Probing New Light Force-Mediators by Isotope Shift

Yotam Soreq

Table-Top Experiments with Skyscraper Reach
Aug. 11, 2017

C. Delaunay, C. Frugiuele, E. Fuchs, YS - work in progress
J.C. Berengut, D. Budker, C. Delaunay, V.V. Flambaum, C. Frugiuele, E. Fuchs, C. Grojean, R. Harnik, R. Ozeri, G. Perez, YS - 1704.06005
C. Delaunay, R. Ozeri, G. Perez, YS 1601.05087

the Standard Model (SM) works great but it is **not** a complete picture

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New Physics (NP) is required but its scale is unknown

The Quest for New Physics

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energy frontier
(TeV scale)

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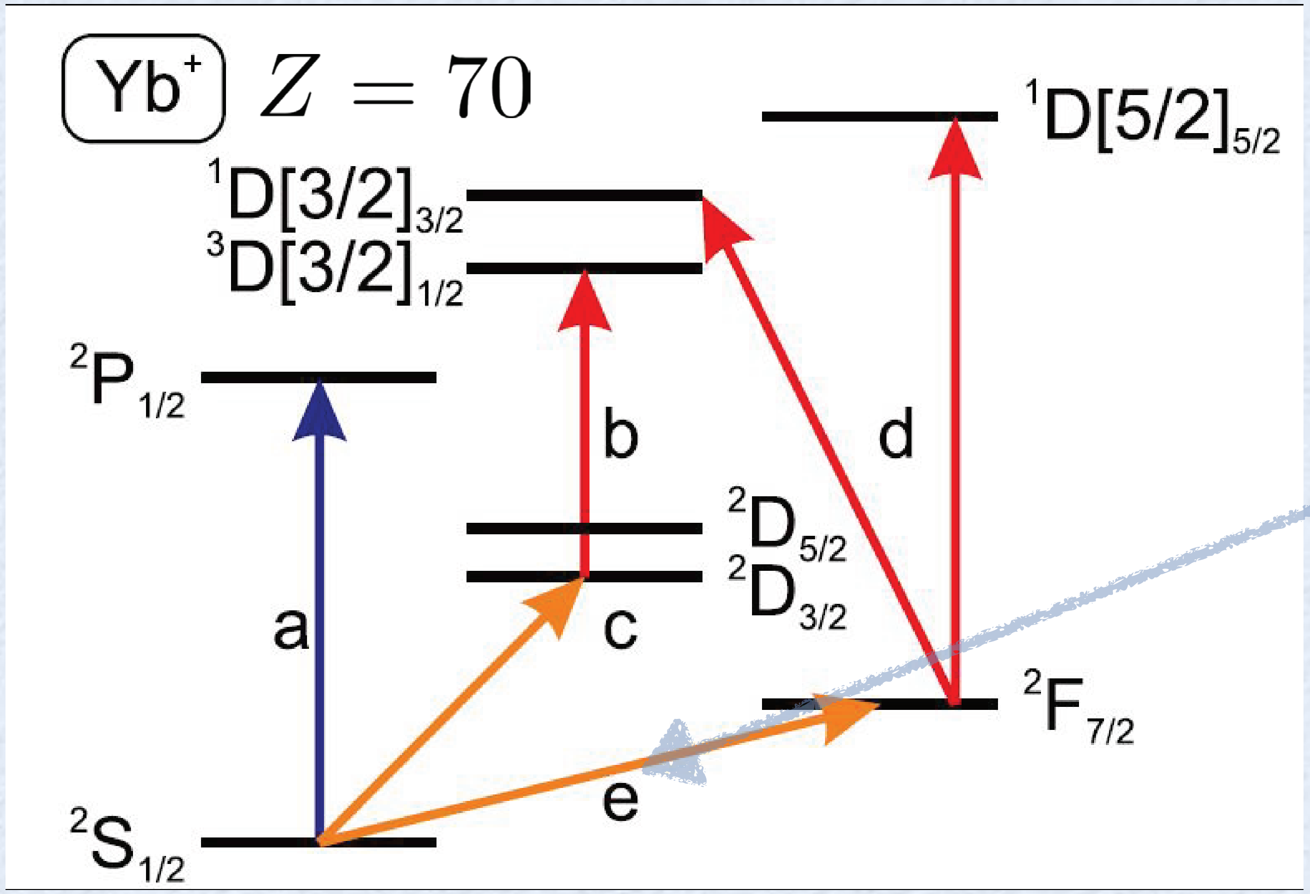
hydrogen and helium

heavy elements, Yb, Ca

Precision spectroscopy

Ytterbium (Yb^+)



experimental error of E3 0.25 Hz

relative error: 4×10^{-16}

Huntenmann et al. 2014
Gouda et al. 2014

PRECISION SPECTROSCOPY

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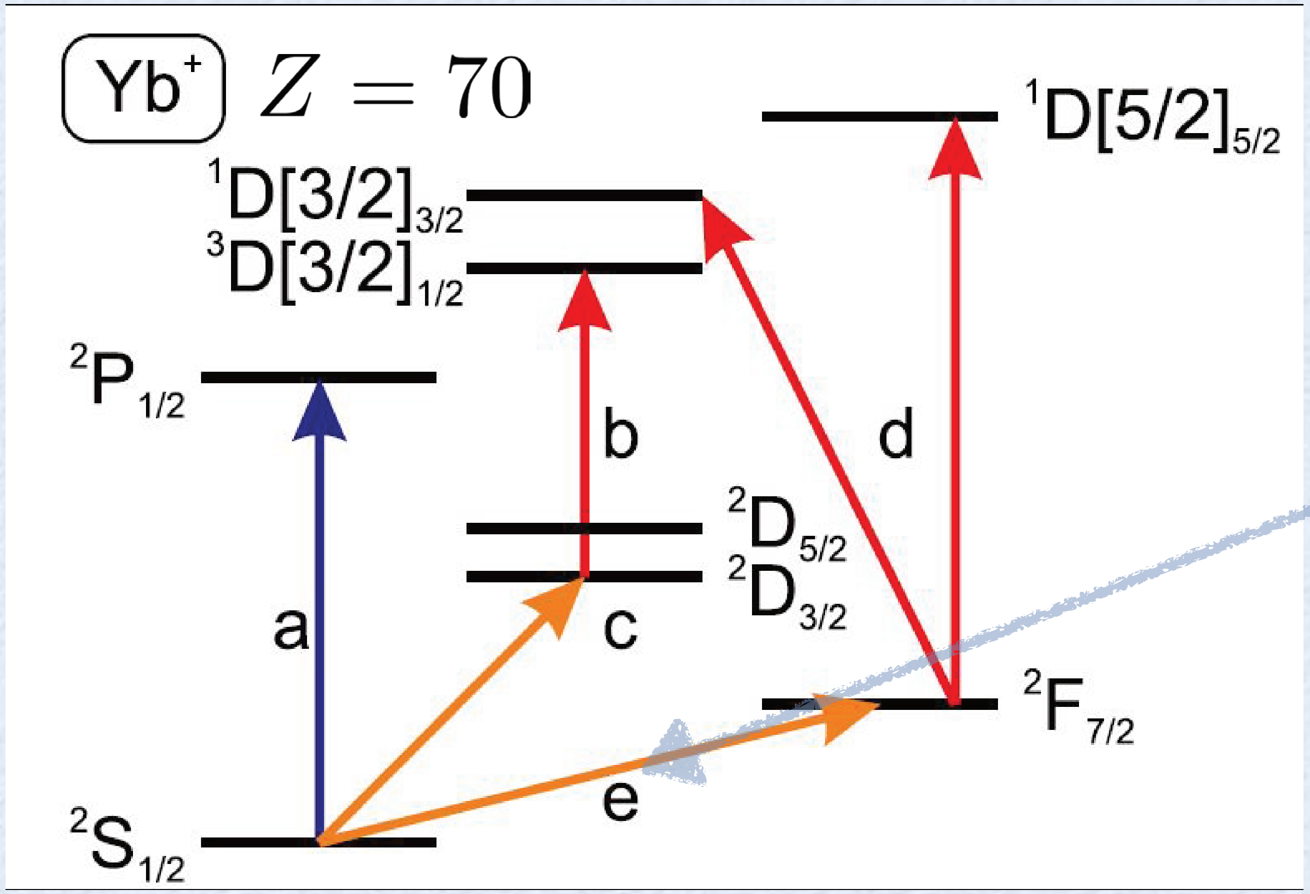

