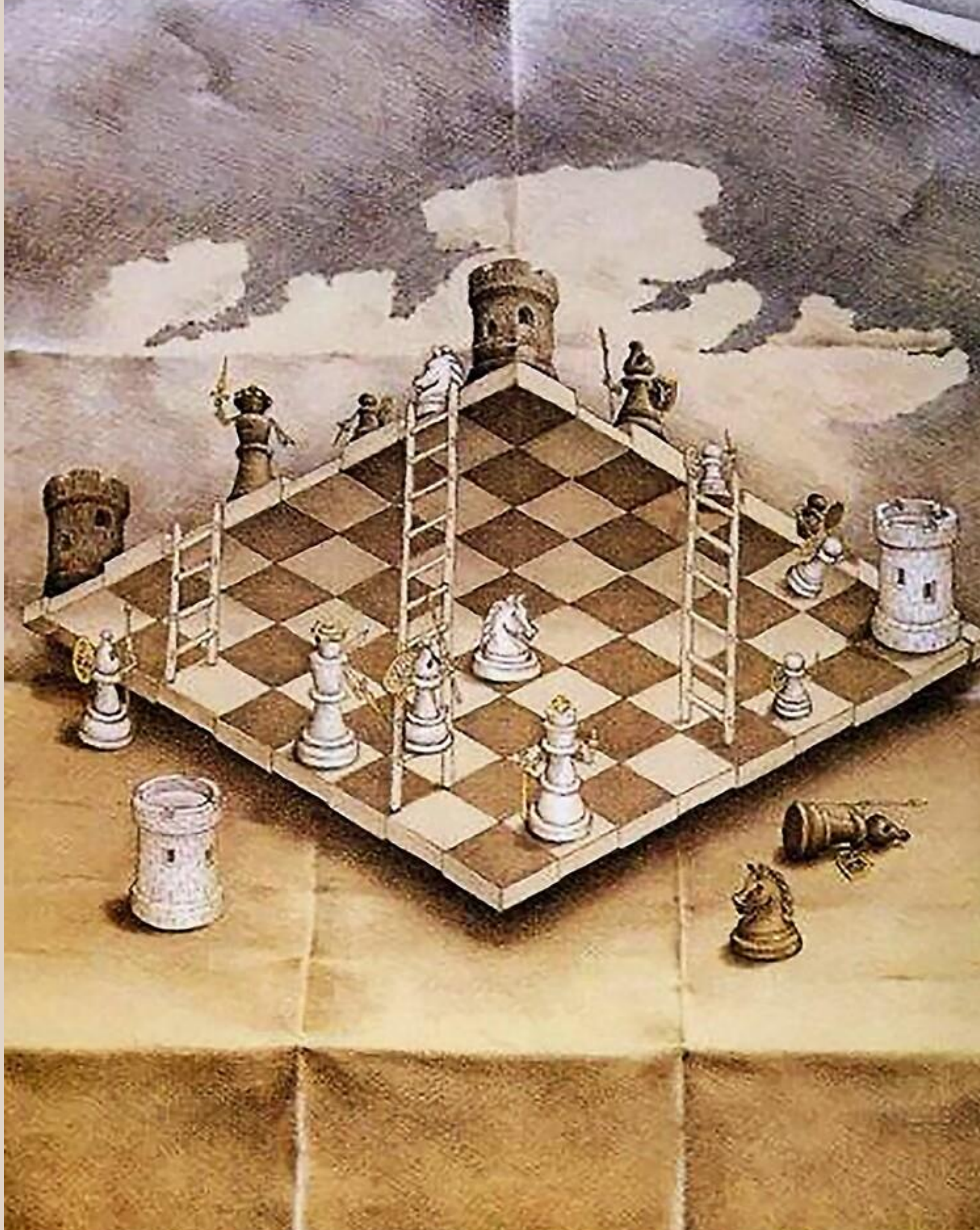
Tabletop experiments for Particle physics

Town hall meeting on the Israeli Input to the European Strategy for Particle Physics

Ben Ohayon
Technion IIT
19.12.2024



Tabletop experiments for Particle physics

- Small(ish)
- AMO methods
- Not covered in other talks

Tabletop experiments for **Particle physics**

- New physics searches (Theory-Experiment, Oscillations, ...)
- Determination of fundamental / useful constants

Today

Tabletop experiments for Particle physics

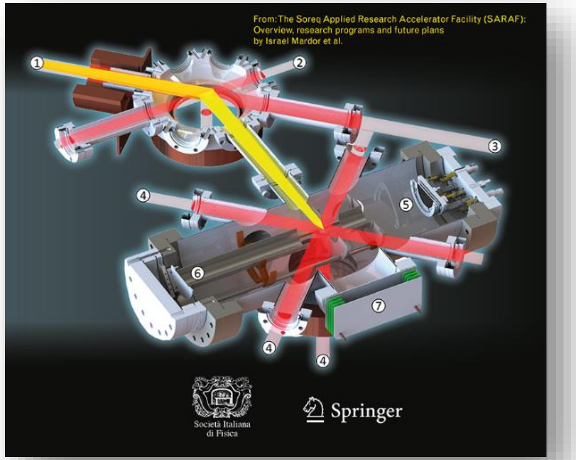
In Israel

Today

Tabletop experiments for Particle physics

In Israel

Nuclear Beta decay



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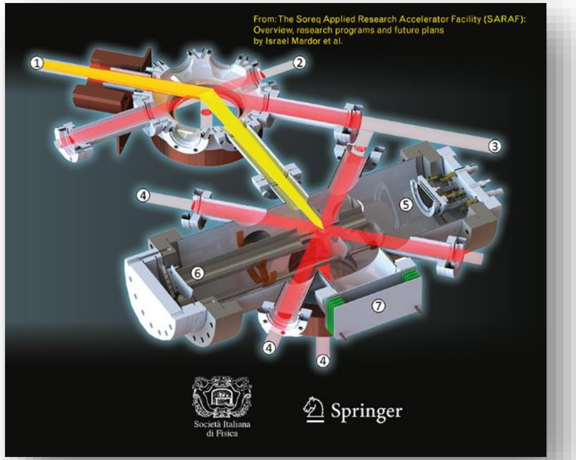
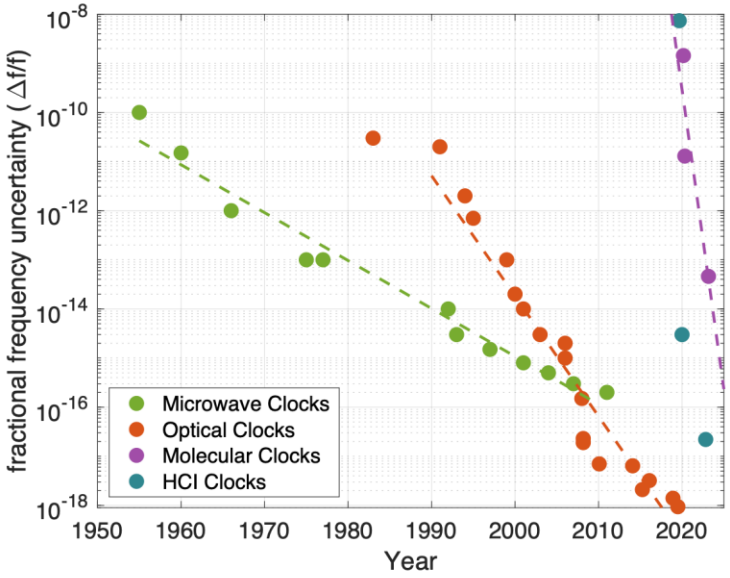


Clocks & interferometers



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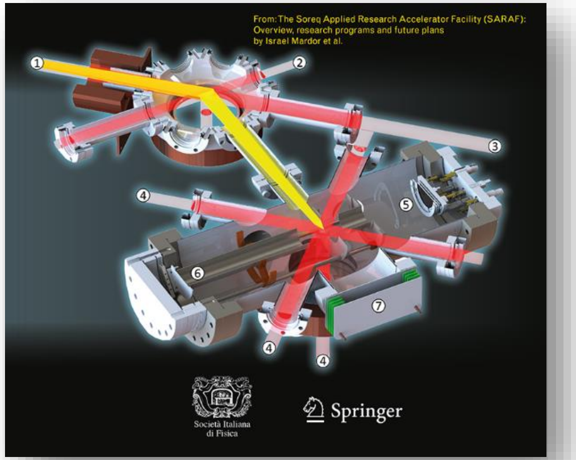

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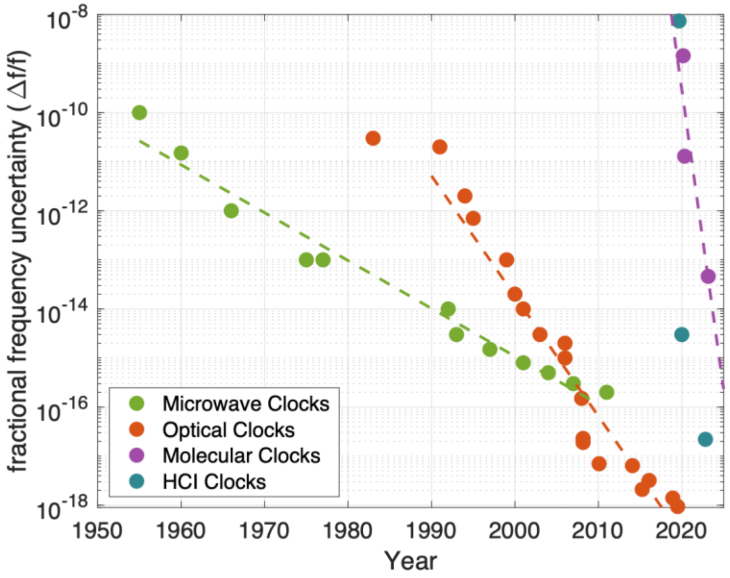
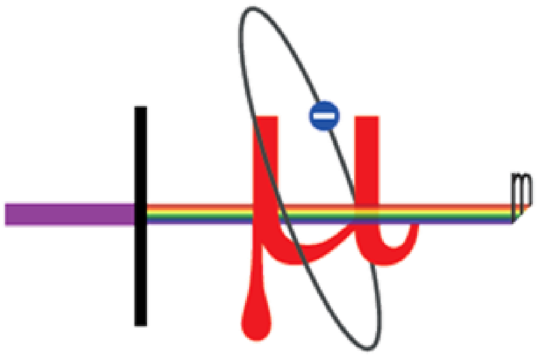


Exotic Atoms



[Today](#)

Tabletop experiments for Particle physics

[In Israel](#)

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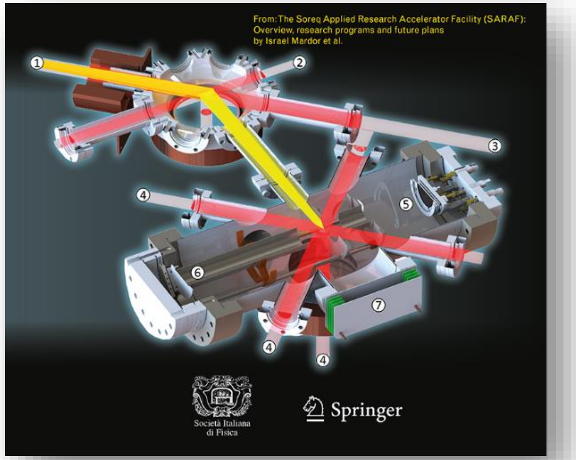

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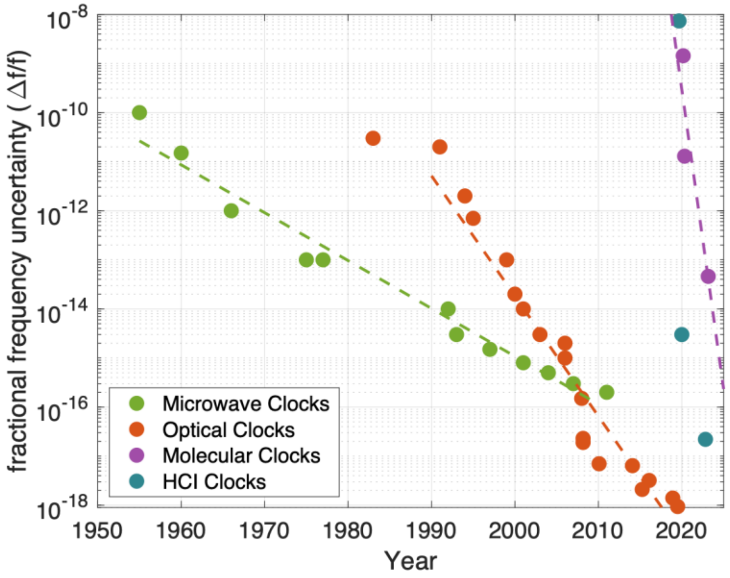

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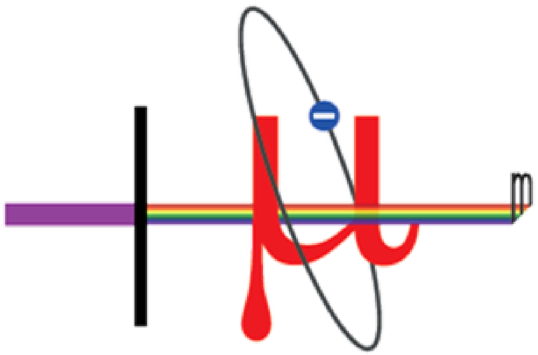

PHYSICAL REVIEW VOLUME 106, NUMBER 3 MAY 1, 1957

Possible Tests of Time Reversal Invariance in Beta Decay

J. D. JACKSON,* S. B. TREIMAN, AND H. W. WYLD, JR.
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received January 28, 1957)

