(More or less exotic) Light New Physics
Motivation and search strategies

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La Thuile 2023 -
Les Rencontres de Physique de la Vallée d'Aoste

March 6th, 2022

CERN
Leibniz Universität Hannover
PTB
QuantumFrontiers
QUANTUM TECHNOLOGY INITIATIVE

Outline

1) Motivation for light New Physics

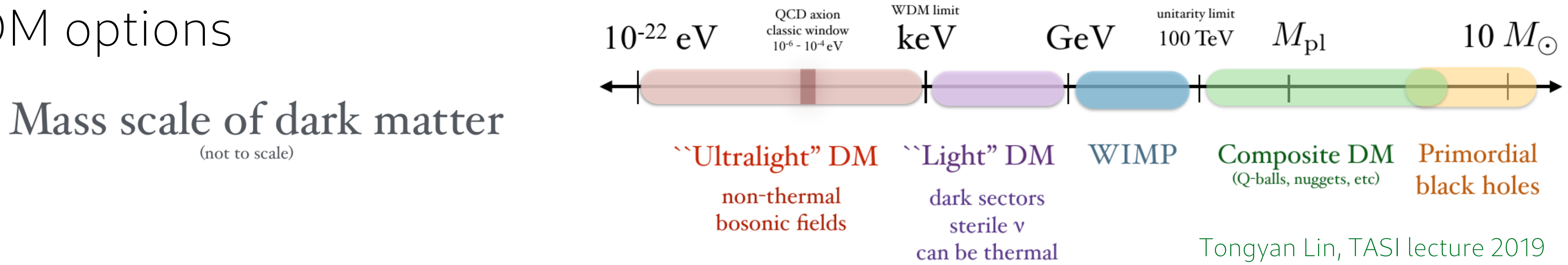
2) Axion

3) Relaxion

4) Quantum sensors for exotic light NP

Why light New Physics

- If symmetries imply massless particles
  - Small symmetry breaking → low mass
  - e.g. dilaton, dark photon, ...
- Still a lot of unexplored model and parameter space
- interplay of cosmo/astro/precision/intensity/precision frontiers
- DM options

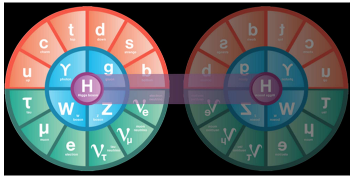


Tongyan Lin, TASI lecture 2019

Approaches to BSM model building

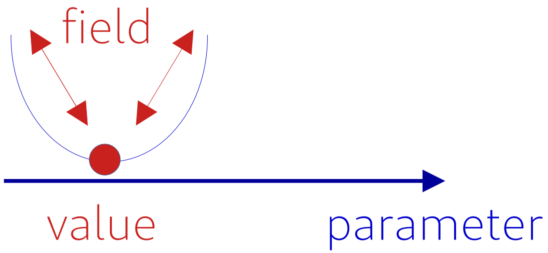
Based on symmetries

- Cancellation of terms due to relations between couplings or masses
- Often requires partner particles for SM particles
- Examples: supersymmetry, neutral naturalness



Based on dynamics

- Parameter → dynamical field
- Vacuum expectation value of the field explains observed parameter
- Examples: axion, relaxion



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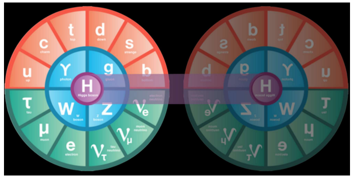
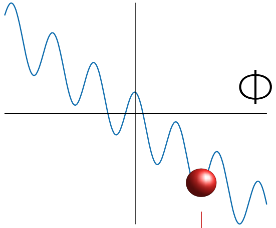


Graham, Kaplan, Rajendran '15

Relaxion potential



Observed Higgs mass

Based on dynamics

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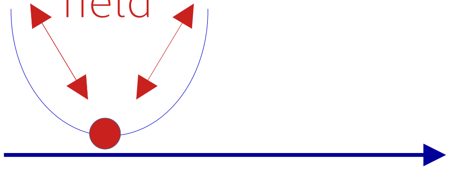
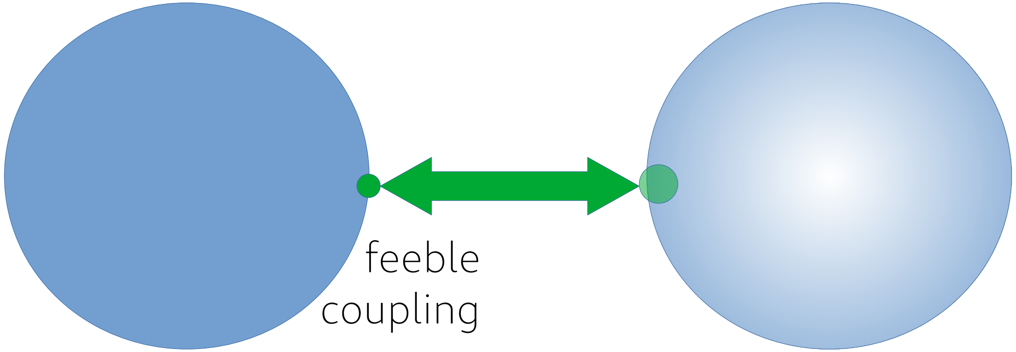


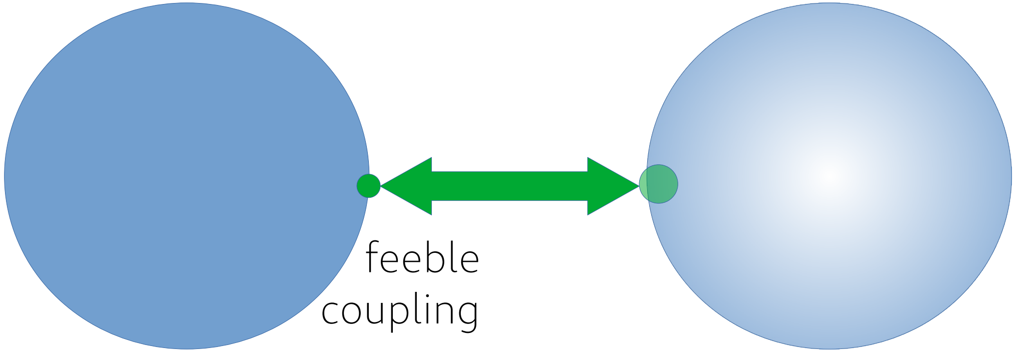
Mediators to Dark Sector



→ Intensity, precision frontiers

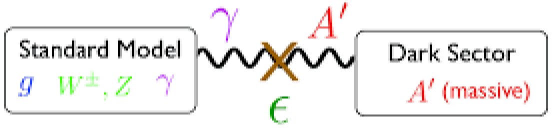
Motivation/need to search for light, feebly interacting particles

Mediators to Dark Sector



→ Intensity, precision frontiers

Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu}B^{\mu\nu}$



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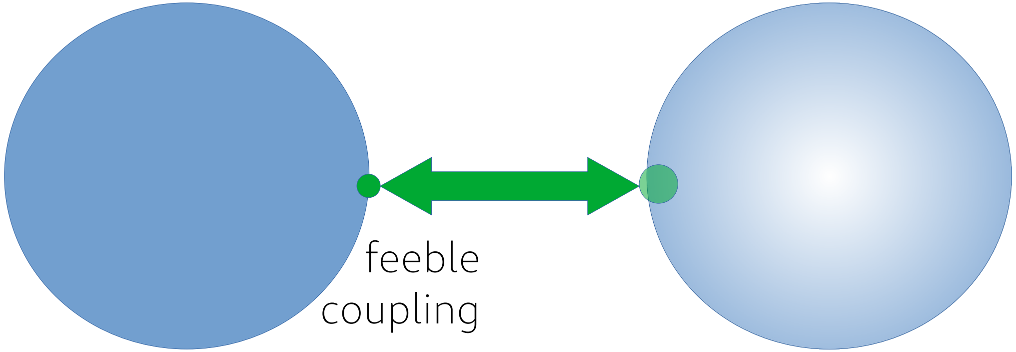
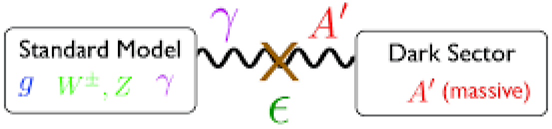


→ Intensity, precision frontiers

Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N L H N$
Pseudo-scalar (Axion, a)	$\frac{a}{f} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f}\bar{\psi}\gamma^\mu\gamma^5\psi$



Motivation/need to search for light, feebly interacting particles

The classic: axion

The SM contains

$$\mathcal{L}_{\rm SM} \supset \theta \frac{g^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}$$

$\theta \sim \mathcal{O}(1)$? ❌

❌ Neutron EDM upper bound $\longrightarrow$ $\bar{\theta} \equiv \theta - \arg \det m_q < 10^{-10}$

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Axion as dynamical solution $\frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2} \frac{a(x)}{f_a} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$

