Precision frontier, brief status report

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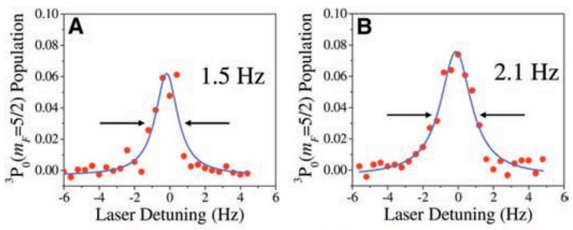
BGU-HU-WIS Inst.

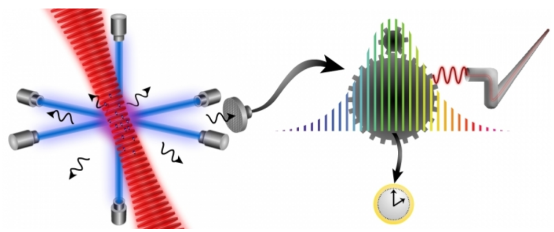
European Strategy for Particle Physics, Israeli Input, Town Hall meeting

Intro: 3 examples to the power of precision

Ex. 1:

Neutral Sr bosons in





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

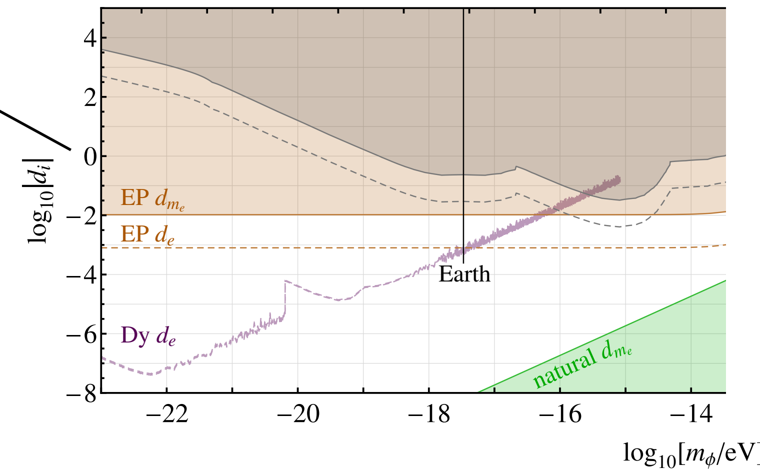
Relative accuracy: few 10^{-18}; few mHz on top of 10^{15} Hz

Equivalent principle tests probe

forces weaker than gravity!

Ex. 2:

Arvanitaki, Dimopoulos, Van Tilburg; Kaplan, Mardon, Rajendran & Terrano (16)



$$\mathcal{L}_{\rm int} \supset -\sqrt{4\pi G_N}\,\phi\left[d_{m_e} m_e \bar{e} e - \frac{d_e}{4} F_{\mu\nu}F^{\mu\nu}\right],$$

where G_N is Newton's constant.

Ex. 3:

ACME: electron electric dipole moment, $|d_e| < 1.1\times10^{-29}$ e · cm @ 90% CL.
Set for instance following bound on composite Higgs models:

ACME, Nature (2018)

$$\frac{d_e}{e} \sim \frac{1}{8\pi^2}\frac{m_e}{f^2} \quad \Rightarrow \quad f \gtrsim 107 \text{ TeV}$$

Panico, Pomarol & Riembau (18)

(Even though we expect $f <$ TeV)

Brief th. introduction

♦ Conventional particle-TeV-physics wisdom is challenged by the null results of the LHC experiments.

♦ Indirect searches often probe higher physics scales.

♦ New paradigms recently proposed suggest alternative solutions.

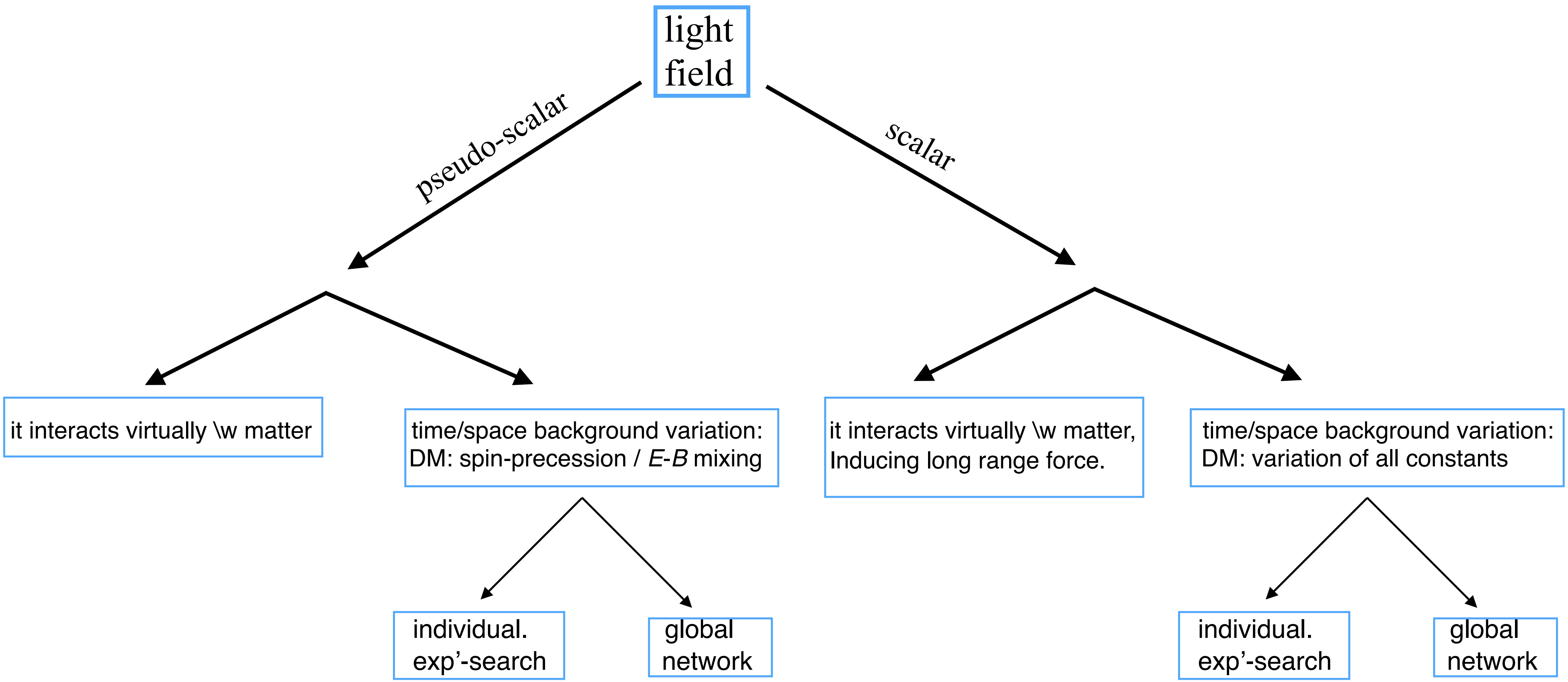
"Cosmic attractors", "dynamical relaxation", "N-naturalness", "relating the weak-scale to the CC" & "inflating the Weak scale".

♦ Presence of light scalar/s is common to most.

♦ In addition we have the well known motivations for light pseudo scalars ("axions") and light moduli/diltaon scalar particles.

Search strategies light scalars vs. pseudo-scalars

Scalars & pseudo-scalars lead to different signatures; thus, generically requires different experimental setup.

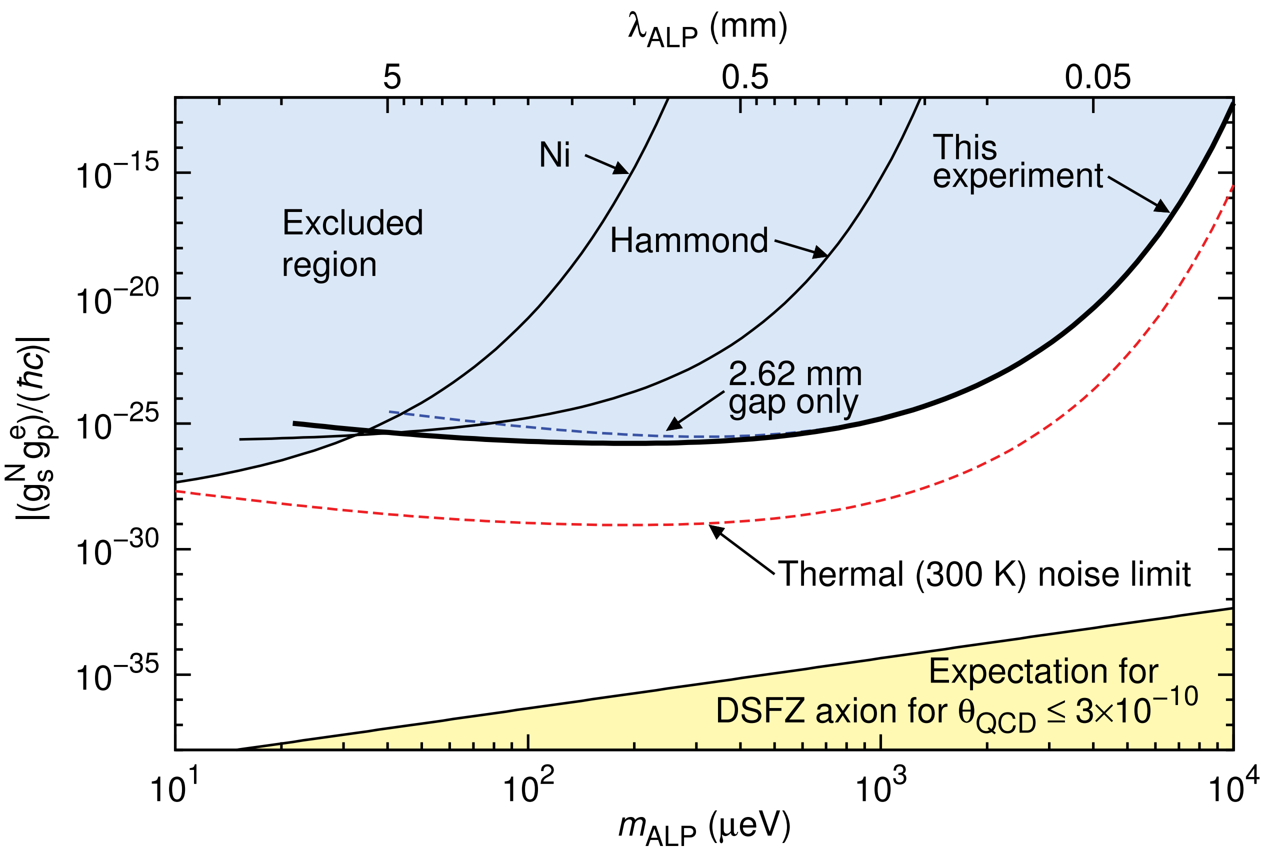


Axions got more attention, partially because scalars have less th. motivation & also due to lack of benchmarking [*cf* celebrated QCD dark matter (DM) axion].