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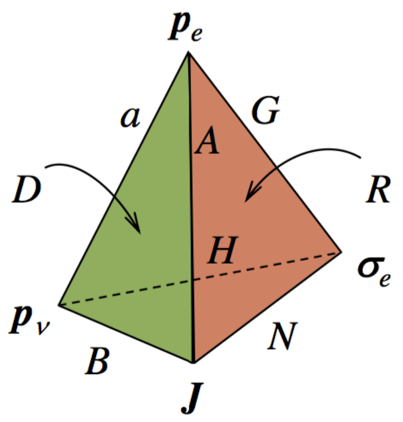
Differential beta decay rate:

$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \frac{<\vec{J}>}{J} \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] \right\}$$



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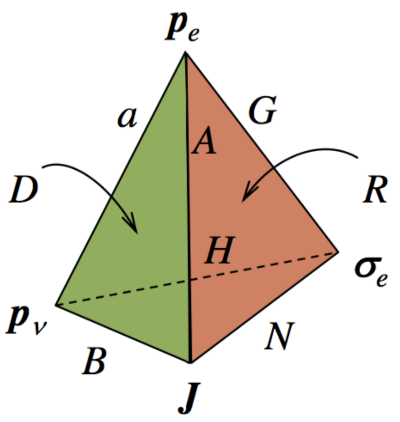

Example:

$$a\xi \approx M_F^2\left(C_V^2 + C_V'^2 - C_S^2 - C_S'^2\right) - M_{GT}^2\left(C_A^2 + C_A'^2 - C_T^2 - C_T'^2\right)/3$$

Decay type

$C_A^2 + C_A'^2$ → ***SM***

$C_T^2 + C_T'^2$ → ***BSM***

T. D. Lee and C. N. Yang, Phys. Rev. 104, 254 (1956)

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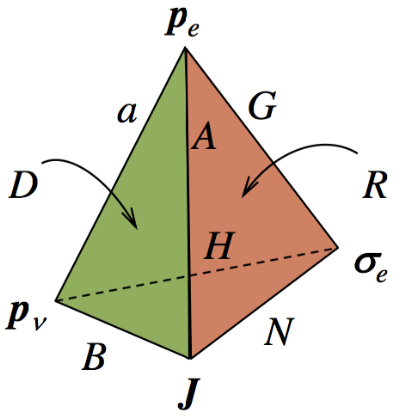
+ various corrections (calculated by Doron Gazit @ HUJI)



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($C_A^2 + C_A'^2$: ***SM***; $C_T^2 + C_T'^2$: ***BSM***)

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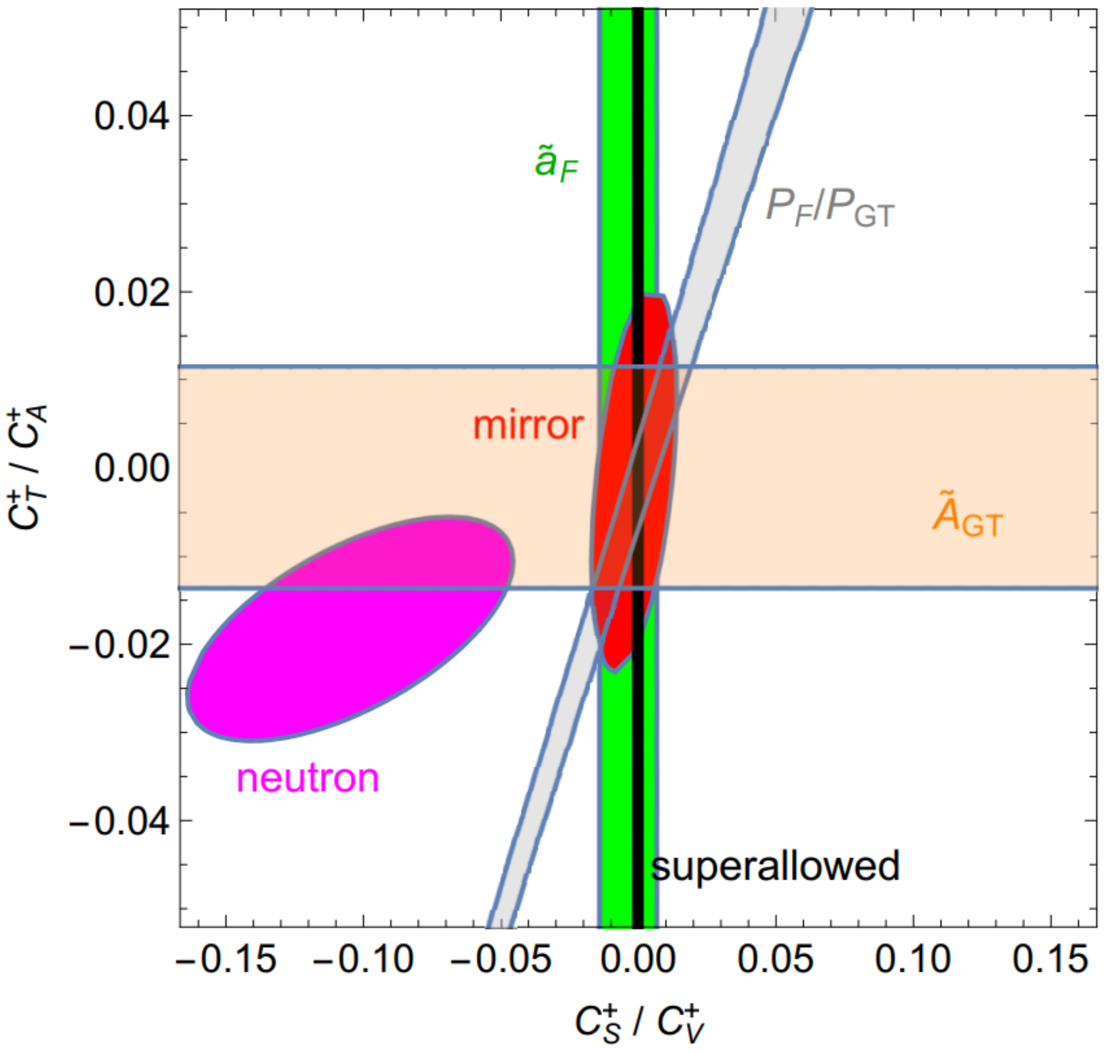
Comprehensive analysis of beta decays within and beyond the Standard Model

Adam Falkowski, Martín González-Alonso, and Oscar Naviliat-Cunci



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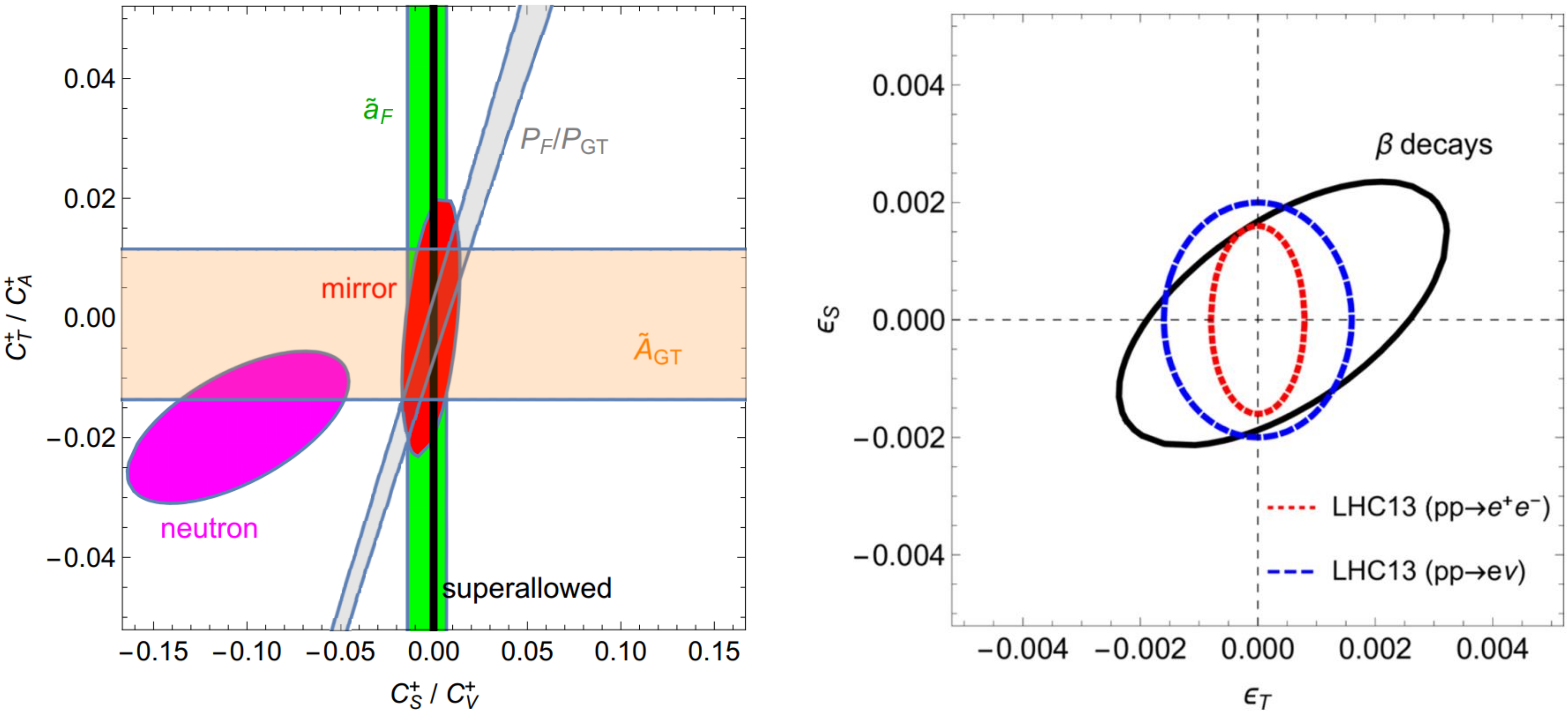

Kinematic measurements benefit from :

Trapped radioisotopes

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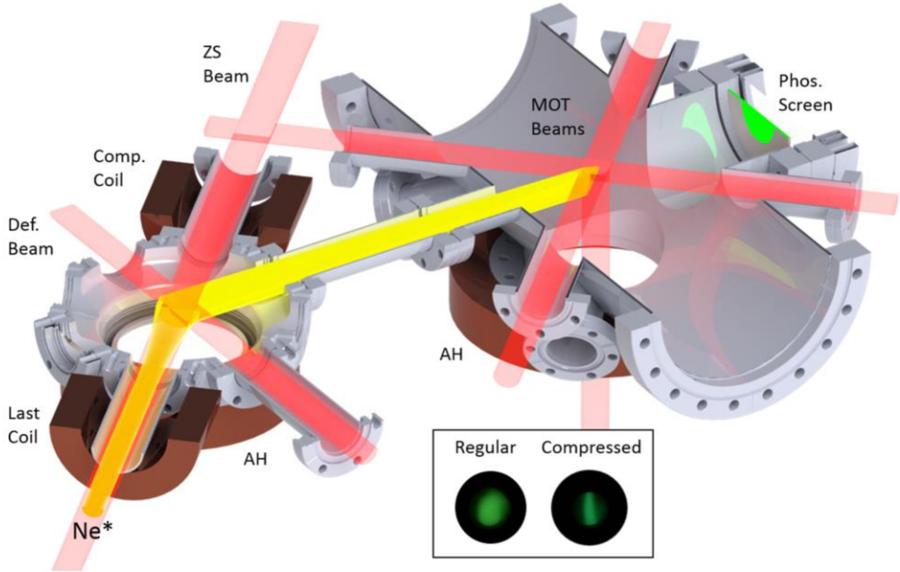
$^{18\text{-}23}$Ne atomic trap @ SARAF



+ Electrostatic Ion Beam Trap (initially 6He).

+ High precision/Stopping power Si(Li) Spectrometer.

SARAF/HUJI:
Guy Ron, Sergey Vaintraub
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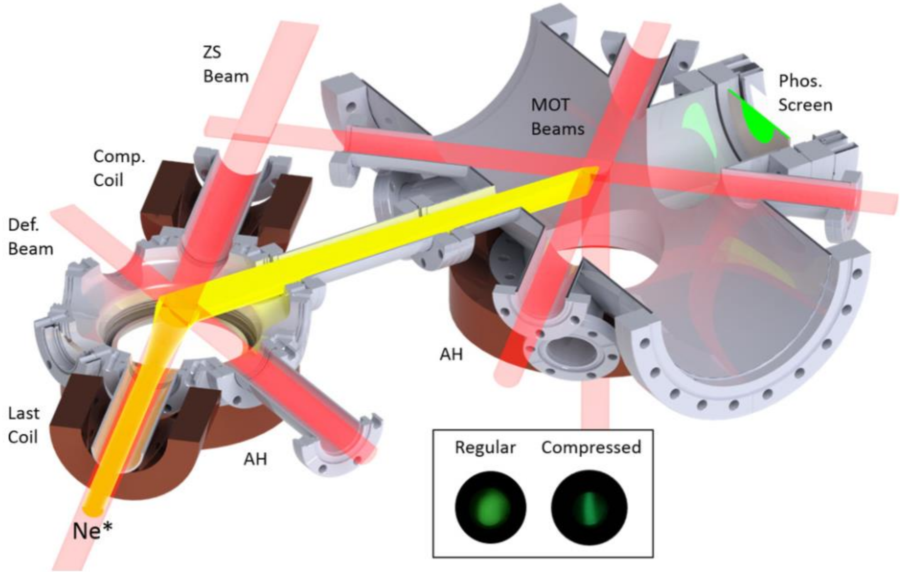

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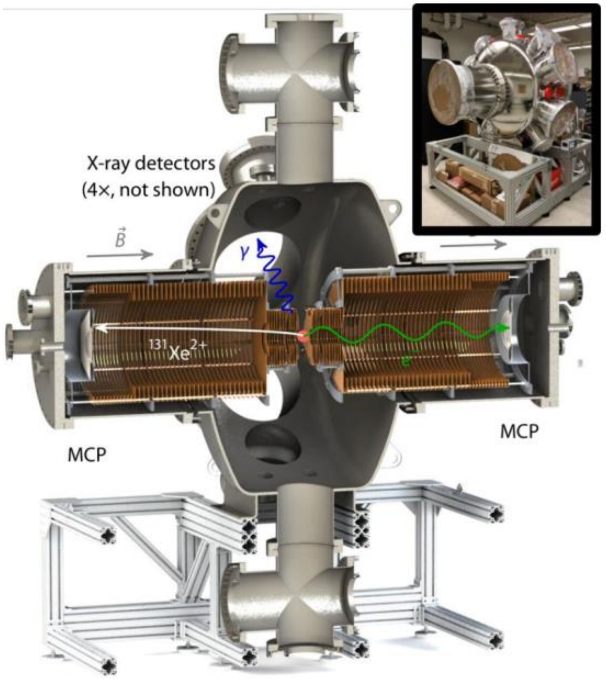
^{131}Cs @ UCLA



HUJI:
Guy Ron

USA: Jeff Martoff, Eric Hudson,
Paul Hamilton ...