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in principle: $$y_e y_n \left(\frac{125\,\mathrm{GeV}}{m_\phi}\right)^2 < 4 \times 10^{-6}$$

stronger than LHC current bounds

PRECISION SPECTROSCOPY

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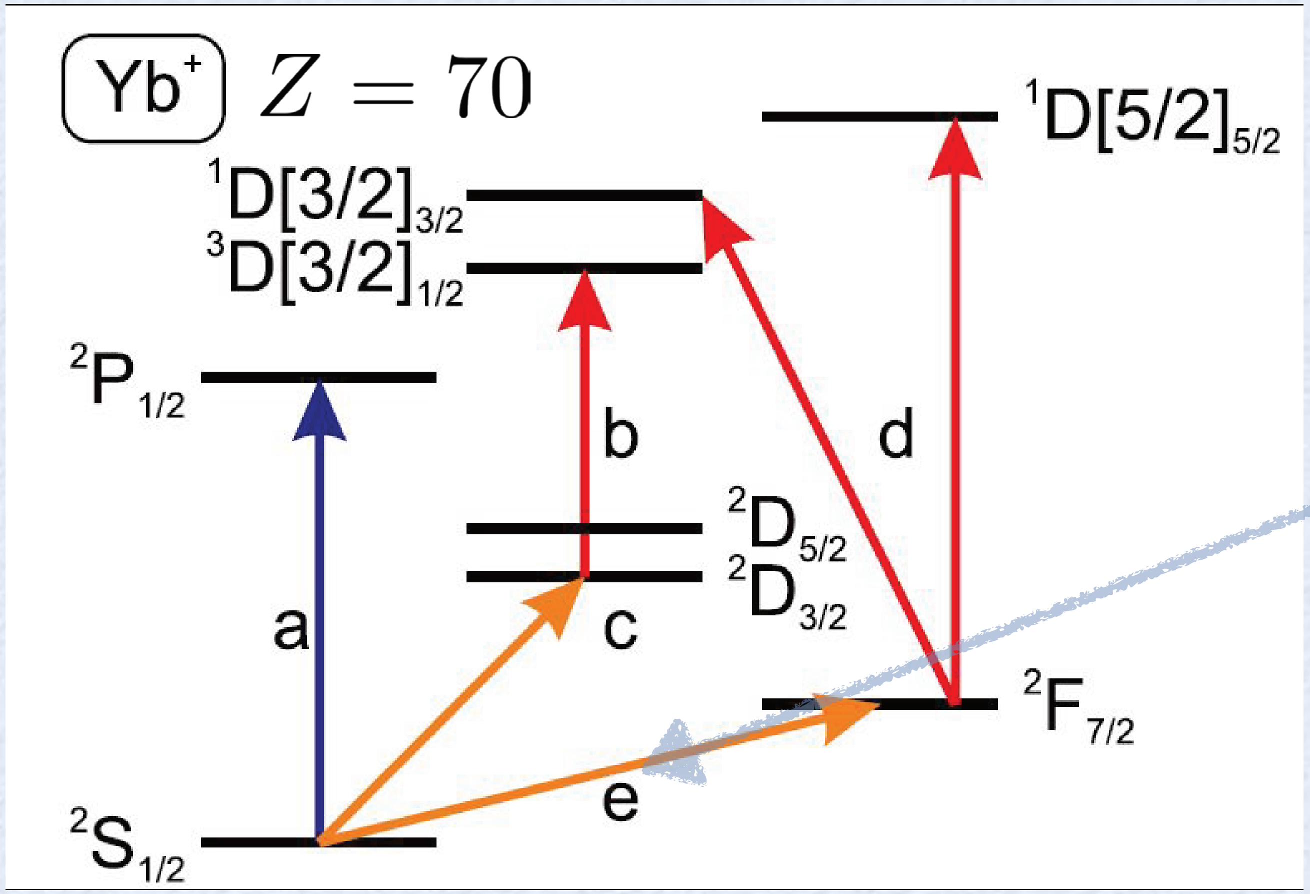

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theory is not good enough

Isotope Shift

Isotope Shift - King Plot

the **same** electronic transition, *i*, in **two** isotopes, *A* and *A′*

$$\nu_i^{AA'} \equiv \nu_i^{A} - \nu_i^{A'}$$

King 63

Isotope Shift - King Plot

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Mass Shift

Field Shift
(short distance)

$$\nu_i^{AA'} \equiv \nu_i^A - \nu_i^{A'} = K_i \mu_{AA'} + F_i \delta \langle r^2 \rangle_{AA'} + \ldots$$

$$\mu_{AA'} \equiv \frac{1}{m_A} - \frac{1}{m_{A'}}$$

electronic
parameters

nucleus
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electronic parameters

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$$\mu_{AA'} \equiv \frac{1}{m_A} - \frac{1}{m_{A'}}$$

$$m\nu_i^{AA'} \equiv \nu_i^{AA'} / \mu_{AA'}$$

$$F_{21} \equiv F_2 / F_1$$

$$K_{21} \equiv K_2 - F_{21} K_1$$

i=1,2

$$m\nu_2^{AA'} = K_{21} + F_{21} m\nu_1^{AA'}$$

factorization → linear relation between two transitions

King 63

Isotope Shift - King Plot

$\overrightarrow{m\nu}_i \equiv \left(m\nu_i^{AA'_1}, m\nu_i^{AA'_2}, m\nu_i^{AA'_3} \right)$

$\overrightarrow{m\mu} \equiv (1, 1, 1)$

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two directions

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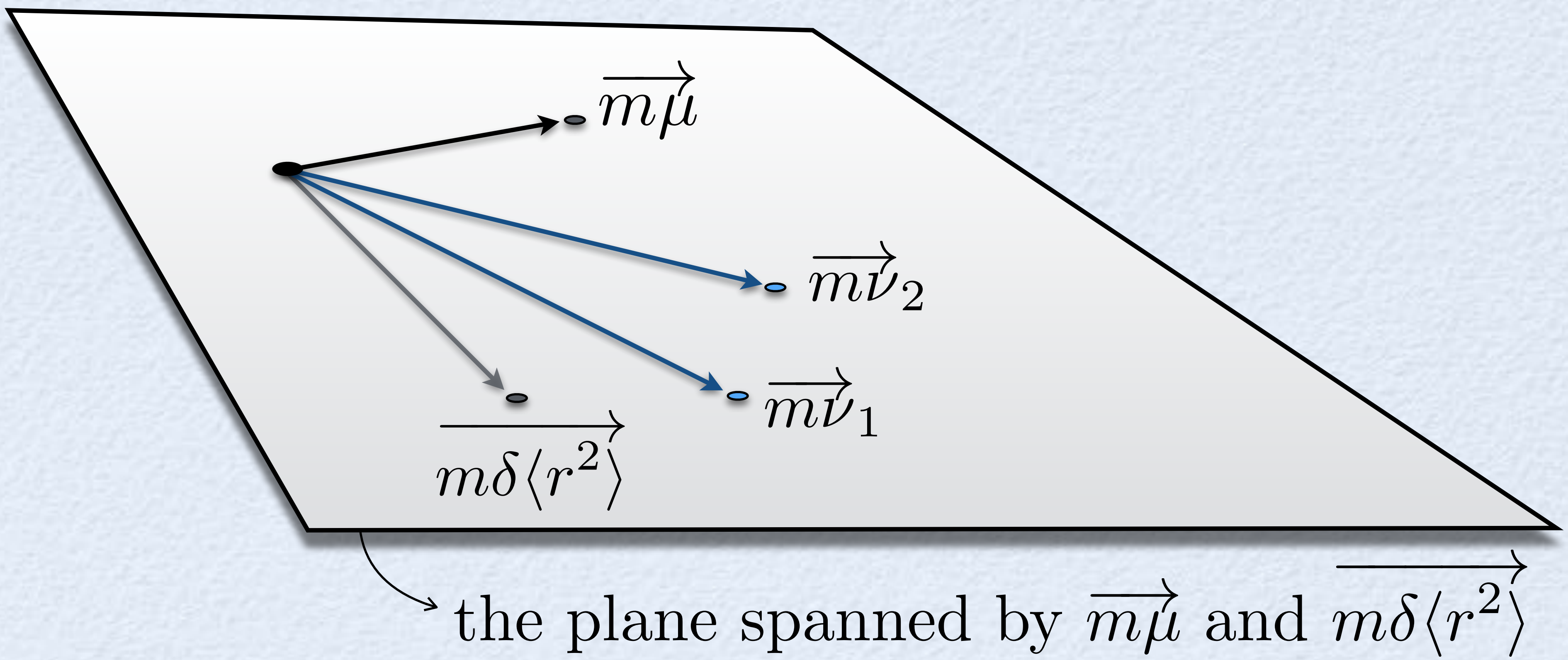
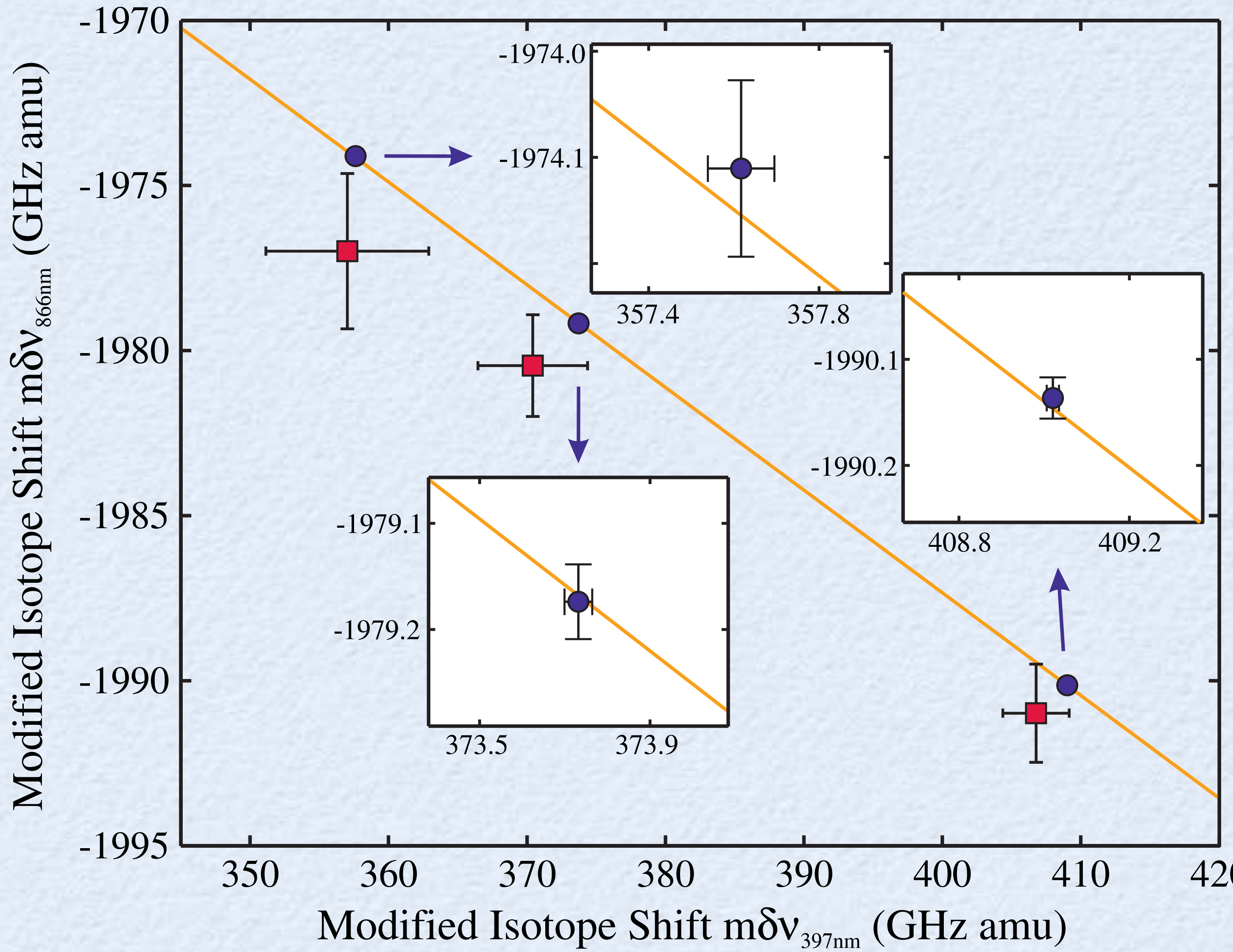