Axion minimizes potential at $\bar{\theta} = \frac{a(x)}{f_a} - \det\,\arg \mathrm{m_q} = 0$

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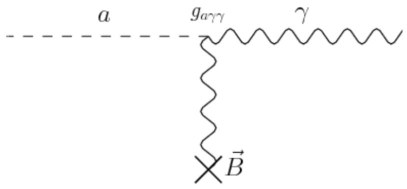
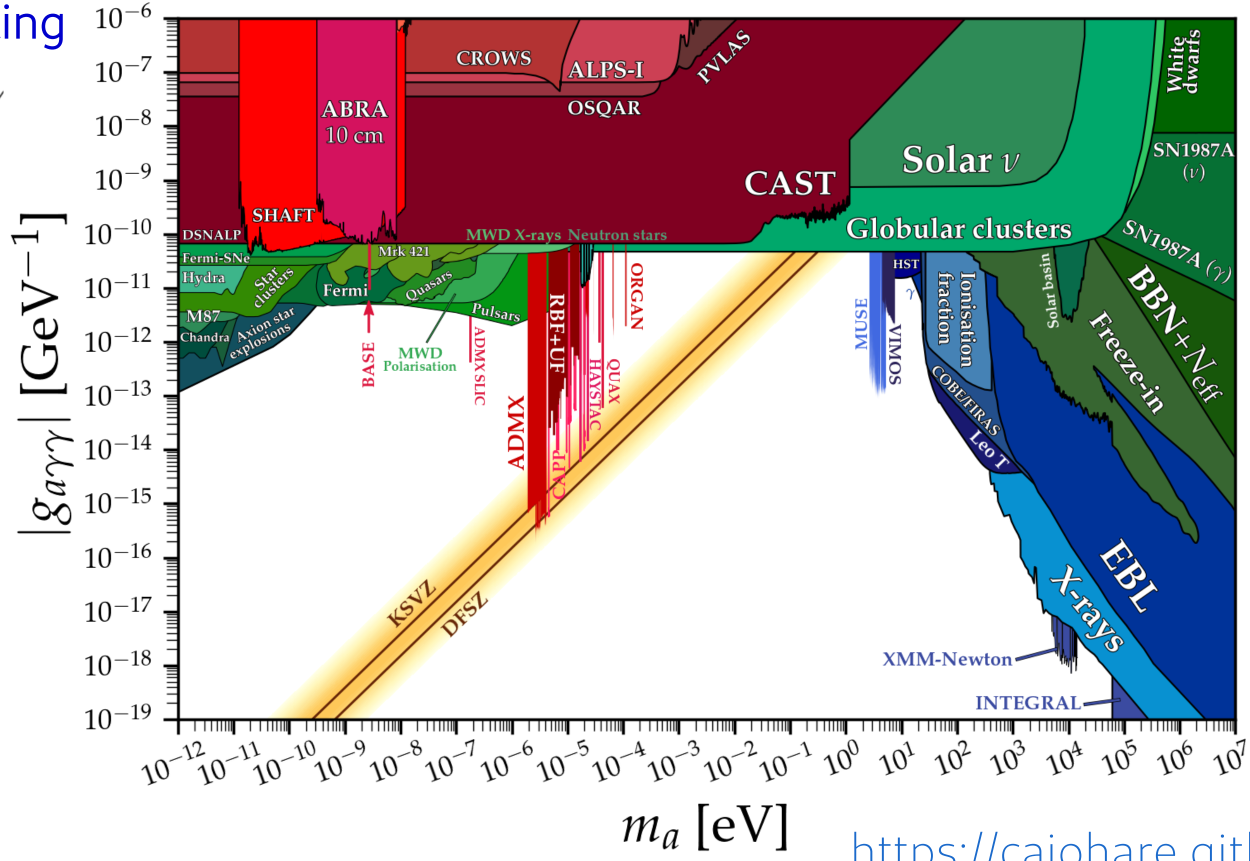
At low energy: non-relativistic Hamiltonian → how to probe the axion couplings

$$\mathscr{H} = \sqrt{\frac{\varepsilon_0}{\mu_0}} g_{a\gamma\gamma} \int a\mathbf{E}\cdot\mathbf{B}dV + g_{aff}\hbar c \nabla a \cdot \hat{\mathbf{S}} + \sqrt{\varepsilon_0(\hbar c)^3} g_{\rm EDM} a \hat{\mathbf{S}} \cdot \mathbf{E},$$

Axion searches: status

axion-photon coupling





Ciaran O'Hare

https://cajohare.github.io/AxionLimits/

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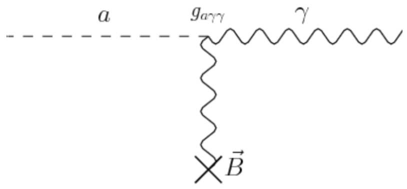

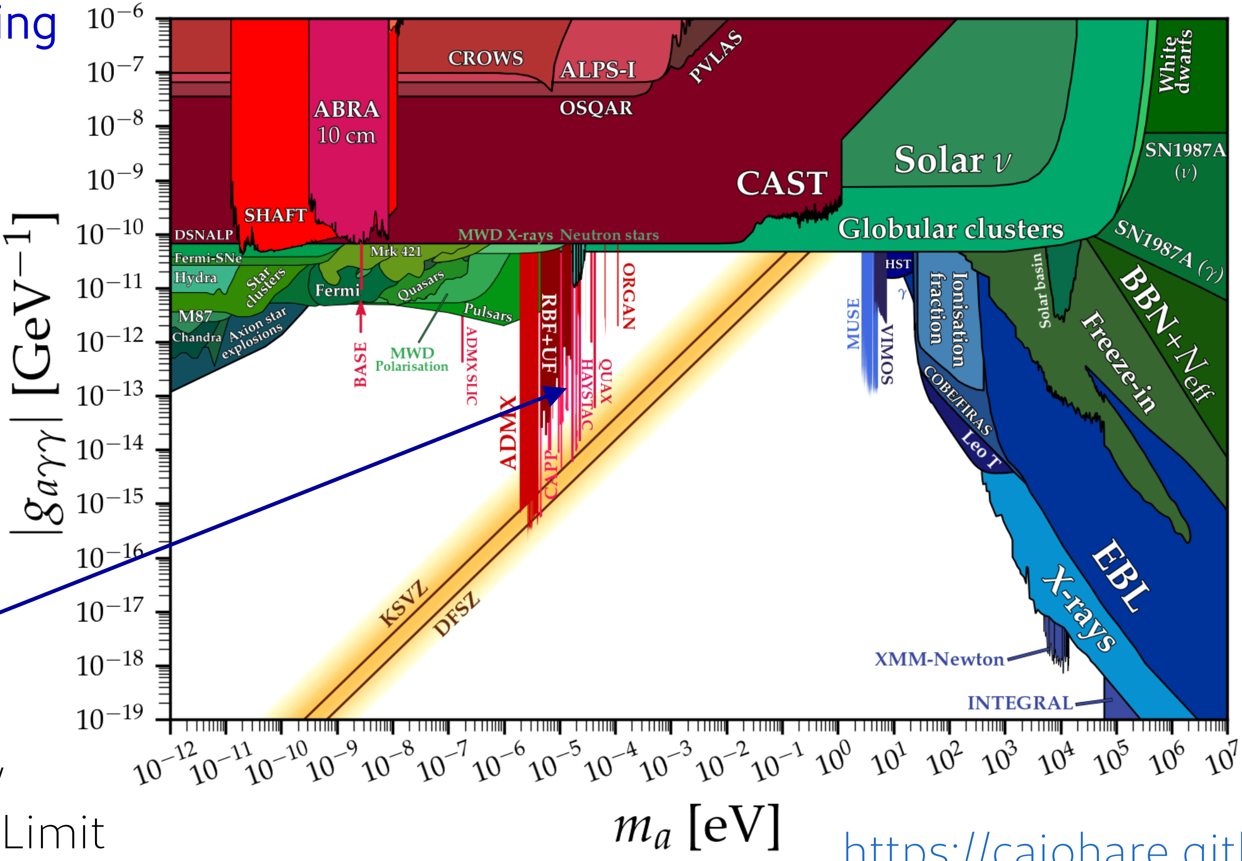

Haystac goes below Standard Quantum Limit

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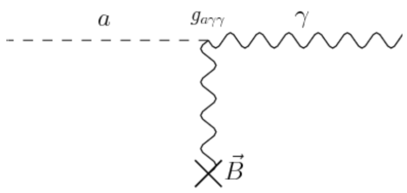

