Atomic Precision Frontier

Probing light force-mediators by isotope shift spectroscopy

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45th SLAC Summer Institute, 2017

Outline

- Introduction: brief motivation for light physics + exp' frontier.

  See also Graham's talk.

- Main idea, pheno. (geometrical picture).

  Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, GP & Soreq (17)
  Frugiuele, Fuchs, GP & Schlaffer; Delaunay, Ozeri, GP & Soreq (16)

- Bounds (with minimal theory).

- Conclusions.

Introduction

♦ Flavor-mass hierarchies, strong-CP problem, compactifications: solid reasons to expect light weakly interacting new fields.

. See e.g.: Kim (87); Feng, Moroi, Murayama & Schnapka (98); Wilczek (82); Gelmini, Nussinov & Yanagida (83)

♦ Solutions typically lead to pseudo-scalar couplings to matter, axions, familons, etc.; with active exp' effort.

Recent reviews: Graham, Irastorza, Lamoreaux, Lindner & Bibber (2015) Jaeckel & Ringwald (10); Kim & Carosi (08)

♦ However, light gauge bosons; CP violation; relaxions (new solution to Higgs-hierarchy problem) => vector/scalar interactions.

Graham, Kaplan & Rajendran (15)

Some reviews & recent work: Stadnik& Flambaum (16); Karshenboim (05); Ginges & Flambaum (04); Pachucki, Patkóš, Yerokhin (17) Safronova, Budker, Derevianko, DeMille, Clark & Kimbal. in prep.

Search strategies ?

- Interaction \w density: Direct DM (collision) or time dependent.

  Talk by: Feng; Monzani; Pyle; Schuster; Bibber. Talks: Bibber; Graham.

- Produce on shell in the sky (low mass) or in the lab (largish-coupling).

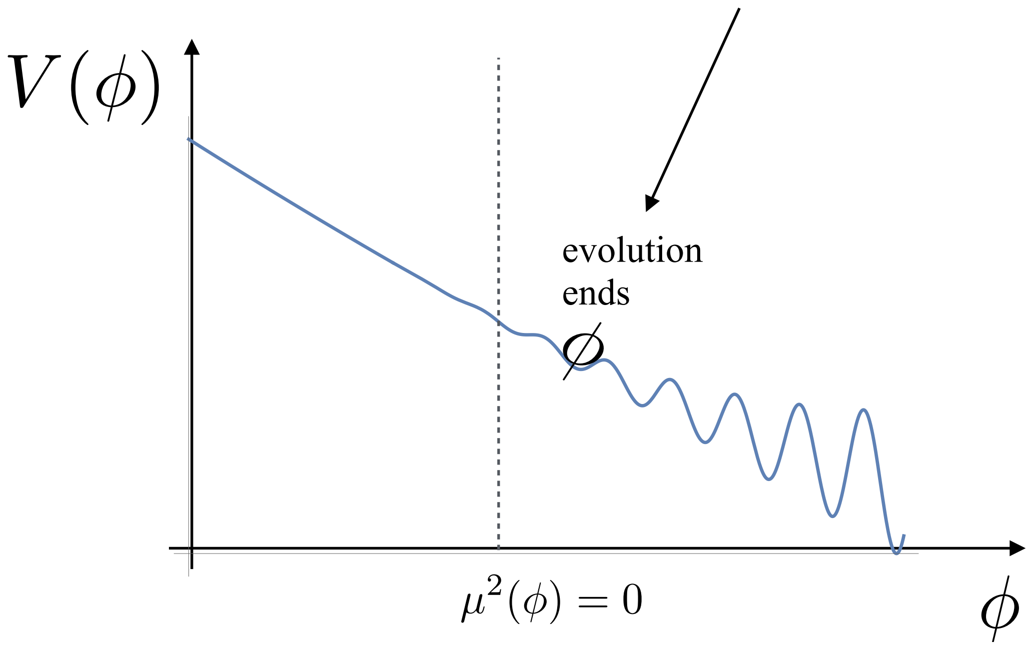
  Talks by: Albert; Toro.

- Virtually (ex. Peskin-Takeuchi) via induced potential/force.

Ex.: The relaxion-axion CP problem

- Let us go back to consider the relaxion properties.

The relaxion halt at generic point, \w O(1) phase, CP is badly broken!



- Generically failed to play the role of axion => CP problem remains.

Graham, Kaplan & Rajendran (15)

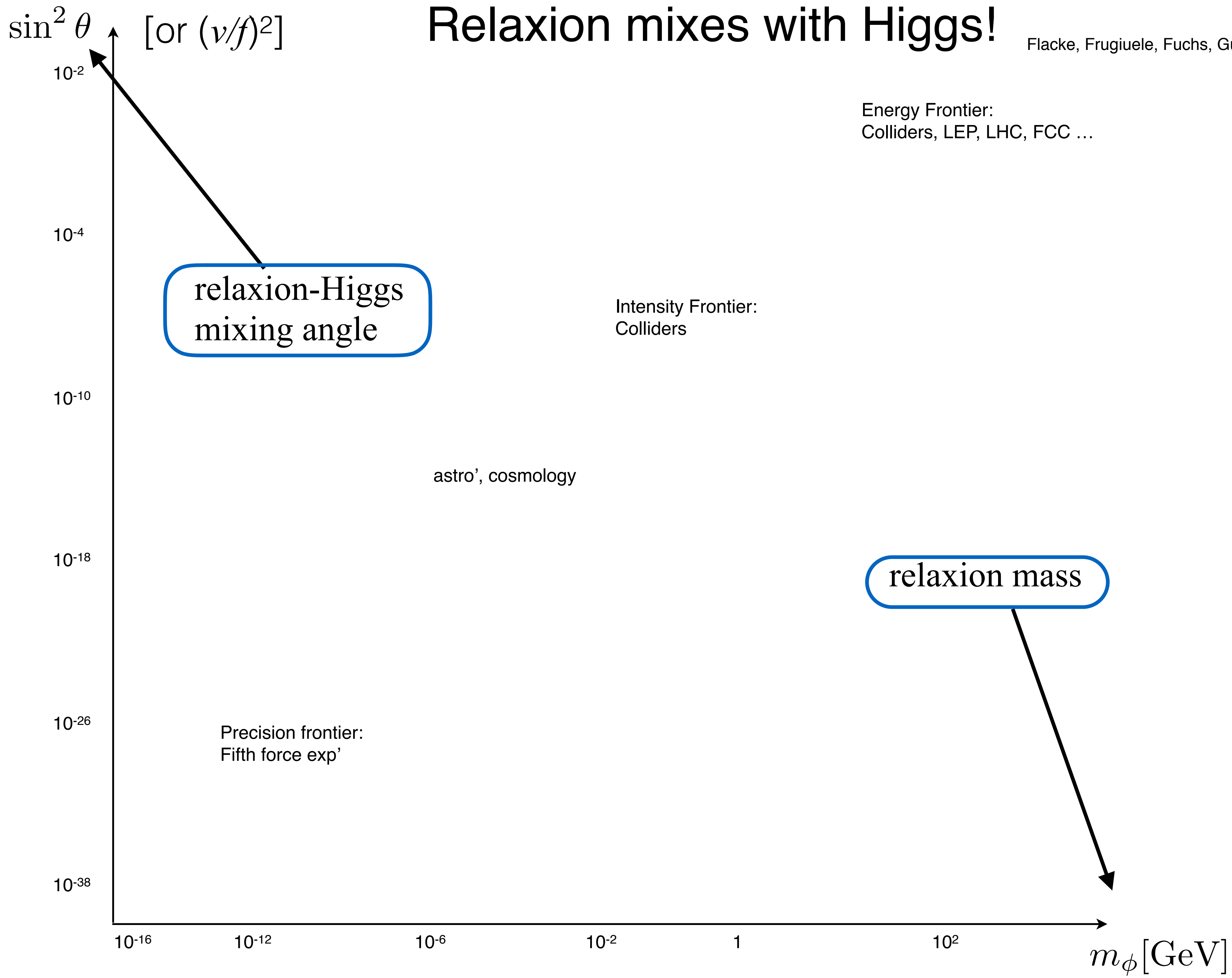
- Leads to interesting implications such as mixing \w Higgs.

Flacke, Frugiuele, Fuchs, Gupta & GP (16)

Illustration: how to search for a relaxion?