testing factorization only by data

Isotope Shift - King Plot

existing isotope shift measurement of Ca^+



$4D \rightarrow 4P_{1/2}$

$4S \rightarrow 4P_{1/2}$

100kHz error

Gebert et al. 2015

the

KING'S QUEST

for new physics

Isotope shift and new physics

$$\nu_i^{AA'} = K_i\,\mu_{AA'} + F_i\,\delta\langle r^2\rangle_{AA'} + \alpha_{\rm NP} X_i\,\gamma_{AA'}$$

new physics

Isotope shift and new physics

$F_{21} \equiv F_2/F_1$

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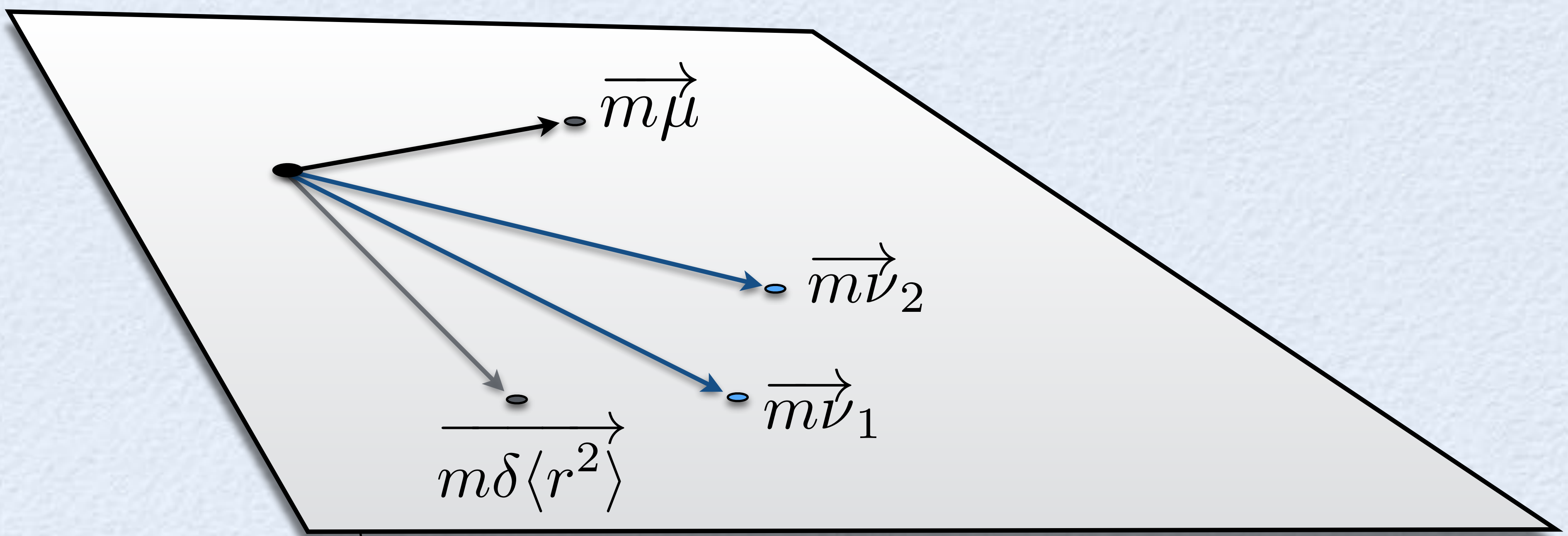
new physics



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

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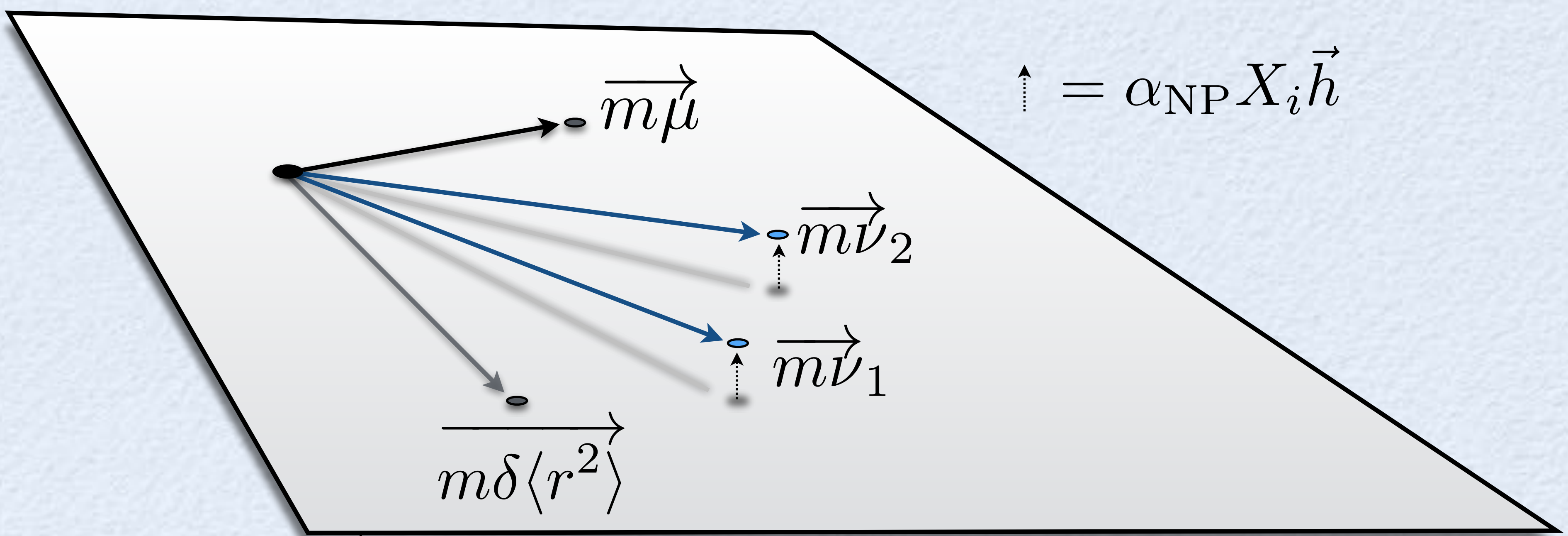

the plane spanned by $\overrightarrow{m\mu}$ and $\overrightarrow{m\delta\langle r^2\rangle}$

- $X_2 \neq X_1 F_{21}$ - long distance NP
- h - is not aligned with $m\nu_1$, $m\nu_2$, $m\mu$

