Precision frontier, brief status report

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European Strategy for Particle Physics, Israeli Input, Town Hall meeting
Ex. 1: Neutral Sr bosons in

Relative accuracy: few $10^{-6}$; few mHz on top of $10^{13}$ Hz

Ex. 2: Equivalent principle tests probe forces weaker than gravity!

$\mathcal{L}_{\text{int}} \supset -\sqrt{4\pi G_N} \phi \left[ d_{m_e} m_e e^2 - \frac{d_e}{4} F_{\mu\nu} F^{\mu\nu} \right]$, where $G_N$ is Newton’s constant.

Ex. 3: ACME: electron electric dipole moment, $|d_e| < 1.1 \times 10^{-29}$ e·cm @ 90% CL.

Set for instance following bound on composite Higgs models:

$\frac{d_e}{e} \sim \frac{1}{8\pi^2} \frac{m_e}{f^2}$

$\Rightarrow f \gtrsim 107$ TeV

Panico, Pomarol & Riemann (18)

(Even though we expect $f < $ TeV)
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].
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.

\[ V(\hat{\mathbf{r}}, r) = \frac{\hbar^2 (\hat{\mathbf{r}} \cdot \hat{\mathbf{r}})}{8 \pi m_e} \left( \frac{g_s^a g_p^e}{\hbar c} \right) \left( \frac{1}{r \lambda_{\text{ALP}}} + \frac{1}{r^2} \right) e^{-r/\lambda_{\text{ALP}}}, \]

where \( r \) is the electron-atom separation vector, \( \lambda_{\text{ALP}} = m_{\text{ALP}}/\hbar c \) is the ALP Compton wavelength, and \( \hat{\mathbf{r}} \) and \( m_e \) are the spin unit vector and mass of the polarized electron, respectively.
Equivalent principle tests probe forces weaker than gravity!

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

where \( G_N \) is Newton’s constant.
The DM front
Looking for oscillating light dark matter

\[ a(t) \equiv \phi(t) = \sqrt{2\rho_{\text{DM}} \over m_a} \cos(m_a t) \]

**light DM**
- **E&M** - drive currents
  - \( a F \tilde{F} \)
- **QCD** - change nuclear properties
  - \( a G \tilde{G} \)
  - spin - cause precession
  - \( (\partial_\mu a) \psi \gamma^\mu \gamma_5 \psi \)
- **scalar** - new force/SM properties
  - \( a H^\dagger H \) (mixing \text{ w Higgs})

Conventional axion searches (e.g. ADMX)

New searches, CASPEr ...

Looking for oscillations of coupling constants & masses.
Ideal for atomic clocks.

Peter Graham, SSI, Stanford (17)
Searching for scalar DM that mixes with 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)


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.

d_{e} stands for the time dependent component of the fine coupling constant, the bound on d_{e} (the coefficient of the time dependent component of \alpha_s, the strong coupling) assumes a working \textsuperscript{229}Th nuclear clock with a 1 : 10^{19} precision, \tau_{\text{int}} stands for the total assumed integration time and \sigma_{I} stands for the corresponding stability. The dashed-red line on the diagonal corresponds to the maximal mixing allowed in this scenario, \Lambda_{br} corresponds to a coupling in the relaxion model.
DM global-networking
Global Network of Optical Magnetometers for Exotic (GNOME): Physics Novel scheme for exotic physics searches

Comparison of a network of atomic clocks through GPS satellite data
One slide about SARAF

♦ New high-current accelerator in Israel.

♦ Dedicated lab space for the two trap experiments.

♦ Sensitive to $\beta$ decay, constraint (well) below 1% level seems feasible.

    Below 0.1% $\Rightarrow$ 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:

\[ R_{\text{star}} \approx \frac{M_{\text{Pl}}^2}{m_\phi^2} \frac{1}{M_{\text{Earth}}} \quad (M_* \ll M_{\text{Earth}}). \]

Eby, Leembruggen, Street, Suranyi & Wijewardhana (18); Budker, Eby, Kim, GP, in Prep.