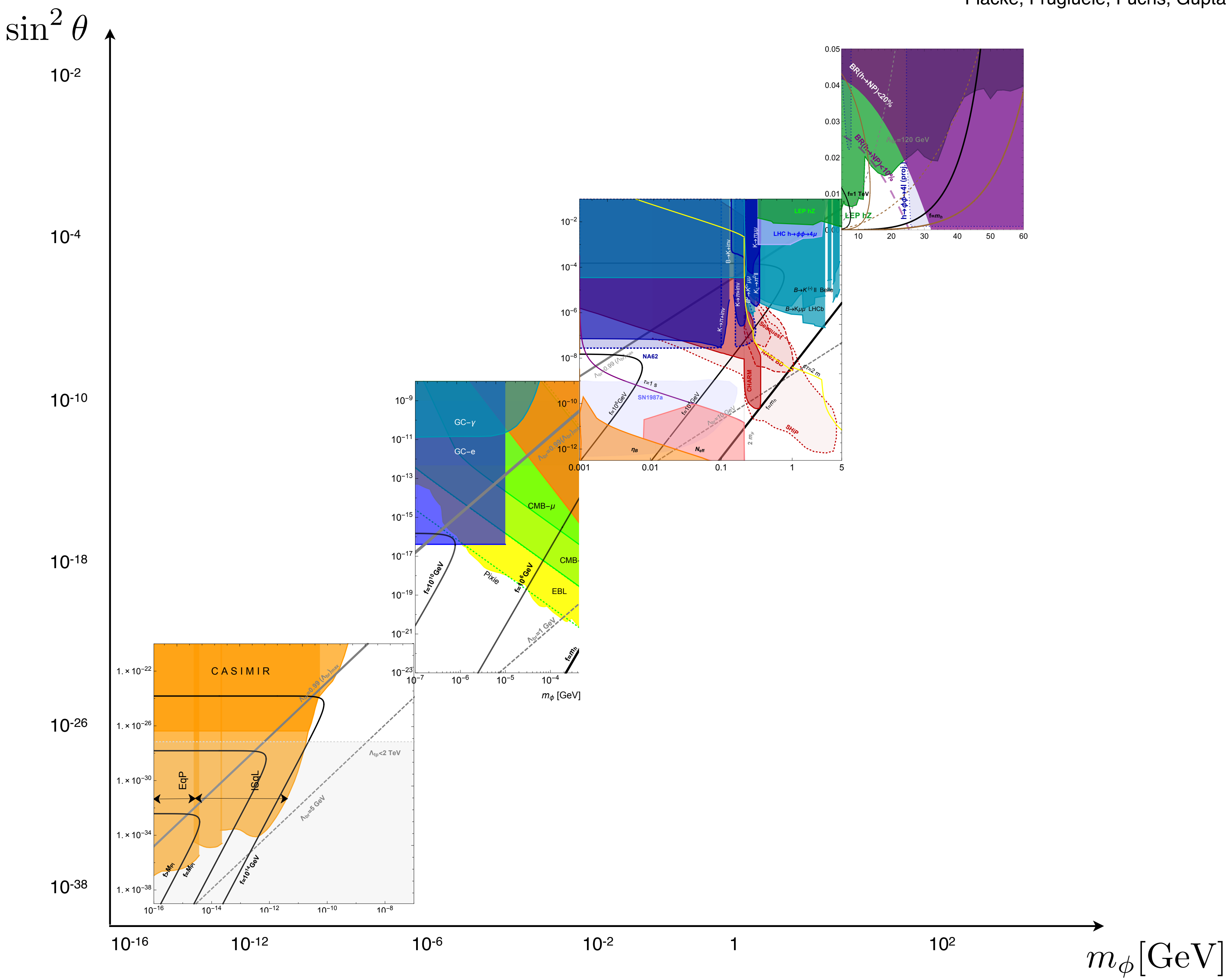
Relaxion mixes with Higgs!

Flacke, Frugiuele, Fuchs, Gupta & GP (16)



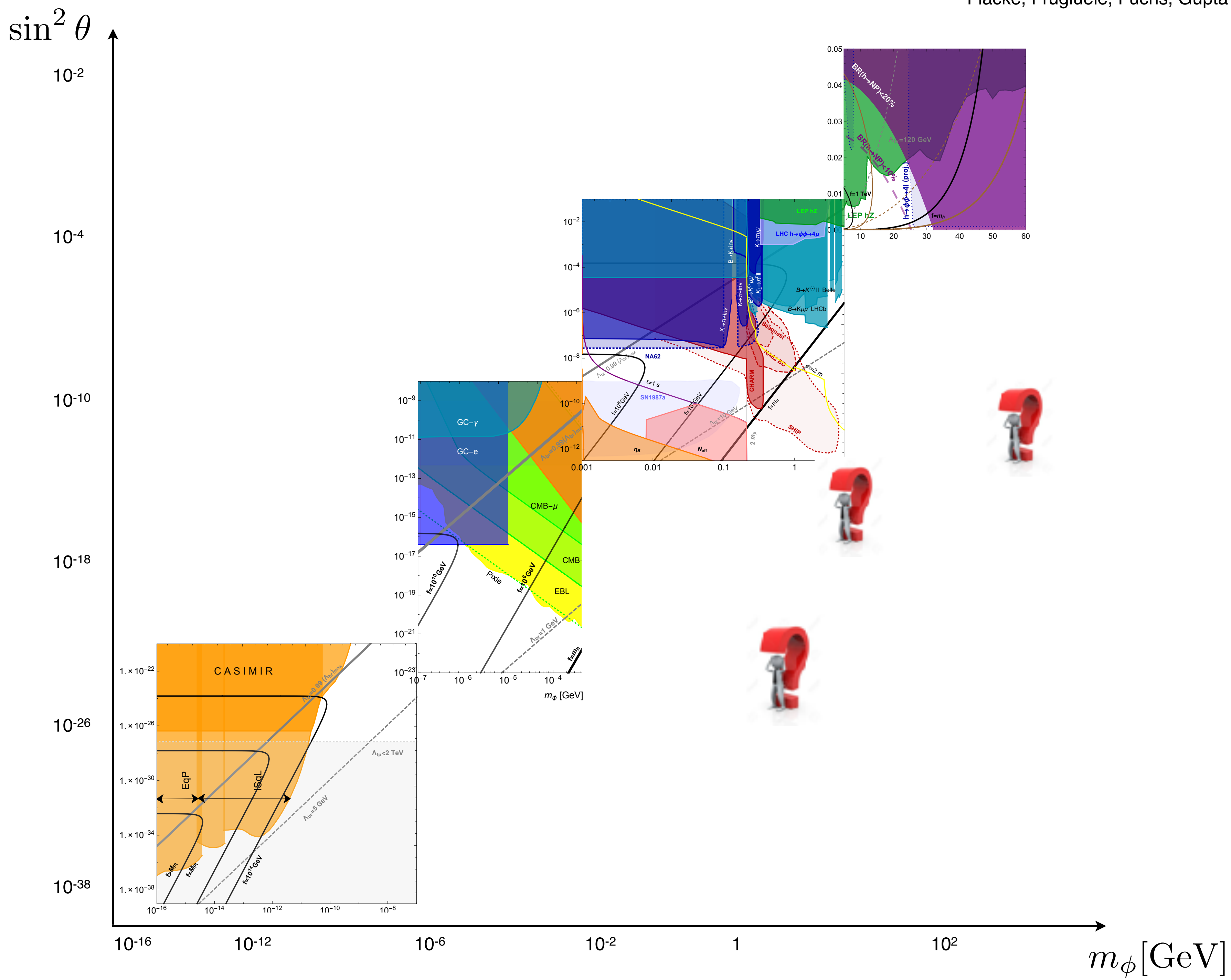
Current-near-future constraints

Flacke, Frugiuele, Fuchs, Gupta & GP (16)



Current-near-future constraints

Flacke, Frugiuele, Fuchs, Gupta & GP (16)



Change gear: the precision frontier of atomic clocks spectroscopy

Current state-of-the-art frequency measurements:

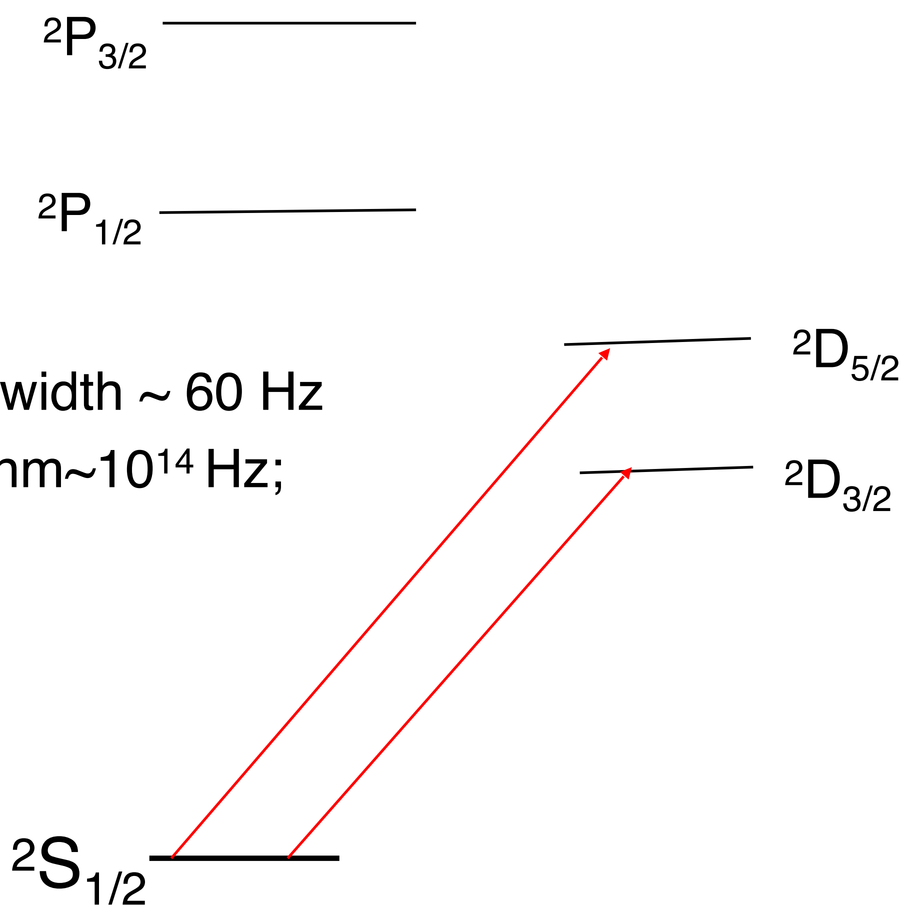
- Optical transitions in laser-cooled atoms/ions
- Relative accuracy: few 10^{-18}; few mHz on top of 10^{15} Hz