⇒ nonlinear King plot from NP

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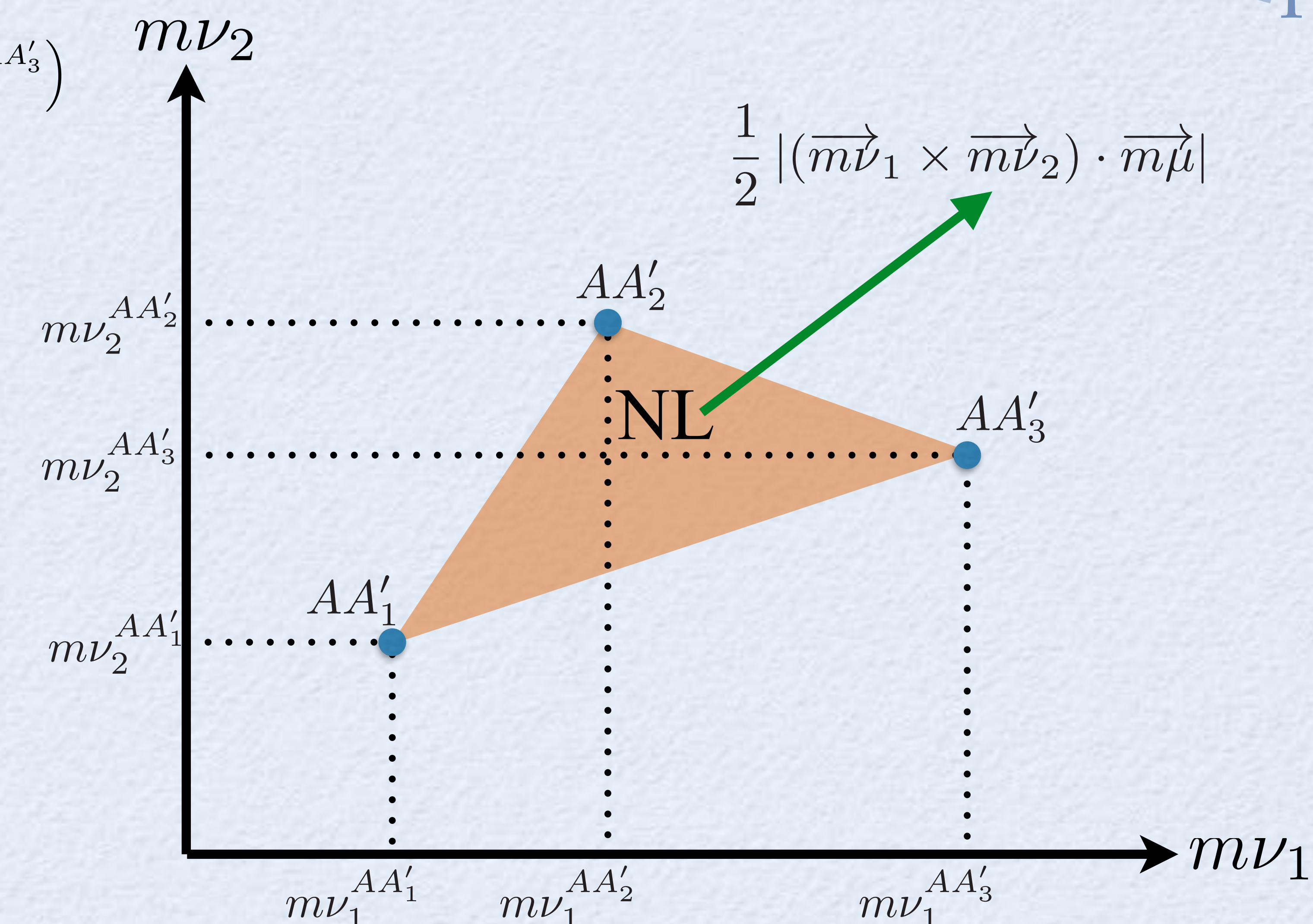

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⇒

$$\alpha_{\rm NP} = \frac{(\overrightarrow{m\nu}_1 \times \overrightarrow{m\nu}_2)\cdot \overrightarrow{m\mu}}{(\overrightarrow{m\mu} \times \vec{h})\cdot (X_1\, \overrightarrow{m\nu}_2 - X_2\, \overrightarrow{m\nu}_1)}$$

the *only* theory inputs

similar to data driven background estimation at the LHC

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data consistent with linearity → constrain NP

Constraining light new bosons

new bosons with
couplings to *e* and *n*
(spin independent)

→

$$V_\phi(r) = \alpha_{\mathrm{NP}}(A - Z)\frac{e^{-m_\phi r}}{r}$$

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$$h_{AA'} \propto AA'$$

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1st order perturbation theory and
multi-body perturbation theory

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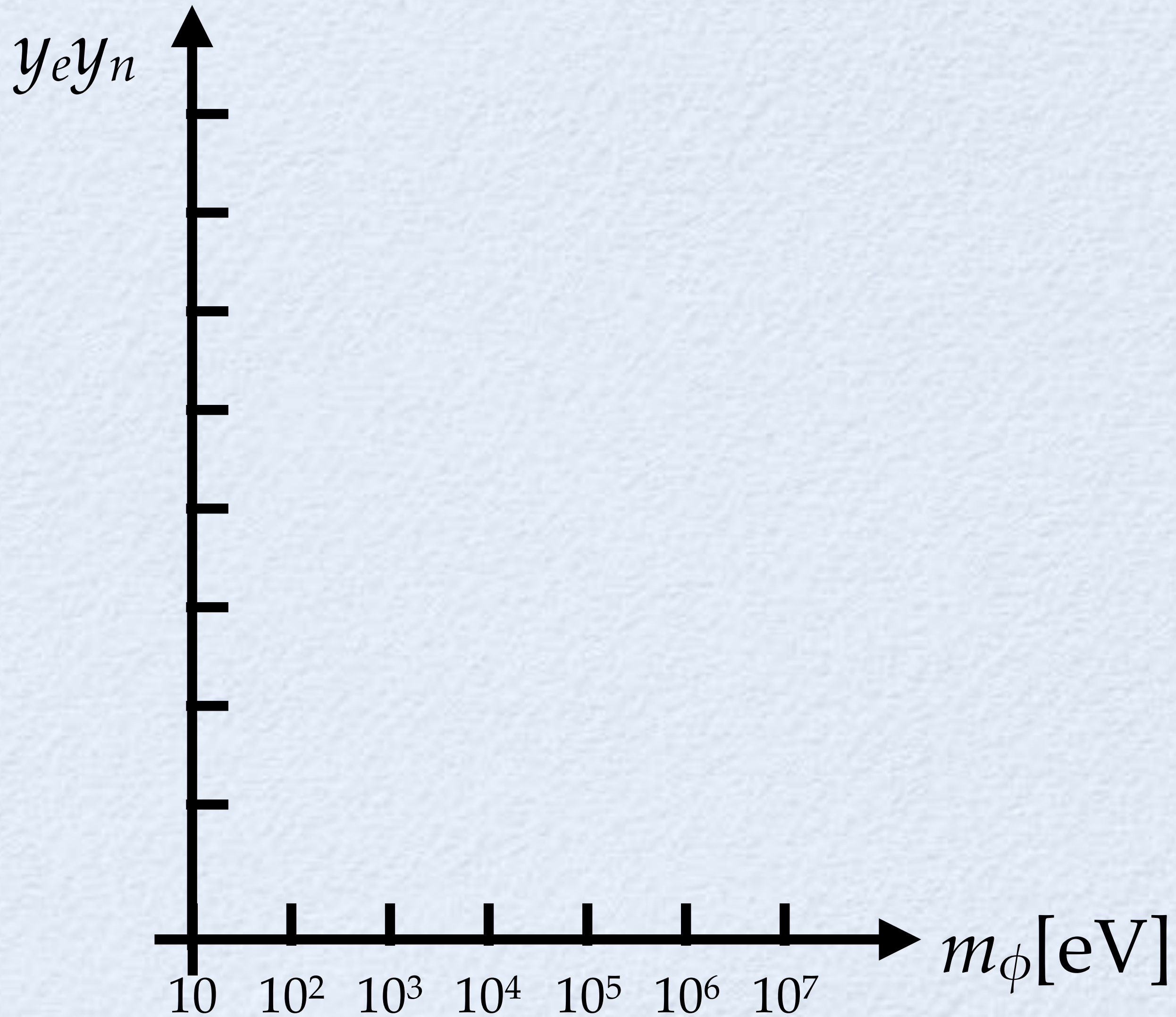
1st order perturbation theory and multi-body perturbation theory

	$m_\phi <$ 4keV	4keV $< m_\phi <$ 50MeV	50MeV $< m_\phi$
$V_\phi(r)$~	$1/r$	$\exp(-m_\phi r)/r$	$\delta(r)/(m_\phi r)^2$
X_i	constant	m_ϕ dependent	$X_2 - X_1 F_{21} \rightarrow 0$

Constraining light new bosons

$$y_e y_n < \sigma_i \frac{\sqrt{1+F_{21}^2}}{X_2 - X_1 F_{21}} \frac{4\pi\, A}{(A-A')^2}$$

experimental error



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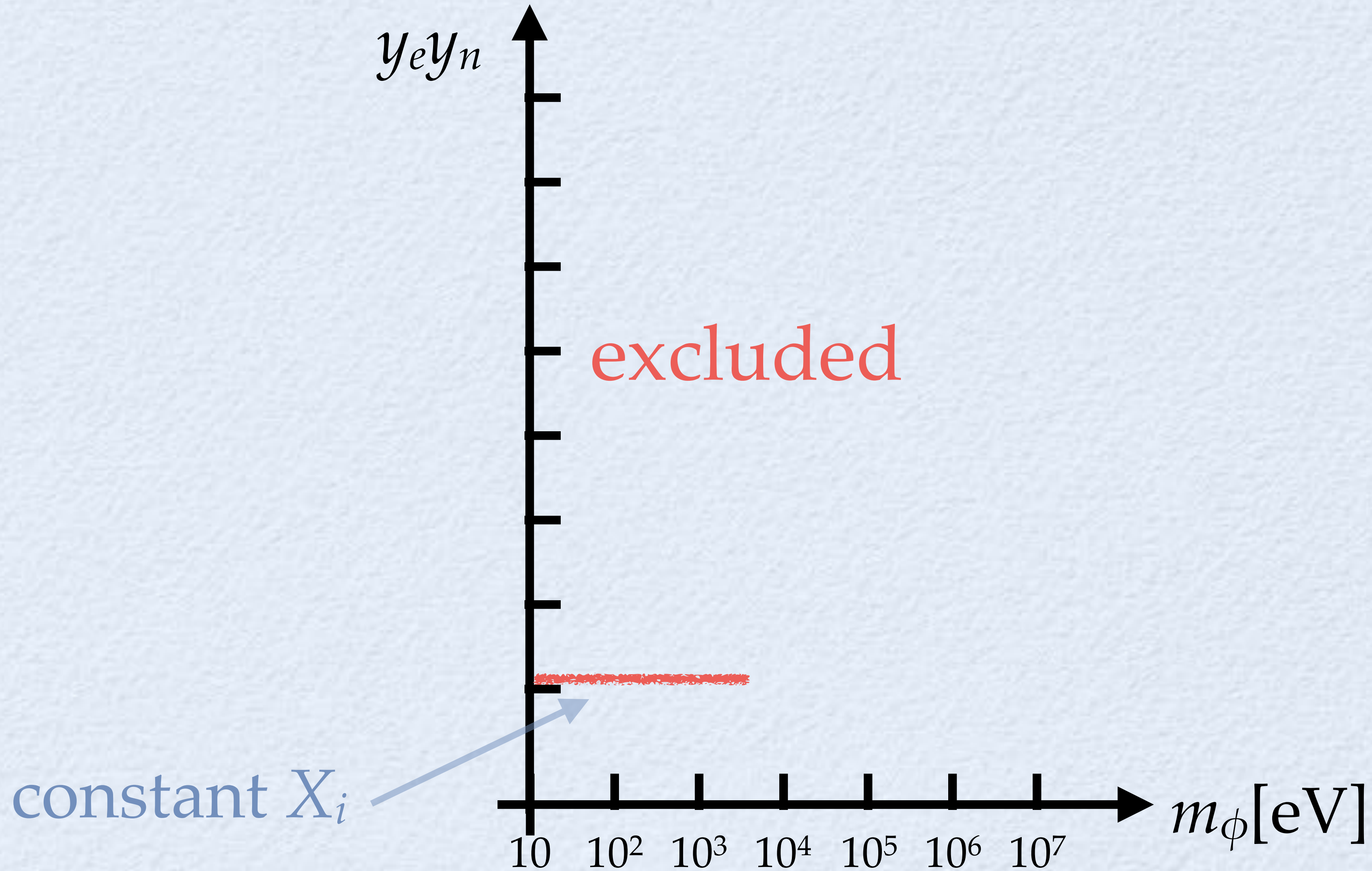