“Improved Constraints on an Axion-Mediated Force”

Hoedl, Fleischer, Adelberger & Heckel (2011)

Low mass pseudoscalars, such as the axion, can mediate macroscopic parity and time-reversal symmetry-violating forces. We searched for such a force between polarized electrons and unpolarized atoms using a novel, magnetically unshielded torsion pendulum. We improved the laboratory bounds on this force by more than 10 orders of magnitude for pseudoscalars heavier than 1 meV and have constrained this force over a broad range of astrophysically interesting masses.



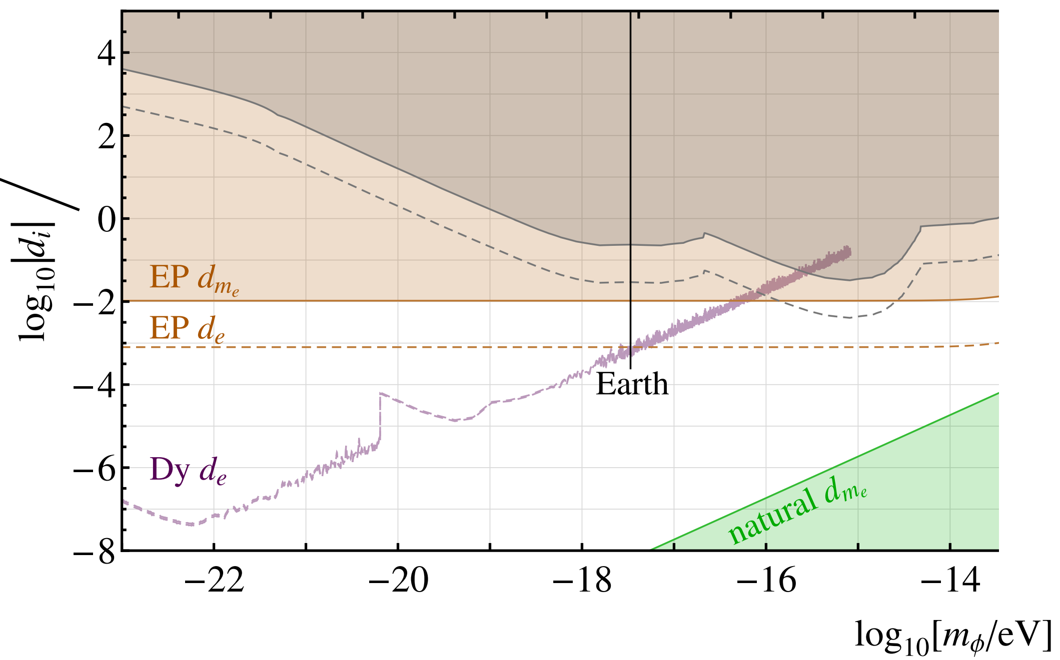
$$V(\hat{\boldsymbol{\sigma}}, \boldsymbol{r}) = \frac{\hbar^2(\hat{\boldsymbol{\sigma}} \cdot \hat{\boldsymbol{r}})}{8\pi m_e}\left(\frac{g_s^a g_p^e}{\hbar c}\right)\left(\frac{1}{r\lambda_{\mathrm{ALP}}} + \frac{1}{r^2}\right)e^{-r/\lambda_{\mathrm{ALP}}},$$

where $\boldsymbol{r}$ is the electron-atom separation vector, $\lambda_{\mathrm{ALP}} = m_{\mathrm{ALP}}/\hbar c$ is the ALP Compton wavelength, and $\hat{\boldsymbol{\sigma}}$ and m_e are the spin unit vector and mass of the polarized electron, respectively.

Scalar 5th force, already discussed

Equivalent principle tests probe

forces weaker than gravity!



$$\mathcal{L}_{\rm int} \supset -\sqrt{4\pi G_N}\phi\left[d_{m_e} m_e \bar{e}e - \frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}\right],$$

where G_N is Newton's constant.

The DM front

Looking for oscillating light dark matter

$$\text{Sorry}: \quad a(t) \equiv \phi(t) = \sqrt{\frac{2\rho_{\text{DM}}}{m_a}}\cos(m_a t)$$

light DM

E&M - drive currents

$a\,F\tilde{F}$

Conventional axion searches

(e.g. ADMX)

QCD - change nuclear properties

$a\,G\tilde{G}$

New searches, CASPEr ...

spin - cause precession

$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$

scalar - new force/SM properties

$aH^\dagger H$ (mixing \w Higgs)

Looking for oscillations of

coupling constants & masses.

Ideal for atomic clocks.

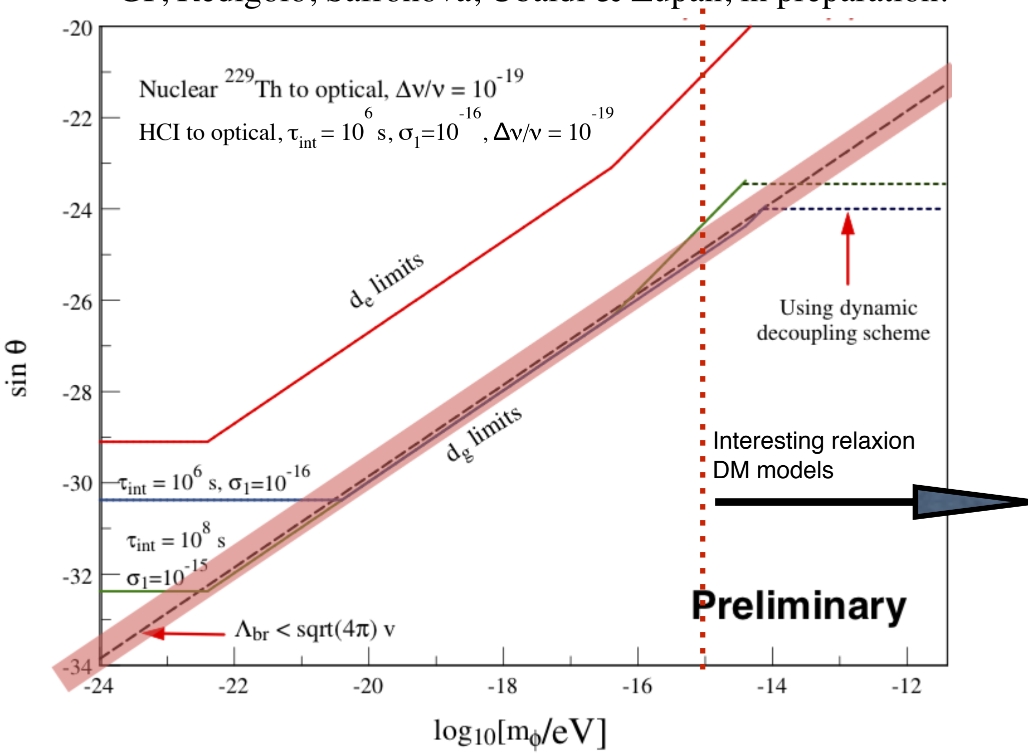
Peter Graham, SSI, Stanford (17)

Searching for scalar DM that mixes \w Higgs via atomic clocks

Scenario motivated by relaxion DM models.

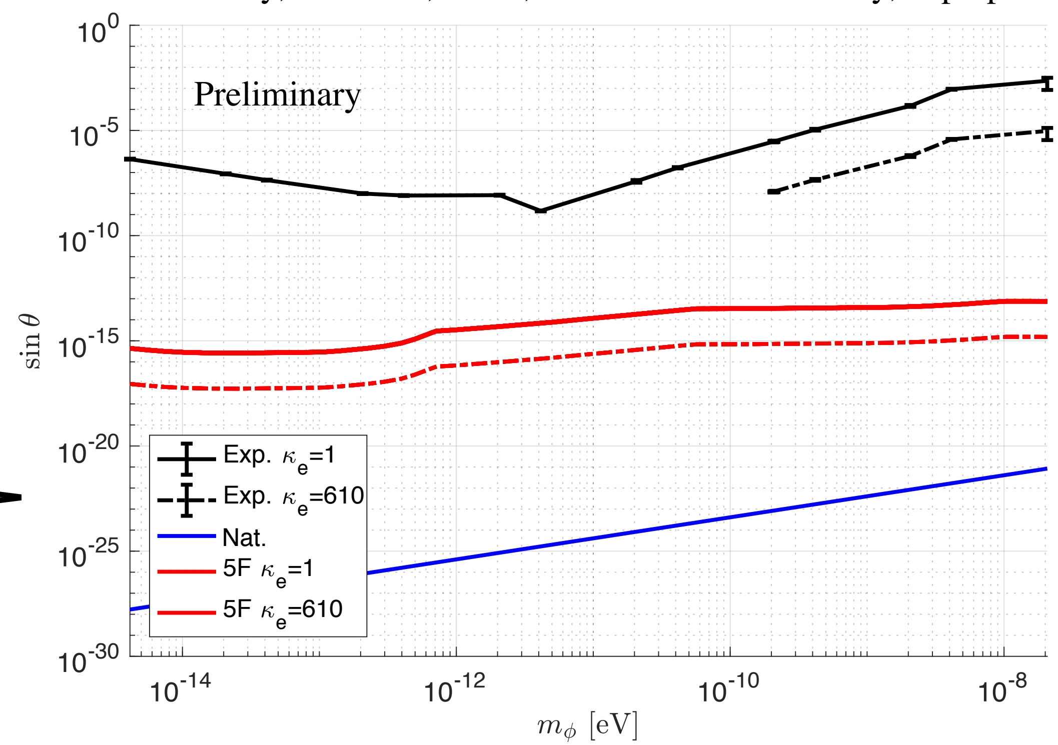
`Graham, Kaplan & Rajendran (15);Flacke, Frugiuele, Fuchs, Gupta & GP; Choi & Im (16); Banerjee, Kim & GP (18)`

GP, Redigolo, Safronova, Ubaldi & Zupan, in preparation.



d_e stands for the time dependent component of the fine coupling constant, the bound on d_g (the coefficient of the time dependent component of α_s, the strong coupling) assumes a working ^{229}Th nuclear clock with a $1:10^{19}$ precision, τ_{int} stands for the total assumed integration time and σ_1 stands for the corresponding stability. The dashed-red line on the diagonal corresponds to the maximal mixing allowed in this scenario, Λ_{br} corresponds to a coupling in the relaxion model.

Aharony, Akerman, Ozeri, GP & Shaniv & Savoray, in prep.



Recasting last year results, ion-cavity comparison, Ozeri-lab @ $1:10^{14}$ accuracy can be improved dramatically.

DM global-networking

Global Network of Optical Magnetometers for Exotic (GNOME): Physics Novel scheme for exotic physics searches

S. Pustelny, D. F. Jackson Kimball, C. Pankow, M. P. Ledbetter, P. Wlodarczyk, P. Wcislo, M. Pospelov, J. Smith, J. Read, W. Gawlik, D. Budker (2013) One node in BGU (Folman's group)!