Huntemann, Sanner, Lipphardt, Tamm & Peik (16); Bloom, Nicholson, Williams, Campbell, Bishof, Zhang, Zhang, Bromley & Ye (14)

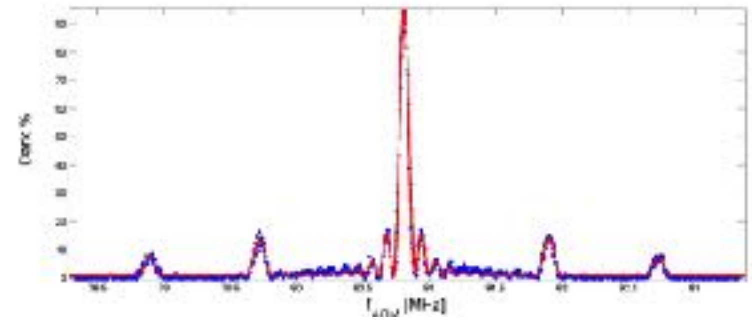
Sr+ ion-clock (Ozeri's lab @ Weizmann)

Linewidth ~ 60 Hz

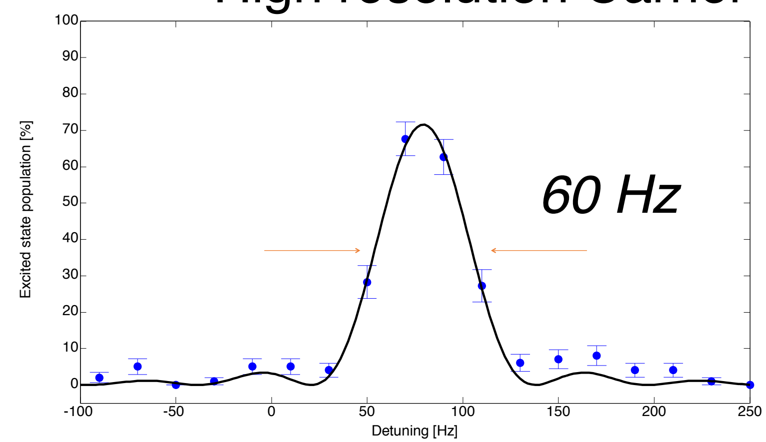
674nm~10^{14} Hz;



Optical quadrupole transition: wide scan



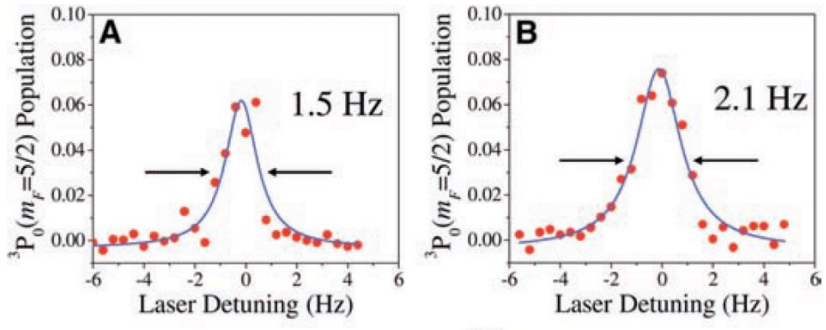
High resolution Carrier

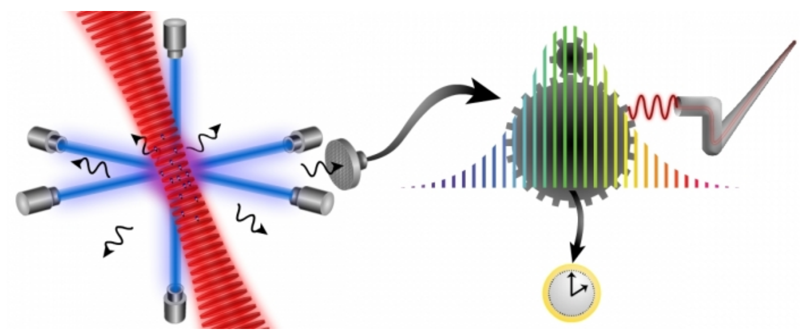


Akerman, N; Navon, N; Kotler, S; Glickman, Y; Ozeri (2015)

Ion – neutral comparison

Neutral Sr bosons in optical lattices





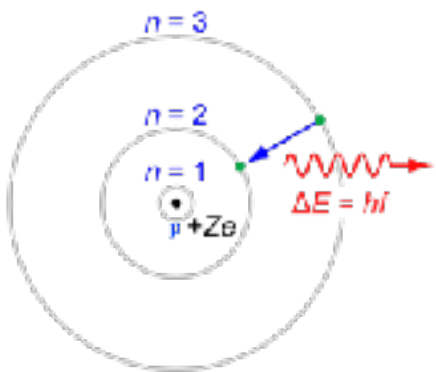
J. Ye group JILA, Science, 314, 1430 (2006)

Can we use fantastic precision to bound new interactions of above type ?

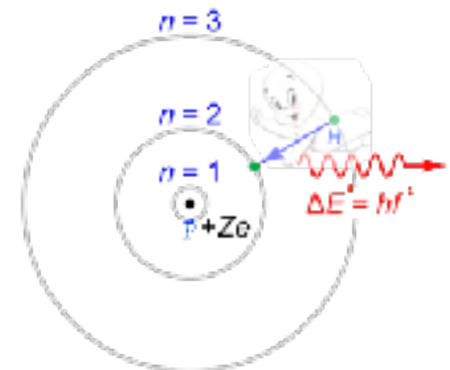
Main idea & Phenomenology (geometry) of Isotope-shifts (ISs) in atomic-clock spectroscopy

Basic concept: precision isotope shift spectroscopy

- New forces acts on electron & quarks leads to change of energy levels.



$$+ \quad \mathcal{L}_h = h\,(g_e \bar{e}e + g_q \bar{q}q)$$



$$\Delta\nu_h \sim 10^2\,\text{kHz} \times \frac{g_e g_n}{10^{-10}} \times \left(\frac{1\text{MeV}}{M_h}\right)^2 ,$$

Delaunay, Ozeri, GP & Soreq (16)

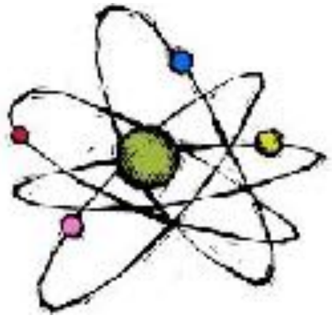
- We cannot switch on and off these light Higgs-like couplings.

- Use different isotopes to effectively compare force mass dependence.

- Suppress nuclear effects via 2 transition comparison => King Linearity.

King (1963)

Consider the following systems



$Ca^{(+)}$, $Sr^{(+)}$, $Yb^{(+)}$

1. Two narrow electronic transitions (< 10 Hz possibility) with the same nucleus;

2. At least four stable (even) isotopes without nuclear spin for three independent IS comparisons.

The observables

- We have 3 isotope shifts $(AA'_{1,2,3})$ for 2 transitions (i=1,2):

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

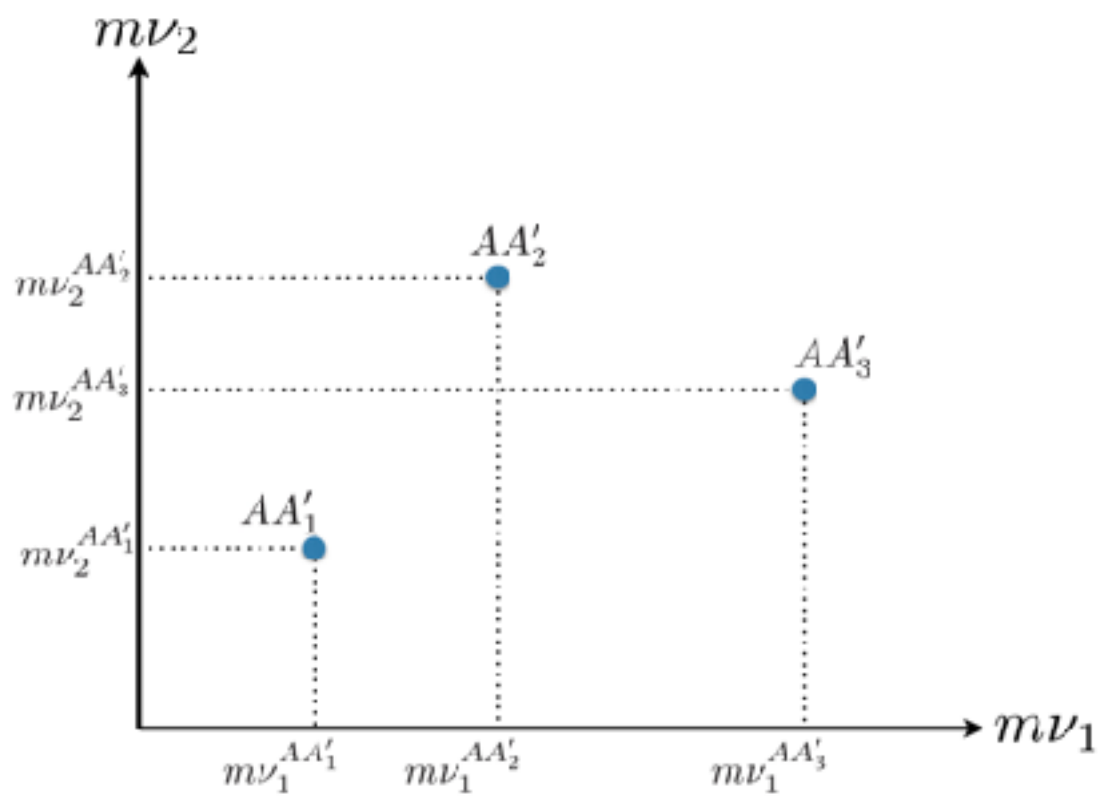
$$\nu_i^{AA'} \equiv \nu_i^{A} - \nu_i^{A'} . \qquad m\nu_i^{AA'} \equiv \nu_i^{AA'} / \mu_{AA'}$$