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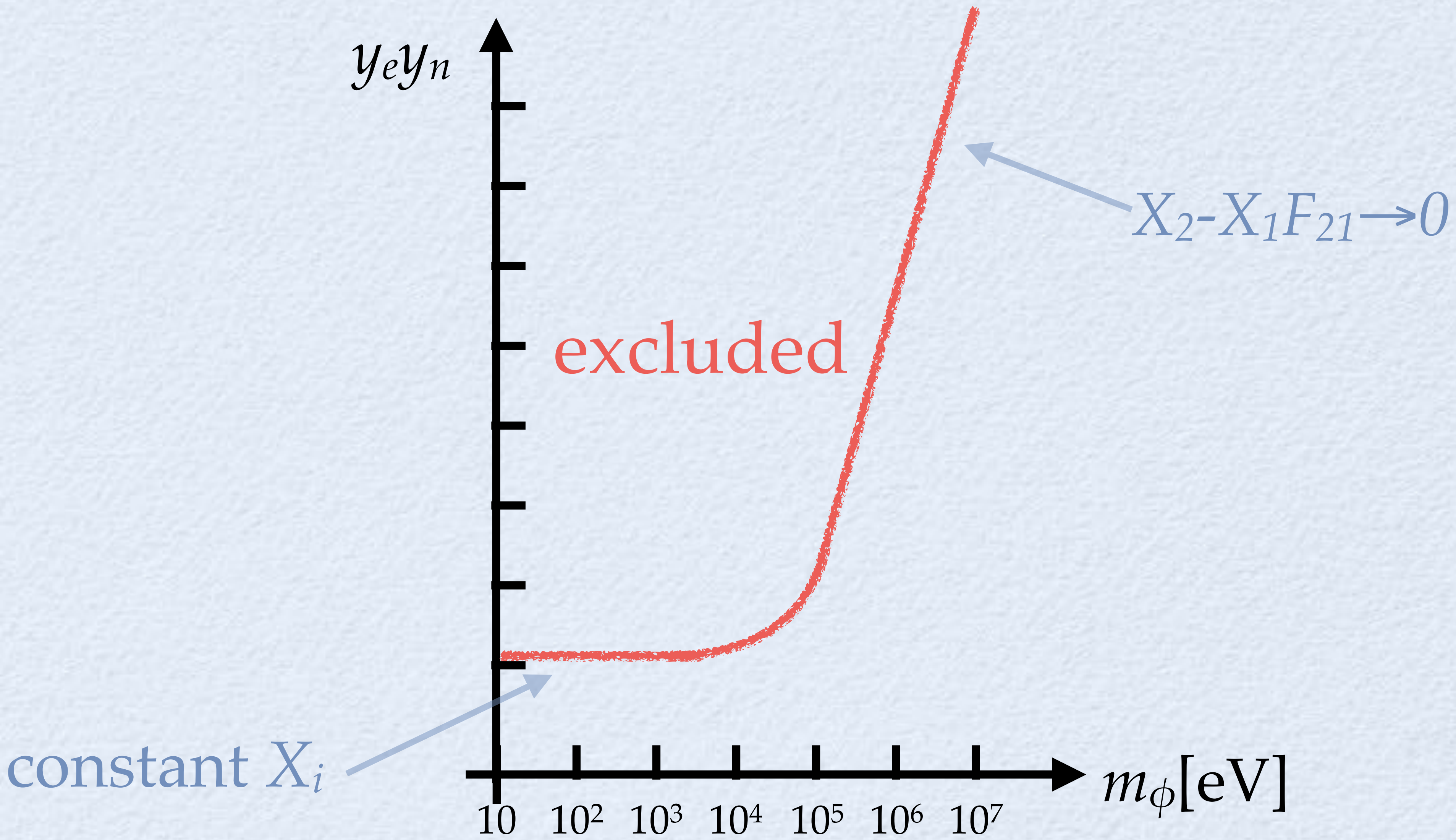