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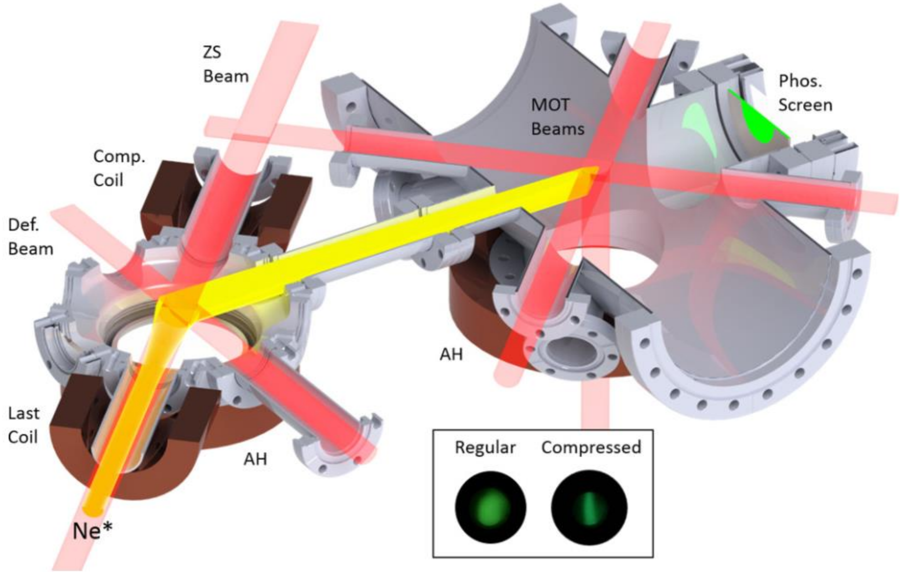

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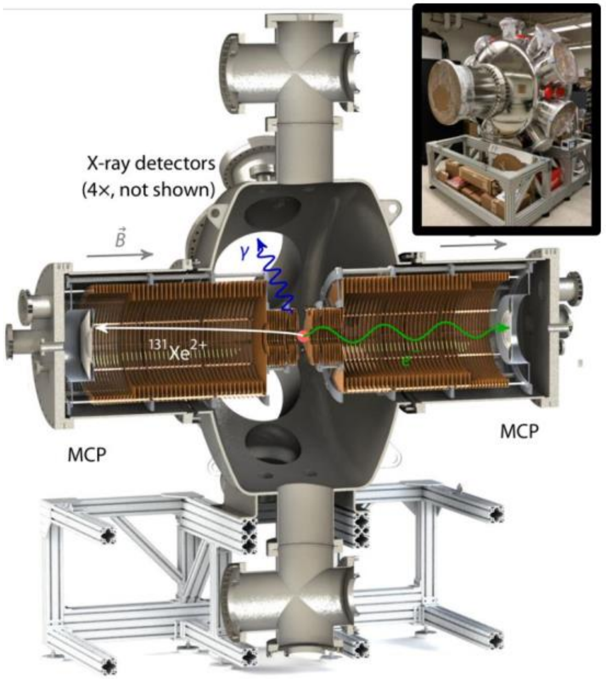

HUJI:
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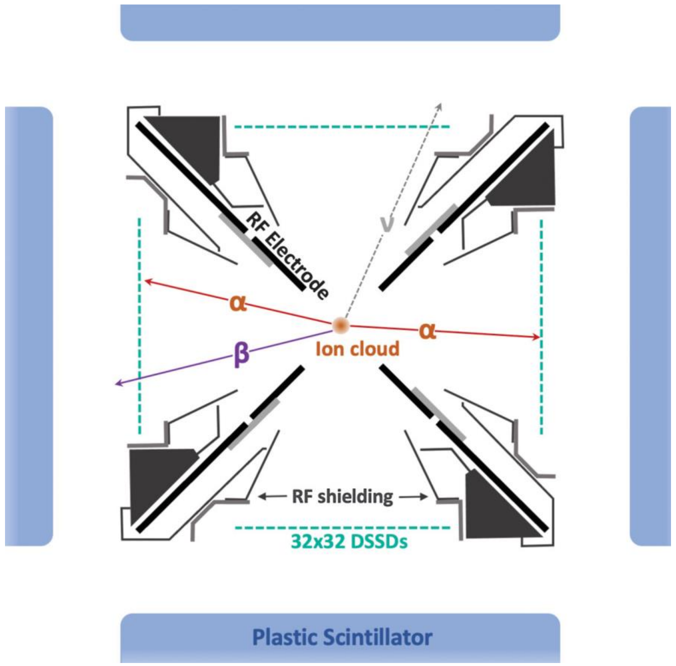
USA: Jeff Martoff, Eric Hudson, Paul Hamilton ...

^{8}Li/^{8}B ion trap @ LLNL



SARAF:
Tsviki Hirsch

USA: AT Gallant, ND Scielzo, G Savard, ...

Today

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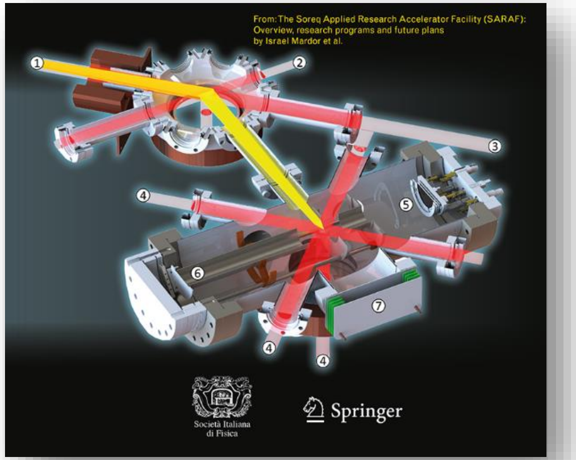
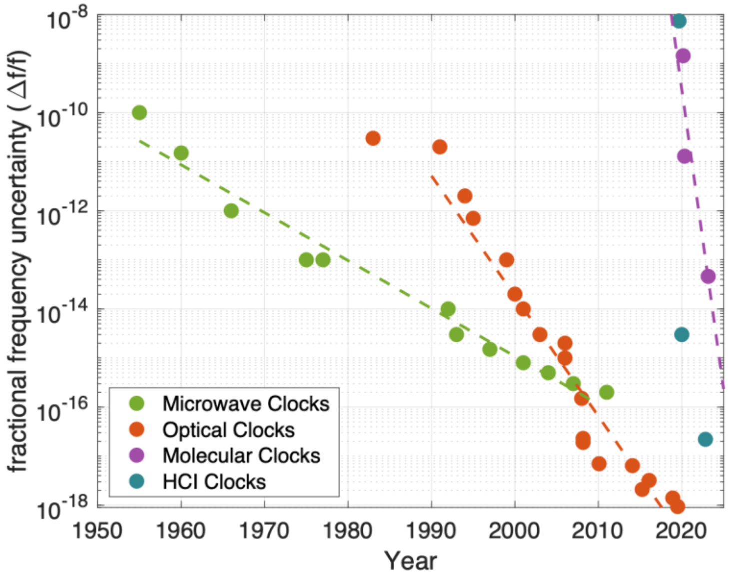
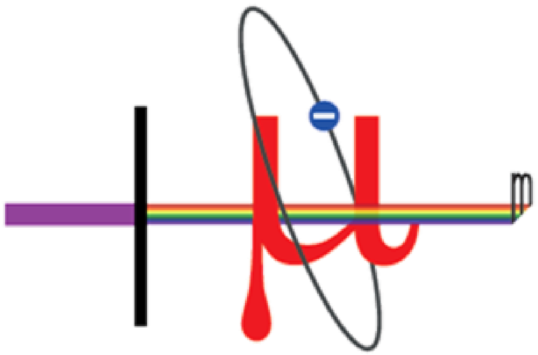


Clocks & interferometers



Exotic Atoms

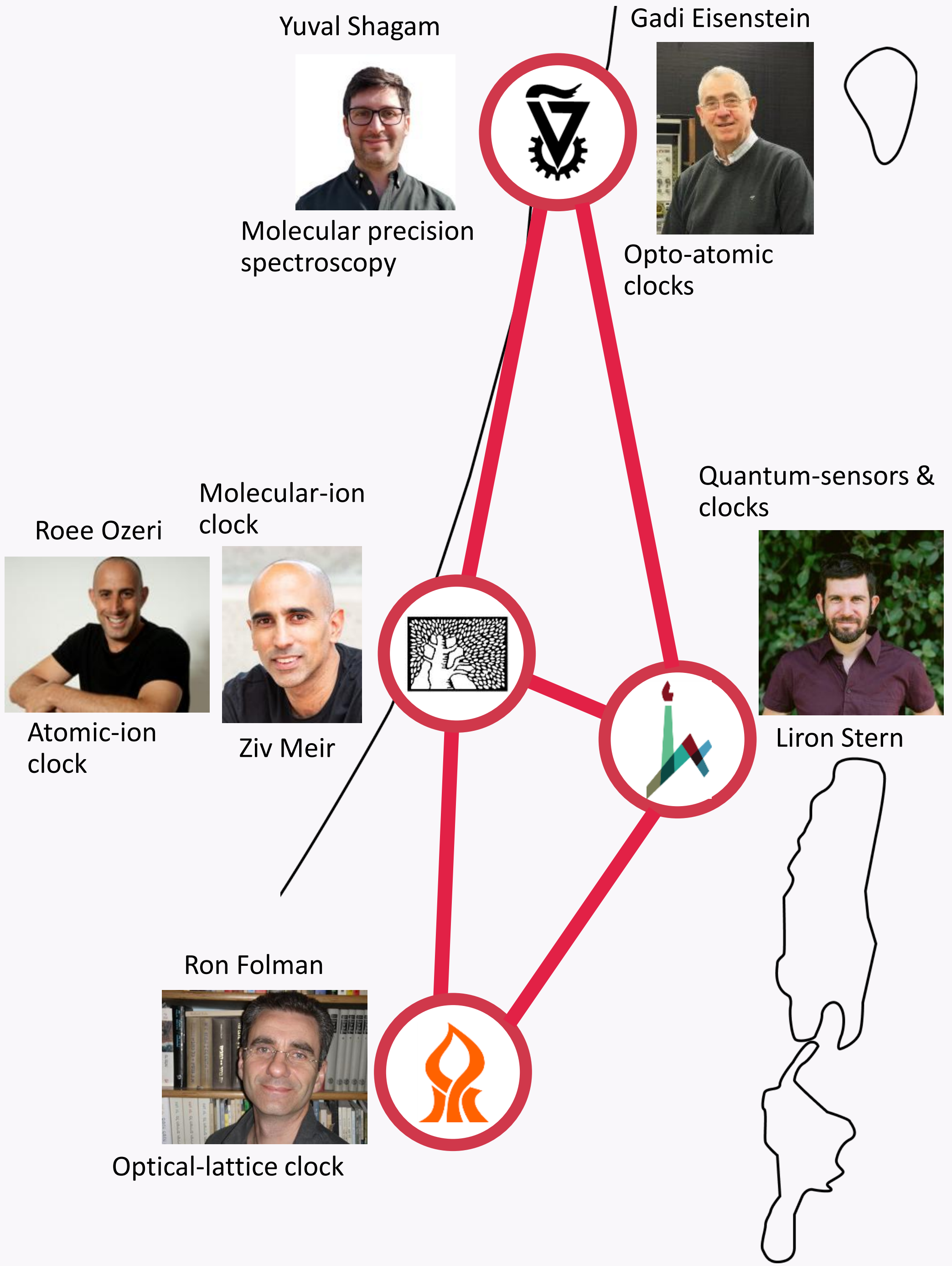


National Quantum-Metrology Network

- Establish time-and-frequency centers in Israel that will be connected to a national network.

- Provide accurate, precise, and stable time and frequency signals to local users, and throughout the network.

- A paradigm shift in metrological capabilities in Israel.