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

Target accuracy: $\Delta m\nu_i^{AA'} / m\nu_i^{AA'} \lesssim 10^{-6}$.
(currently: 10^{-4}, projected $< 10^{-9}$)

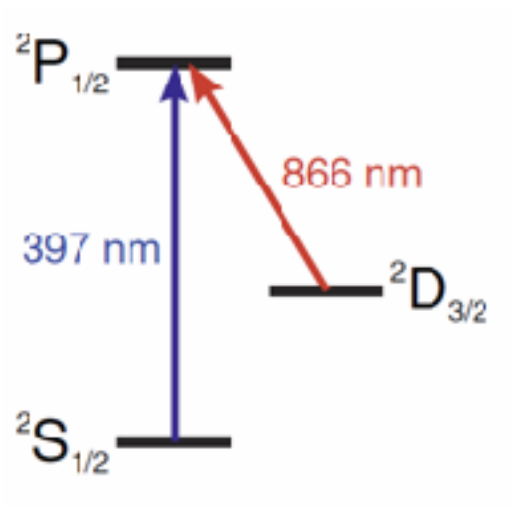
The observable: King comparison (1964)

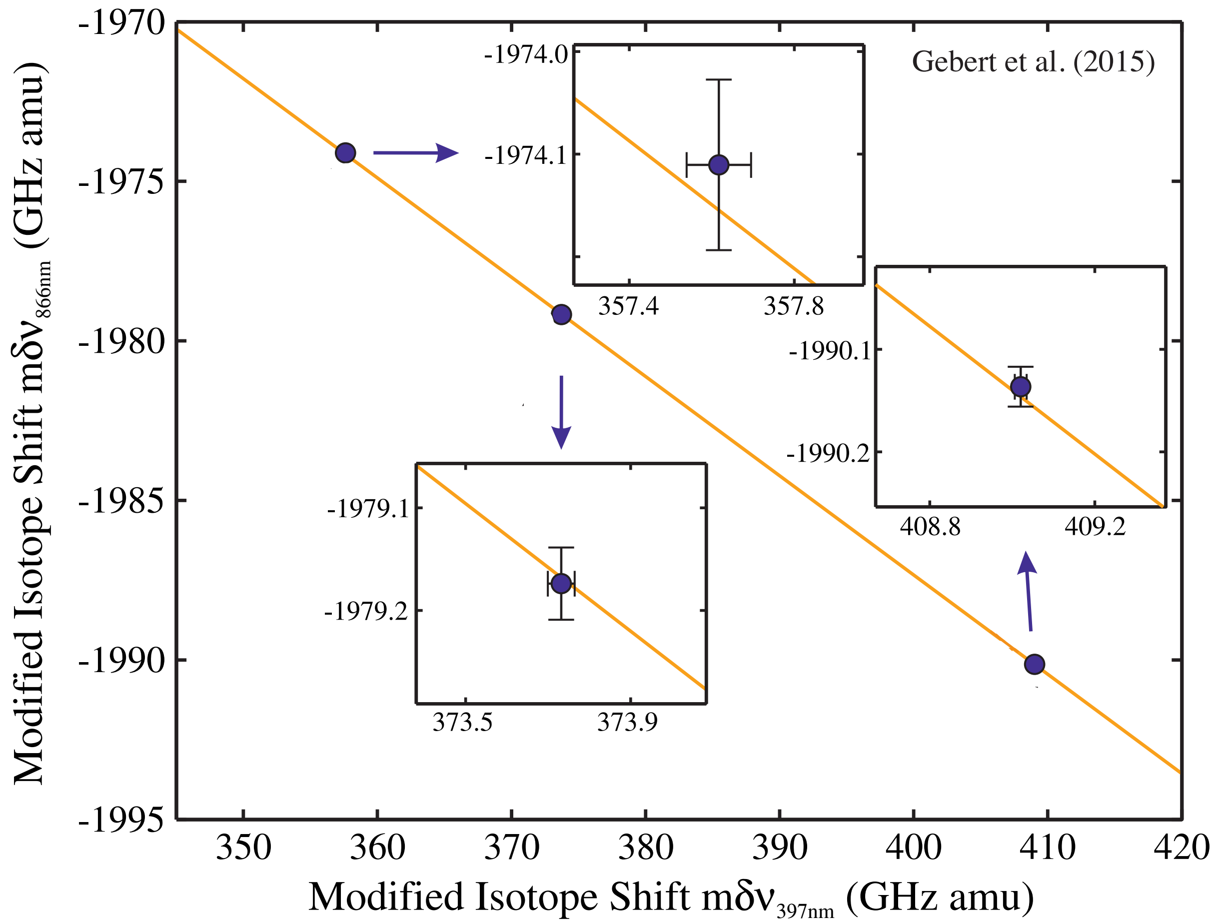
- What would be the generic form of $\overrightarrow{m\nu}_2$ vs. $\overrightarrow{m\nu}_1$?
- 3 ISs - $m\nu_2 = am\nu_1^2 + bm\nu_1 + c$:



What about existing data ?

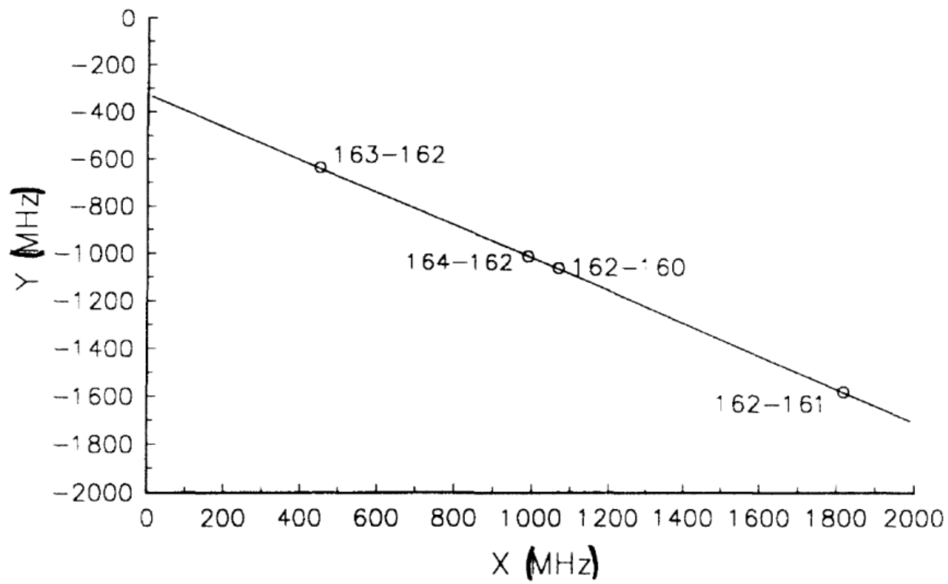
State of the art: King Linearity holds in Ca^+ (1:10^4)





No indication for King-linearity-violation (KLV), down to 100 kHz.

King Linearity in Dy



Dy King plot. Budker et al 1994

King-linearity-violation (KLV) seem to be suppressed in variety of systems.

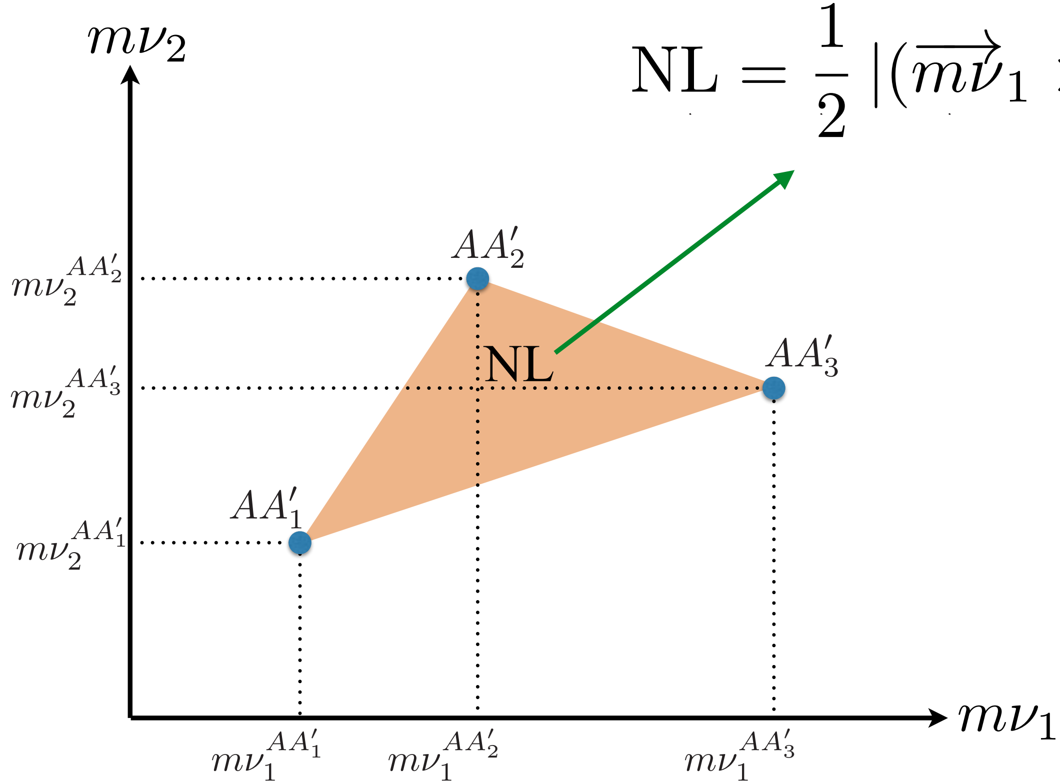
$$m\nu_2 = am\nu_1^2 + bm\nu_1 + c \quad \Longrightarrow \quad a \text{ is very small!}$$