Can obtain large density enhancement:

\[ r \equiv \frac{\rho_{\text{star}}}{\rho_{\text{loc--DM}}} \sim \xi \frac{M_{\text{Earth}}^4 m_\phi^6}{M_{\text{Pl}}^6 \rho_{\text{loc--DM}}} \sim \xi \times 10^{28} \times \left( \frac{m_\phi}{10^{-10}} \right)^6 \quad \xi \equiv M_{\text{star}}/M_{\text{Earth}} \]
Large star DM density $\Rightarrow$ visible effect

Aharony, Akerman, Ozeri, GP & Shaniv & Savoray, in prep. (ion-cavity comparison) Budker, Eby, Kim, GP, in Prep.
Large star DM density => visible effect

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Large star DM density => visible effect

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Backups
Subjective particle physicist perspective

Theoretical motivation

Exp. sensitivity
Precision frontier

Lorentz violation
CPT
Dilaton dark matter
Topological dark matter
Relaxions
Axion-like particles
Axion dark matter
QCD axion

Supersymmetry;
Composite Higgs

Theoretical motivation
Beyond 1Hz DM mass \( \omega \) dynamical decoupling

Aharony, Akerman, Ozeri, GP & Shaniv & Savoray, in prep.
Beyond 1Hz DM mass w dynamical decoupling

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

\[ g_{\phi} \frac{[eV]}{} \]

\[ m_{\phi} [eV] \]

current experimental bound at 95% CL
5th Force
Excluded
Complementarity with astro/cosmo’ bounds:

$U(1)_{B-L}$
Level of linearity can be quantified by comparing area of triangle to that of a cube: \[ \frac{\text{NL}}{|\mathbf{m}_2| |\mathbf{m}_1|} \ll 1 . \]

\[ \mathbf{m}_{NP} \equiv (1, 1, 1) . \]

\[ \text{NL} = \frac{1}{2} |(\mathbf{m}_1 \times \mathbf{m}_2) \cdot \mathbf{m}_{NP}| . \]

Or volume of parallelepiped:
King linearity implications

- Linearity implies that $\vec{m}_2 \mathcal{v}_2$ & $\vec{m}_1 \mathcal{v}_1$ must be linearly dependent:

$$
\vec{m}_2 \mathcal{v}_2 = K_2 \vec{m}_\mu + F_2 \vec{v} + \mathcal{O} (10^{-4})
$$

$$
\vec{m}_1 \mathcal{v}_1 = K_1 \vec{m}_\mu + F_1 \vec{v} + \mathcal{O} (10^{-4})
$$

$$
\vec{m}_2 \mathcal{v}_2 \approx K_{21} \vec{m}_\mu + F_{21} \vec{m}_1 \mathcal{v}_1,
$$

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.

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

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)

\[
\begin{align*}
\overrightarrow{m\nu}_i &= K_i \overrightarrow{m}_\mu + F_i \overrightarrow{\nu} + y_e y_n X_i \overrightarrow{h}, \\
\overrightarrow{m\nu}_2 &= K_{21} \overrightarrow{m}_\mu + F_{21} \overrightarrow{m\nu}_1 + \alpha_{NP} \overrightarrow{h}X_1 (X_{21} - F_{21}) ,
\end{align*}
\]

Delaunay, Ozeri, GP & Soreq (16)

and \( X_{21} \equiv X_2/X_1 \).
Constraining new light force mediators by isotope shift spectroscopy

I. VISUALIZING THE VECTOR SPACE

In the main text we define the following vectors in the vector space:

\[ \mathbf{v} = m\mathbf{\delta}(r^2) \]

As long as \( \mathbf{v} \) are spanned by \( \mathbf{\mu} \) and \( m\mathbf{\nu} \), the resulting King plot will be linear. In Fig. S1, we illustrate the vector space of the various components related to isotope shifts that leads to the nonlinearities. The NP contribution to IS, \( \mathbf{\alpha}_{\text{NP}} X_i \hbar \), may lift the IS vectors from the \((\mathbf{\mu}, m\mathbf{\nu})\) plane, resulting in a nonlinear King plot. Fig. S2 illustrates a nonlinear King plot, where the area of the triangle corresponds to the NL of Eq. (6).