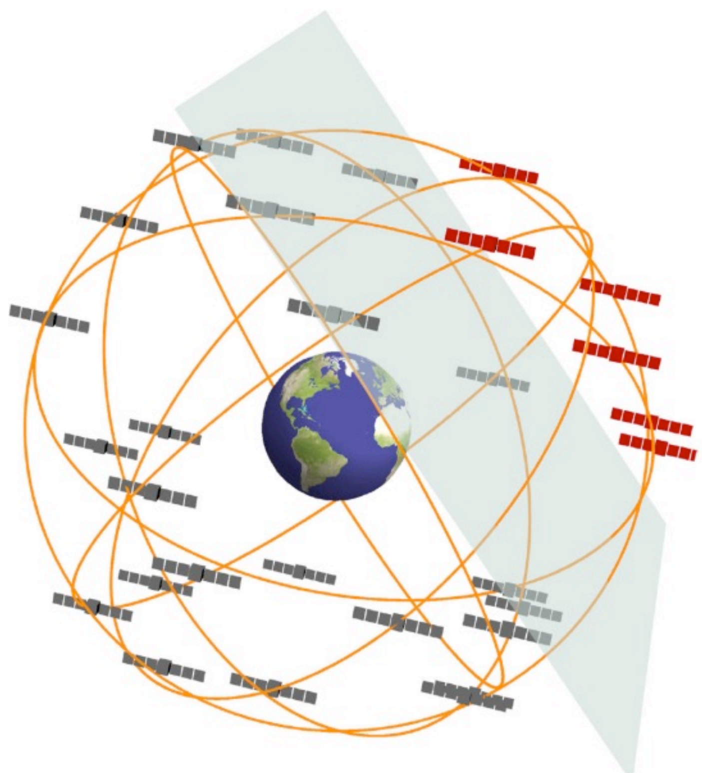
Comparison of a network of atomic clocks through GPS satellite data

ARTICLE

DOI: 10.1038/s41467-017-01440-4 OPEN

Search for domain wall dark matter with atomic clocks on board global positioning system satellites

Benjamin M. Roberts[1], Geoffrey Blewitt[1,2], Conner Dailey[1], Mac Murphy[1], Maxim Pospelov[3,4], Alex Rollings[1], Jeff Sherman[5], Wyatt Williams[1] & Andrei Derevianko[1]



One slide about SARAF

- New high-current accelerator in Israel.

- Dedicated lab space for the two trap experiments.

- Sensitive to β decay, constraint (well) below 1% level seems feasible.

  Below 0.1% => better than LHC.   Bhattacharya, et. al. (16)

- Can probe light new physics that couples to neutrons?

Conclusions

- Null-LHC + new paradigms => searches for light elusive fields!
- In parallel, precision front is seeing dramatic sensitivity-increase.
- Should be integrated into particle physics program.
- Ultra light DM searches can be done individually & via networks.
- Can we use SARAF to search for (light-mass) new physics?

Back to our 2 questions

(i) Notice that relevant models have osc. freq. 1 - 10^{14} Hz.
Can we probe these? 

(ii) Is the amplitude large enough to probe meaningful models?

However, gravity can help: dark matter might form "relaxion-planets" that might be trapped around earth-gravitational field.

Budker, Eby, Kim, GP, in Prep.

(similar to axion-stars requiring stability and assuming capturing & coherence)

Kimball, et al. (17)

Searching for a relaxion DM planet around us

Assume small DM density & large radius => mass-radii relation:

$$R_{\rm star} \approx \frac{M_{\rm Pl}^2}{m_\phi^2}\frac{1}{M_{\rm Earth}} \qquad (M_* \ll M_{\rm Earth})\,.$$

Eby, Leembruggen, Street, Suranyi & Wijewardhana (18);

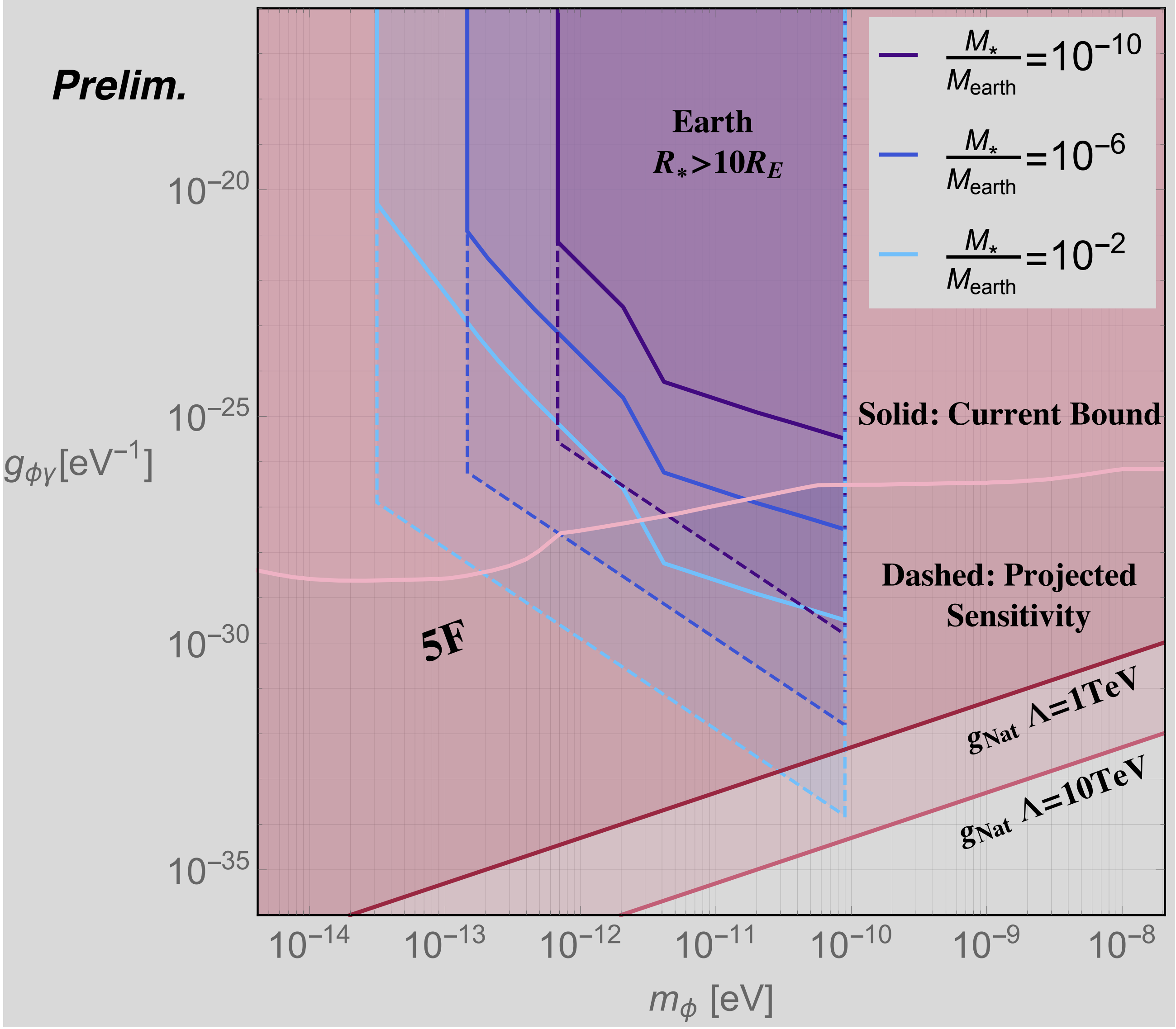
Budker, Eby, Kim, GP, in Prep.

Can obtain large density enhancement:

$$r \equiv \frac{\rho_{\rm star}}{\rho_{\rm loc-DM}} \sim \xi \frac{M_{\rm Earth}^4\, m_\phi^6}{M_{\rm Pl}^6\, \rho_{\rm loc-DM}} \sim \xi \times 10^{28} \times \left(\frac{m_\phi}{10^{-10}}\right)^6 \qquad \xi \equiv M_{\rm star}/M_{\rm Earth}$$

Large star DM density => visible effect

Aharony, Akerman, Ozeri, GP & Shaniv & Savoray, in prep. (ion-cavity comparison) Budker, Eby, Kim, GP, in Prep.



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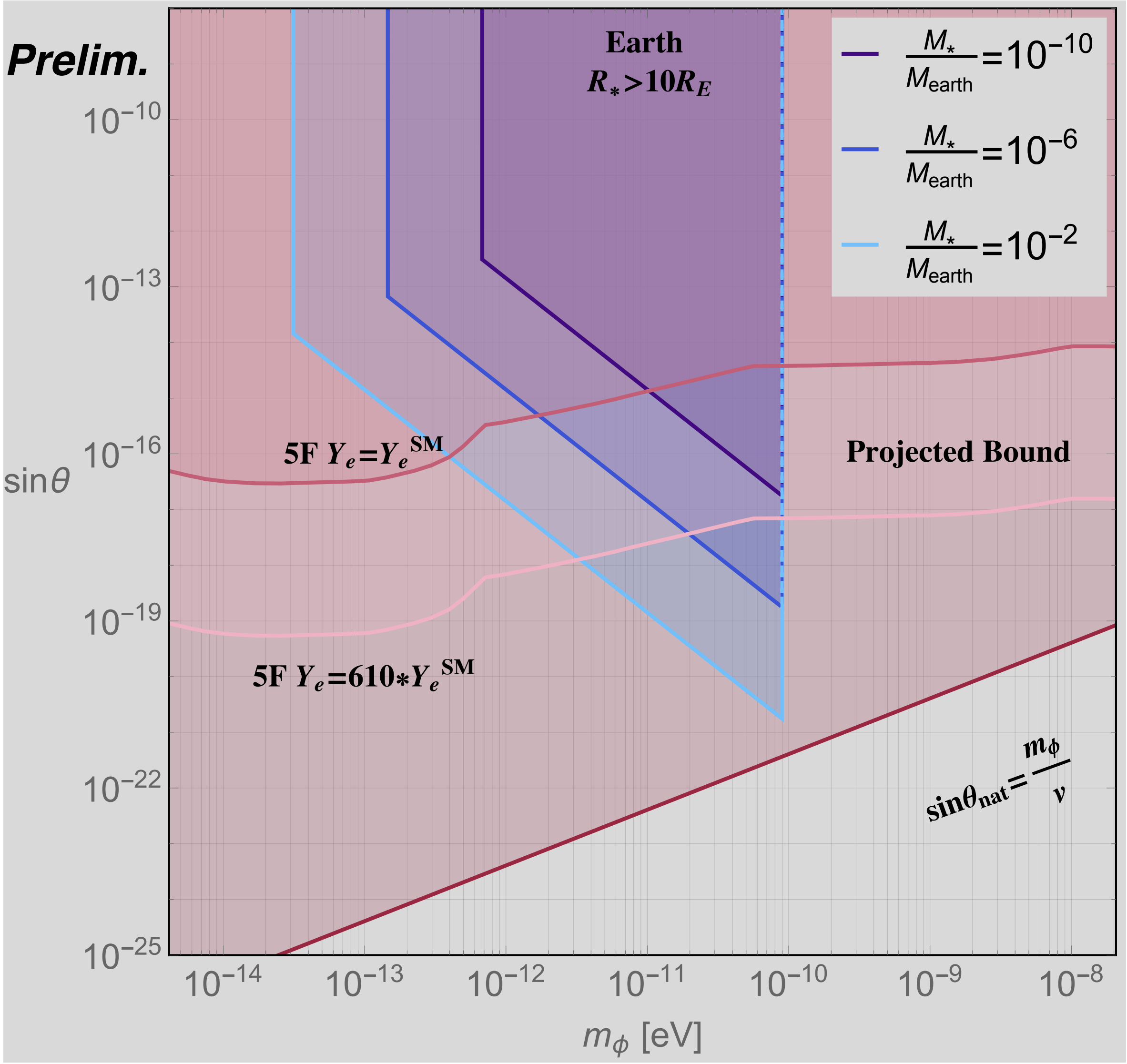