King comparison

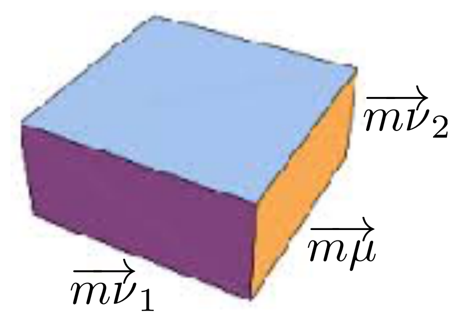
- Level of linearity can be quantified by comparing area of triangle to that of a cube: $\mathrm{NL}/|\overrightarrow{m\nu}_2||\overrightarrow{m\nu}_1| \ll 1\,.$

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

$$\mathrm{NL} = \frac{1}{2}\left|(\overrightarrow{m\nu}_1 \times \overrightarrow{m\nu}_2)\cdot\overrightarrow{m\mu}\right|\,.$$



Or volume of prallelepiped:



King linearity implications

◆ Linearity implies that $\overrightarrow{m\nu}_2$ & $\overrightarrow{m\nu}_1$ must be linearly dependent:

$$\overrightarrow{m\nu}_2 = K_2\,\overrightarrow{m_\mu} + F_2\,\vec{v} + \mathcal{O}\left(10^{-4}\right)$$
$$\overrightarrow{m\nu}_1 = K_1\,\overrightarrow{m_\mu} + F_1\,\vec{v} + \mathcal{O}\left(10^{-4}\right)$$

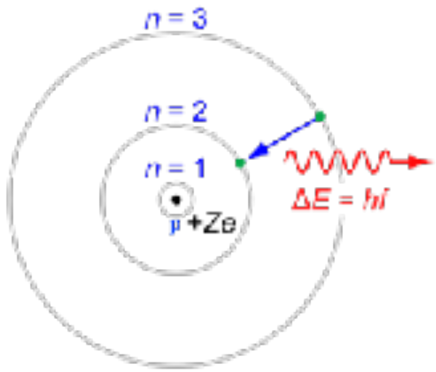
$$\overrightarrow{m\nu}_2 \cong K_{21}\,\overrightarrow{m\mu} + F_{21}\,\overrightarrow{m\nu}_1\,,$$

$$\text{with } F_{21} \equiv F_2/F_1 \text{ and } K_{21} \equiv K_2 - F_{21}K_1\,.$$

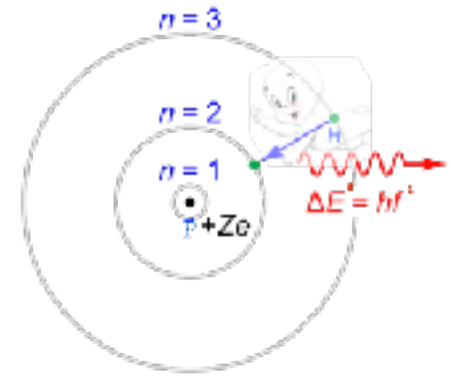
F_i & $\vec{v}$ are unknown but F_{21} & K_{21} can be measured precisely.

Adding light new physics (NP)

New forces acts on electron & quarks leads to change of energy levels.



$$+ \quad \mathcal{L}_\phi = \phi(y_e \bar{e} e + y_n \bar{n} n)$$



- New physics part known, precisely calculated:

CI+MBPT: Dzuba, Flambaum & Kozlov (96) Berengut, Flambaum & Kozlov (06);
GRASP2K: Jonsson, Gaigalas, Biero, Fischer & Grant (2013)

(Combination of the many-body perturbation theory with the configuration-interaction method)

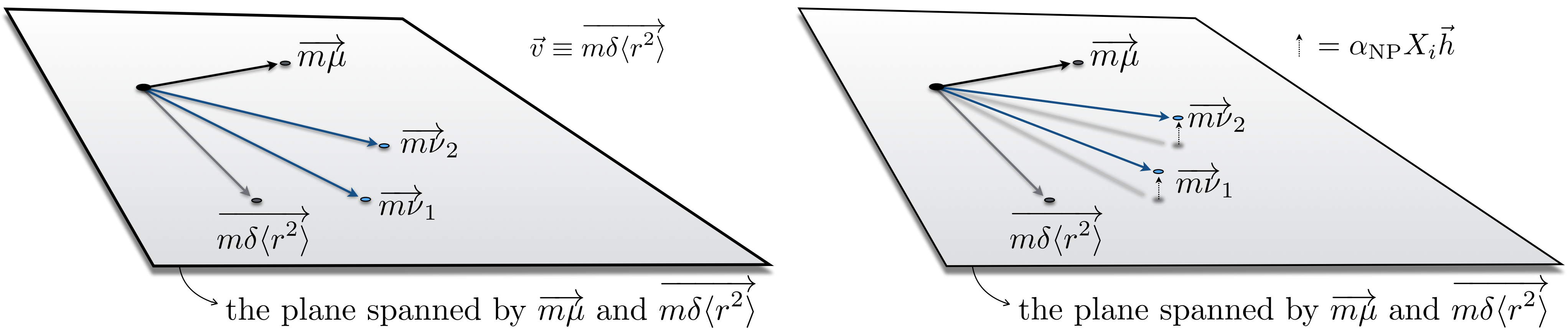
$$\overrightarrow{m\nu}_i = K_i \, \overrightarrow{m_\mu} + F_i \, \vec{v} + \boxed{y_e y_n X_i \vec{h}},$$

Delaunay, Ozeri, GP & Soreq (16)

$$\overrightarrow{m\nu}_2 = K_{21} \overrightarrow{m\mu} + F_{21} \overrightarrow{m\nu}_1 + \alpha_{\rm NP} \vec{h} X_1 \left(X_{21} - F_{21}\right) ,$$

and $X_{21} \equiv X_2/X_1$.

Illustration: adding light new physics (NP)



Limitation of method

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

Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, GP & Soreq (17)

- Only useful to bound new physics (barring cancellation).
- Short range NP: $X_i \propto F_i \;\Rightarrow\; \vec{v}$ is redefined to absorb NP; requires extra carefulness when approaching this limit.
- As long as linearity holds bounds are limited by exp' accuracy:

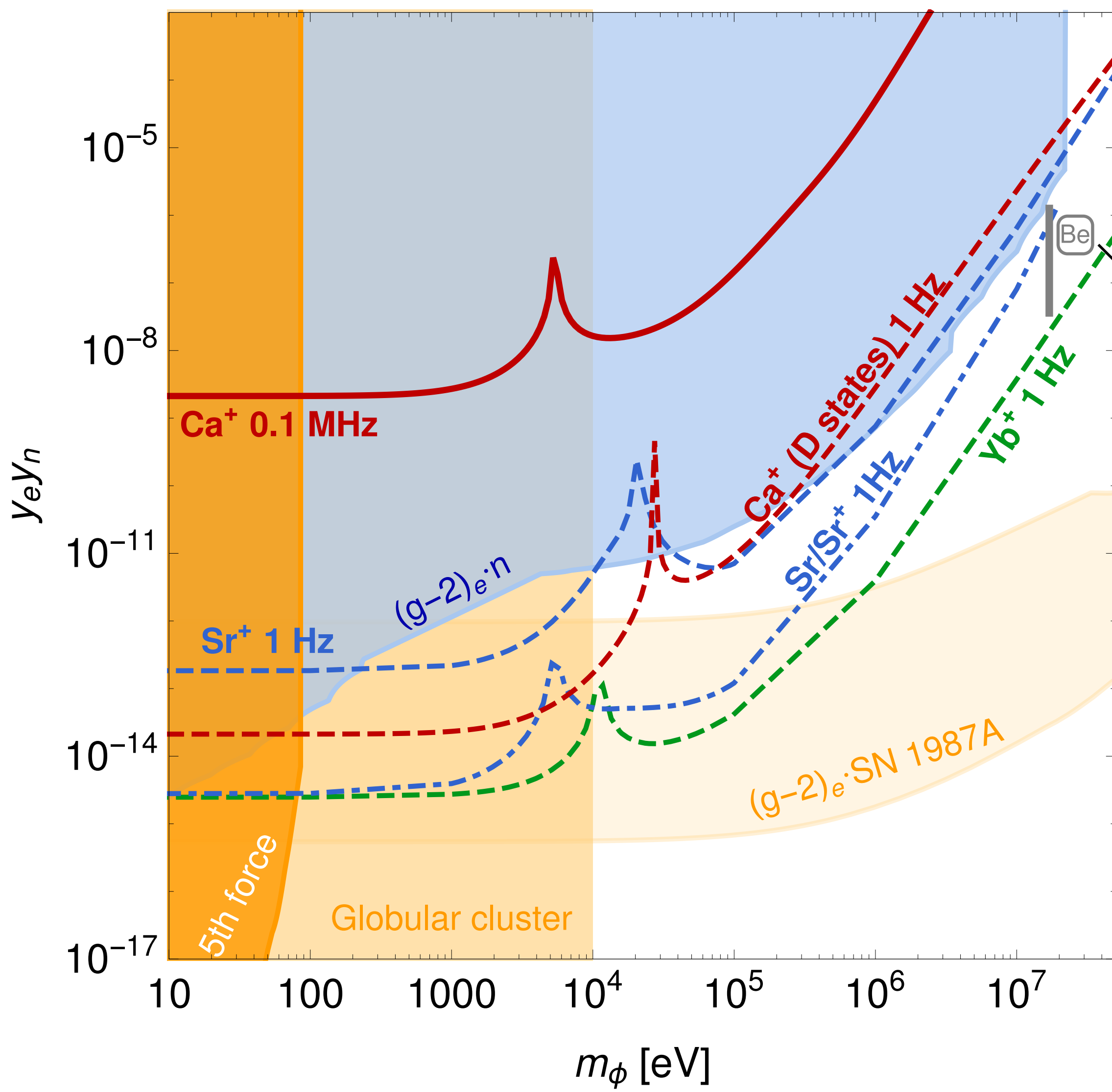
$$\alpha_{\rm NP} \lesssim \sigma_{\alpha_{\rm NP}} = \sqrt{\Sigma_k (\partial\alpha_{\rm NP}/\partial O_k)^2 \sigma_k^2}\,,$$

