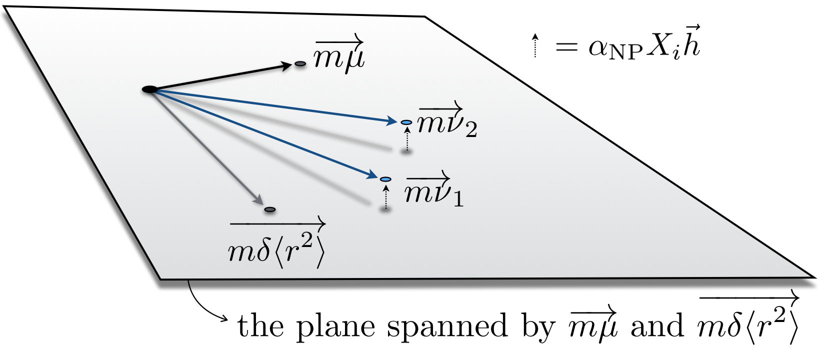


NP orthogonal to linearity plane

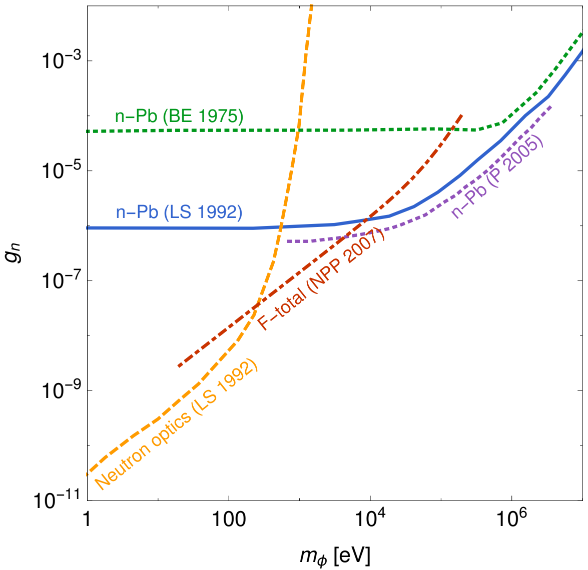


the plane spanned by $\overrightarrow{m\mu}$ and $\overrightarrow{m\delta\langle r^2\rangle}$

NP orthogonal to linearity plane



Bounds on g_n



n–Pb (BE 1975)
n–Pb (LS 1992)
n–Pb (P 2005)
F–total (NPP 2007)
Neutron optics (LS 1992)
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
g_n
1
100
10^4
10^6
m_ϕ [eV]

Higgs portal, enhanced y_e: n scattering vs. KLV