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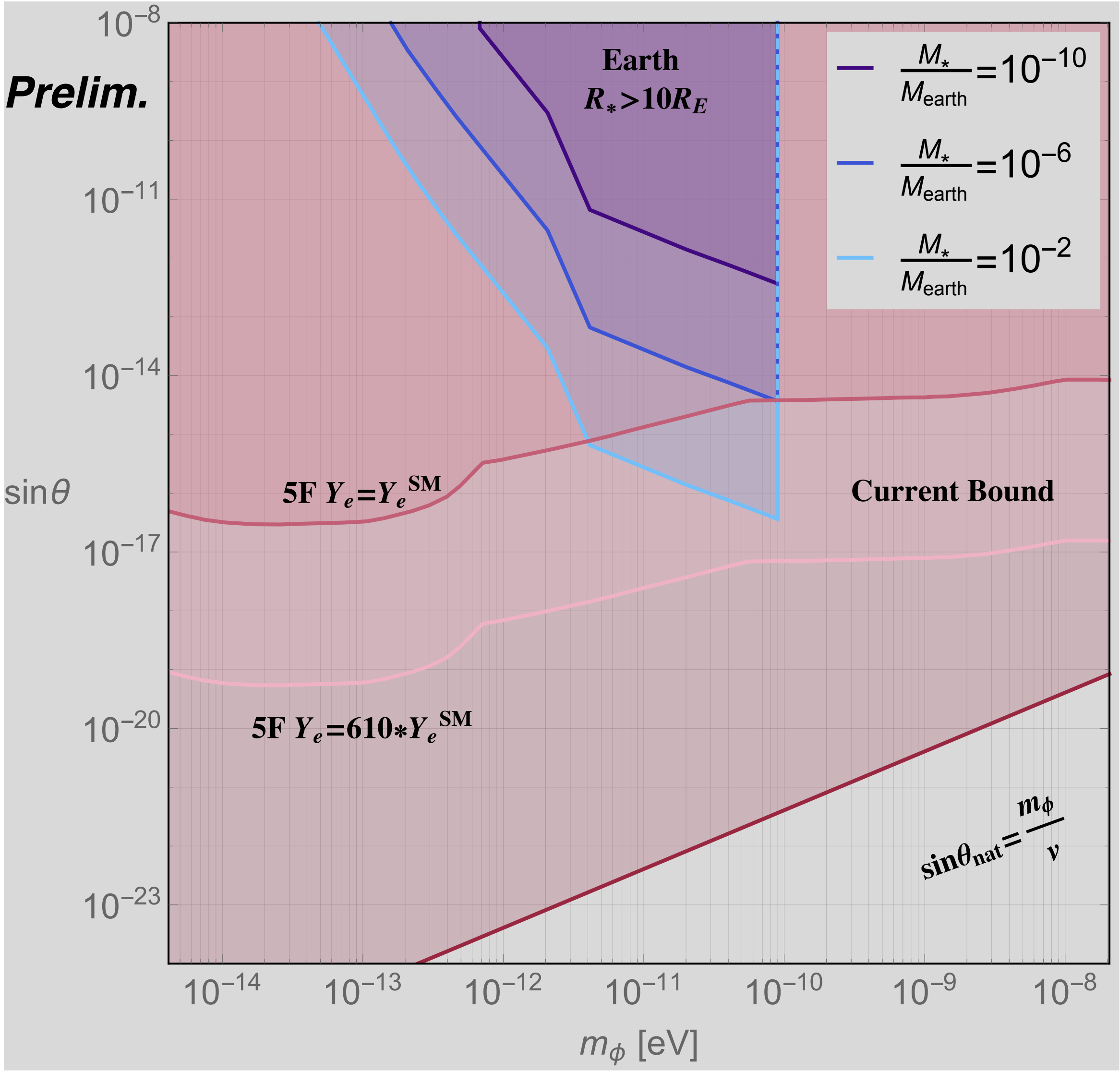
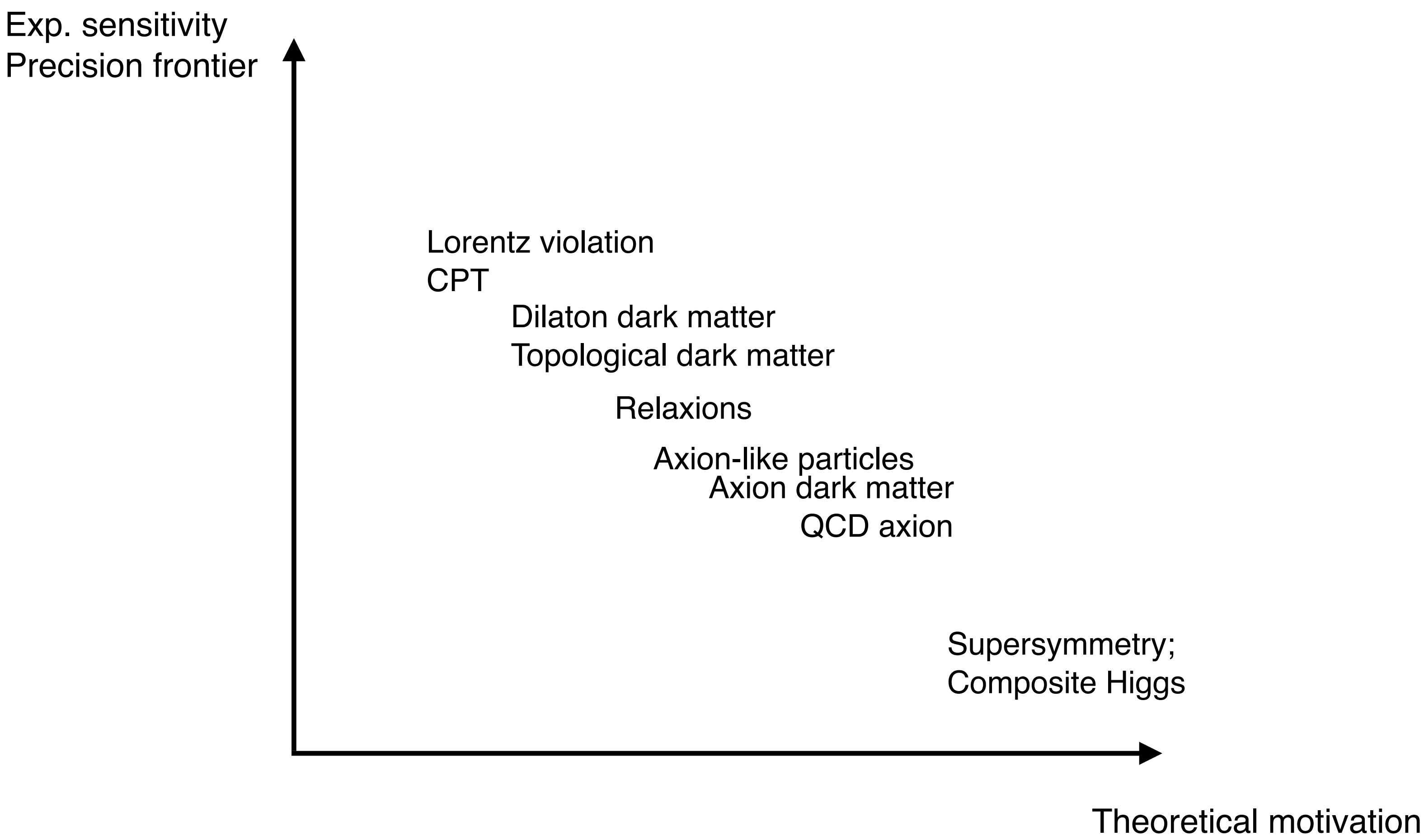


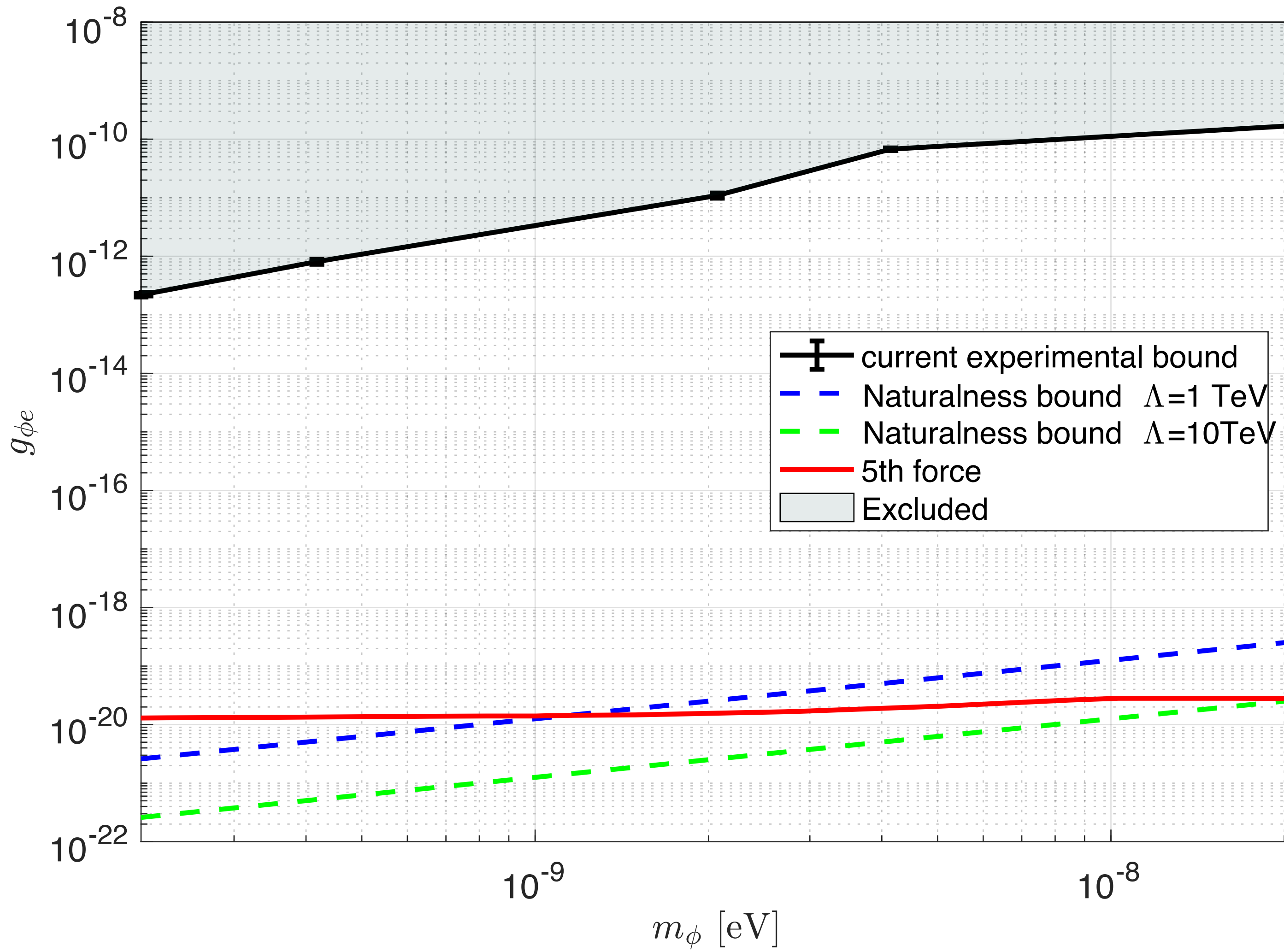
Backups

Subjective particle physicist perspective



Beyond 1Hz DM mass \w dynamical decoupling

Aharony, Akerman, Ozeri, GP & Shaniv & Savoray, in prep.