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  - **Ca^+**: 866/397nm, σ~0.1MHz
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- current data:
  - **Ca^+**: 866/397nm, σ~0.1MHz
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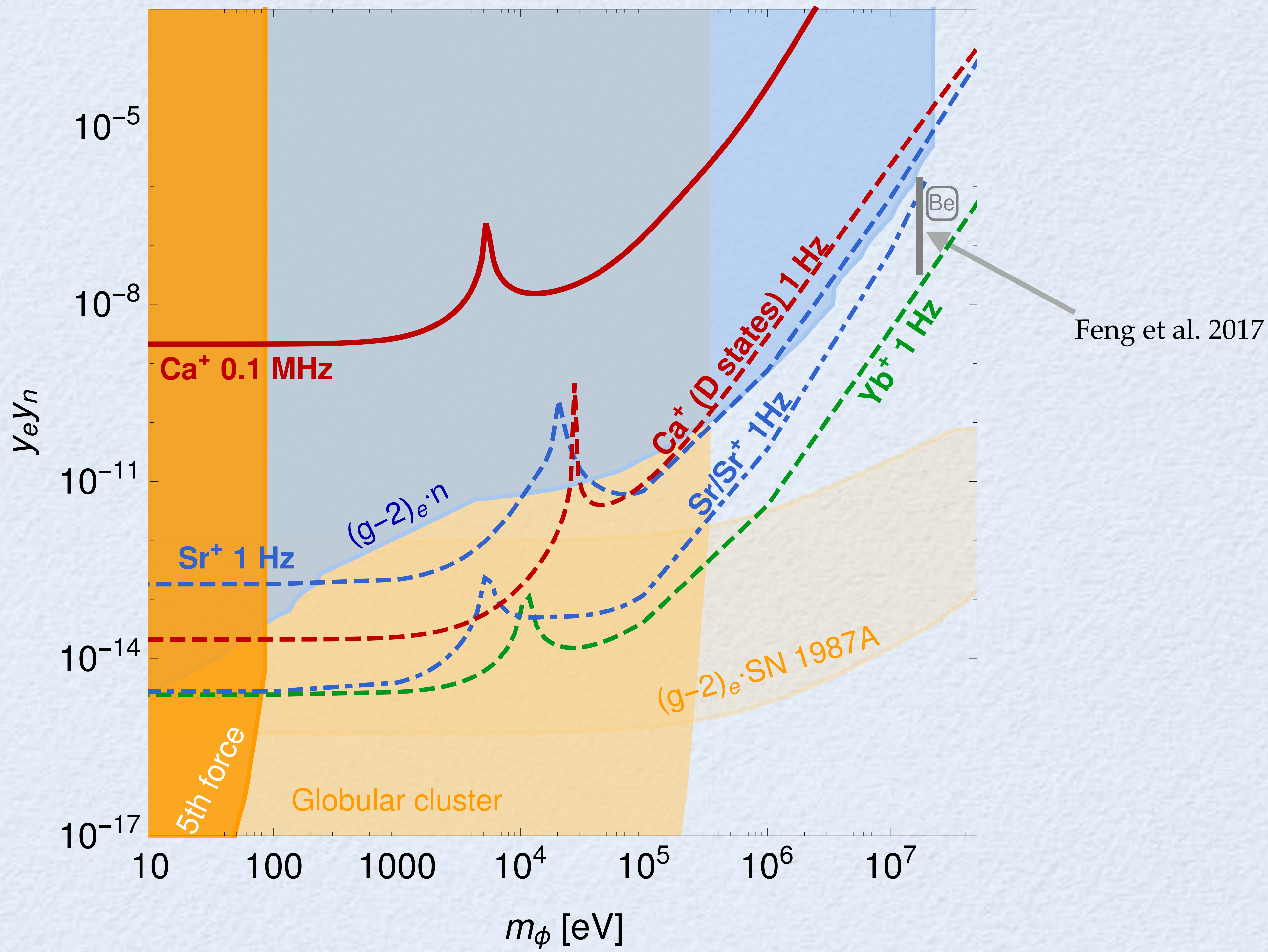
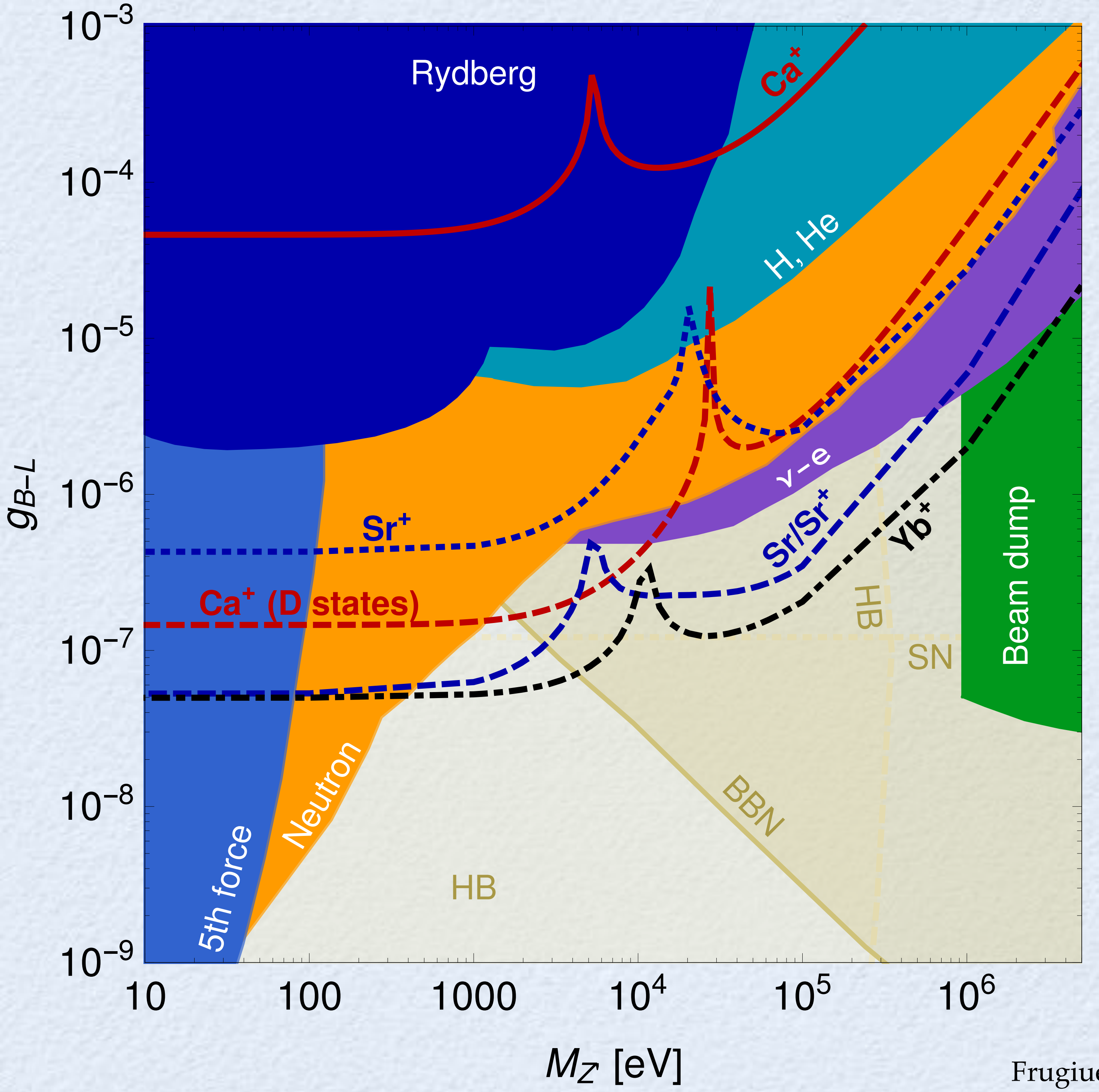
- candidates for future measurements:
  - **Ca^+**: $S \rightarrow D_{5/2}$ / $S \rightarrow D_{3/2}$
  - **Sr^+**: $S \rightarrow D_{5/2}$ / $S \rightarrow D_{3/2}$
  - **Sr^+/Sr**: $S \rightarrow P$ / $S \rightarrow D_{5/2}$
  - **Yb^+**: $S \rightarrow D_{3/2}$ / $S \rightarrow F_{7/2}$

Bounds and Projections



Bounds and Projections

B-L:



Frugiuele, Fuchs, Perez, Schlaffer - 1602.04822

few electrons atoms

Hydrogen and Helium Spectroscopy

direct comparison of theory to experiment
(not limited by theory error)

bound Yukawa like force with spin independent interactions:

$$\frac{y_e(y_p Z + (A-Z)y_n)}{4\pi}\frac{e^{-m_\phi r}}{r}$$

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He summary: Pachuki, Patkos, Yerokhin, 1704.06902

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hydrogen → $y_e y_p$

helium → $y_e y_p, y_e y_n, y_e$

isotope shift (He3-He4, H-D) → $y_e y_n$

positronium → y_e

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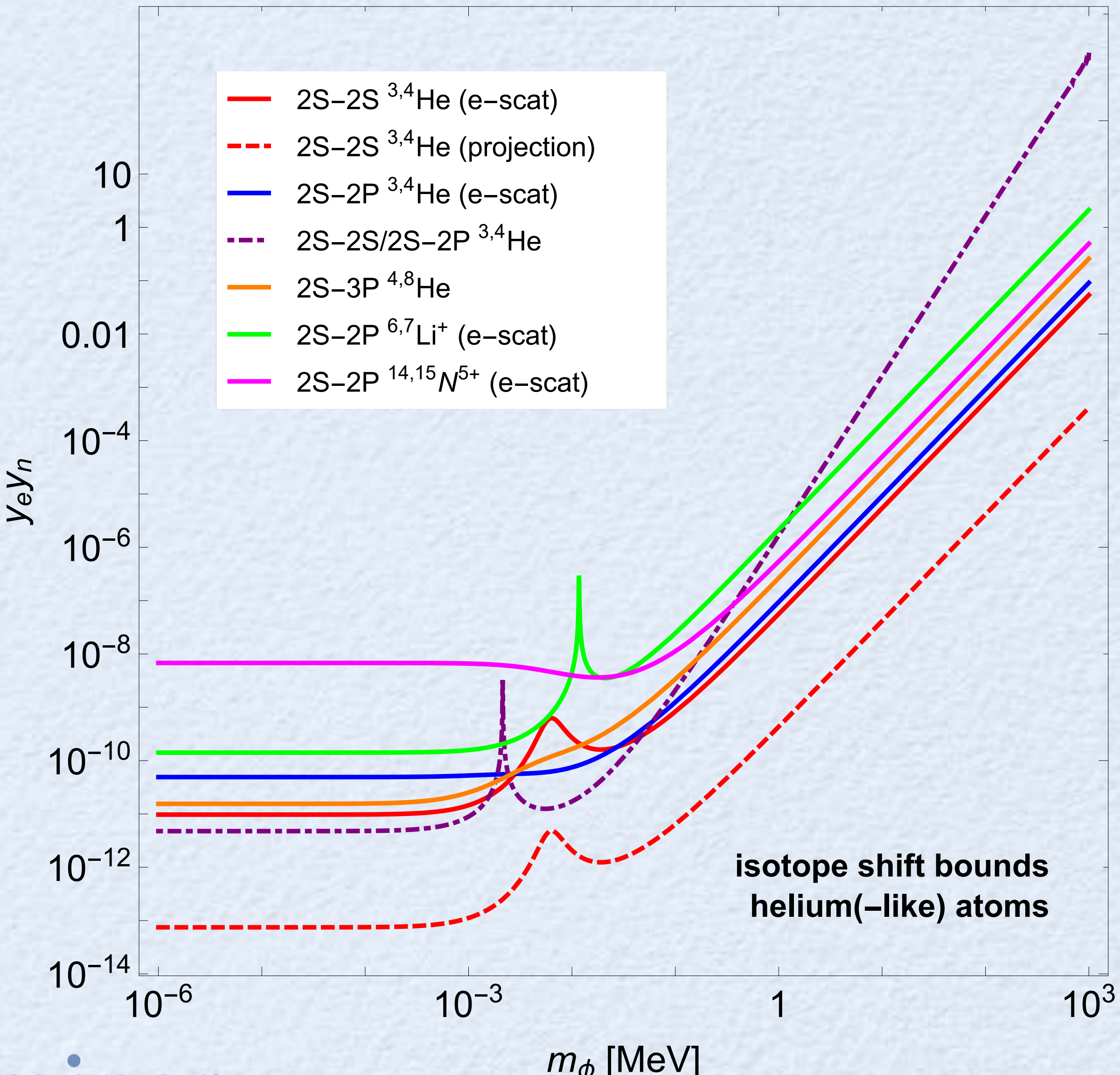
Hydrogen and helium spectroscopy

isotopes	transition	$\delta_{\rm NP}\nu$	$\sigma_{\nu_{\rm exp}}$	σ_{ν_0}	$\sigma_{\delta\langle r^2\rangle}$
^{3}He/^{4}He	$2^1S - 2^3S$	$+9 \pm 14$	2.4	0.19	14
	$2^3P - 2S$	-2 ± 78	3.3	0.9	78