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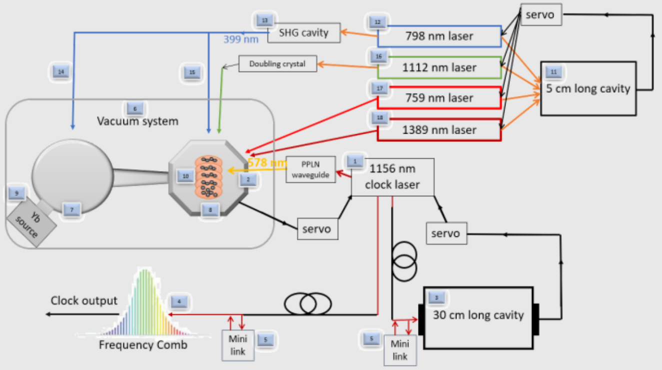
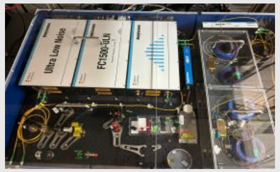
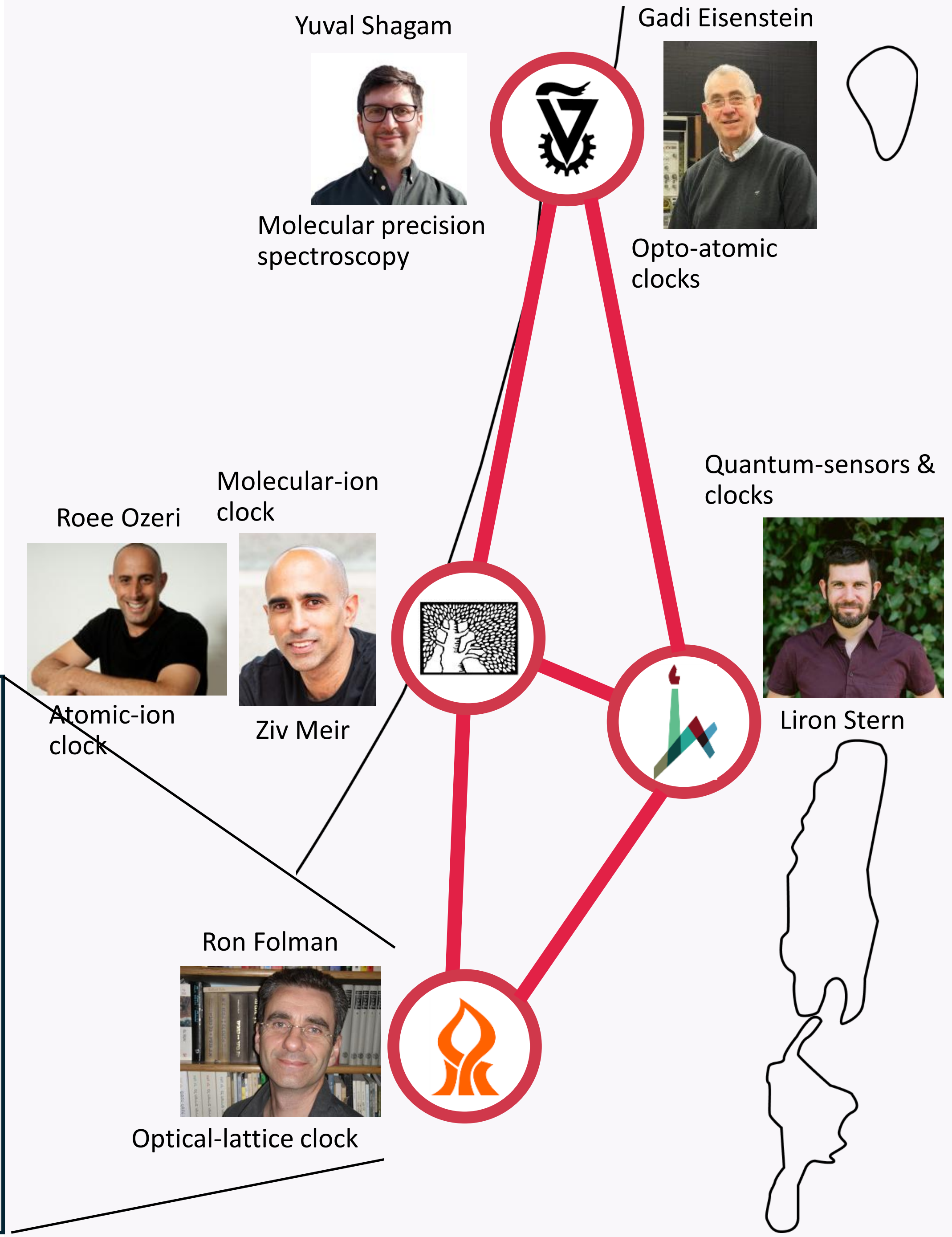
Yb Optical Lattice clock (goal: 10^{-18} precision)

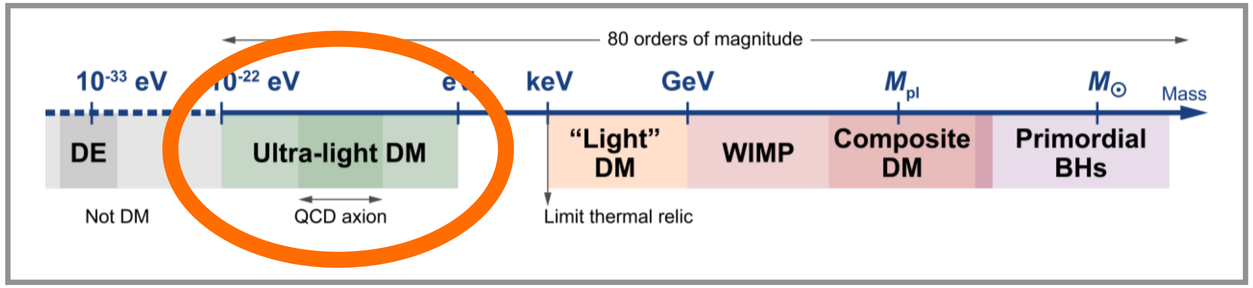






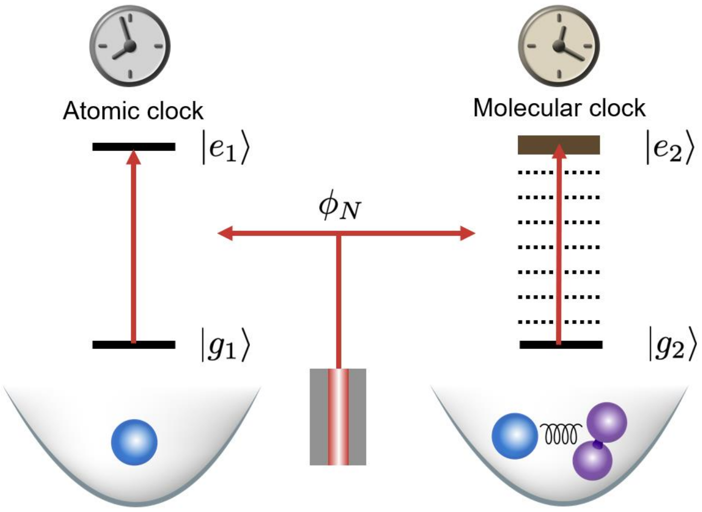
WI: Meir-Perez collaboration

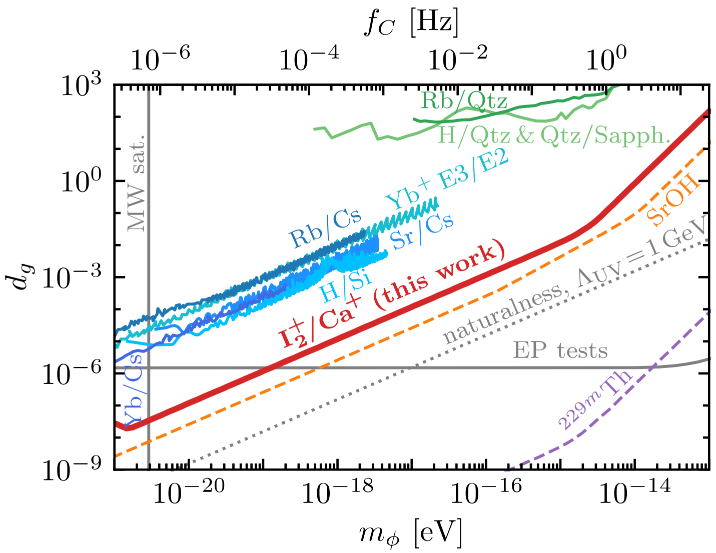
Dark-matter searches with I_2^+



Ferreira, Astron Astrophys Rev 29, 1-186 (2021)

Coupling to the **strong sector** – gives rise to oscillations of **vibration energy levels in molecules**.

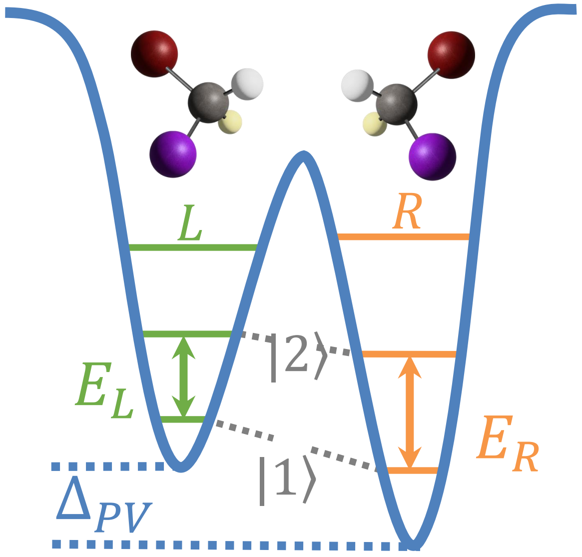




Precision spectroscopy of chiral molecules

- Weak force induced Parity violation:

  Vibrational spectroscopy of chiral molecular ions – $CHDBrI^+$
  ~1Hz shift expected between L and R enantiomers

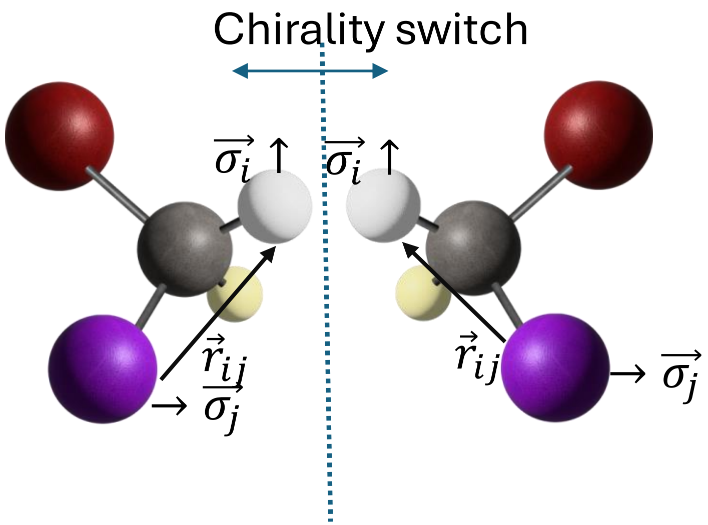


- Search for inter-nucleus BSM force:

  Rotational Spectroscopy of radical chiral molecules with nuclear spins $\vec{\sigma_i}$

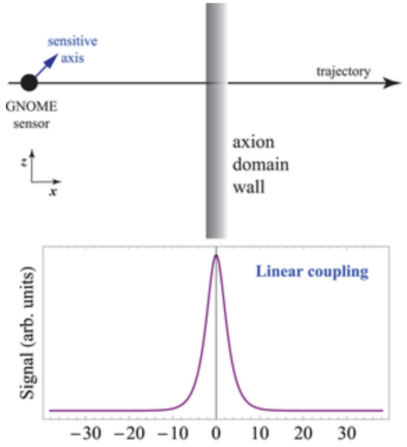
$$\Delta E_{BSM} \propto \langle(\vec{\sigma_i} \times \vec{\sigma_j}) \cdot \hat{r}_{ij}\rangle$$

Parity switch suppresses SM effects



Searching for exotic physics that couples with atomic spin

Goal: detect different DM interactions with atomic spin (e.g., domain wall)

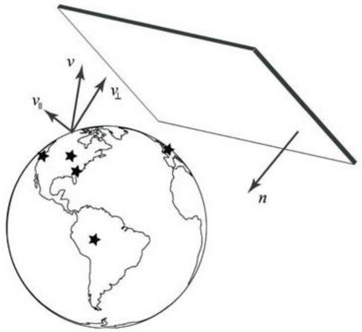


Tool: comagnetometer (Rb-K-^{3}He)

Attenuates low-frequency magnetic noise

GNOME collaboration (led by D. Budker)**:**

In Israel:
Folman group +
Ophir Ruimi (HUJI)



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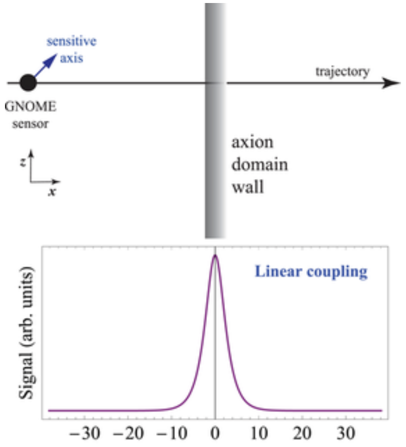