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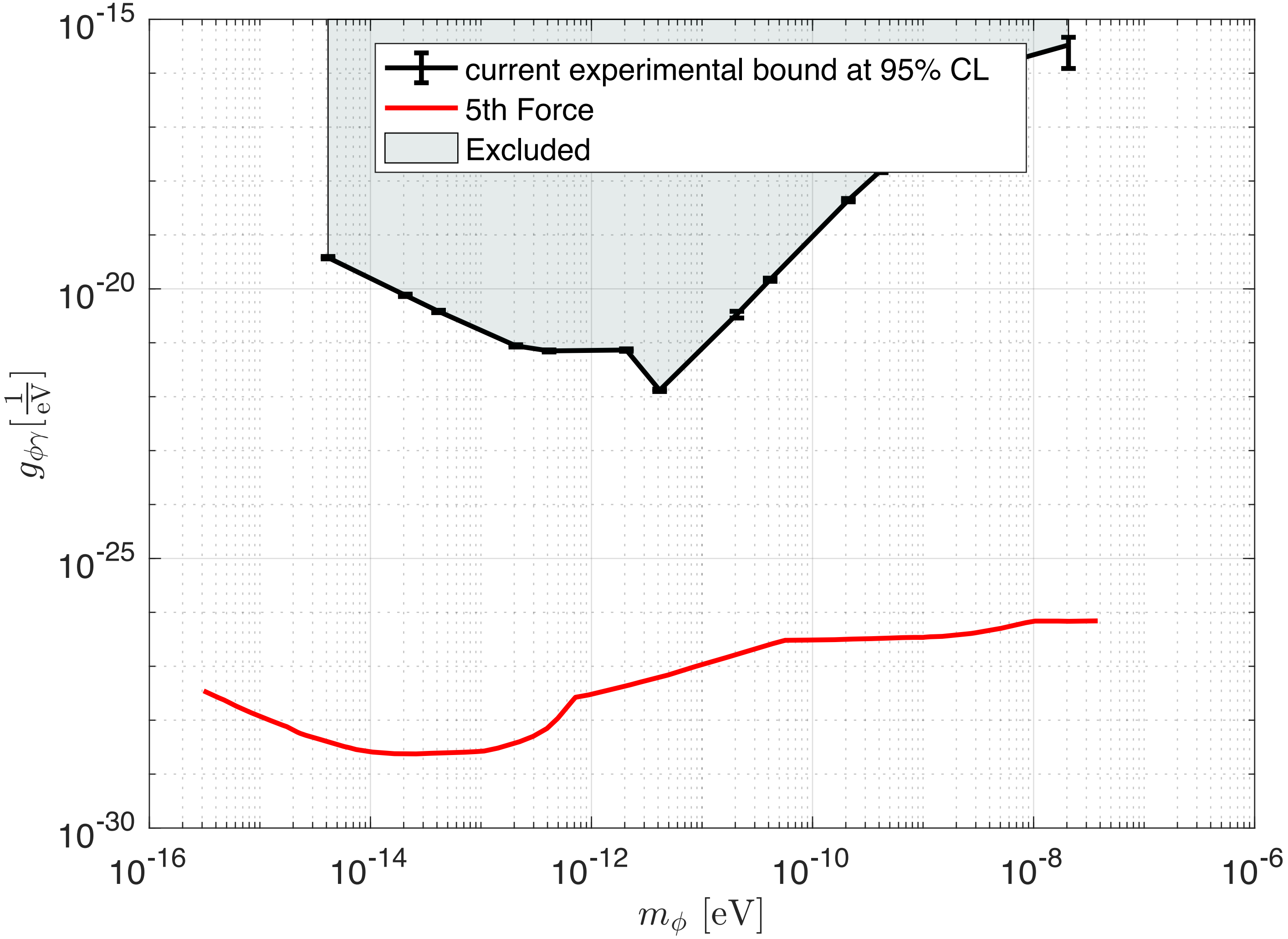
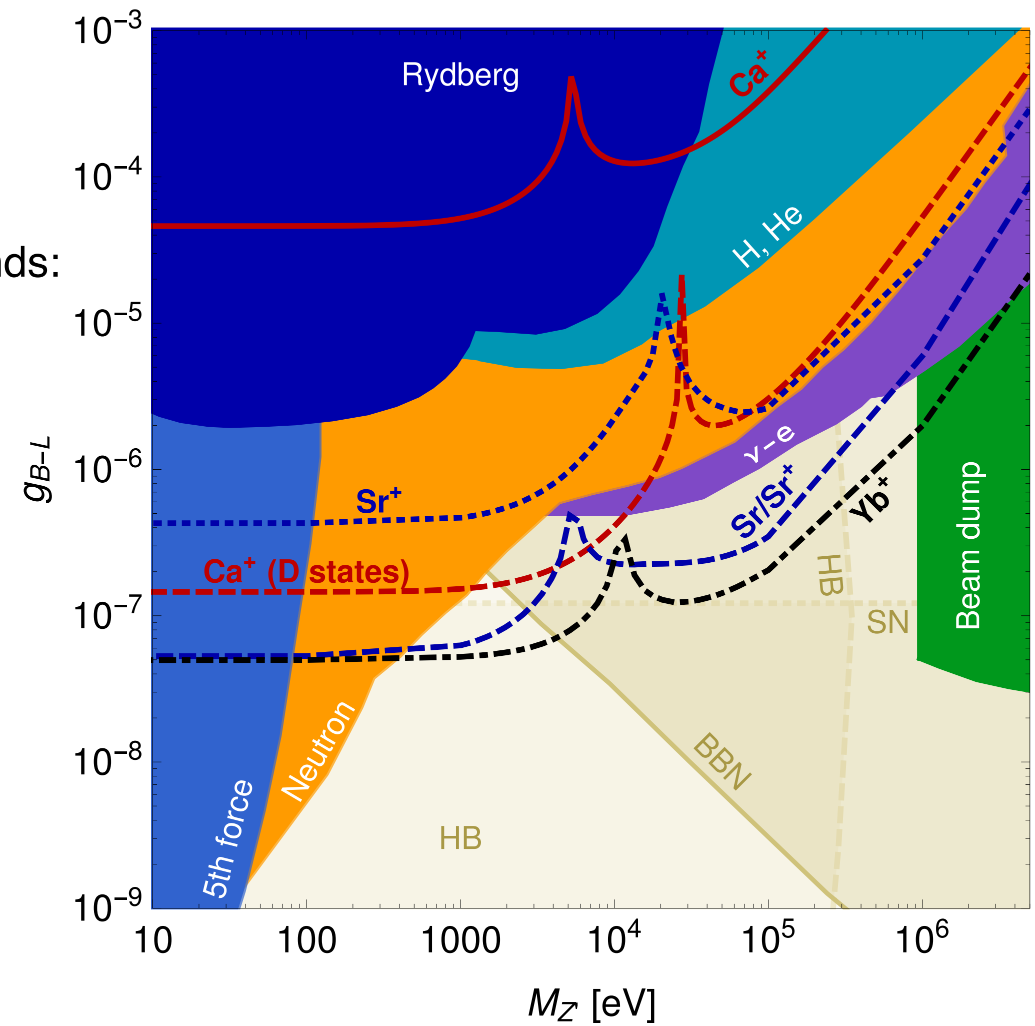


$U(1)_{B-L}$

Frugiuele, Fuchs, GP & Schlaffer (16)

Complementarity with astro/cosmo' bounds:

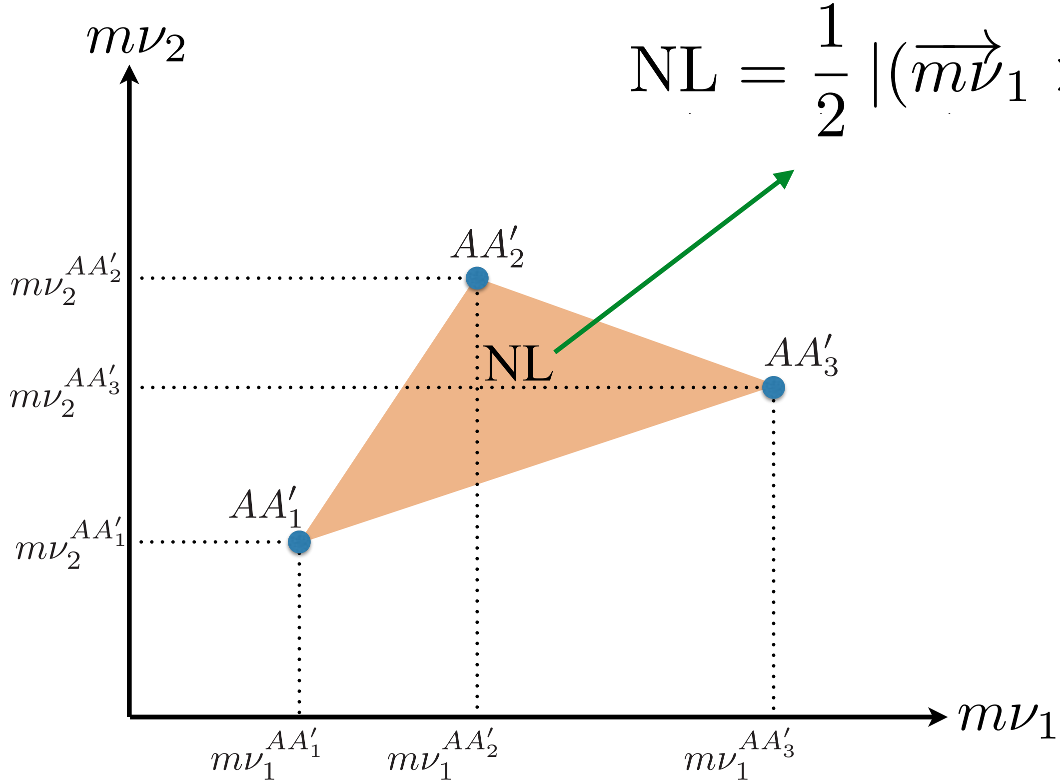


King comparison

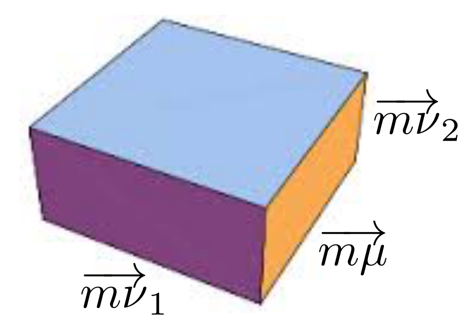
- Level of linearity can be quantified by comparing area of triangle to that of a cube: $\mathrm{NL}/|\overrightarrow{m\nu}_2||\overrightarrow{m\nu}_1| \ll 1\,.$