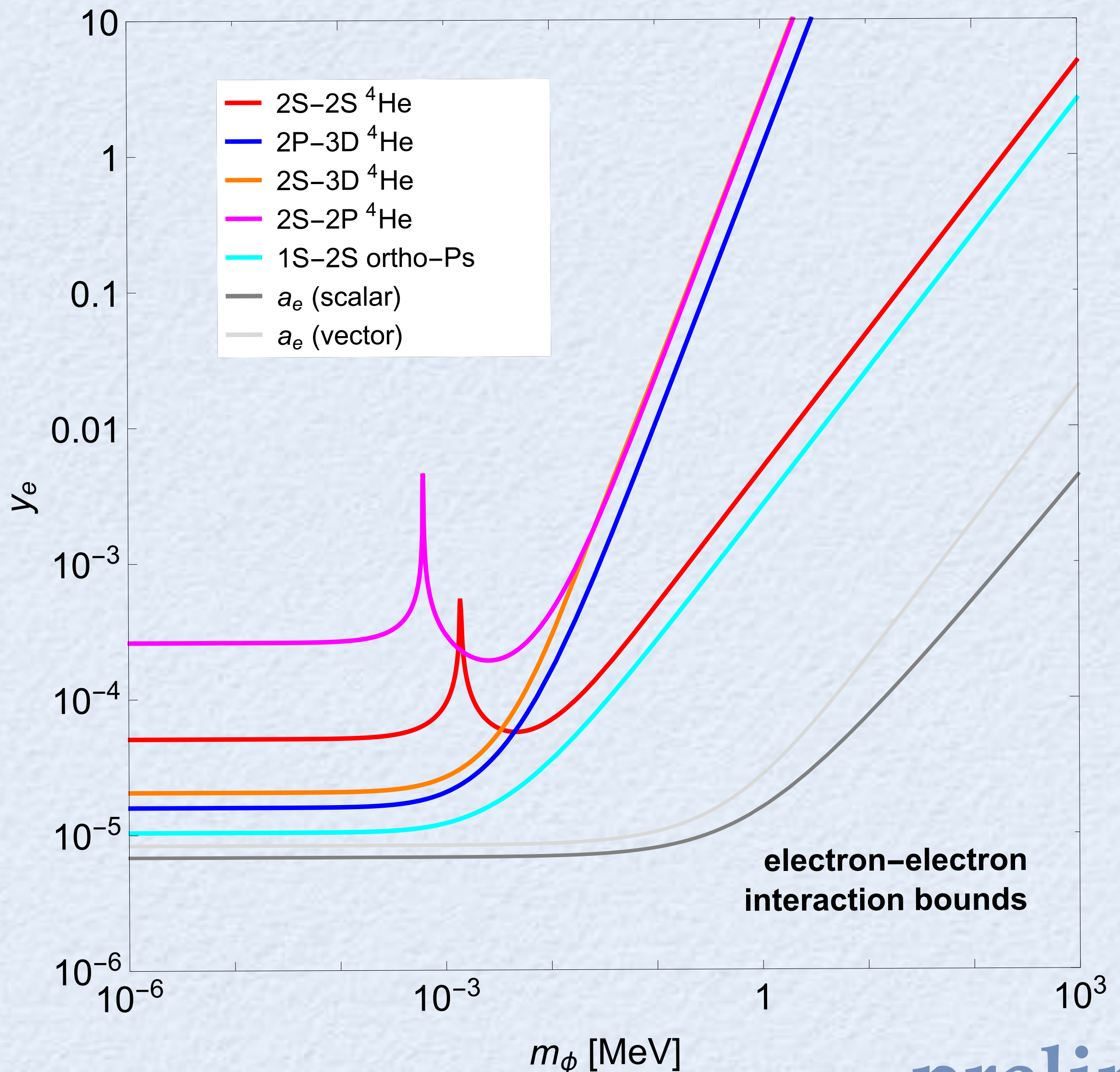
isotope shift



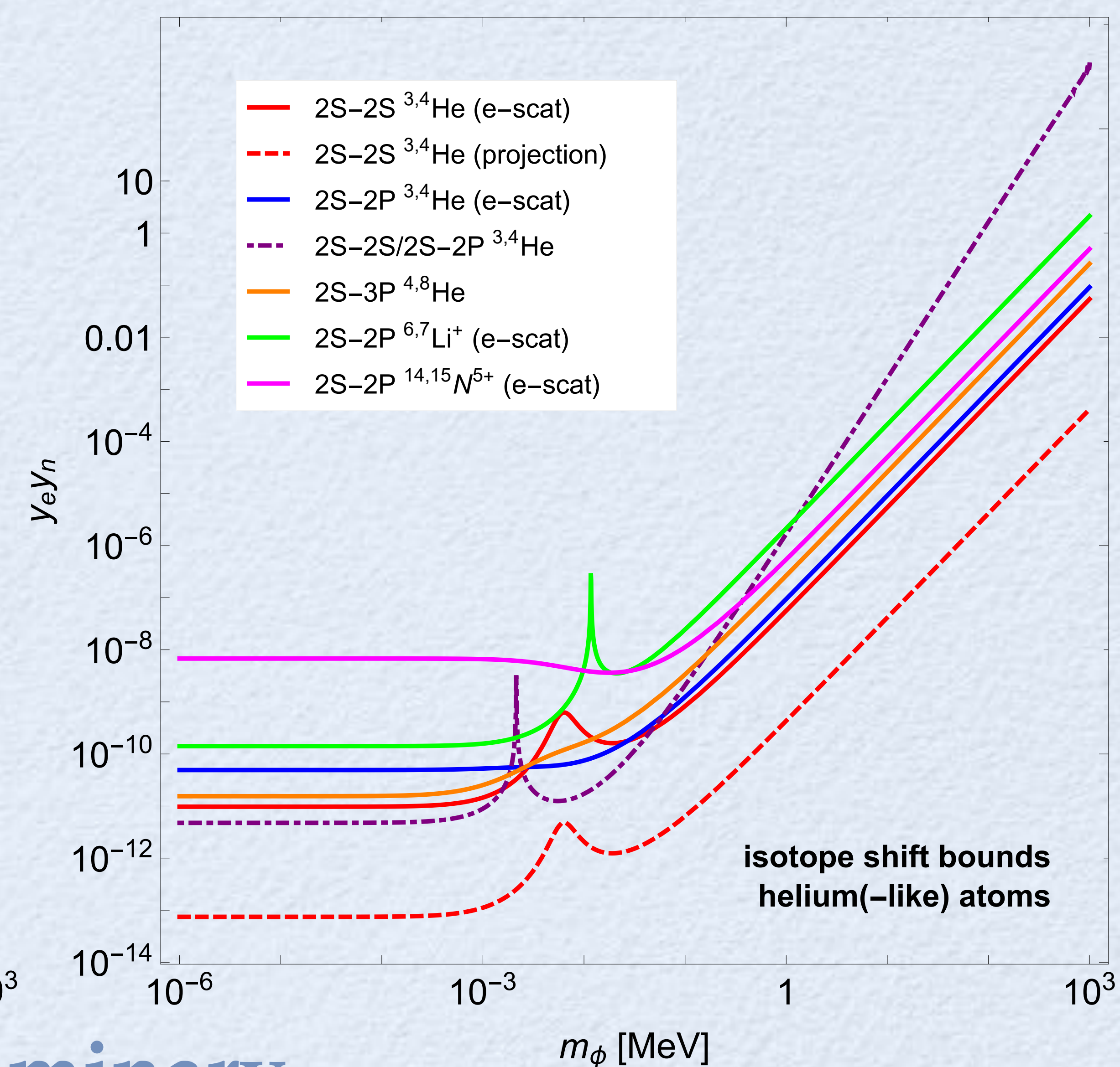
preliminary

Hydrogen and Helium Spectroscopy

electron interaction

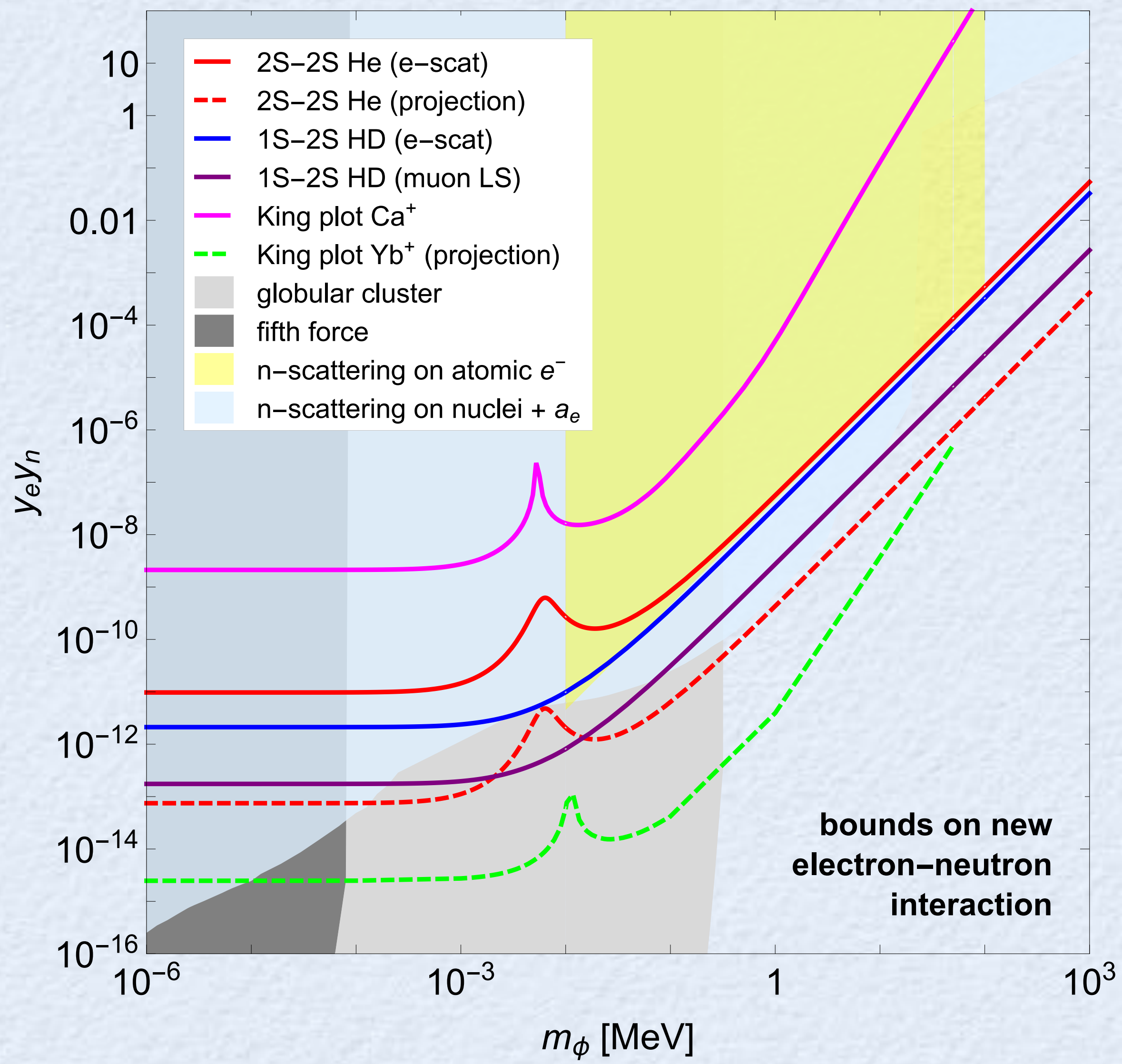


isotope shift



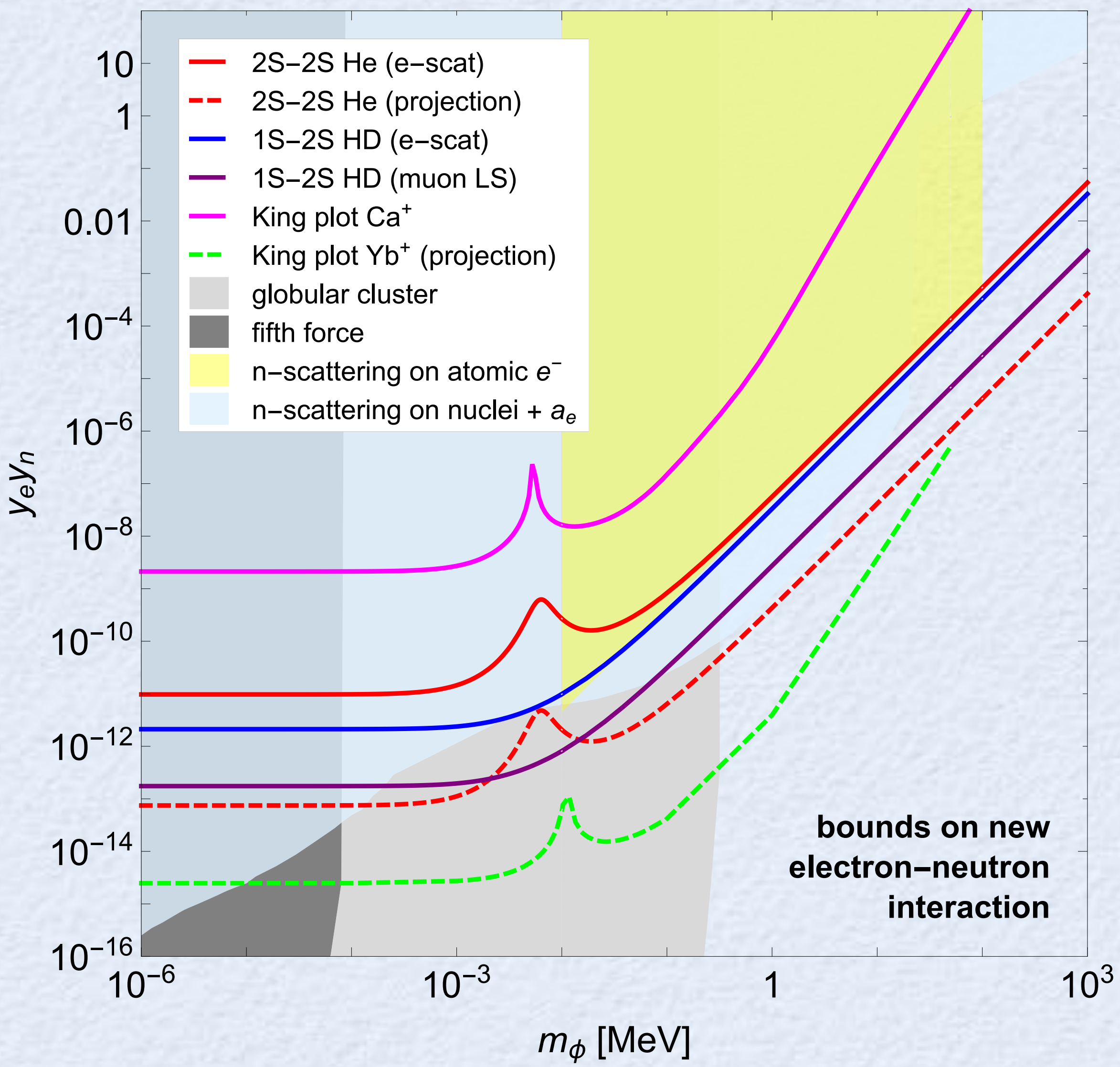
preliminary

SUMMARY



preliminary

SUMMARY

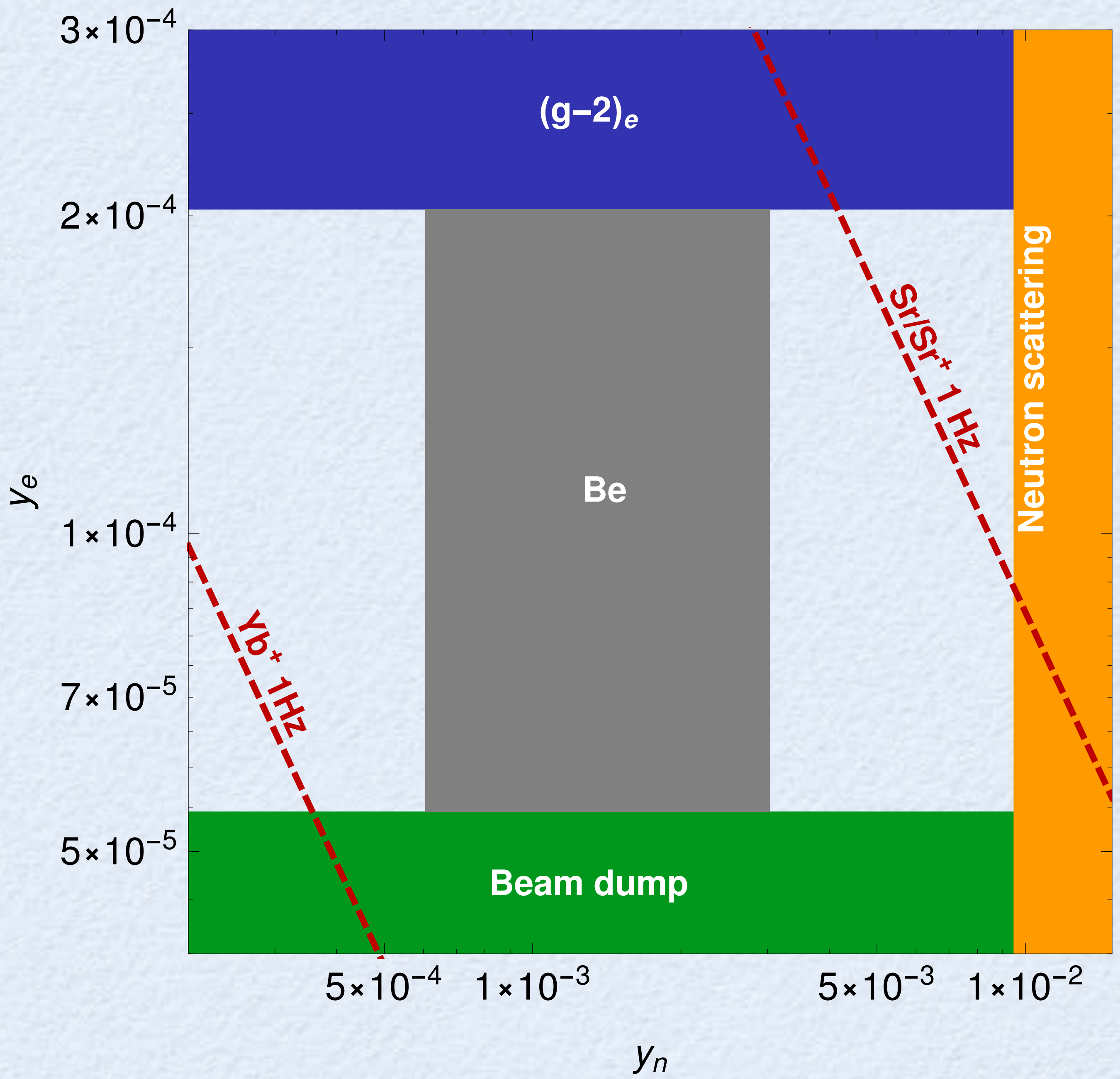


preliminary

- precision isotope spectroscopy can probe new light force-carriers with spin independent couplings to the electron and neutron
- King analysis has minimal theory inputs ("data-driven background")
- current constraints from King analysis are weak - but future measurements may improve the state-of-the-art bounds

Backup Slides

Be anomaly



Frugiuele, Fuchs, Perez, Schlaffer - 1602.04822