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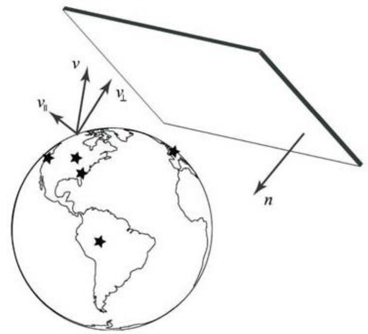
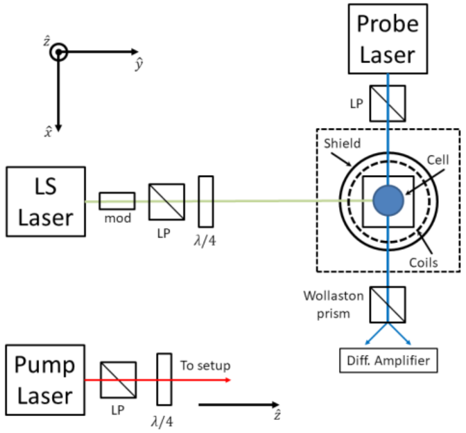
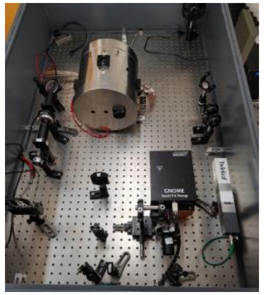
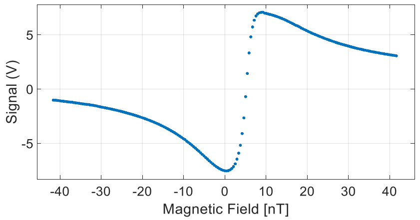


Future: corollate the comagnetometer with the Yb optical clock to search for exotic physics



BGU tabletop experiment and error signal from GNOME science run #5



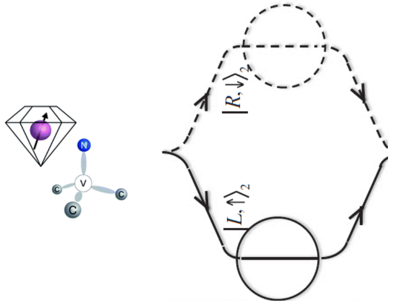


Current date: 2024/12/17 13:21:46 GPS

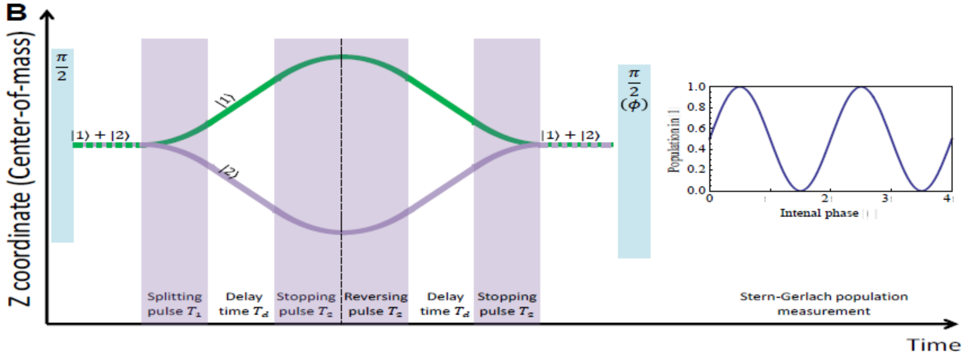
Show Map Legend

Nano-diamond spatial interferometry: Probing the Quantum-Gravity interface

Goal:

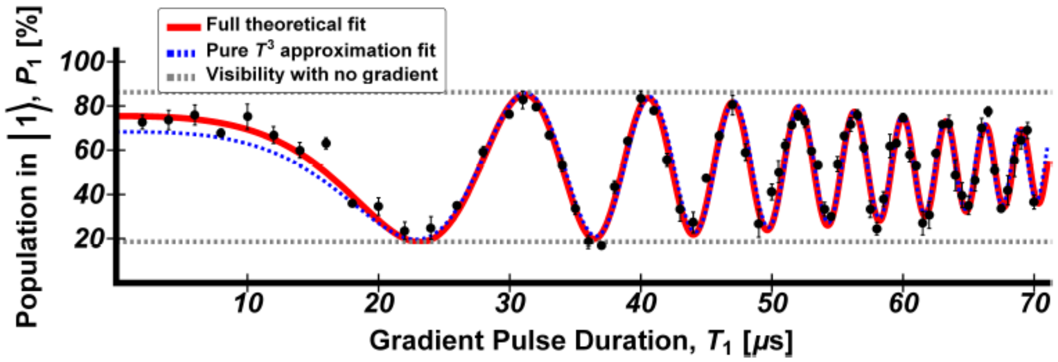


Tool: Stern-Gerlach interferometry on the atom chip



Expected signal: T^3 phase accumulation in spin population measurement

A preliminary experiment was performed with Rb atoms



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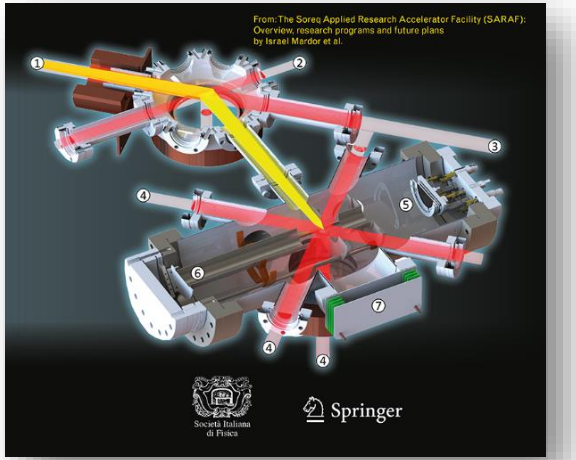

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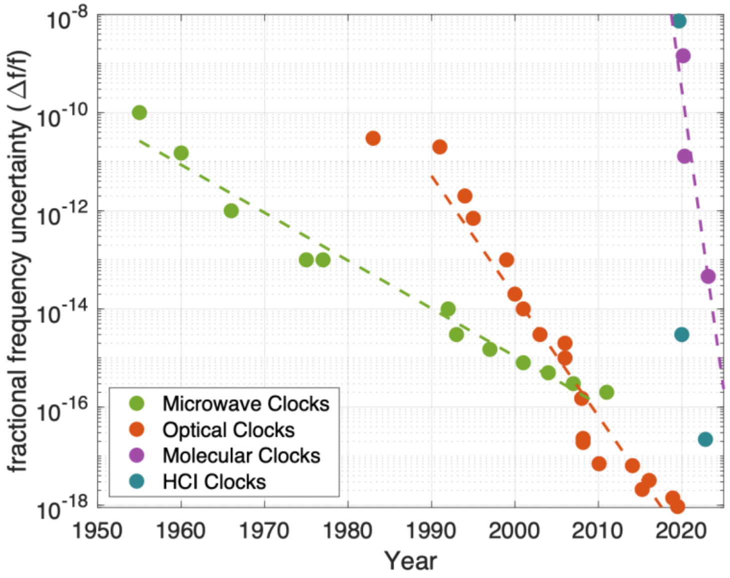

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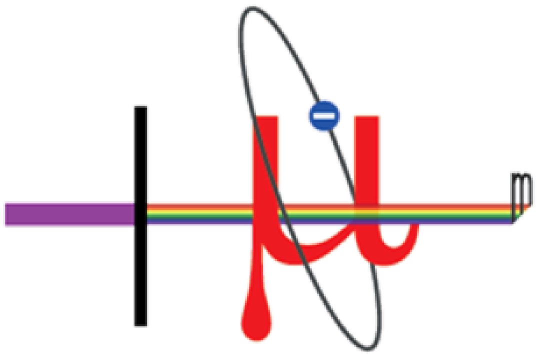

Israeli membership: Eli Sarid, Ben Gurion University

ALPHA Collaboration, CERN: spectroscopy and gravity measurements in Trapped Antihydrogen Atoms

Motivation: CPT tests

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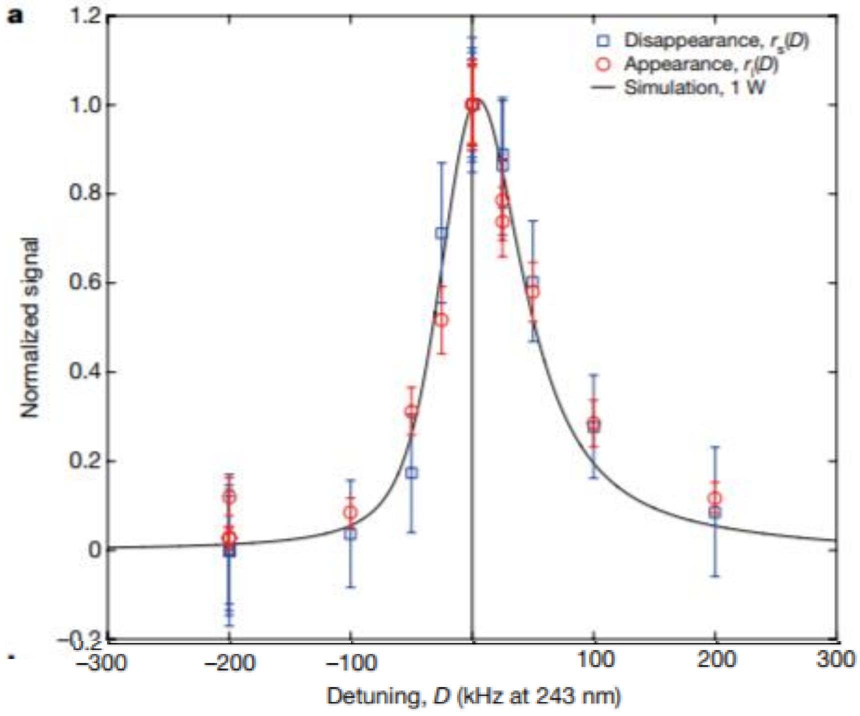
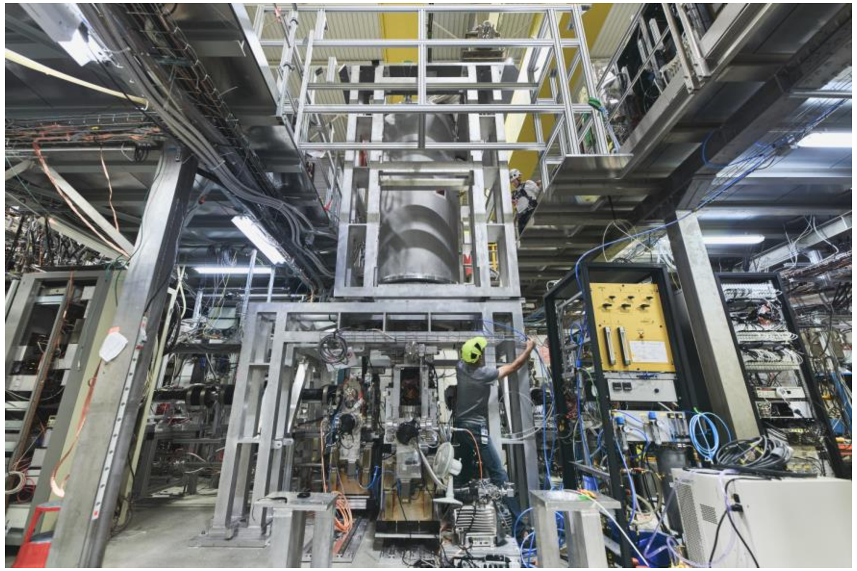
Characterization of the 1S–2S transition in antihydrogen





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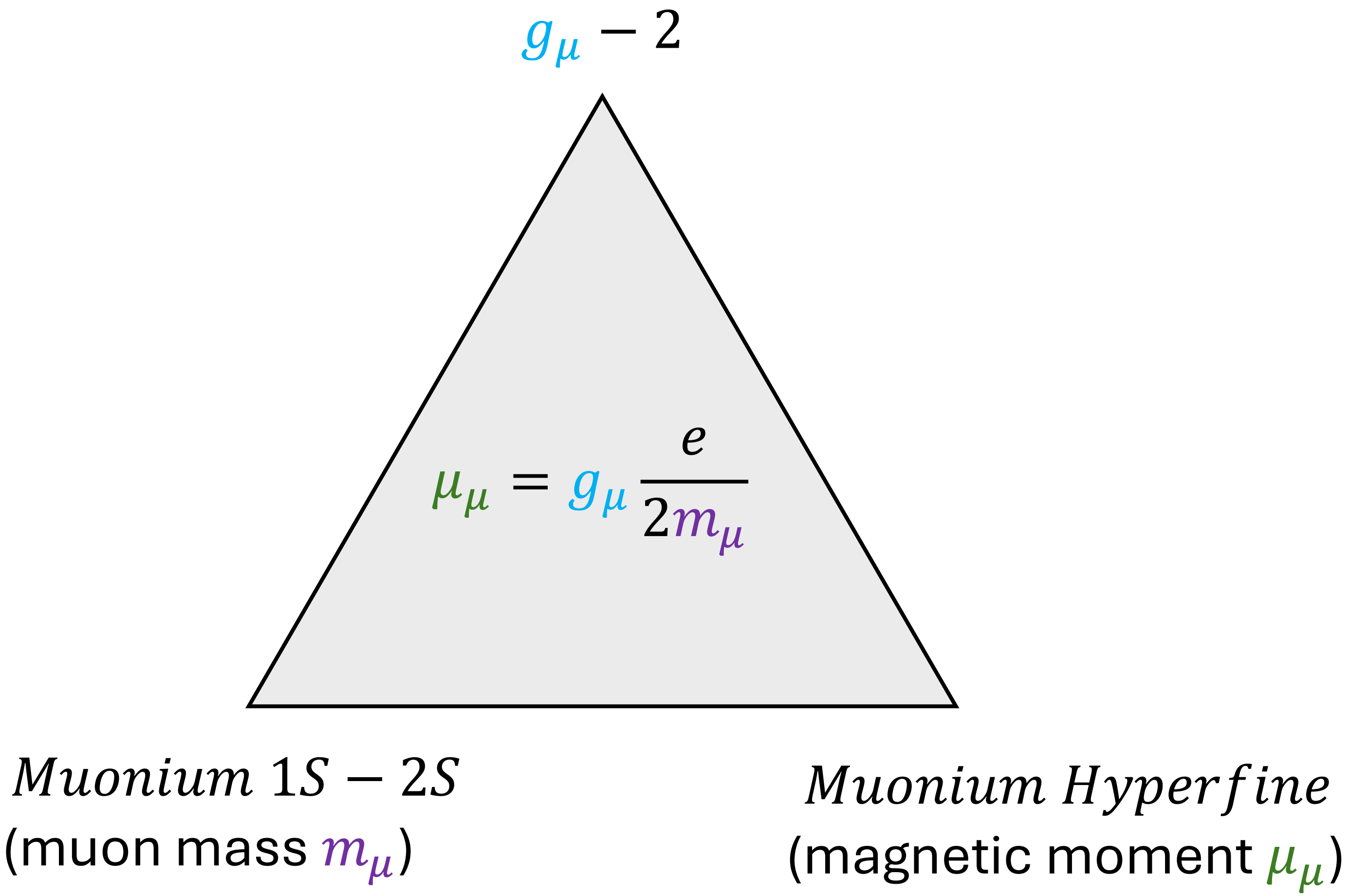
Observation of the effect of gravity on the motion of antimatter