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

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



Or volume of prallelepiped:



King linearity implications

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

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

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

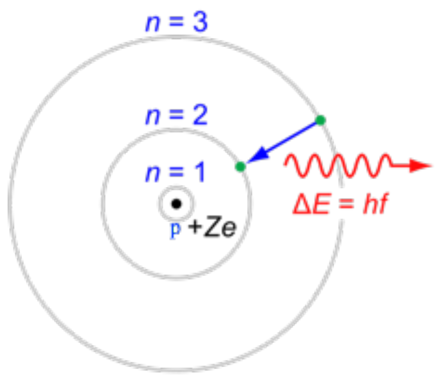
$$\overrightarrow{m\nu}_2 \cong K_{21}\,\overrightarrow{m\mu} + F_{21}\,\overrightarrow{m\nu}_1\,,$$

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

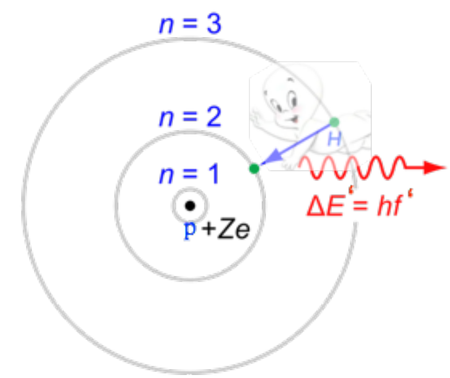
F_i & $\vec{v}$ are unknown but F_{21} & K_{21} can be measured precisely.

Adding light new physics (NP)

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



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



- 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)

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

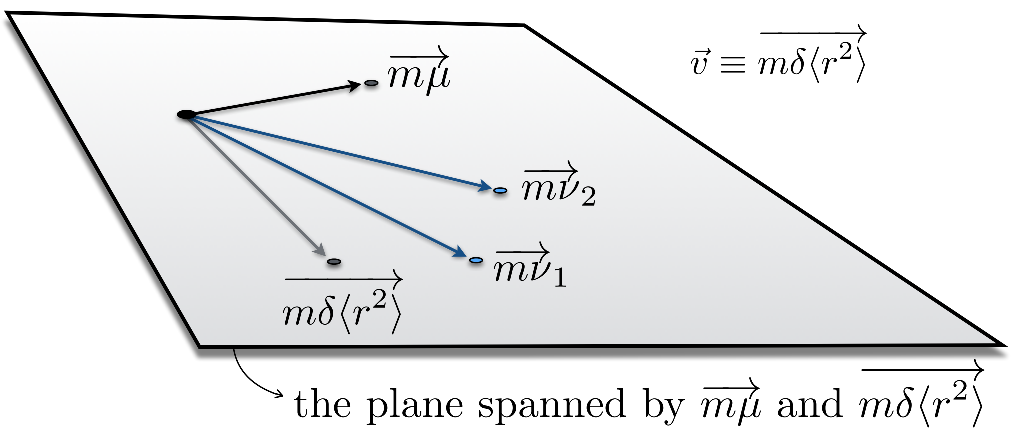
Delaunay, Ozeri, GP & Soreq (16)

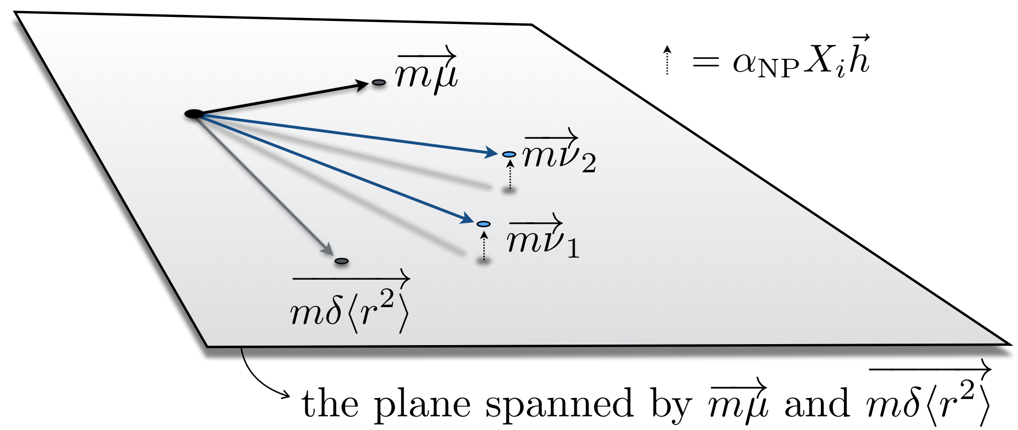
$$\Downarrow$$

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

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

Illustration: adding light new physics (NP)





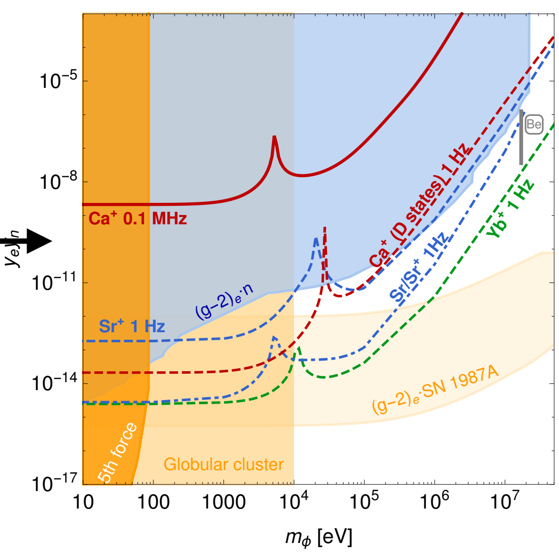
Light mediators

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.

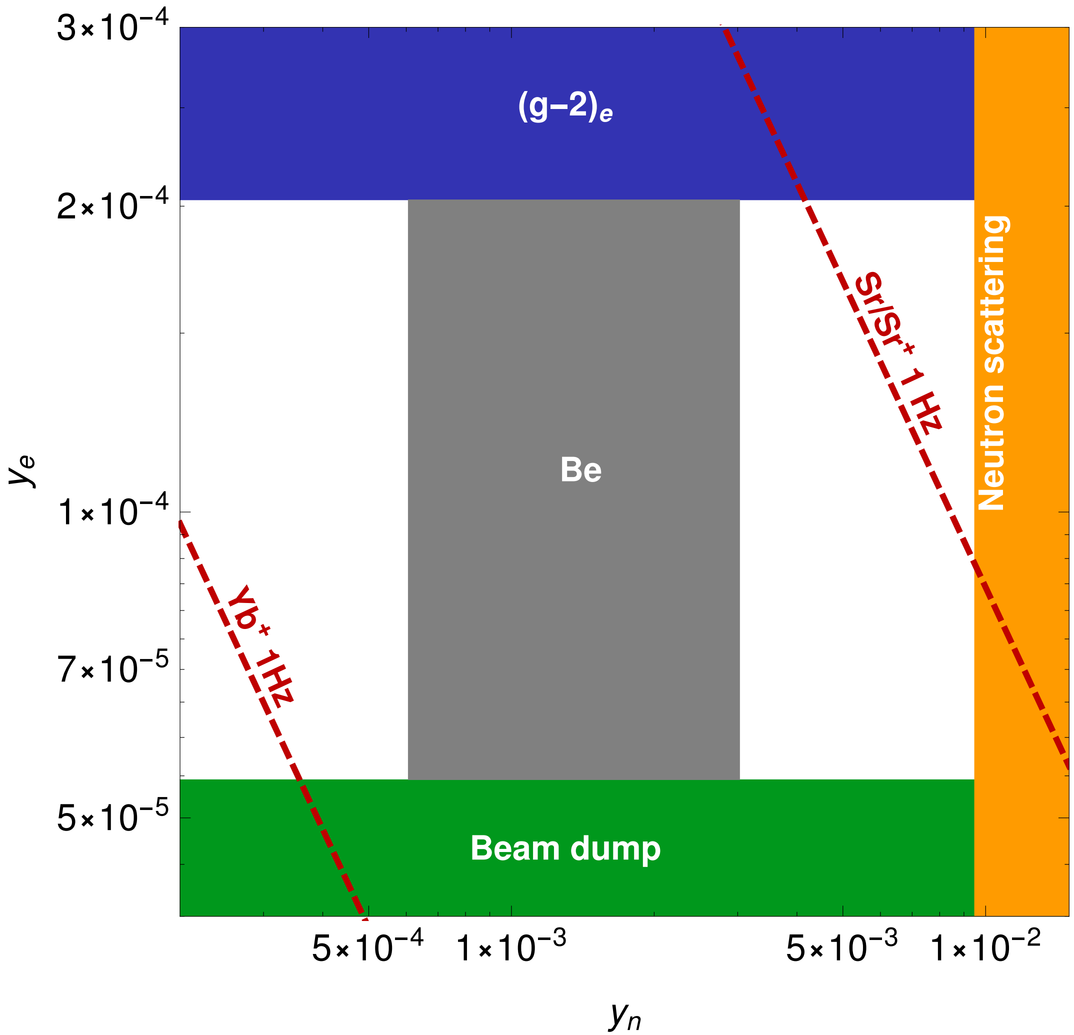
Otherwise the potential is described via a delta function.

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

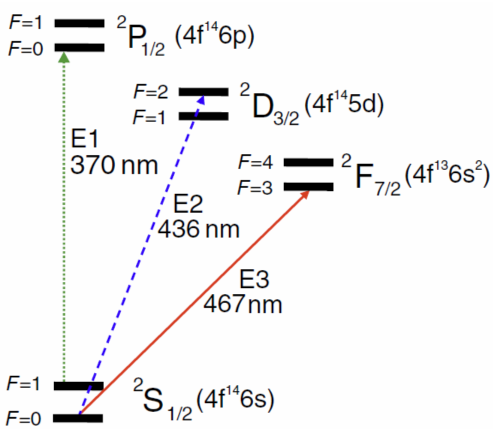


Be 17 MeV anomaly

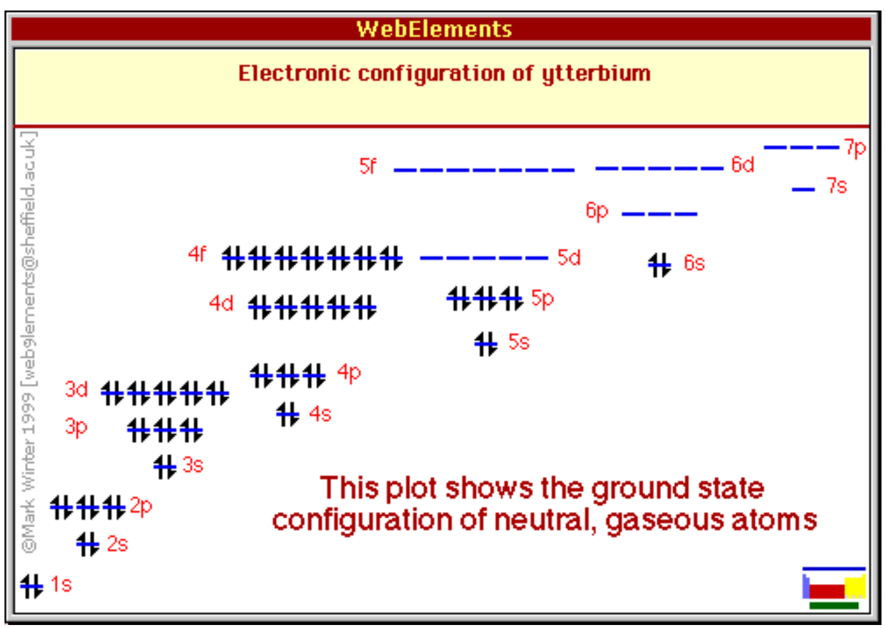
Frugiuele, Fuchs, GP & Schlaffer v2 (16)



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



The Kossel shell structure of ytterbium.