$(O_K$ various exp' observables.$)$

- Once non-linearity observed bound will be set by observation.

Bounds & sensitivity

Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, GP & Soreq (17)

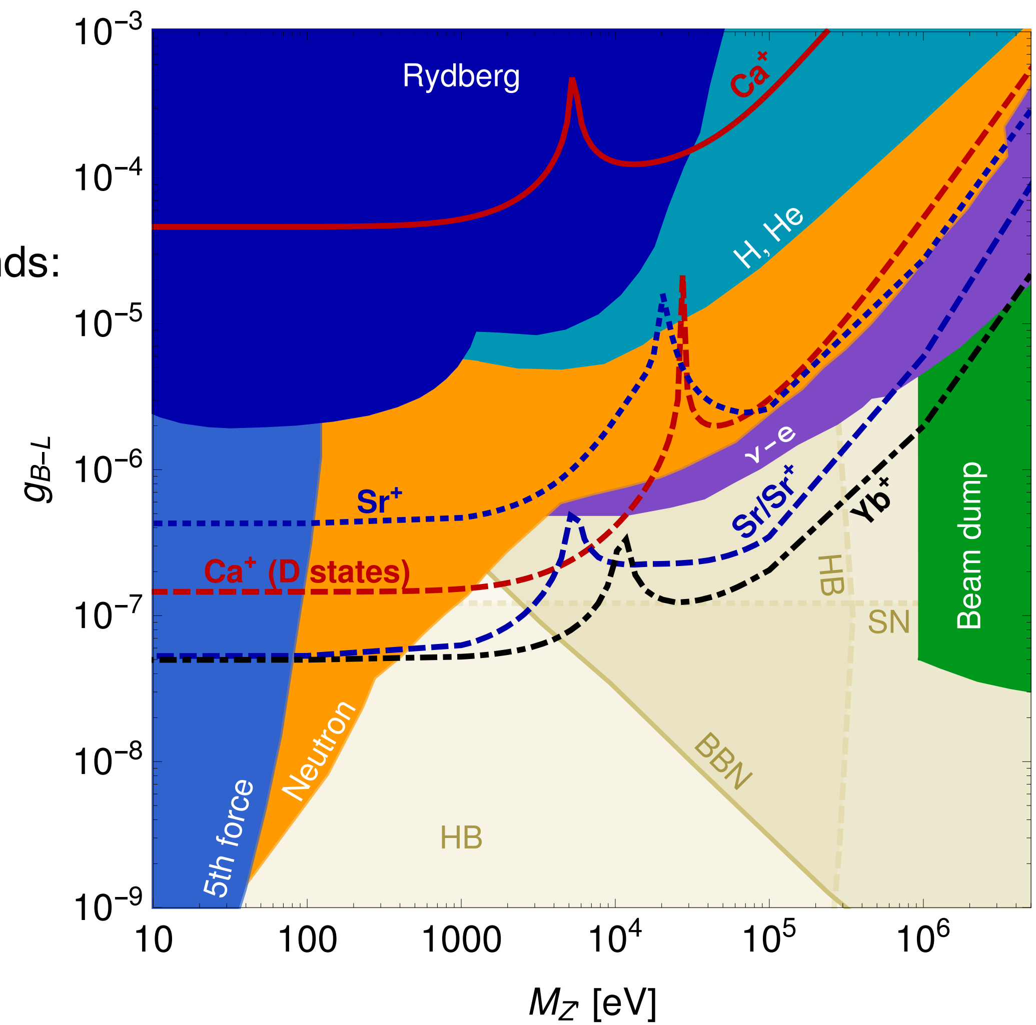


See e.g. Feng et al. (16)

$U(1)_{B-L}$

Frugiuele, Fuchs, GP & Schlaffer (16)

Complementarity with astro/cosmo' bounds:



non-univ. Higgs portal

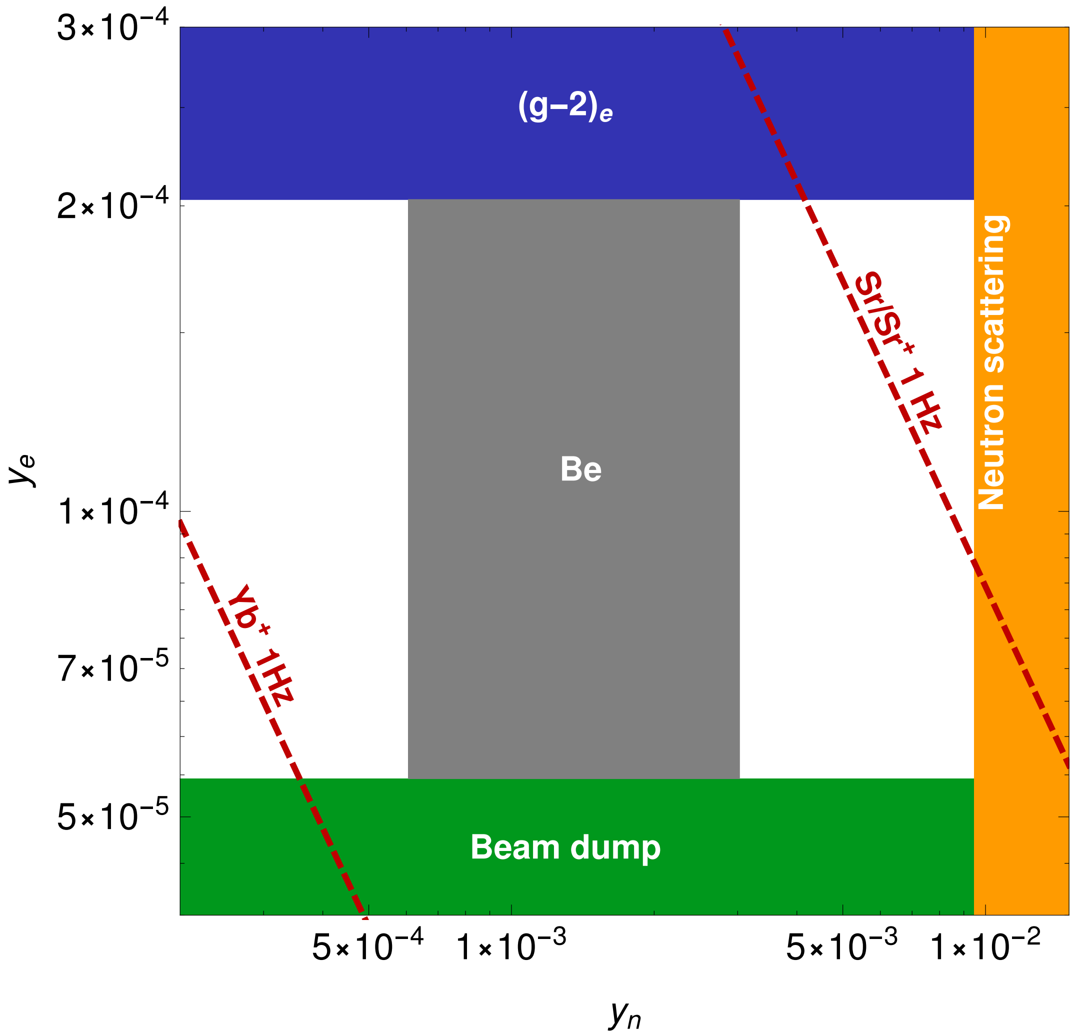
Frugiuele, Fuchs, GP & Schlaffer v2 (16)

$$\sin^2\theta_{h\phi} \lesssim 2\cdot 10^{-6} \;\cdot\; \left[\frac{4\cdot 10^{-9}}{y_e y_n}\right] \frac{\sigma}{\mathrm{Hz}}\,,$$

Factor of 10 away from relaxion/Higgs portal bound.

Be 17 MeV anomaly

Frugiuele, Fuchs, GP & Schlaffer v2 (16)



Conclusions

- Proposal to probe light forces via precision spectroscopy.

- Sensitivity seems to probe interesting ranges.

- Experimental measurements: Mainz, PTB, Weizmann …

- Precision will be improved by 5 orders of mag.

- Current theory close to predict non-linearities.