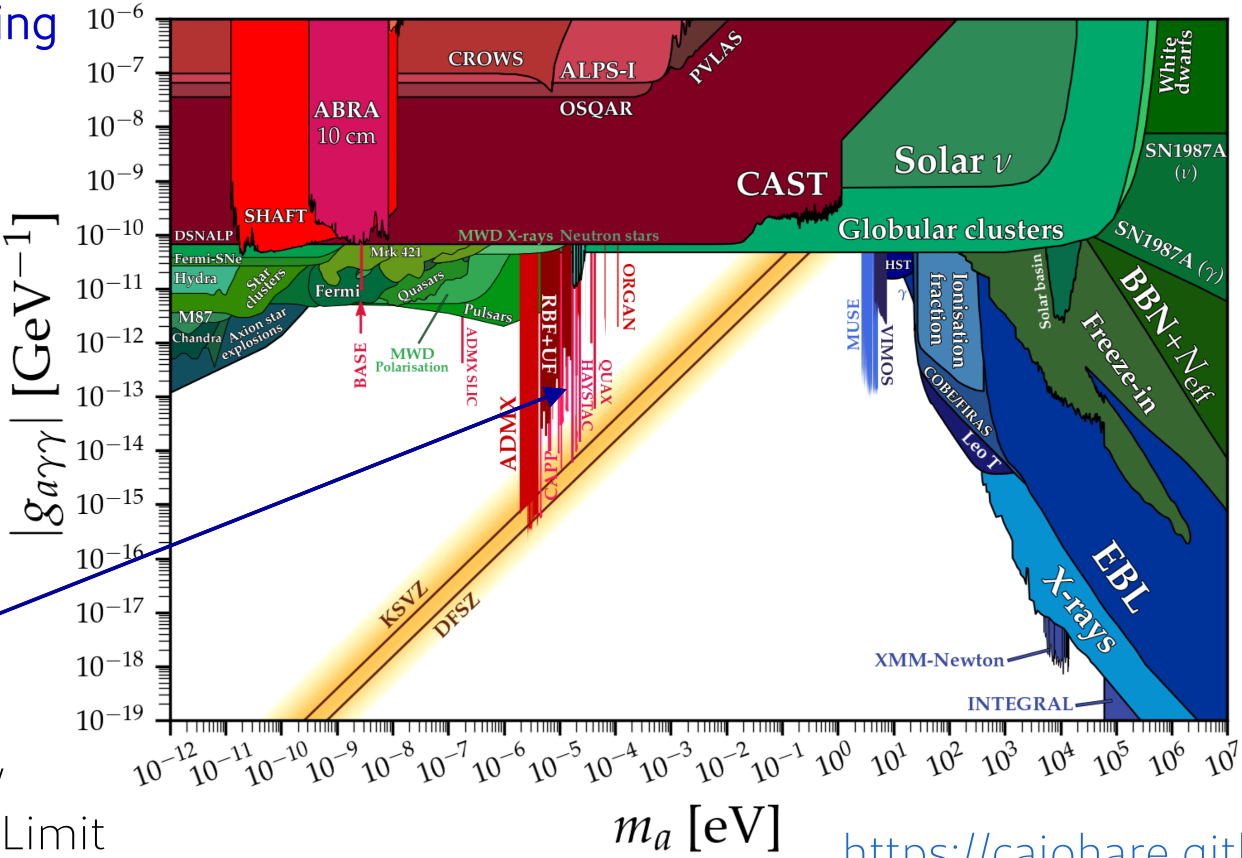

Haystac goes below Standard Quantum Limit

+Axion-Like Particless at colliders

[Bauer, Neubert, Thamm '17, '18]

[Bonilla, Brivio, Machado-Rodriquez, Troconiz '22]

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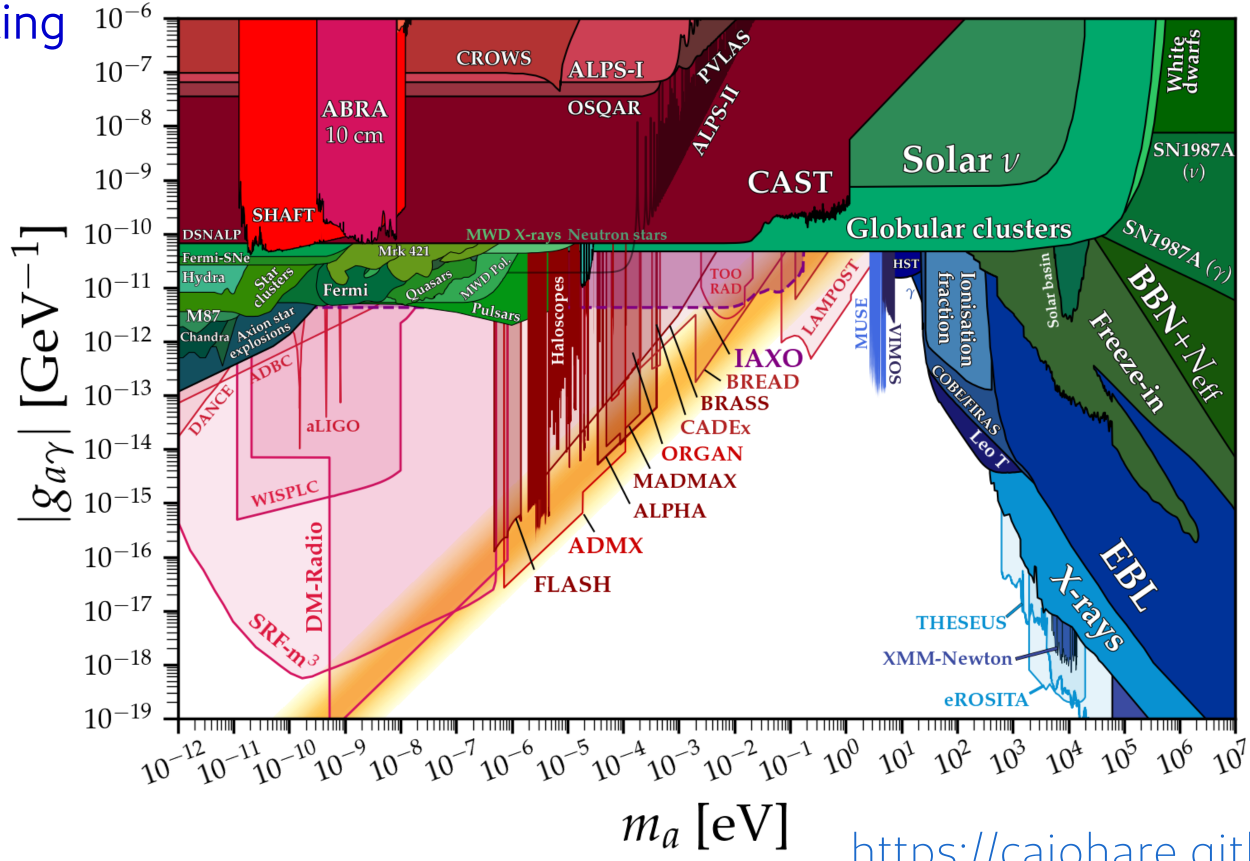
Axion searches: prospects

axion-photon coupling



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SM+Singlet: General vs Relaxion

$$V(\Phi, H) = V_\phi + \mu^2(\phi) H^\dagger H + \lambda_h \left(H^\dagger H\right)^2$$

General renormalizable scalar singlet

special case

Relaxion (pseudoscalar)

Graham, Kaplan, Rajendran '15

$$V_\phi = t\phi + \frac{1}{2} m_0^2 \phi^2 + \frac{a_\phi}{3}\phi^3 + \frac{\lambda_\phi}{4}\phi^4$$

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Relaxion and Higgs potential

Graham, Kaplan, Rajendran '15

$$V(\Phi) = rg\Lambda^3\Phi$$

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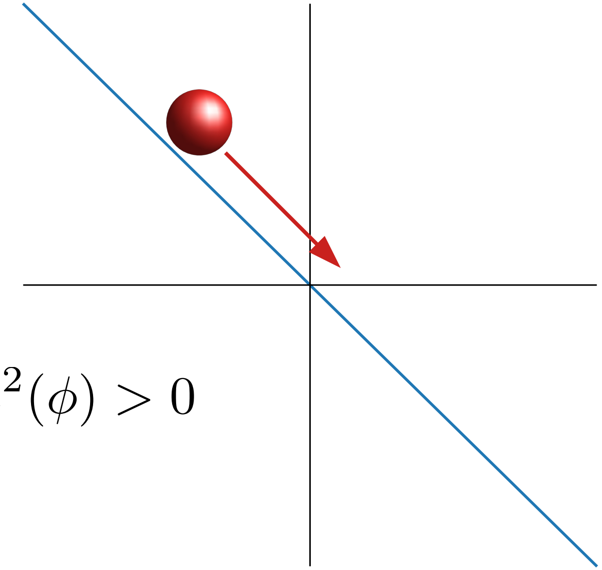
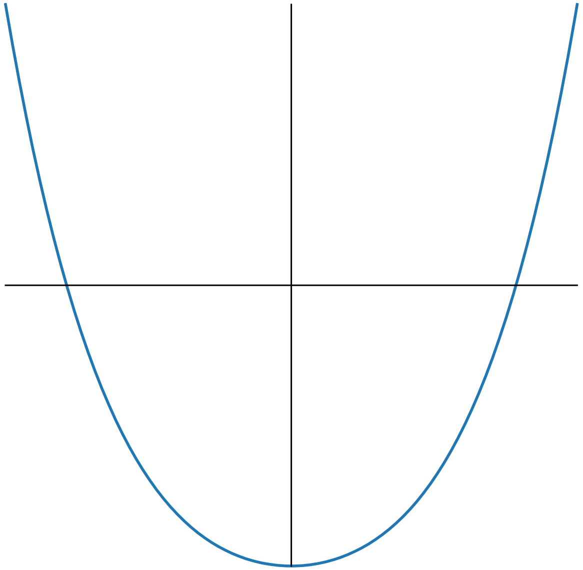
Relaxion V(**Φ**)