Muonium Spectroscopy

The simplest atom

"Jungmann's Triangle"



Muonium Spectroscopy

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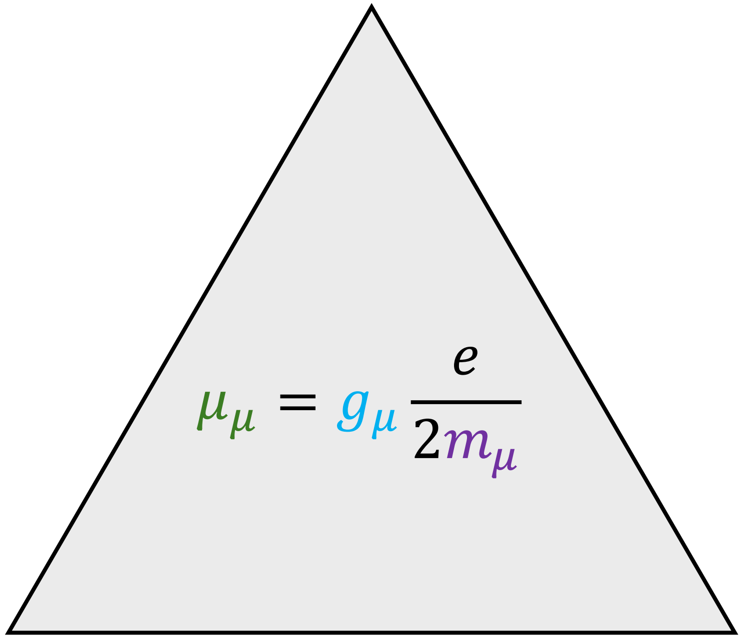
$g_\mu - 2$



Technion & ETH

MuMASS collaboration

Independent determination of muon g-2 (PRL 251801)

$Muonium\ 1S - 2S$
(muon mass m_μ)

$Muonium\ Hyperfine$
(magnetic moment μ_μ)

Experiments by Exotic Atoms Group @ Technion, pheno by Soreq group @ Technion., Nuclear Theory by Barnea group @ HUJI

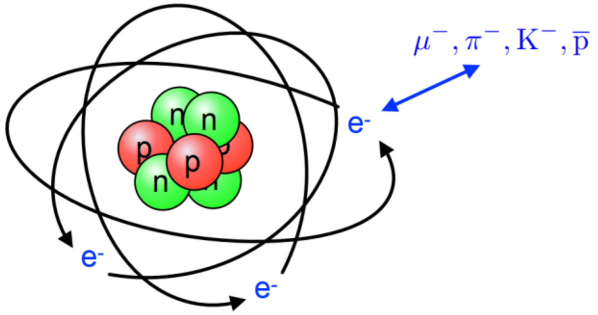
New physics searches with compact systems

Small size: $a = \frac{a_0}{Z^2}\frac{m_e}{m}$

Short-range new physics (heavy mediators)

High energy: $E_n = -R_\infty Z^2 \frac{m}{m_e}$

X-ray spectroscopy



Experiments by Exotic Atoms Group @ Technion, pheno by Soreq group @ Technion., Nuclear Theory by Barnea group @ HUJI

New physics searches with compact systems

Small size: $a = \frac{a_0}{Z^2}\frac{m_e}{m}$

Short-range new physics (heavy mediators)

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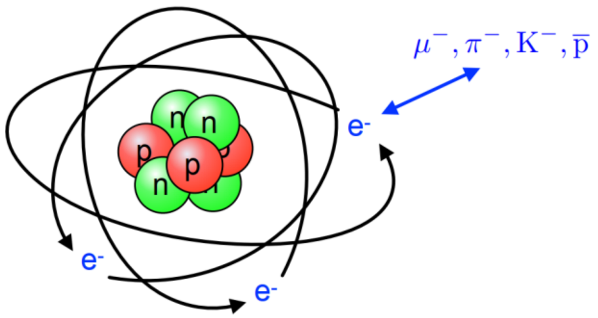
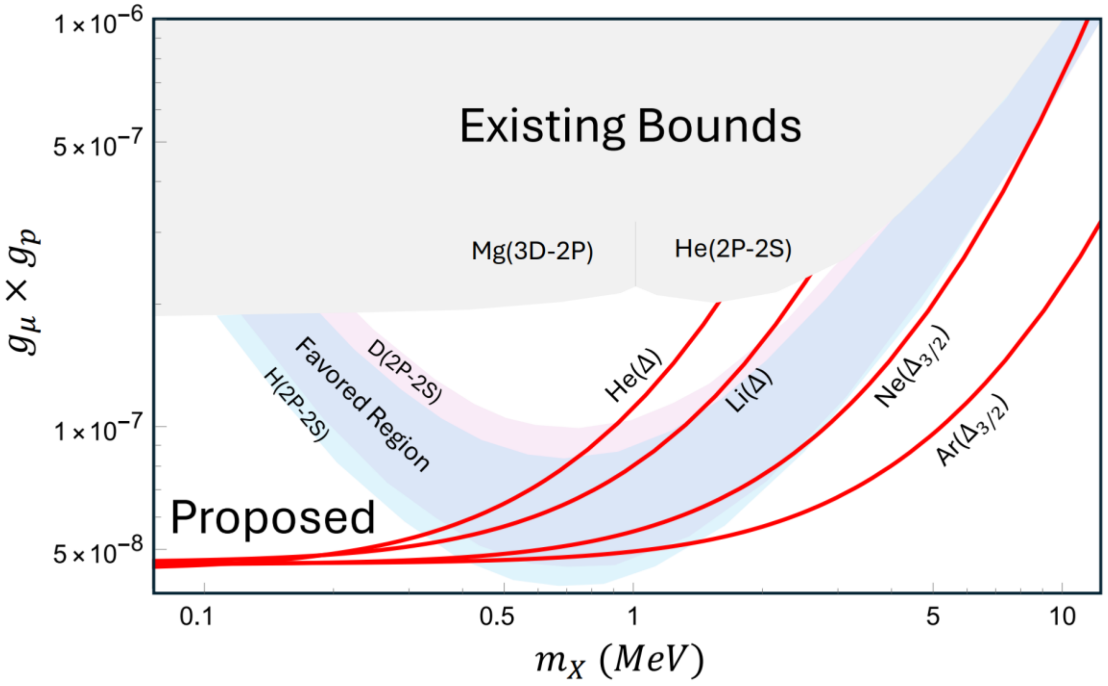


Contact-free muonic atoms:



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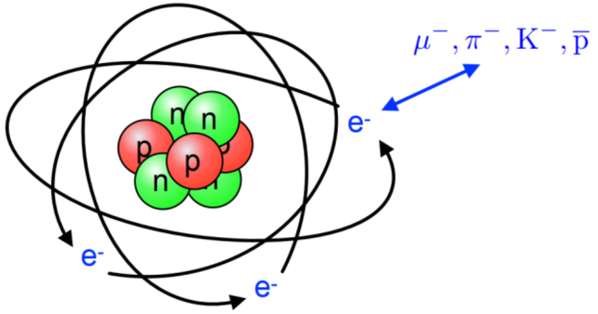

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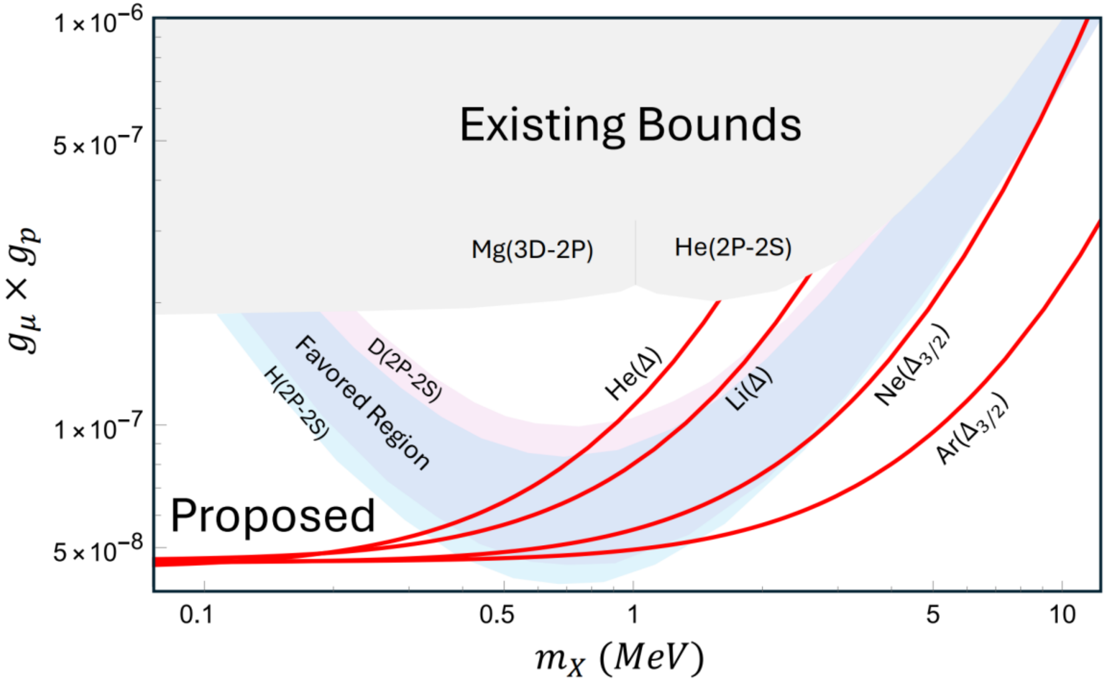
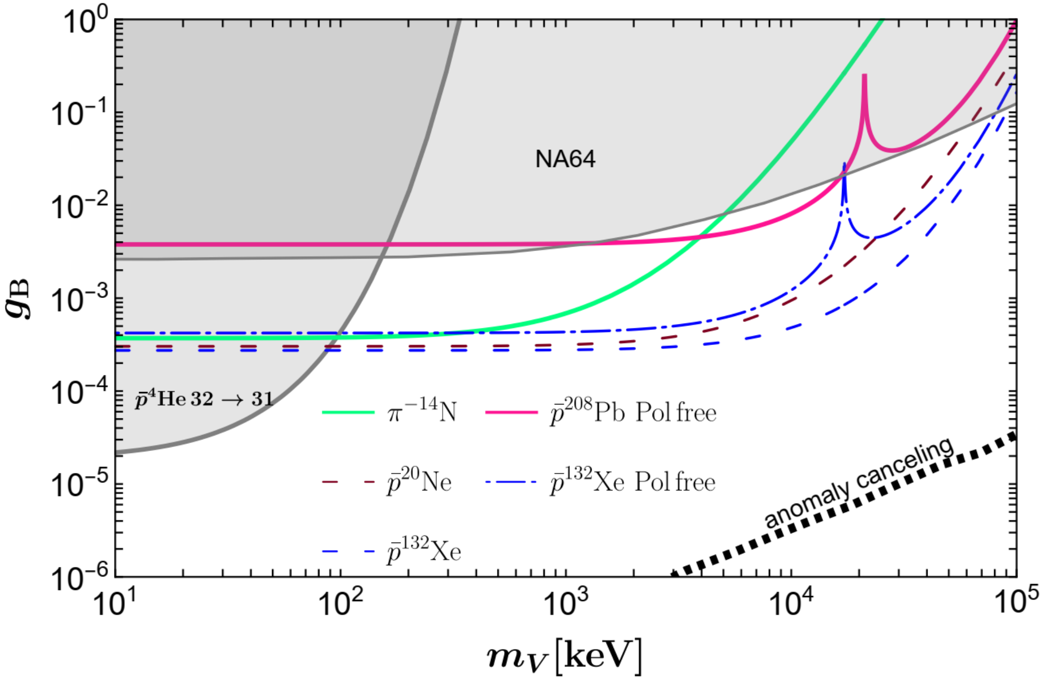


Contact free antiProtonic atoms:



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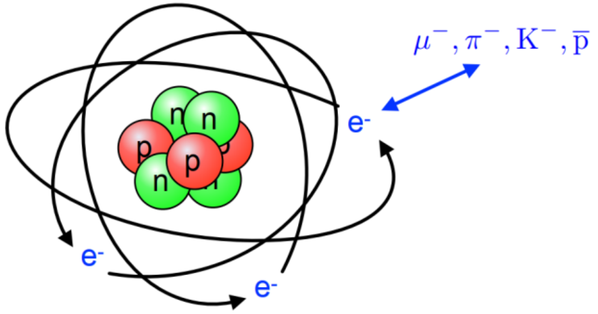