The electronic configuration of ytterbium.

nuclide symbol	Z(p)	N(n)	isotopic mass (u)	half-life	decay mode(s)[2][n 1]	daughter isotope(s)[n 2]	nuclear spin	representative isotopic composition (mole fraction)	range of natural variation (mole fraction)
	excitation energy								
^{148}Yb	70	78	147.96742(64)#	250# ms	β^+	^{148}Tm	0+		
^{149}Yb	70	79	148.96404(54)#	0.7(2) s	β^+	^{149}Tm	(1/2+,3/2+)		
^{150}Yb	70	80	149.95842(43)#	700# ms [>200 ns]	β^+	^{150}Tm	0+		
^{151}Yb	70	81	150.95540(32)	1.6(5) s	β^+	^{151}Tm	(1/2+)		
					β^+, p (rare)	^{150}Er			
^{151m1}Yb	750(100)# keV			1.6(5) s	β^+	^{151}Tm	(11/2−)		
					β^+, p (rare)	^{150}Er			
^{151m2}Yb	1790(500)# keV			2.6(7) μs			19/2−#		
^{151m3}Yb	2450(500)# keV			20(1) μs			27/2−#		
^{152}Yb	70	82	151.95029(22)	3.04(6) s	β^+	^{152}Tm	0+		
					β^+, p (rare)	^{151}Er			
^{153}Yb	70	83	152.94948(21)#	4.2(2) s	α (50%)	^{149}Er	7/2−#		
					β^+ (50%)	^{153}Tm			
					β^+, p (.008%)	^{152}Er			
^{153m}Yb	2700(100) keV			15(1) μs			(27/2−)		
^{154}Yb	70	84	153.946394(19)	0.409(2) s	α (92.8%)	^{150}Er	0+		
					β^+ (7.119%)	^{154}Tm			
^{155}Yb	70	85	154.945782(18)	1.793(19) s	α (89%)	^{151}Er	(7/2−)		
					β^+ (11%)	^{155}Tm			
^{156}Yb	70	86	155.942818(12)	26.1(7) s	β^+ (90%)	^{156}Tm	0+		
					α (10%)	^{152}Er			
^{157}Yb	70	87	156.942628(11)	38.6(10) s	β^+ (99.5%)	^{157}Tm	7/2−		
					α (.5%)	^{153}Er			
^{158}Yb	70	88	157.939866(9)	1.49(13) min	β^+ (99.99%)	^{158}Tm	0+		
					α (.0021%)	^{154}Er			
^{159}Yb	70	89	158.94005(2)	1.67(9) min	β^+	^{159}Tm	5/2(−)		
^{160}Yb	70	90	159.937552(18)	4.8(2) min	β^+	^{160}Tm	0+		
^{161}Yb	70	91	160.937902(17)	4.2(2) min	β^+	^{161}Tm	3/2−		
^{162}Yb	70	92	161.935768(17)	18.87(19) min	β^+	^{162}Tm	0+		
^{163}Yb	70	93	162.936334(17)	11.05(25) min	β^+	^{163}Tm	3/2−		
^{164}Yb	70	94	163.934489(17)	75.8(17) min	EC	^{164}Tm	0+		
^{165}Yb	70	95	164.93528(3)	9.9(3) min	β^+	^{165}Tm	5/2−		
^{166}Yb	70	96	165.933882(9)	56.7(1) h	EC	^{166}Tm	0+		
^{167}Yb	70	97	166.934950(5)	17.5(2) min	β^+	^{167}Tm	5/2−		
^{168}Yb	70	98	167.933897(5)	Observationally Stable[n 3]			0+	0.0013(1)	
^{169}Yb	70	99	168.935190(5)	32.026(5) d	EC	^{169}Tm	7/2+		
^{169m}Yb	24.199(3) keV			46(2) s	IT	^{169}Yb	1/2−		
^{170}Yb	70	100	169.9347618(26)	Observationally Stable[n 4]			0+	0.0304(15)	
^{170m}Yb	1258.46(14) keV			370(15) ns			4−		
^{171}Yb	70	101	170.9363258(26)	Observationally Stable[n 5]			1/2−	0.1428(57)	
^{171m1}Yb	95.282(2) keV			5.25(24) ms	IT	^{171}Yb	7/2+		
^{171m2}Yb	122.416(2) keV			265(20) ns			5/2−		
^{172}Yb	70	102	171.9363815(26)	Observationally Stable[n 6]			0+	0.2183(67)	
^{173}Yb	70	103	172.9382108(26)	Observationally Stable[n 7]			5/2−	0.1613(27)	
^{173m}Yb	398.9(5) keV			2.9(1) μs			1/2−		
^{174}Yb	70	104	173.9388621(26)	Observationally Stable[n 8]			0+	0.3183(92)	
^{175}Yb	70	105	174.9412765(26)	4.185(1) d	β^-	^{175}Lu	7/2−		
^{175m}Yb	514.865(4) keV			68.2(3) ms			1/2−		
^{176}Yb	70	106	175.9425717(28)	Observationally Stable[n 9]			0+	0.1276(41)	
^{176m}Yb	1050.0(3) keV			11.4(3) s			(8)−		
^{177}Yb	70	107	176.9452608(28)	1.911(3) h	β^-	^{177}Lu	(9/2+)		
^{177m}Yb	331.5(3) keV			6.41(2) s	IT	^{177}Yb	(1/2−)		
^{178}Yb	70	108	177.946647(11)	74(3) min	β^-	^{178}Lu	0+		
^{179}Yb	70	109	178.95017(32)#	8.0(4) min	β^-	^{179}Lu	(1/2−)		

Precision mass measurements: 10^{-10}

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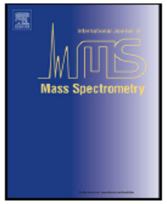

The most precise atomic mass measurements in Penning traps

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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 $\approx 0.931\,\mathrm{GeV}$)

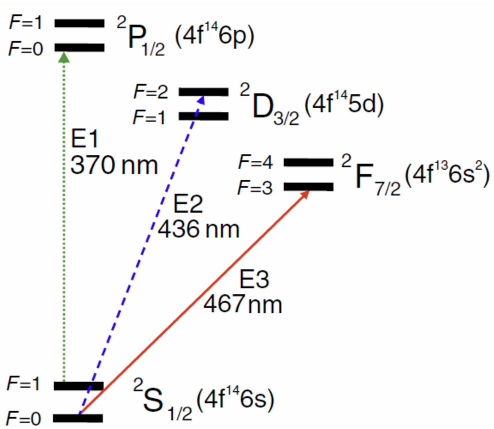
only depend on nucleus

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

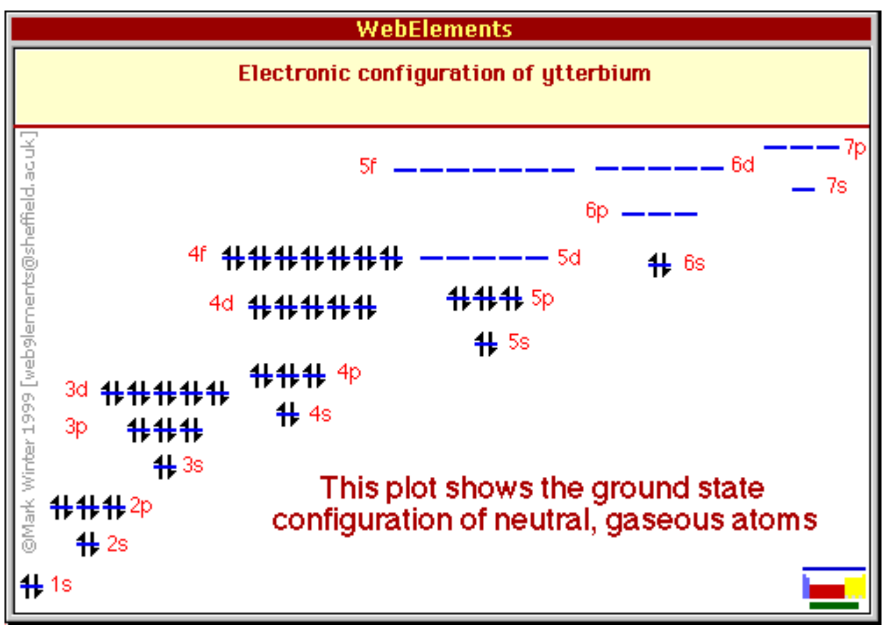
$$\boxed{m\delta\nu^2_{AA'} = F_{21} m\delta\nu^1_{AA'} + K_{21}\,,}$$

(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).



The Kossel shell structure of ytterbium.