$\mu^2(\phi) > 0$

slow-roll

Higgs V(**H**)



$v = 0$

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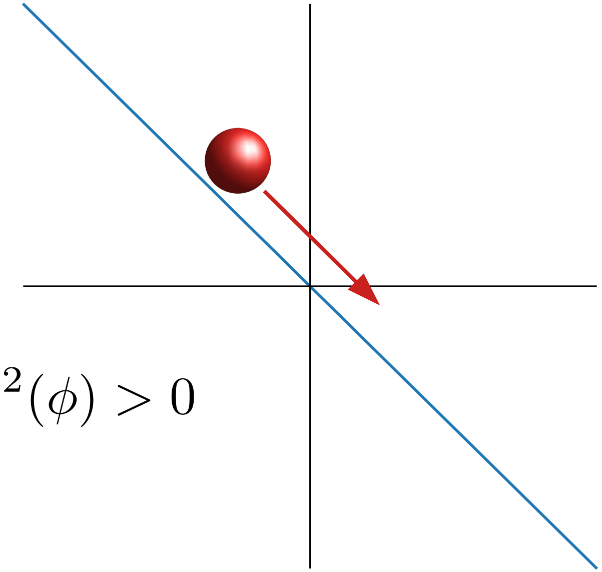

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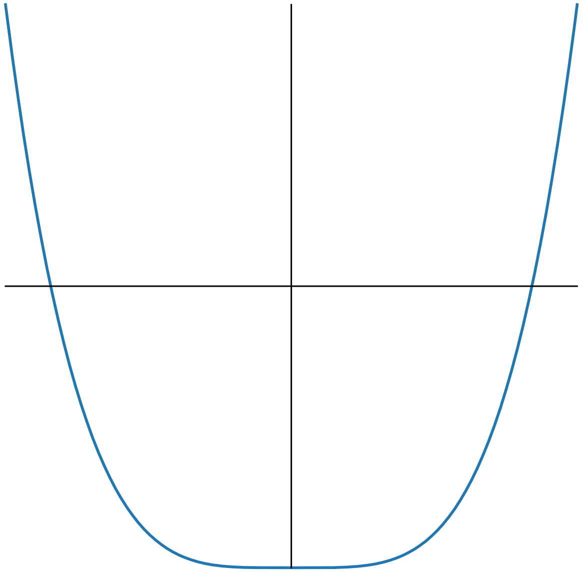

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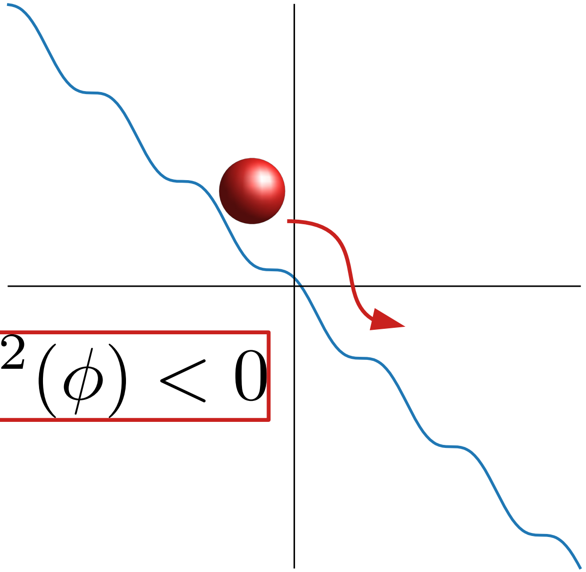

$$\mu^2(\phi) < 0$$

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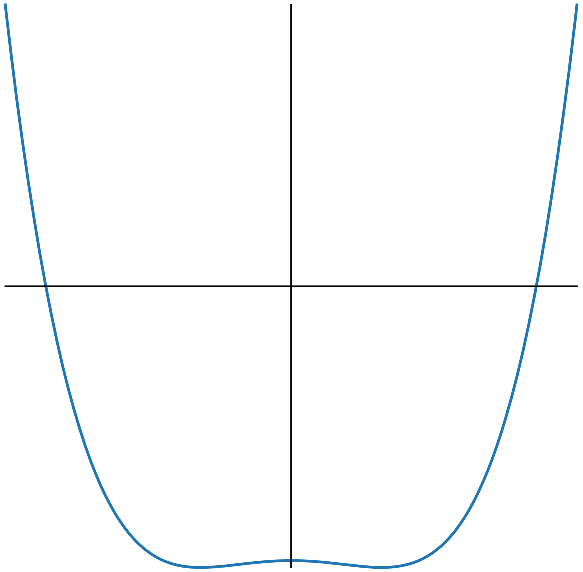


$$v = v(\phi) \neq 0$$

$$V_{\rm br} = \frac{1}{2}\tilde{M}^2 v^2(\phi) \cos\left(\frac{\phi}{f}\right)$$

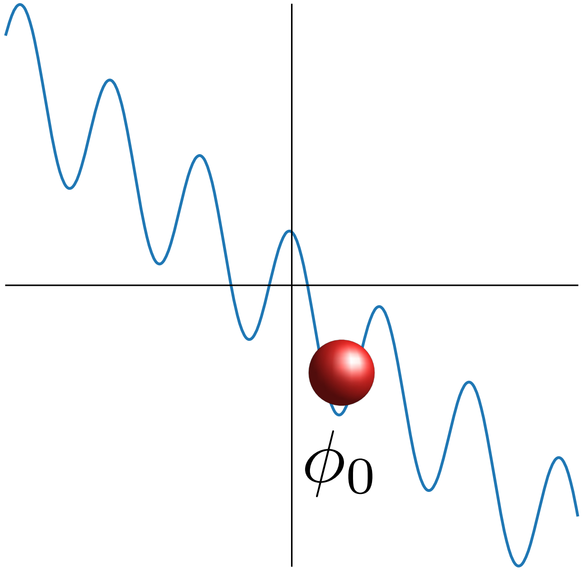
Backreaction barrier→ wiggles grow

Relaxion and Higgs potential

Flacke, Frugiuele, **EF**, Gupta, Perez '16
Choi, Im '16

Graham, Kaplan, Rajendran '15

Relaxion V(**Φ**)



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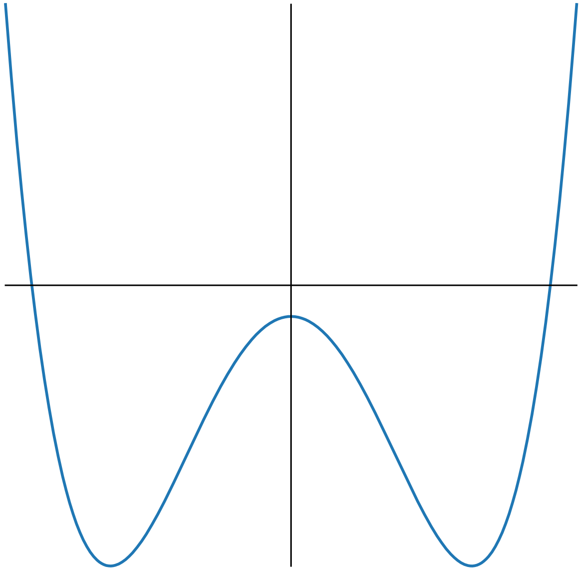

Backreaction: when
$V'_{\rm roll} = -V'_{br}$ → relaxion stops

$v \neq 0$
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Relaxion and Higgs potential

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relaxion stopping point breaks CP

Relaxion & Higgs mix

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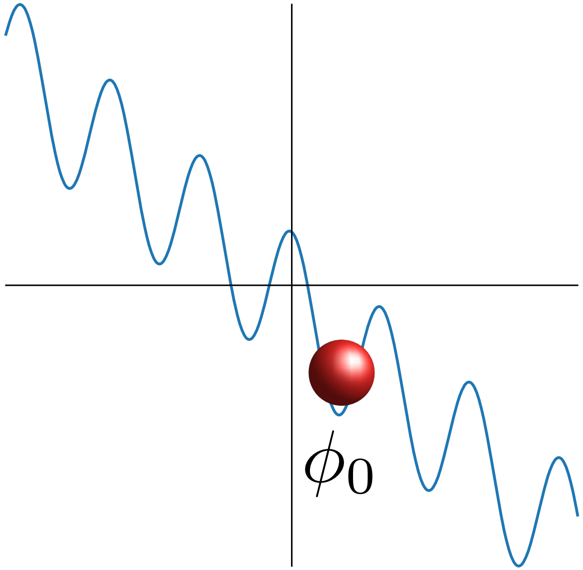