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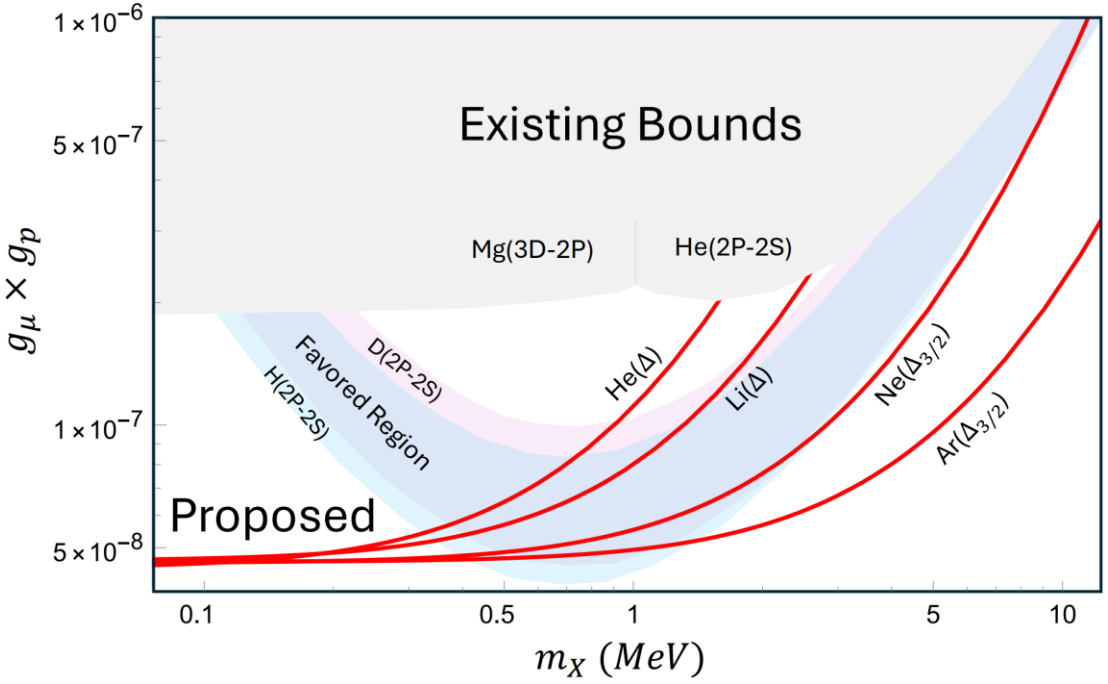

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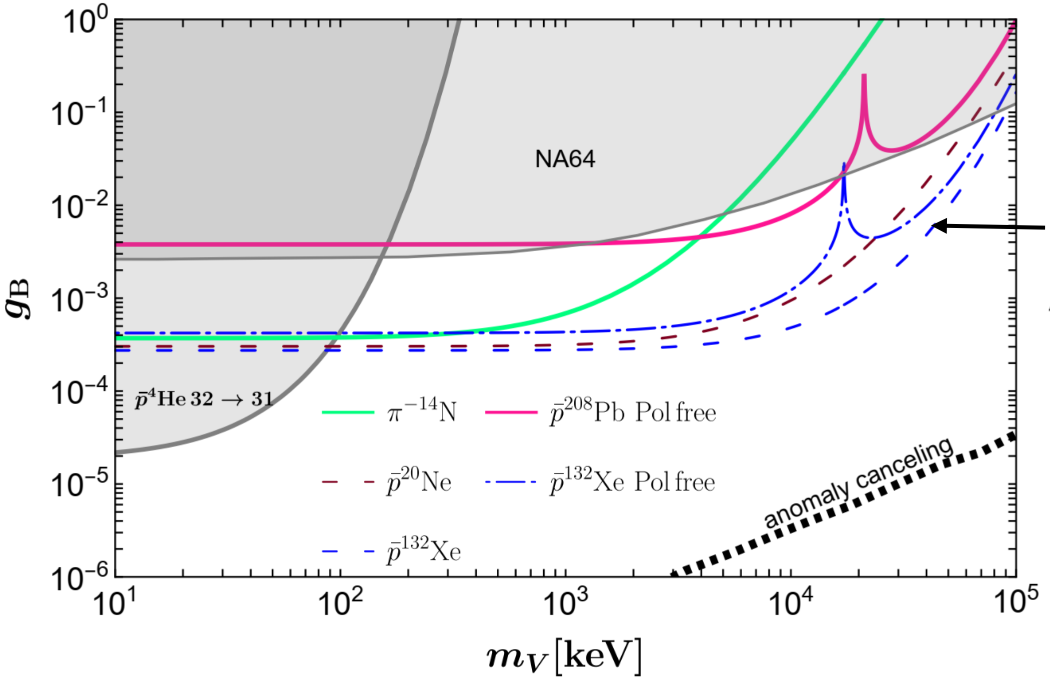

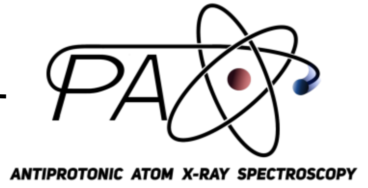

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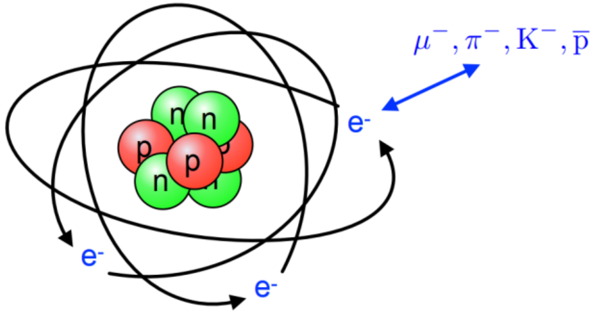
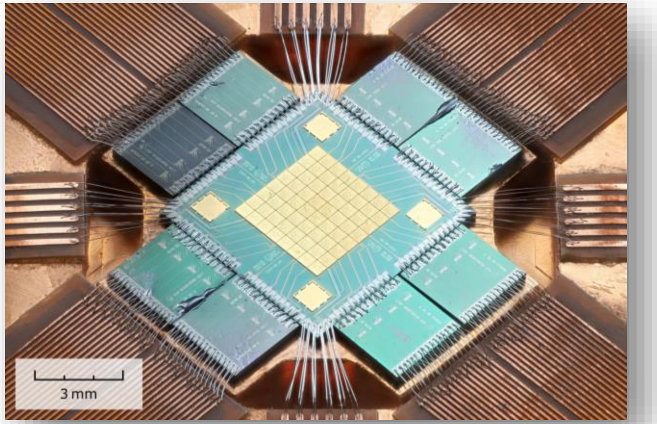
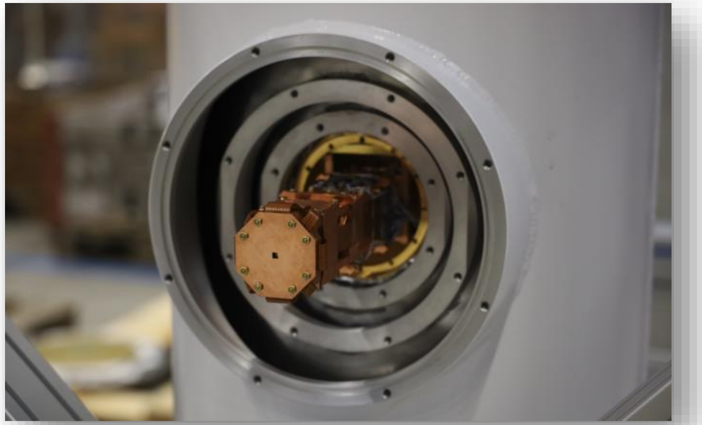


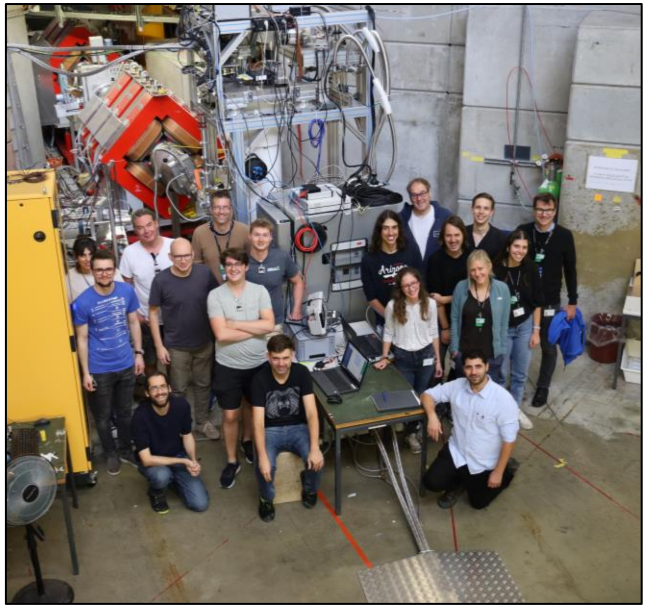
Enabling quantum-sensing technology: **Cryogenic Microcalorimeters**





arXiv:2310.03846

QUARTET collaboration

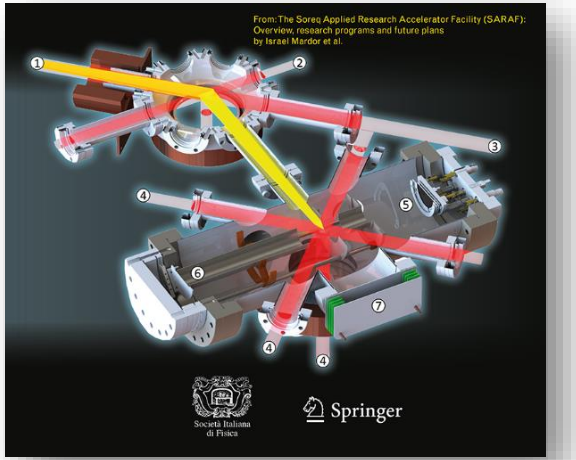


Summary

Tabletop experiments for Particle physics

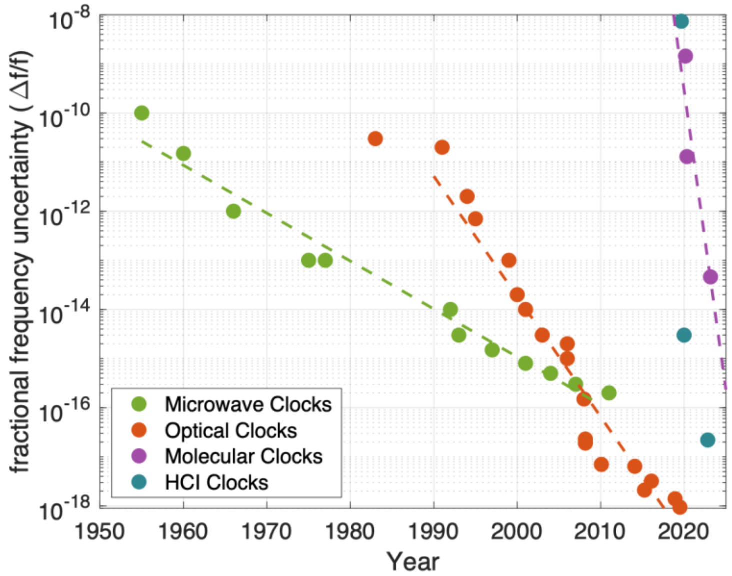
In Israel

Nuclear Beta decay



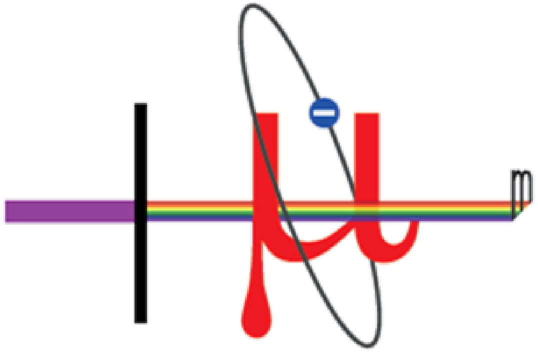
HUJI: Ron, Gazit
NRC: Vaintraub, Hirsch, Mishnayot, Beck

Clocks & interferometers



Technion: Shagam, Soreq
WI: Meir, Perez
BGU: Folman, Sarid
+ Clock Network
+ Thorium clock ?

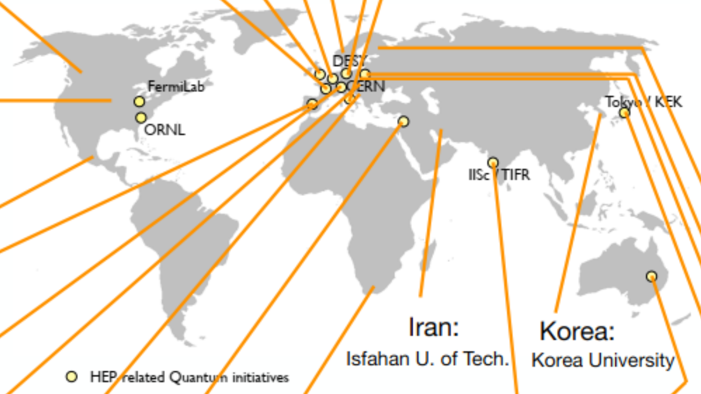
Exotic Atoms



Technion: Ohayon, Soreq
BGU: Sarid
HUJI: Barnea

DRD5: A global initiative on R&D on quantum sensors and emerging technologies for particle physics

~95 groups (as of 3.6.2024)



UK: Oxford University, Univ. of Warwick, Univ. of Birmingham, NPL, Imperial College, Univ. of Southhampton, Univ. of Sussex

France: SYRTE / OBSPM, CNRS - U. Sorbonne Paris Nord, LKB

Canada: McGill Univ., TRIUMF

USA: UCLA, ORNL, Northwestern Univ., Caltech, MIT, Arizona State Univ., Yale, Univ. of Arizona, NIST, LBNL, Univ. of Delaware, FNAL, SLAC

Mexico: U. de Aguascalientes

Spain: U. de Zaragoza, U. de Cartagena, U. de Valencia, U. de Lleida

Switzerland: U. of Geneva, U. of Zürich, CERN, ETHZ

Netherlands: U. of Groningen

Norway: Oslo University

Austria: IQOQI Vienna

Croatia: Inst. of Physics, Zagreb

Israel: Technion, Haifa

South Africa: U. of Cape Town

Iran: Isfahan U. of Tech.