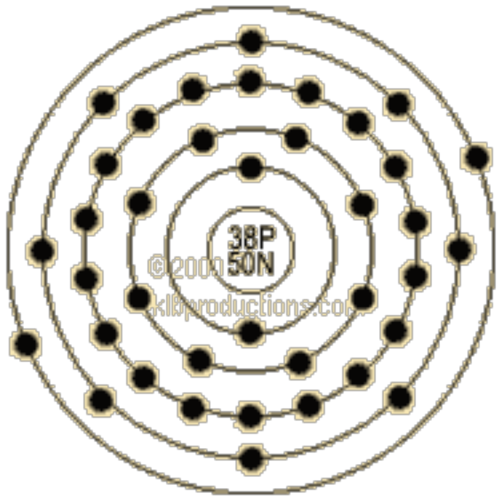


The electronic configuration of ytterbium.

nuclide symbol	Z(p)	N(n)	isotopic mass (u)	half-life	decay mode(s)[2][n 1]	daughter isotope(s)[n 2]	nuclear spin	representative isotopic composition (mole fraction)	range of natural variation (mole fraction)
	excitation energy								
^{148}Yb	70	78	147.96742(64)#	250# ms	β$^+$	^{148}Tm	0+		
^{149}Yb	70	79	148.96404(54)#	0.7(2) s	β$^+$	^{149}Tm	(1/2+,3/2+)		
^{150}Yb	70	80	149.95842(43)#	700# ms [>200 ns]	β$^+$	^{150}Tm	0+		
^{151}Yb	70	81	150.95540(32)	1.6(5) s	β$^+$	^{151}Tm	(1/2+)		
					β$^+$, p (rare)	^{150}Er			
^{151m1}Yb	750(100)# keV			1.6(5) s	β$^+$	^{151}Tm	(11/2−)		
					β$^+$, p (rare)	^{150}Er			
^{151m2}Yb	1790(500)# keV			2.6(7) μs			19/2−#		
^{151m3}Yb	2450(500)# keV			20(1) μs			27/2−#		
^{152}Yb	70	82	151.95029(22)	3.04(6) s	β$^+$	^{152}Tm	0+		
					β$^+$, p (rare)	^{151}Er			
^{153}Yb	70	83	152.94948(21)#	4.2(2) s	α (50%)	^{149}Er	7/2−#		
					β$^+$ (50%)	^{153}Tm			
					β$^+$, p (.008%)	^{152}Er			
^{153m}Yb	2700(100) keV			15(1) μs			(27/2−)		
^{154}Yb	70	84	153.946394(19)	0.409(2) s	α (92.8%)	^{150}Er	0+		
					β$^+$ (7.119%)	^{154}Tm			
^{155}Yb	70	85	154.945782(18)	1.793(19) s	α (89%)	^{151}Er	(7/2−)		
					β$^+$ (11%)	^{155}Tm			
^{156}Yb	70	86	155.942818(12)	26.1(7) s	β$^+$ (90%)	^{156}Tm	0+		
					α (10%)	^{152}Er			
^{157}Yb	70	87	156.942628(11)	38.6(10) s	β$^+$ (99.5%)	^{157}Tm	7/2−		
					α (.5%)	^{153}Er			
^{158}Yb	70	88	157.939866(9)	1.49(13) min	β$^+$ (99.99%)	^{158}Tm	0+		
					α (.0021%)	^{154}Er			
^{159}Yb	70	89	158.94005(2)	1.67(9) min	β$^+$	^{159}Tm	5/2(−)		
^{160}Yb	70	90	159.937552(18)	4.8(2) min	β$^+$	^{160}Tm	0+		
^{161}Yb	70	91	160.937902(17)	4.2(2) min	β$^+$	^{161}Tm	3/2−		
^{162}Yb	70	92	161.935768(17)	18.87(19) min	β$^+$	^{162}Tm	0+		
^{163}Yb	70	93	162.936334(17)	11.05(25) min	β$^+$	^{163}Tm	3/2−		
^{164}Yb	70	94	163.934489(17)	75.8(17) min	EC	^{164}Tm	0+		
^{165}Yb	70	95	164.93528(3)	9.9(3) min	β$^+$	^{165}Tm	5/2−		
^{166}Yb	70	96	165.933882(9)	56.7(1) h	EC	^{166}Tm	0+		
^{167}Yb	70	97	166.934950(5)	17.5(2) min	β$^+$	^{167}Tm	5/2−		
^{168}Yb	70	98	167.933897(5)	Observationally Stable[n 3]			0+	0.0013(1)	
^{169}Yb	70	99	168.935190(5)	32.026(5) d	EC	^{169}Tm	7/2+		
^{169m}Yb	24.199(3) keV			46(2) s	IT	^{169}Yb	1/2−		
^{170}Yb	70	100	169.9347618(26)	Observationally Stable[n 4]			0+	0.0304(15)	
^{170m}Yb	1258.46(14) keV			370(15) ns			4−		
^{171}Yb	70	101	170.9363258(26)	Observationally Stable[n 5]			1/2−	0.1428(57)	
^{171m1}Yb	95.282(2) keV			5.25(24) ms	IT	^{171}Yb	7/2+		
^{171m2}Yb	122.416(2) keV			265(20) ns			5/2−		
^{172}Yb	70	102	171.9363815(26)	Observationally Stable[n 6]			0+	0.2183(67)	
^{173}Yb	70	103	172.9382108(26)	Observationally Stable[n 7]			5/2−	0.1613(27)	
^{173m}Yb	398.9(5) keV			2.9(1) μs			1/2−		
^{174}Yb	70	104	173.9388621(26)	Observationally Stable[n 8]			0+	0.3183(92)	
^{175}Yb	70	105	174.9412765(26)	4.185(1) d	β$^-$	^{175}Lu	7/2−		
^{175m}Yb	514.865(4) keV			68.2(3) ms			1/2−		
^{176}Yb	70	106	175.9425717(28)	Observationally Stable[n 9]			0+	0.1276(41)	
^{176m}Yb	1050.0(3) keV			11.4(3) s			(8)−		
^{177}Yb	70	107	176.9452608(28)	1.911(3) h	β$^-$	^{177}Lu	(9/2+)		
^{177m}Yb	331.5(3) keV			6.41(2) s	IT	^{177}Yb	(1/2−)		
^{178}Yb	70	108	177.946647(11)	74(3) min	β$^-$	^{178}Lu	0+		
^{179}Yb	70	109	178.95017(32)#	8.0(4) min	β$^-$	^{179}Lu	(1/2−)		

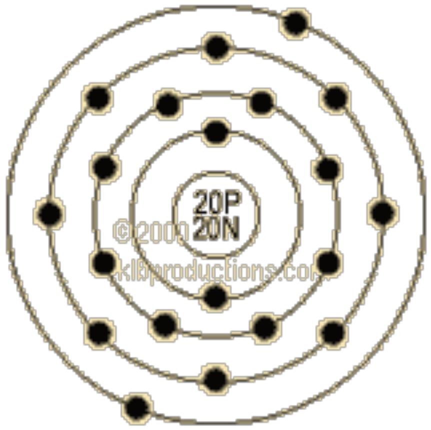
Ex.: $Sr^{(+)}$ with Z=38, n=5 and A=84-88 (90).

- **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)

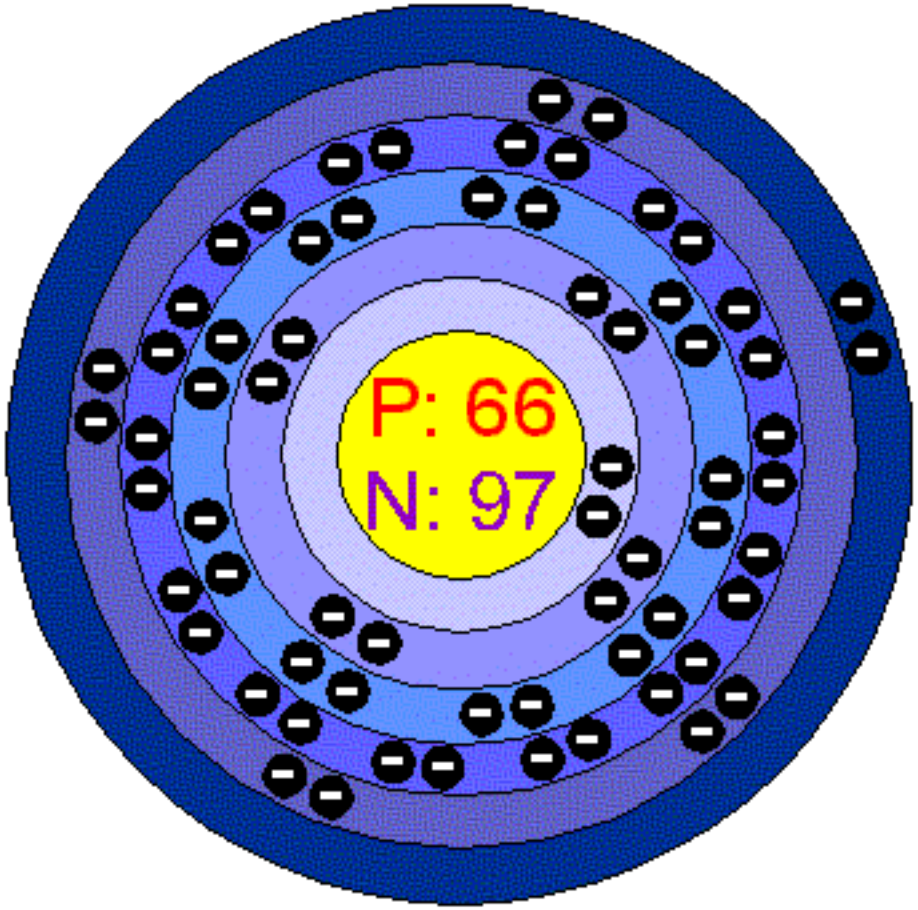


Ex.: Ca$^{(+)}$ with Z=20, n=4 and A=40-48.

- **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

The observables

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

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

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

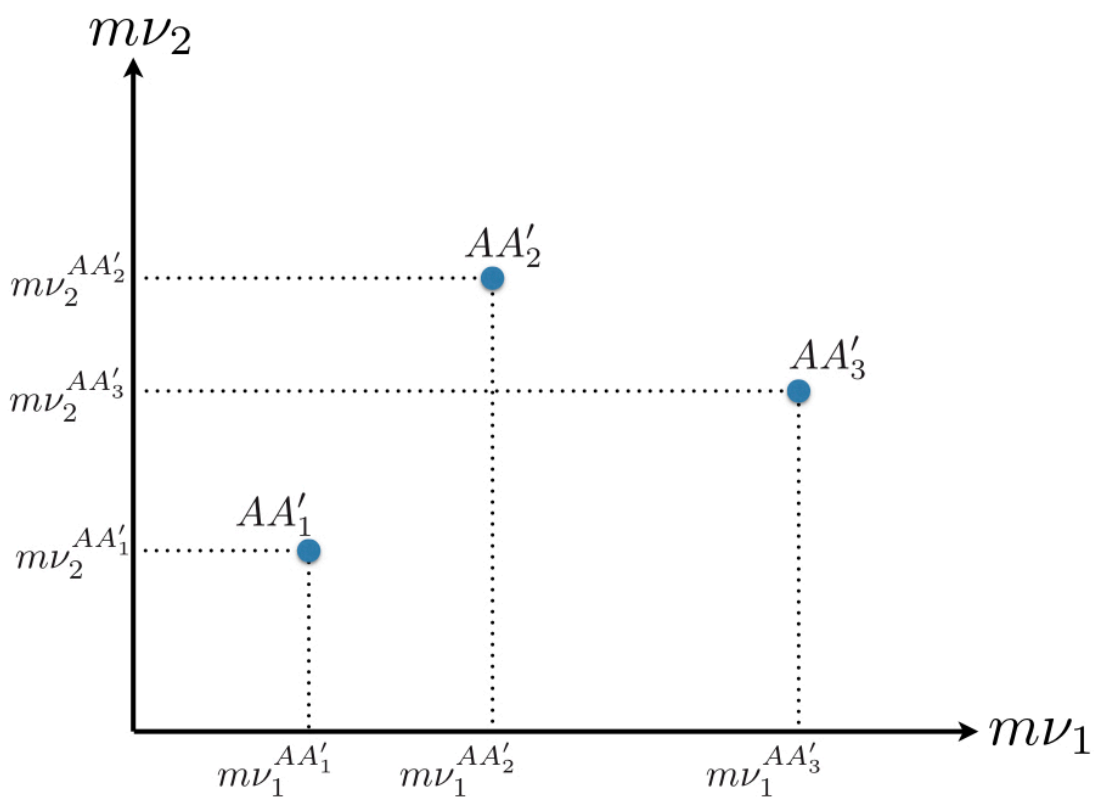
$$\mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1}$$

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 ?

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.