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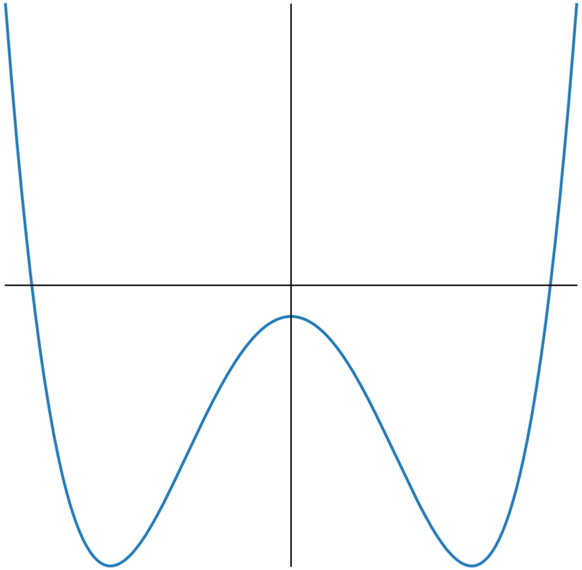

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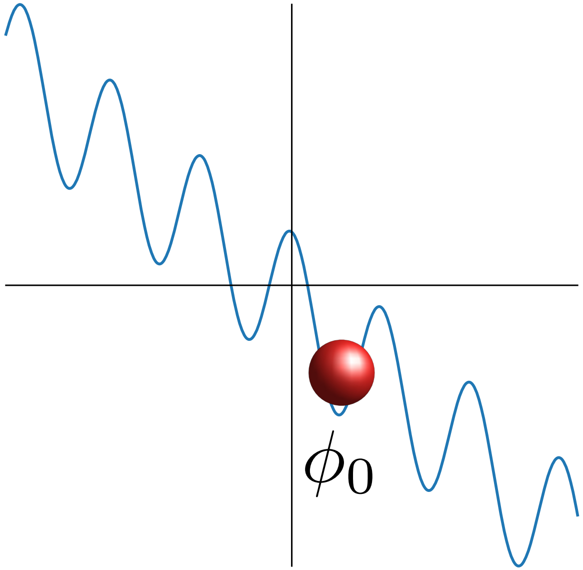
Relaxion inherits H couplings

Higgs couplings reduced

Relaxion V(**Φ**)



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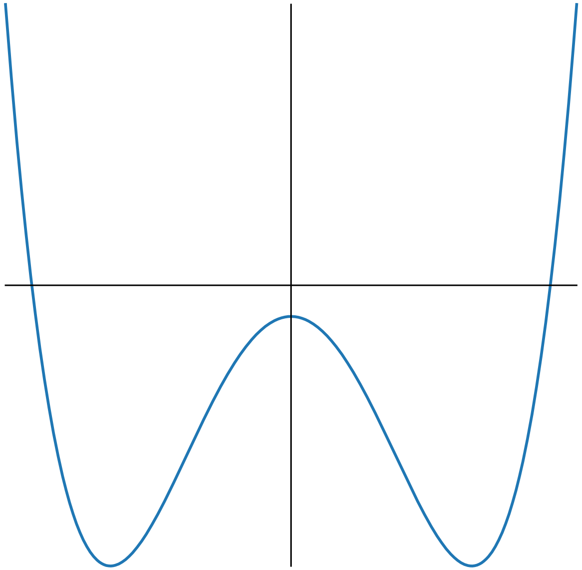

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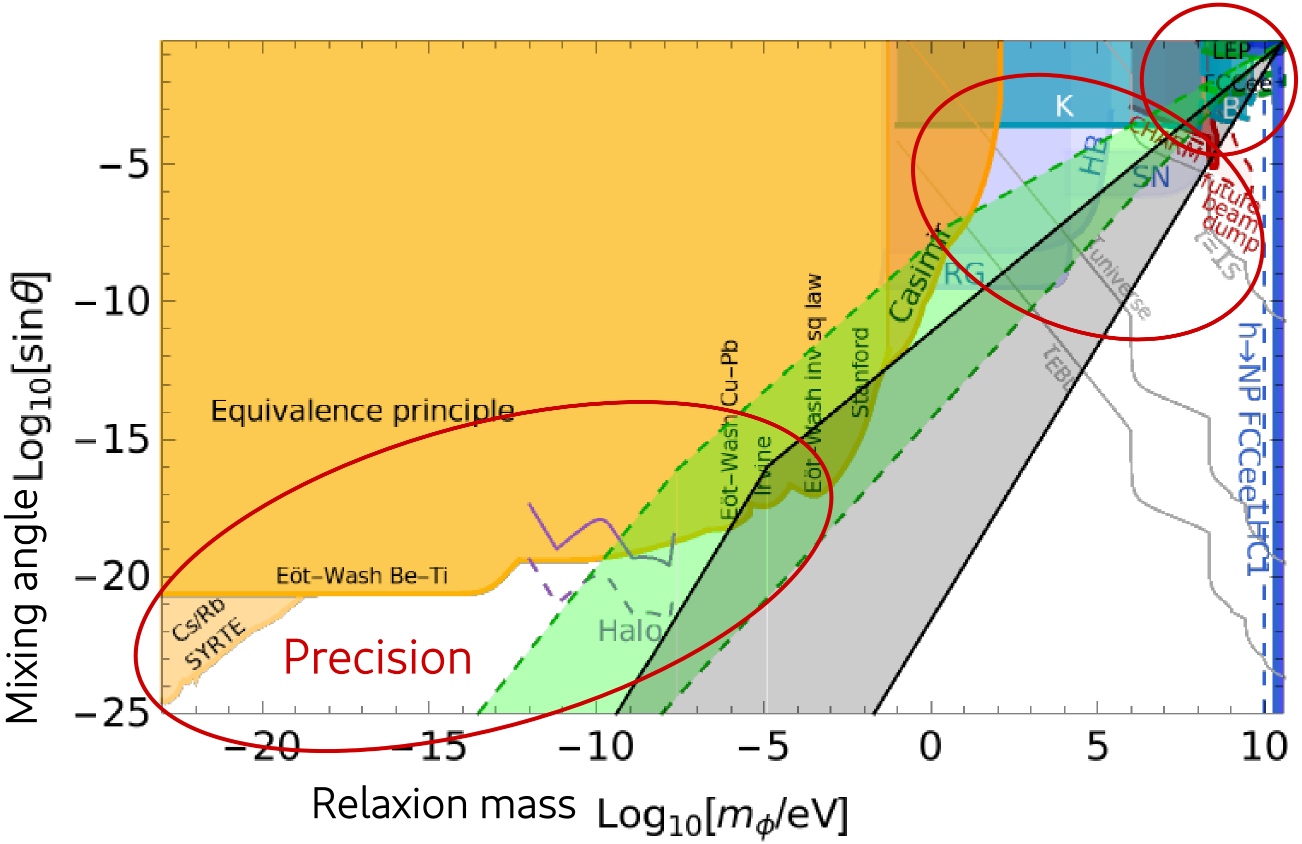
→ Singlet-Higgs Mixing angle $\sin\theta \approx \frac{a_{h\phi}}{v\lambda_h}$

$$s_\theta \approx \frac{\tilde{M}^2}{2vf\lambda_h} \sin\left(\frac{\phi_0}{f}\right)$$

+ CP-odd couplings to SM (like axion)