India: IITTP, Tirupati, IISER, Kolkata, TIFR, Mumbai, University SOA Bhuvaneswar

Korea: Korea University

Australia: University of Queensland, University of Western Australia, Swinburne University of Technology

Germany: PTB, Univ. Ulm, Leibnitz Univ. Hannover, KIT, Karlsruhe, TU München, DESY, MPP Garching, HU Berlin, FBH Berlin, Univ. Heidelberg, Univ. Tübingen, Univ. Düsseldorf, Univ. Mainz, Univ. Bremen / ZARM, Semiconductor Lab HLL / MPG, TU Darmstadt

Italy: U. of Pisa & INFN, U. of Pavia, U. of Firenze, U. of Milano-Bicocca, Fondazione Bruno Kessler, Trento, IOM CNR, Elettra Sincrotrone, Trieste, Univ. of Bari / INFN, INFN Padova, Univ. Roma 1 & 3, Univ. Napoli, INFN Roma Tor Vergata, INFN LNF, INFN Trento (TIFPA), INFN Torino, INFN LNL, INFN Lecce, INFN Roma Tor Vergata, U. of Camerino

Finland: Helsinki Inst. of Physics, VTT

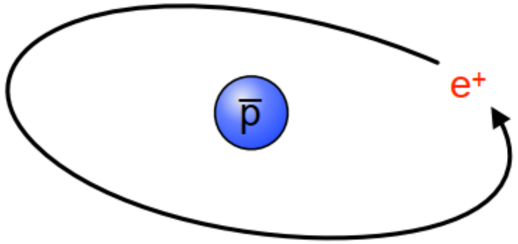
Poland: Warsaw TU, Nat. Centre Nucl. Research / Warsaw, Nat. Lab. FAMO / Torun

Czech Republic: Czech Tech. University

Japan: QUP / KEK, Kyoto University, Tokyo University / ICEPP

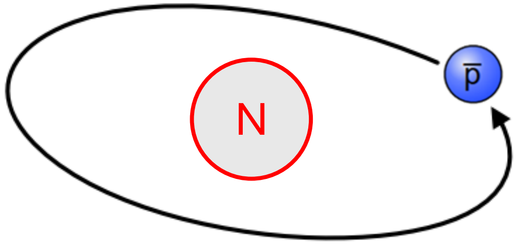
Efforts

Anti-Hydrogen



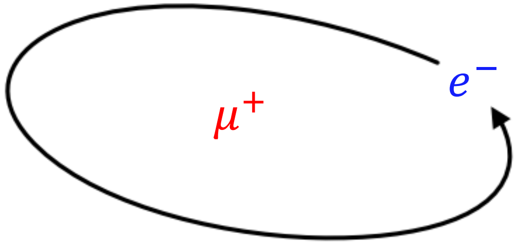
GBAR

Antiprotonic atoms



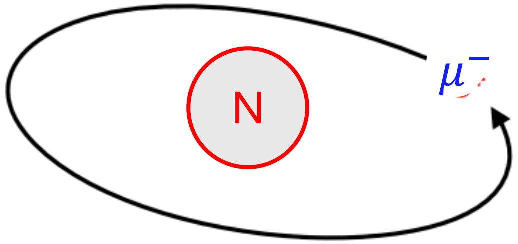
PAX
ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

Muonium



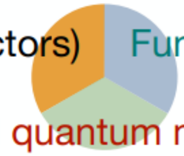
MU-MASS

Muonic atoms



QUARTET
$2p_{3/2}$
$2p_{1/2}$
2s
1s

Potential HEP impact

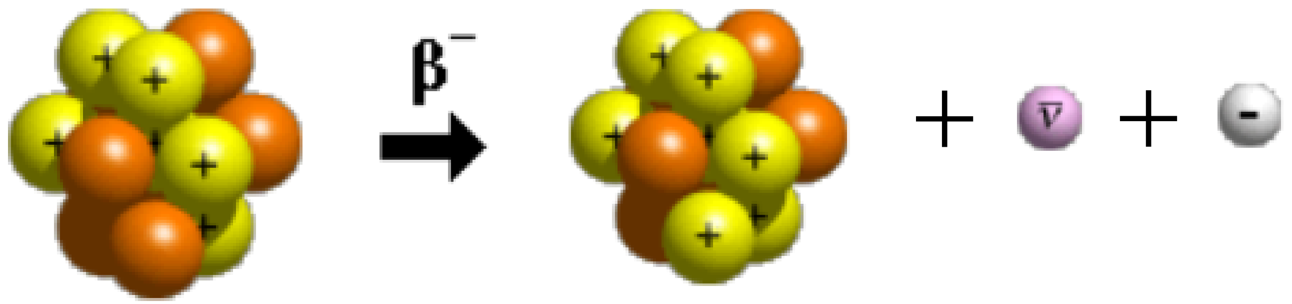


HEP function / Work package	Tracking	Calorimetry	Timing	PID	Helicity
WP 1 (Quantum systems in traps and beam)	Rydberg TPC	BEC WIMP scattering (recoil)	O(fs) reference clock for time-sensitive synchronization (photon TOF)	Rydberg dE/dx amplifiers	
WP2 (Quantum materials: 0-, 1- and 2-D)	"DotPix"; improved GEM's; chromatic tracking (sub-pixel); active scintillators	Chromatic calorimetry	Suspended / embedded quantum dot scintillators	Photonic dE/dx through suspended quantum dots in TPC	
WP 3 (Superconducting quantum devices)	O(ps) SNSPD trackers for diffractive scattering (Roman pot)	FIR, UV & x-ray calorimetry	O(ps) high Tc SNSPD	Milli- & microcharged particle trackers in beam dumps	
WP 4 (scaled-up bulk systems for mip's)	Multi-mode trackers (electrons, photons)	Multi-mode calorimeters (electrons, photons, phonons)	Wavefront detection (e.g. O(ps) embedded devices)		Helicity detector via ultra-thin NV optically polarized scattering / tracking stack
WP 5 (Quantum techniques)				Many-to-one entanglement detection of interaction	
WP 6 (capacity building)	Technical expertise of future workforce (detector construction); broadened career prospects and thus enhanced attractiveness; cross-departmental networking and collaboration; broadened user base for infrastructure (beam tests, dilution refrigerators, processing technologies)				

(under way; in preparation; under discussion or imaginable applications; long-range potential)

Nuclear decay

Father : *Daughter :*



Nuclear spin : J_i J_f $1/2$ $1/2$

$$\left|J_f - J_{\beta\nu}\right| \le J_i \le J_f + J_{\beta\nu}$$

$\uparrow\downarrow - \downarrow\uparrow = |0,0\rangle$ $J_{\beta\nu} = 0$ *Fermi* $\Delta J = 0$

$\uparrow\uparrow = |1,1\rangle$

$\uparrow\downarrow + \downarrow\uparrow = |1,0\rangle$ $J_{\beta\nu} = 1$ *GT* $\Delta J = 0, \pm 1$

$\downarrow\downarrow = |1,-1\rangle$ *No* $(0 \to 0)$

Example : $n\left(1/2^+\right) \to p\left(1/2^+\right) + e + \bar{\nu}$

Fermi : 18%

GT : 82%

Why study nuclear beta decay?

$$a_{\beta,\nu}^{LO\xi LO} = |M_F|^2 \left(|C_V^{(l)}|^2 + |C_V'^{(l)}|^2 - |C_S^{(l)}|^2 - |C_S'^{(l)}|^2\right)$$
$$- |M_{GT}|^2 \left(|C_A^{(l)}|^2 + |C_A'^{(l)}|^2 - |C_T^{(l)}|^2 - |C_T'^{(l)}|^2\right)$$
$$\pm 2\frac{\alpha Z m_e}{p_e}\mathrm{Im}\left(C_S^{(l)}C_V^{(l)*} + C_S'^{(l)}C_V'^{(l)*}\right)$$
$$b^{LO\xi LO} = \pm 2\gamma \mathrm{Re}\Big[|M_F|^2 \left(C_S^{(l)}C_V^{(l)*} + C_S'^{(l)}C_V'^{(l)*}\right)$$
$$+ |M_{GT}|^2 \left(C_T^{(l)}C_A^{(l)*} + C_T'^{(l)}C_A'^{(l)*}\right)\Big]$$
$$B^{LO\xi LO} = 2\mathrm{Re}\left\{-|M_{GT}|^2 \left[\left(C_T^{(l)}C_T'^{(l)*} + C_A^{(l)}C_A'^{(l)*}\right) + \left(C_T^{(l)}C_A'^{(l)*} + C_T'^{(l)}C_A^{(l)*}\right)\right]\right\}$$

J.D. Jackson, S.B. Treiman, & H.W. Wyld, Phys. Rev. 106, 517 (1957)

Correlation Coefficients:

Differential Beta-Decay rate:

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto \xi \left\{ 1 + a_{\beta\nu} \frac{p_e \cdot p_\nu}{E_e E_\nu} + b_{Fierz} \frac{m_e}{E_e} + \frac{\langle I \rangle}{I} \cdot \left[A_\beta \frac{p_e}{E_e} + B_\nu \frac{p_\nu}{E_\nu} + D \frac{p_e \times p_\nu}{E_e E_\nu} \right] \right\}$$

$$a_{\beta\nu}\xi \sim |M_F|^2 (C_V^2 + C_V'^2 - C_S^2 - C_S'^2) - |M_{GT}|^2 (C_A^2 + C_A'^2 - C_T^2 - C_T'^2)/3$$

$$b_f \sim |M_F|^2 \frac{C_S + C_S'}{2C_V} + |M_{GT}|^2 \frac{C_T + C_T'}{2C_A} = 0 \text{ SM, right-handed BSM}$$

$\left(\frac{M_W}{M_{New}}\right)^2$ ~ Precision in coefficients, sub 1% probes TeV physics!

Traditional

Total decay rate:

$$ft \propto \frac{1}{1 + b_f < \frac{m}{E} >}$$

$0^+ \rightarrow 0^+$

Neutron, Mirror

Traditional

Beta Spectrum:

Allowed

$$\Gamma(E_e) \propto 1 + b_f \frac{m}{E_e}$$

Traps!

Recoil ion spectrum:

$$\Gamma(E_e, r) \propto 1 + a_{\beta\nu} \frac{\cos(\theta_{\beta\nu}) p_e}{E_e} + b_f \frac{m}{E_e}$$

Best to fit:

$$\hat{a} = a_{\beta\nu} + \alpha b_f$$

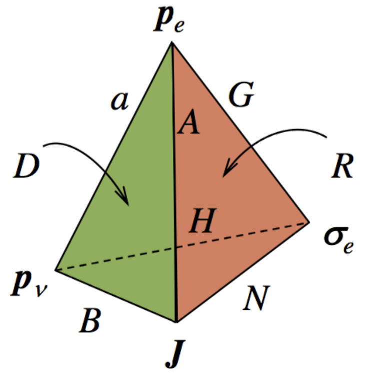
$$\alpha_{6He} \sim 0.1$$

See: Gonzalez-Alonso and O. Naviliat-Cuncic 2016

β decay 101

Differential decay rate

$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \frac{<\vec{J}>}{J} \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] \right\}$$



Parameter	Observable	Sensitivity	SM Prediction
a	β-ν (recoil) correlation	Tensor & Scalar terms	1 for pure Fermi -1/3 for pure GT or combination
b (Fierz term)	Comparison of β^+ to EC rate	SV/T/A interference	0
A	β asymmetry for polarized nuclei	Tensor, ST/VA Parity	Nucleus dependent
B	ν asymmetry (recoil) for polarized nuclei	Tensor,TA/ST/VA/SA/VT Parity	Nucleus dependent
D	Triple product	ST/VA Interference TRI	0

Fundamental & Useful constants

Physical Parameters in the SM (w. o. m_ν) + G_N :

- Higgs Sector: Mass and Vacuum expectation value
- Yukawa Sector: 9 fermion masses (e.g. m_e),
  3 CKM mixing angles and 1 phase
- Guage sector: 3 gauge couplings (e.g. fine structure α)

"In principle" calculable:

- Masses of composites (proton, neutron, pion , helion, ...)
- Magnetic moments of composites
- Nuclear low energy constants (e.g. nuclear EM moments)
- *...ad infinitum*

Hydrogen-like energy levels:

$$E_n = -\frac{\boldsymbol{R}_\infty}{n^2}\frac{1}{1+m/M}\left(1 + a_{FS}\alpha^2 + a_{LS}\alpha^3 + a_{HFS}\alpha^2 g_N \frac{m}{M}(1 + a_z \alpha m r_Z + \cdots) + a_{FNS}\alpha^2 m^2 r_C^2 + a_F \alpha^3 m^3 r_F^3 + \cdots\right)$$

Role of bound state QED theory: calculate dimensionless numbers $a_i(n, l, j)$

Best Experiment + Theory determines $\boldsymbol{R}_\infty$ (ppt level)