Backups

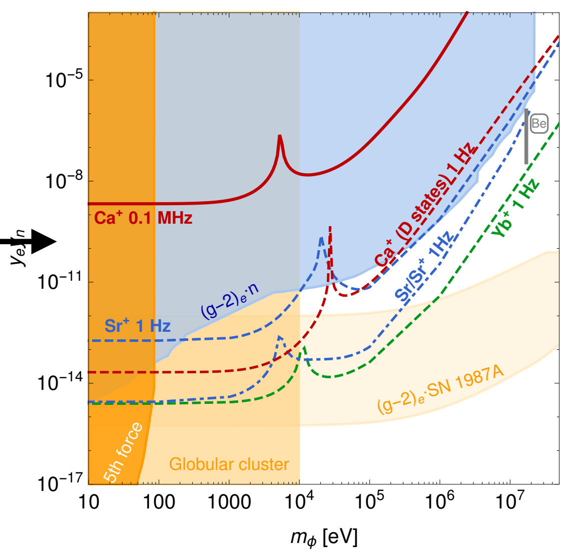
Light mediators

If mediator's mass, m_X, is smaller than inverse of outer electrons than the potential is Coulombic.

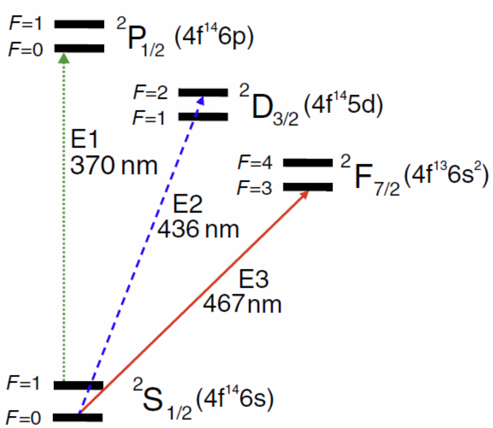
If mediator's mass is smaller than inverse distance of most inner electron from the nucleus then the full Yukawa potential is required.

Otherwise the potential is described via a delta function.

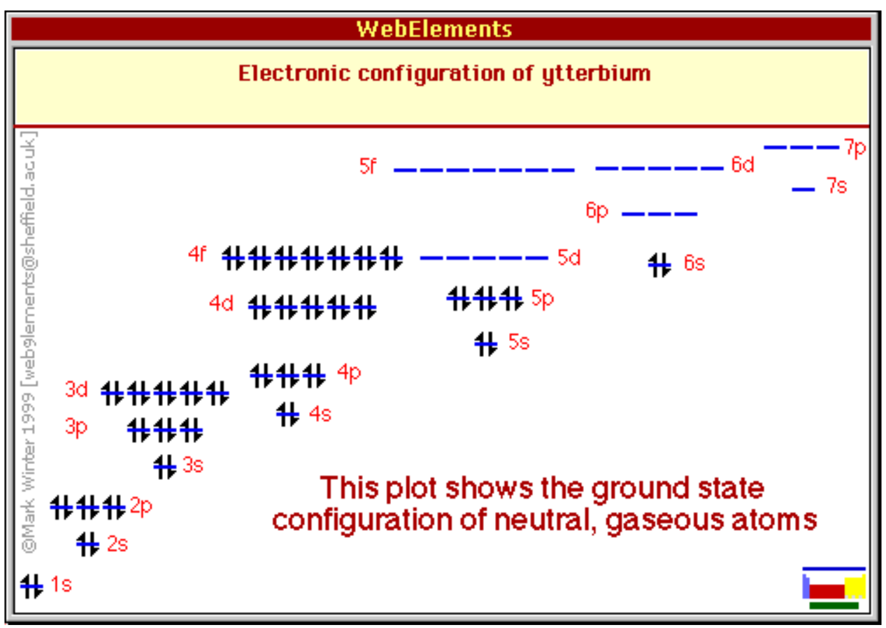
$$V(r) = \begin{cases} \dfrac{1}{r} \quad \text{for} \quad m_X \lesssim \alpha m_e \,, \\[2ex] \dfrac{e^{-r m_X}}{r} \quad \text{for} \quad \alpha m_e \lesssim m_X \lesssim \alpha m_e Z \,, \\[2ex] \dfrac{1}{m_X^2}\, \delta^3(r) \quad \text{otherwise} \,. \end{cases}$$



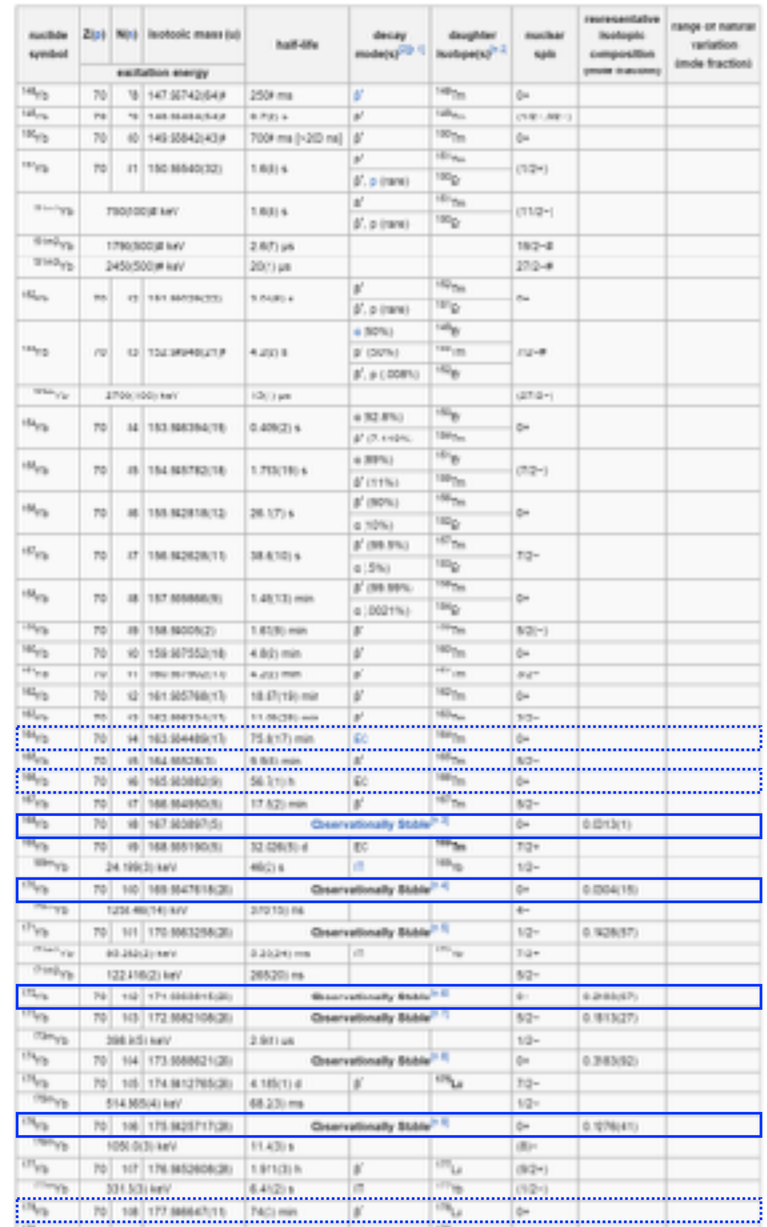
Ex.: Yb^+ with Z=70, n=6 and A=168(4)-174(6).



The Kossel shell structure of ytterbium.



The electronic configuration of ytterbium.



Precision mass measurements: 10^{-10}

Contents lists available at ScienceDirect

International Journal of Mass Spectrometry

journal homepage: www.elsevier.com/locate/ijms

The most precise atomic mass measurements in Penning traps

Edmund G. Myers*

Florida State University, Department of Physics, Tallahassee, FL 32306-4350 USA

Table 10
Atomic masses of the most abundant isotopes of strontium and ytterbium measured at FSU [109].

Atom	FSU mass (u)	σ_m/m (ppt)
^{86}Sr	85.909 260 730 9(91)	105
^{87}Sr	86.908 877 497 0(91)	105
^{88}Sr	87.905 612 257 1(97)	110
^{170}Yb	169.934 767 241(18)	105
^{171}Yb	170.936 331 514(19)	110
^{172}Yb	171.936 386 655(18)	105
^{173}Yb	172.938 216 213(18)	105
^{174}Yb	173.938 867 539(18)	105
^{176}Yb	175.942 574 702(22)	125

Partial solution, comparing different isotope shift, searching of nonlinearity in "King plot"

King's factorisation formula (King, 1963):

only depend on e-transition

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

($\mu_{AA'} \equiv 1/m_A - 1/m_{A'} = (A' - A)/(AA')\,\mathrm{amu}^{-1}$, where amu ≈ 0.931 GeV)

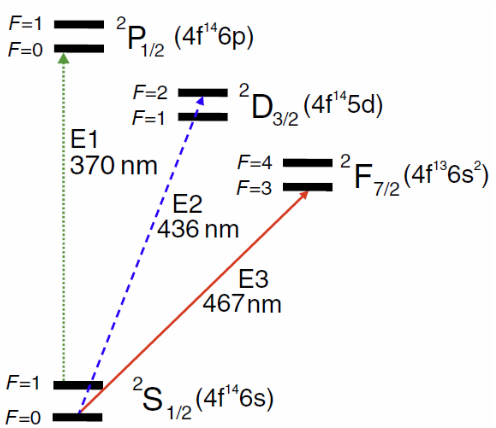
only depend on nucleus

We can solve for $\delta\langle r^2\rangle_{AA'}$ to get a linear relation:

$$\boxed{m\delta\nu^2_{AA'} = F_{21} m\delta\nu^1_{AA'} + K_{21}\,,}$$

(with $K_{21} \equiv (K_2 - F_{21}K_1)$ and $F_{21} \equiv F_2/F_1$ and $m\delta\nu^i_{AA'} \equiv \delta\nu^i_{AA'}/\mu_{AA'}$.)