Relaxion mass and mixing

relaxion phenomeno-logy across many frontiers



Collider → **Energy**

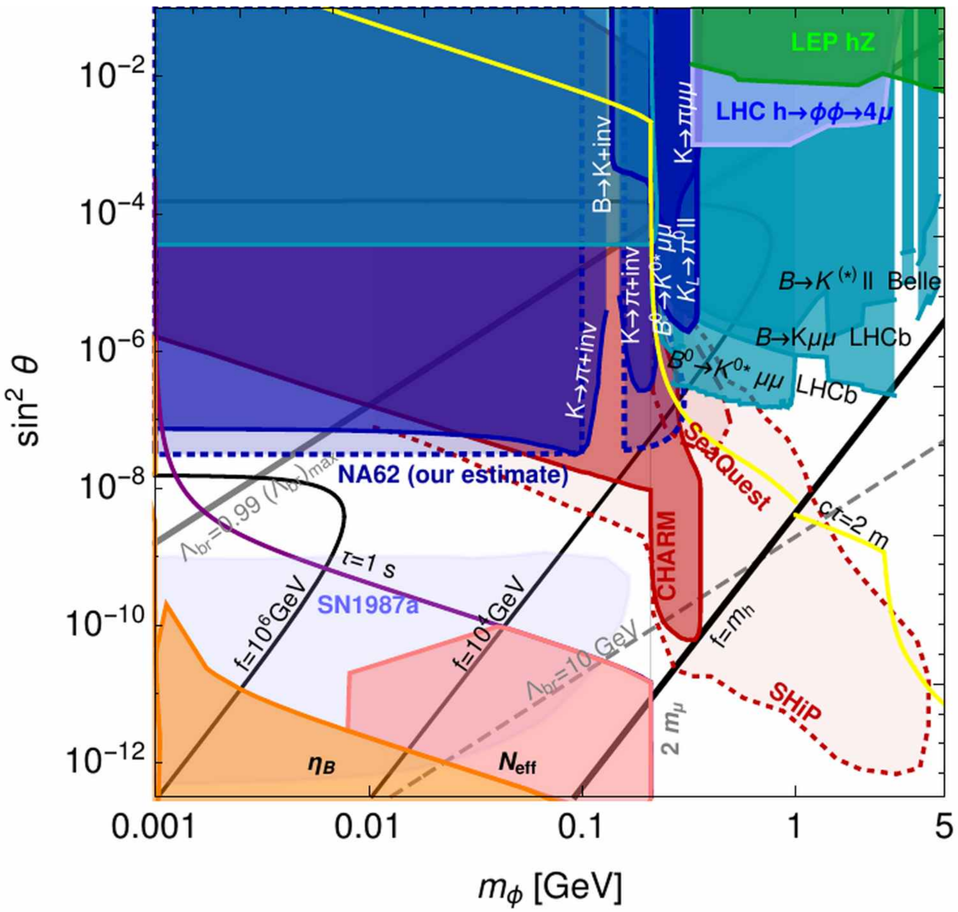
Beam dump, flavour → **Intensity**

Cosmology/ Astrophysics
Star cooling, CMB,… (not shown here)

[Frugiuele, EF, Schlaffer, Perez '18]
[Banerjee, Kim, Matsedonskyi, Perez, Safronova '20]
[Banerjee, Budker, Eby, Kim, Perez '19]
[Flacke, Frugiuele, EF, Gupta, Perez '16]

Several methods needed to probe broad range of unknown mass/coupling

MeV – GeV relaxion



[Flacke, Gupta, Frugiuele, EF, Perez '16]

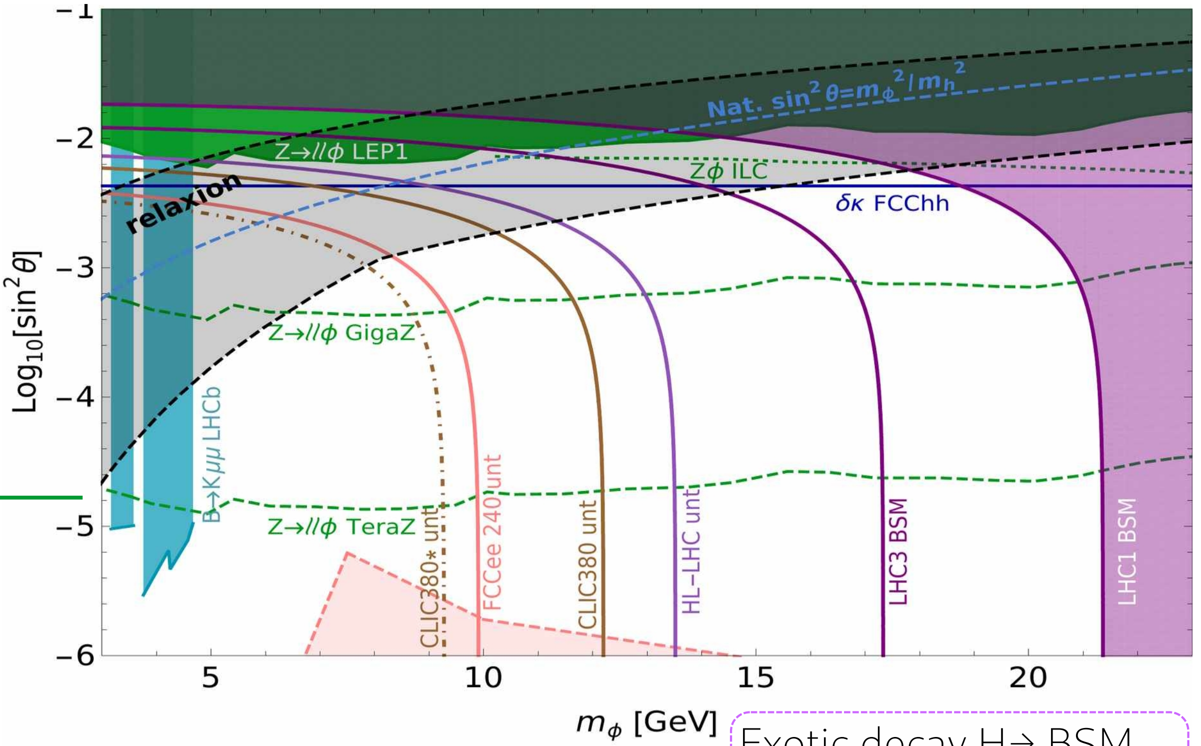
Relaxion vs light scalar at colliders

EF, Matsedonskyi, Schlaffer, Savoray '20

- 'Relaxion band' of natural mixing angle $\sin\theta$ Banerjee, Matsedonskyi, Kim, Perez, Safronova '20

  Larger mixing allowed than for SM+S

TeraZ can exclude Relaxion >3 GeV



Exotic decay H→ BSM excluded heavy relaxion

European Strategy Update

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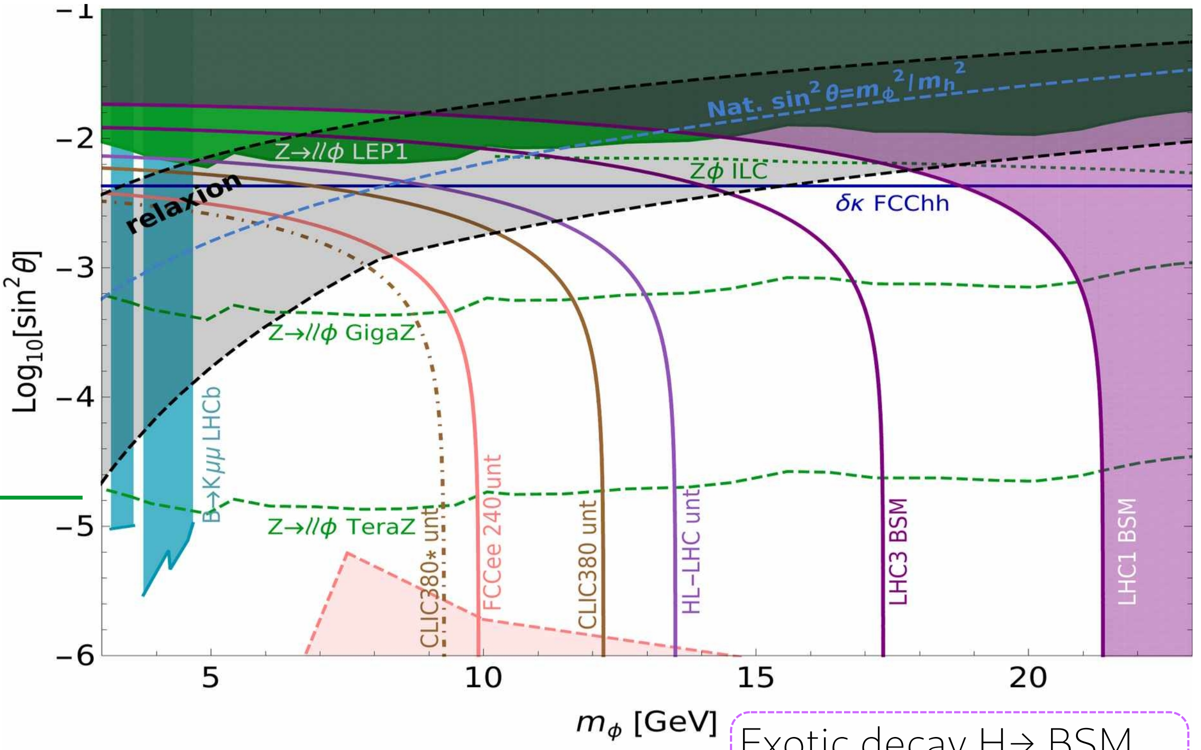

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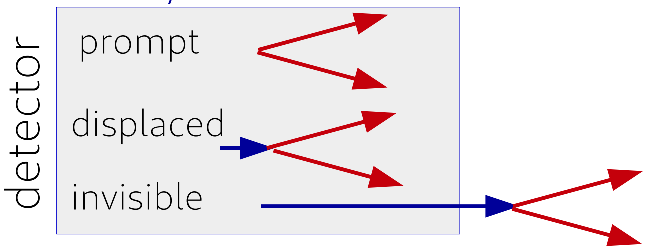
Decays of Φ:

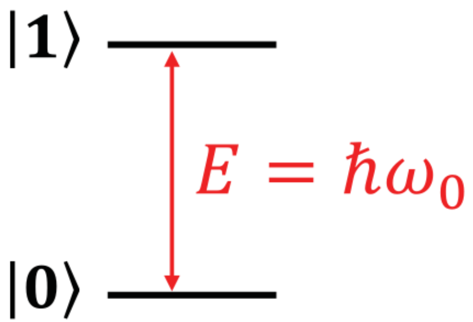


Long-lived singlet
Displaced, delayed, invisible

Quantum Sensors

Degen, Reinhard, Cappallaro '16

i) Discrete, resolvable energy levels, typically 2-level system



ii) possible to initialize quantum system in known state
& read it out

iii) quantum system can be coherently manipulated

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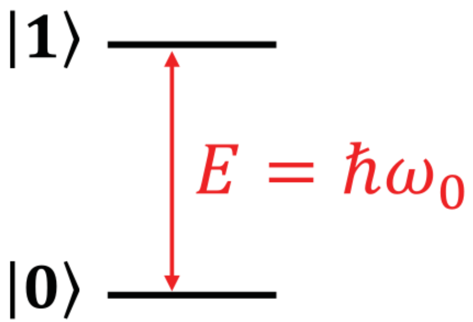

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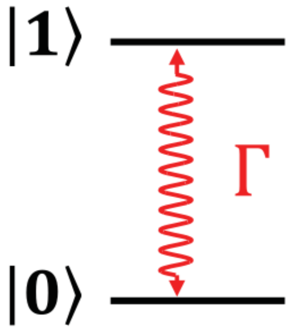

iv) interaction with external field
→ energy shift or transition between levels

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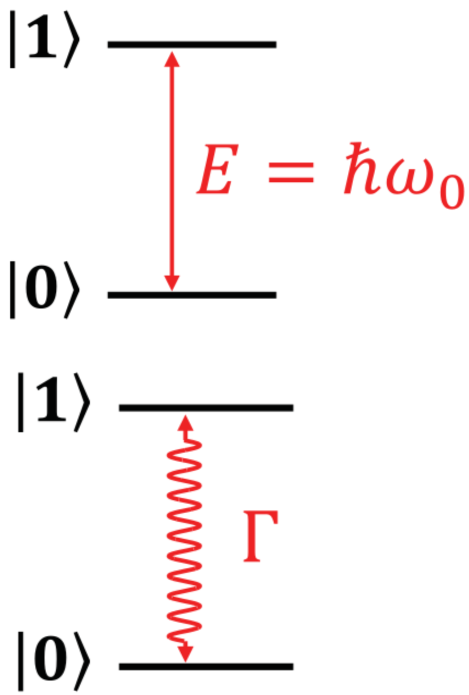
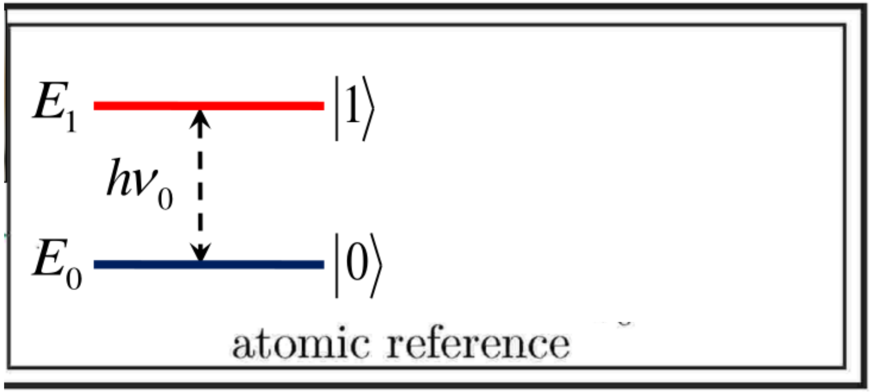


e.g.: atoms, ions, Rydberg states, superconducting circuits, cavities, clocks, interferometers, …
&entaglement/squeezing → **well suited for light DM/NP, GWs, also for HEP detectors**

Atomic clocks as Quantum Sensor

M. Safronova



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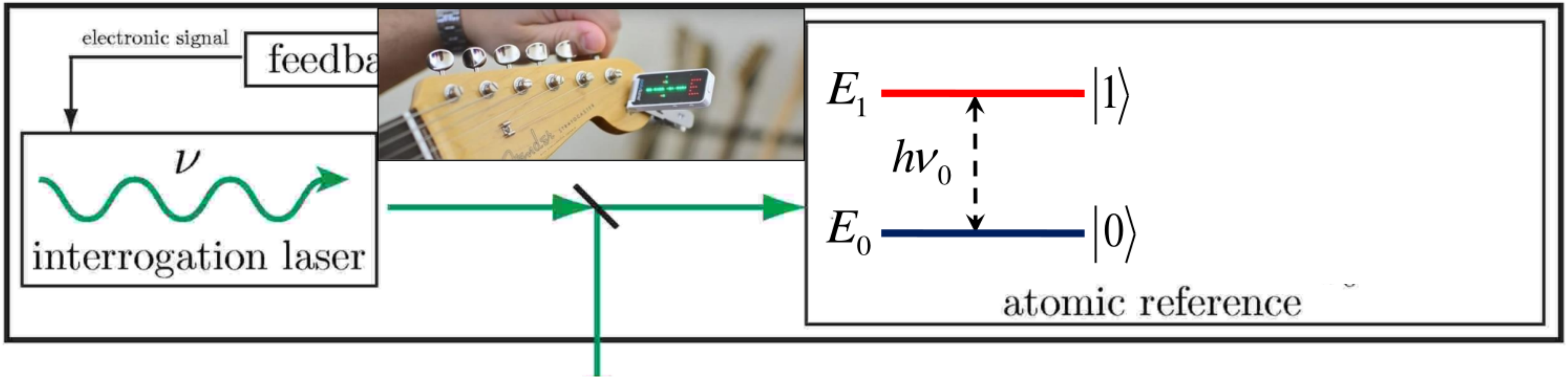

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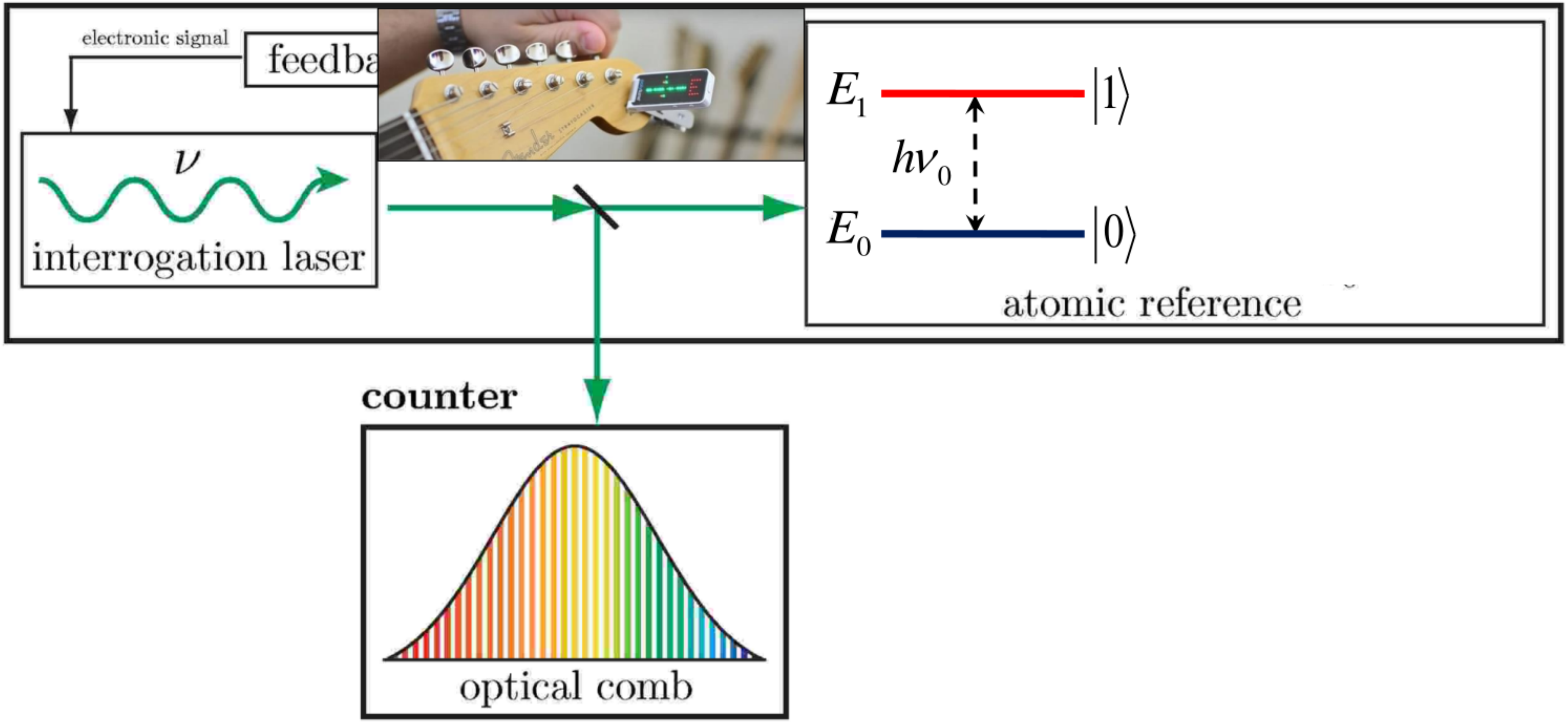