**FIG. S1:** Left: A cartoon of the prediction of factorization, Eq. (5) in vector language. All of the isotope shift measurements (which are here three dimensional vectors) are in the plane spanned by \( \mathbf{\mu} \) and \( m\mathbf{\nu} \). This coplanarity can be tested by measuring whether \( \mathbf{\nu} \) are coplanar. Right: In the presence of new physics the isotope shift get a contribution which can point out of the plane. A new long range force can spoil the coplanarity of \( \mathbf{\nu} \).

**FIG. S2:** Illustration of nonlinearity in the King plot of the isotope shifts \( \mathbf{\nu} \), as defined in Eq. (4), in isotope pairs \( AA_0 j, j = 1, 2, 3 \). The area of the triangle corresponds to the NL of Eq. (6).
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.

$$V(r) = \begin{cases} 
\frac{1}{r} & \text{for } m_X \lesssim \alpha m_e , \\
e^{-r m_X} & \text{for } \alpha m_e \lesssim m_X \lesssim \alpha m_e Z , \\
\frac{1}{m_X^2} & \delta^3(r) \text{ otherwise} . 
\end{cases}$$
Be 17 MeV anomaly

Frugiuele, Fuchs, GP & Schlaffer v2 (16)
Ex.: Yb$^+$ with $Z=70$, $n=6$ and $A=168(4)-174(6)$. 

The electronic configuration of ytterbium.
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].

<table>
<thead>
<tr>
<th>Atom</th>
<th>FSU mass (u)</th>
<th>( \sigma_{m}/m ) (ppt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{86})Sr</td>
<td>85.909 260 730 9(91)</td>
<td>105</td>
</tr>
<tr>
<td>(^{87})Sr</td>
<td>86.908 877 497 0(91)</td>
<td>105</td>
</tr>
<tr>
<td>(^{88})Sr</td>
<td>87.905 612 257 1(97)</td>
<td>110</td>
</tr>
<tr>
<td>(^{170})Yb</td>
<td>169.934 276 341 18</td>
<td>105</td>
</tr>
<tr>
<td>(^{171})Yb</td>
<td>170.936 331 514 19</td>
<td>110</td>
</tr>
<tr>
<td>(^{172})Yb</td>
<td>171.936 386 655 18</td>
<td>105</td>
</tr>
<tr>
<td>(^{173})Yb</td>
<td>172.938 216 213 18</td>
<td>105</td>
</tr>
<tr>
<td>(^{174})Yb</td>
<td>174.938 867 539 18</td>
<td>105</td>
</tr>
<tr>
<td>(^{176})Yb</td>
<td>175.942 574 702(22)</td>
<td>125</td>
</tr>
</tbody>
</table>
Partial solution, comparing different isotope shift, searching of nonlinearity in “King plot”

King’s factorisation formula (King, 1963):

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

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

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

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

(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 electronic configuration of ytterbium.

This plot shows the ground state configuration of neutral, gaseous atoms.

The Kossel shell structure of ytterbium.
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 \((\AA A'_{1,2,3})\) for 2 transitions \((i=1,2)\):

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

\[
\nu_i^{\AA A'} \equiv \nu_i^{\AA} - \nu_i^{\AA'} . \quad m\nu_i^{\AA A'} \equiv \nu_i^{\AA A'}/\mu_{\AA A'}
\]

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

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

\[ \alpha_{\text{NP}} = \frac{(m\vec{\nu}_1 \times m\vec{\nu}_2) \cdot m\vec{\mu}}{(m\vec{\mu} \times \hbar) \cdot (X_1 m\vec{\nu}_2 - X_2 m\vec{\nu}_1)} \]

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:

\[ \alpha_{\text{NP}} \lesssim \sigma_{\alpha_{\text{NP}}} = \sqrt{\sum_k (\partial\alpha_{\text{NP}} / \partial O_k)^2 \sigma_k^2}, \]

\( (O_K \text{ various exp’ observables.}) \)

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