Ex.: Yb^+ with Z=70, n=6 and A=168(4)-174(6).



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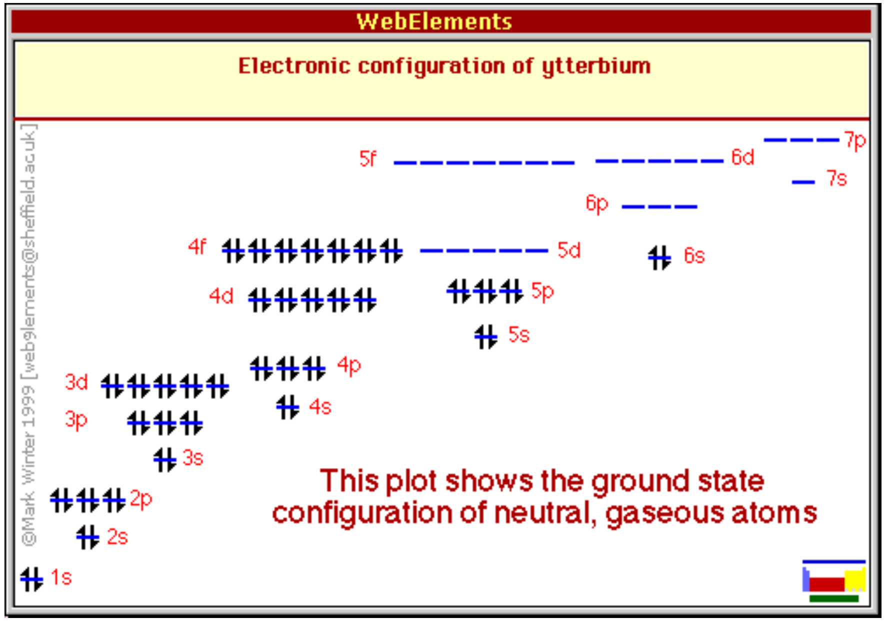

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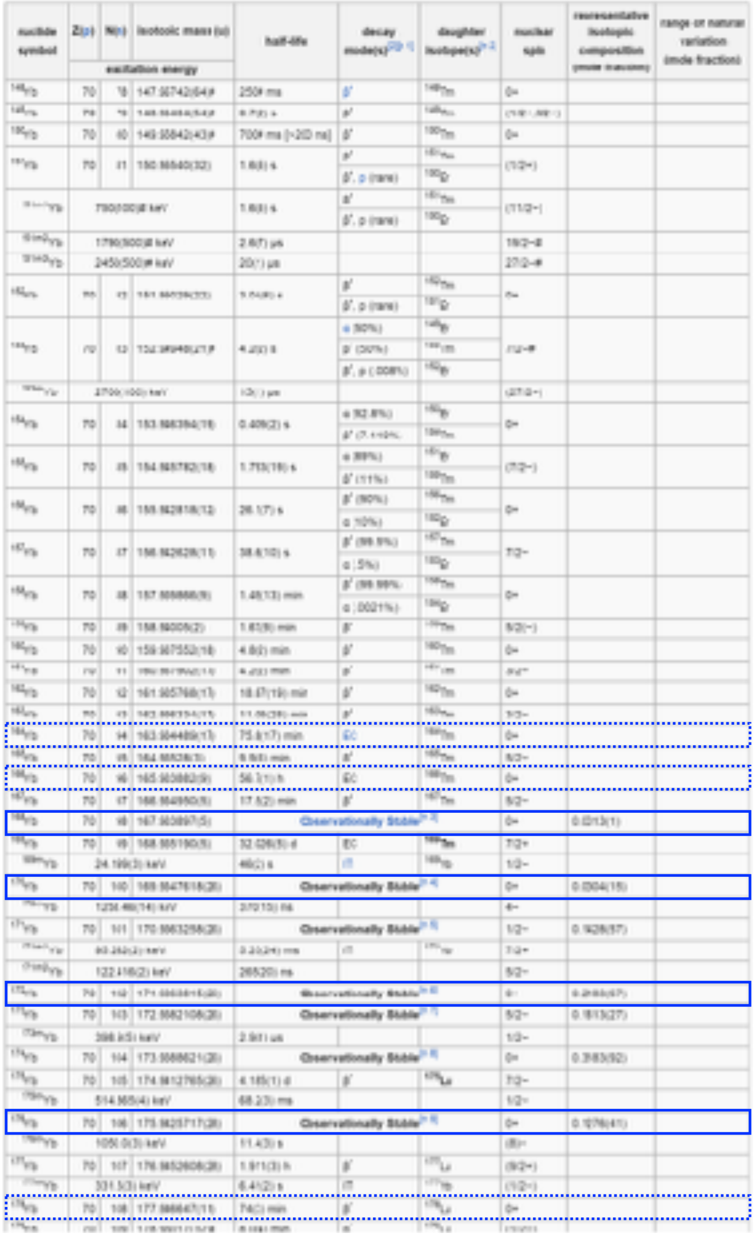
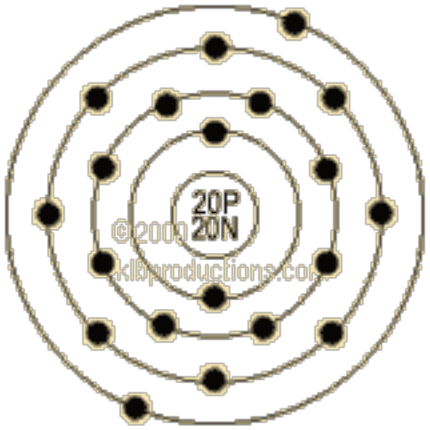


Ex.: $Sr^{(+)}$ with Z=38, n=5 and A=84-88 (90).

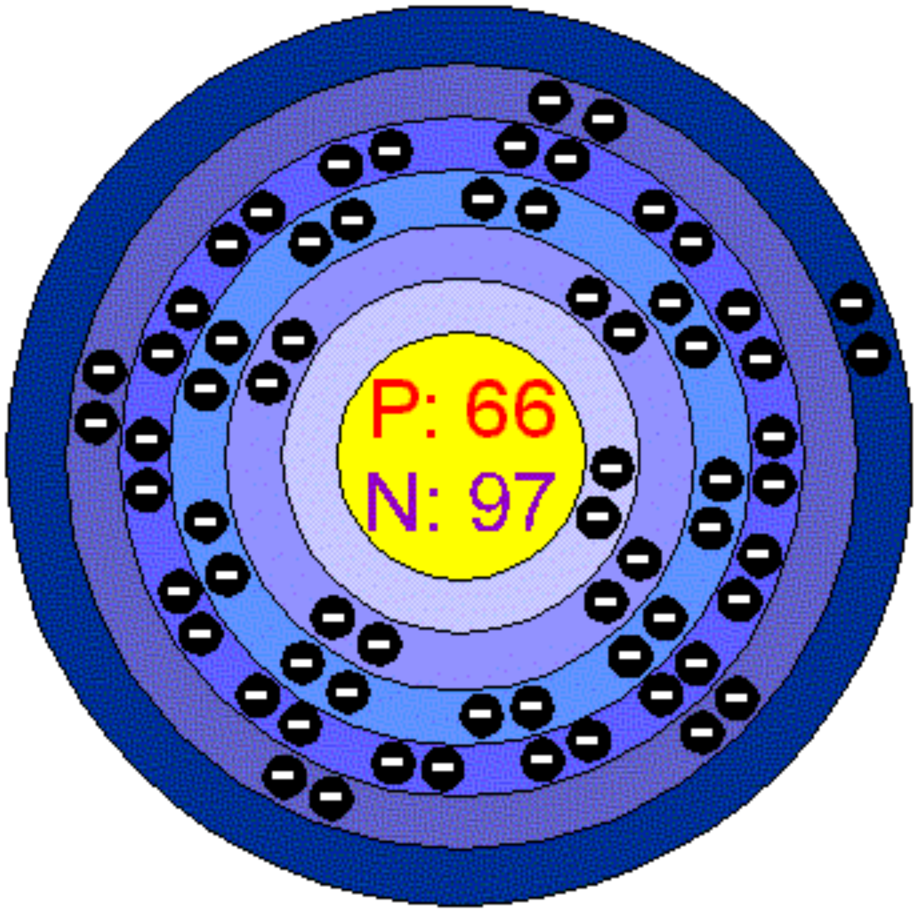
- **Electron Configuration:** $1s^2\ 2s^2p^6\ 3s^2p^6d^{10}\ 4s^2p^6\ 5s^{2(1)}$
- **Electrons per Energy Level:** 2,8,18,8,2(1)

Ex.: $Ca^{(+)}$ with Z=20, n=4 and A=40-48.

- **Electron Configuration:** $1s^2\ 2s^2p^6\ 3s^2p^6\ 4s^1$
- **Electrons per Energy Level:** 2,8,8,2(1)
-



Ex.: Dy with Z=66, n=6 and A=158-164.



Number of Energy Levels: 6
First Energy Level: 2
Second Energy Level: 8
Third Energy Level: 18
Fourth Energy Level: 28
Fifth Energy Level: 8
Sixth Energy Level: 2