Atomic clocks as Quantum Sensor

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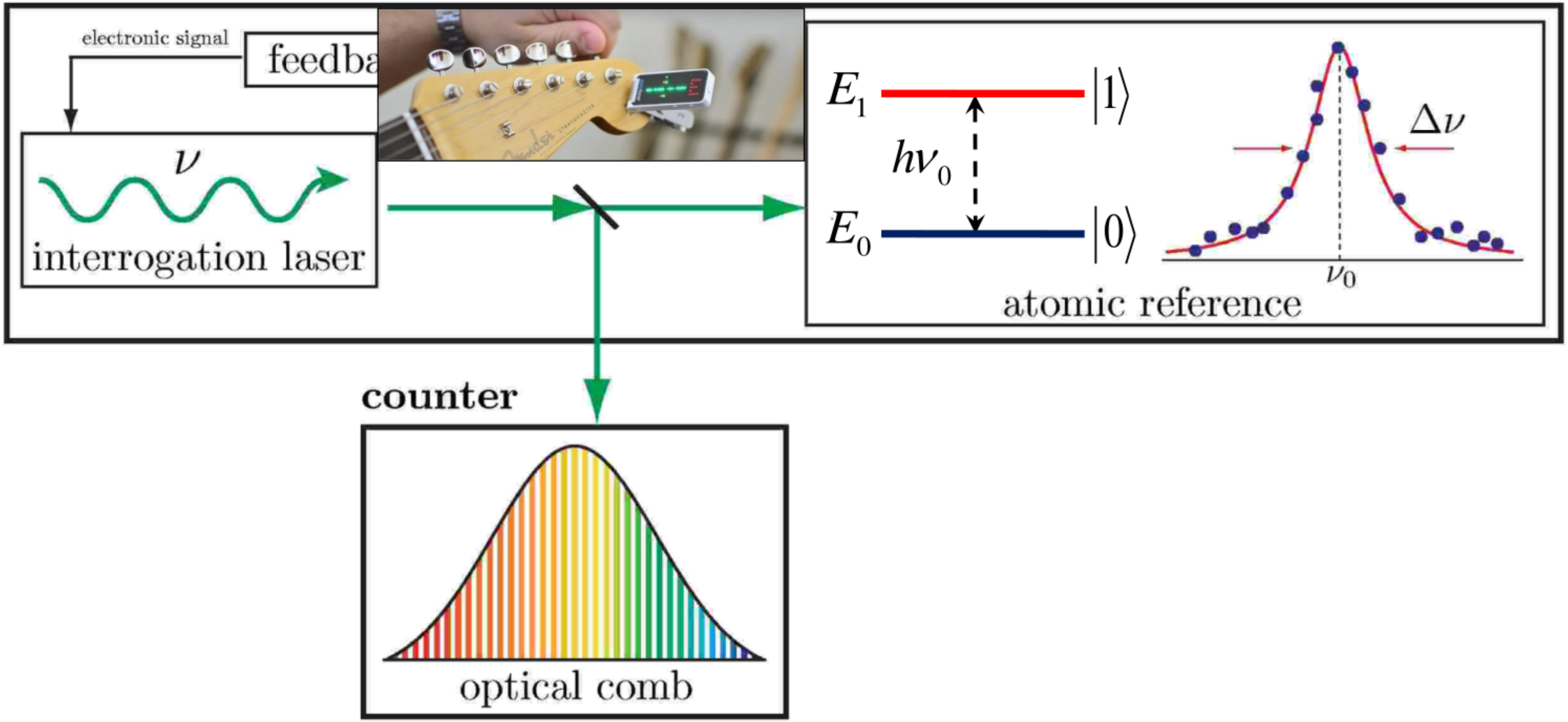

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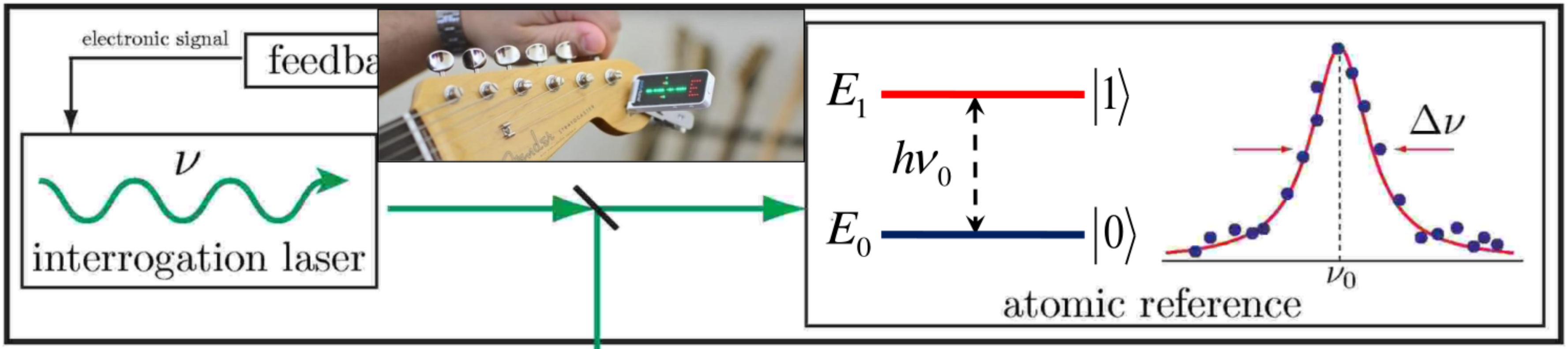
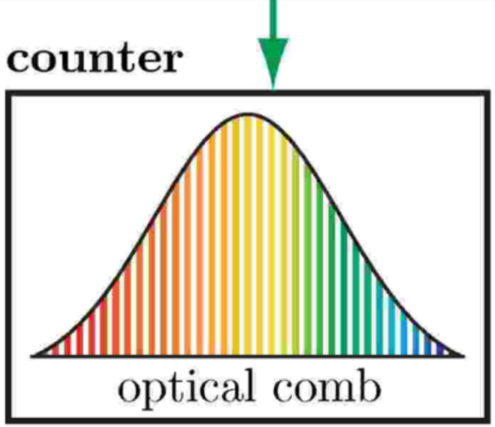
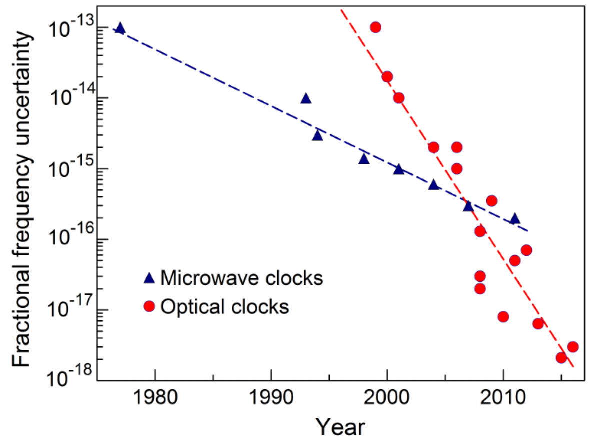
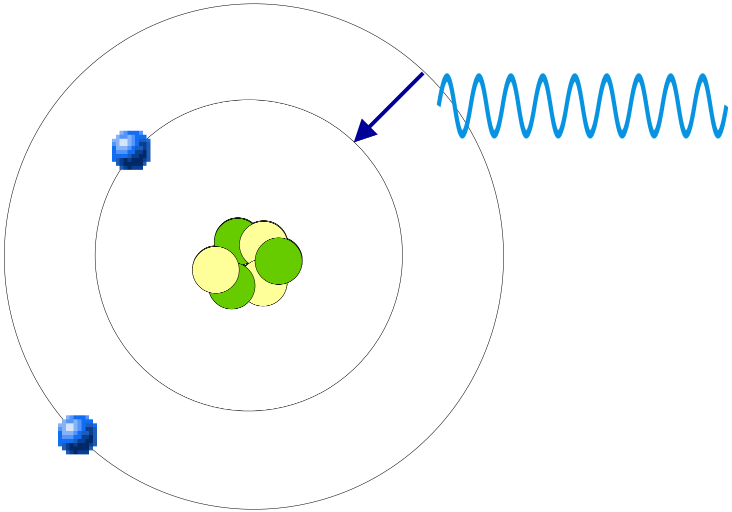






Light scalar in atomic spectrum?

- Motivation: search for light new boson Φ that couples to electrons and neutrons
- Φ perturbs electron levels → only tiny frequency change



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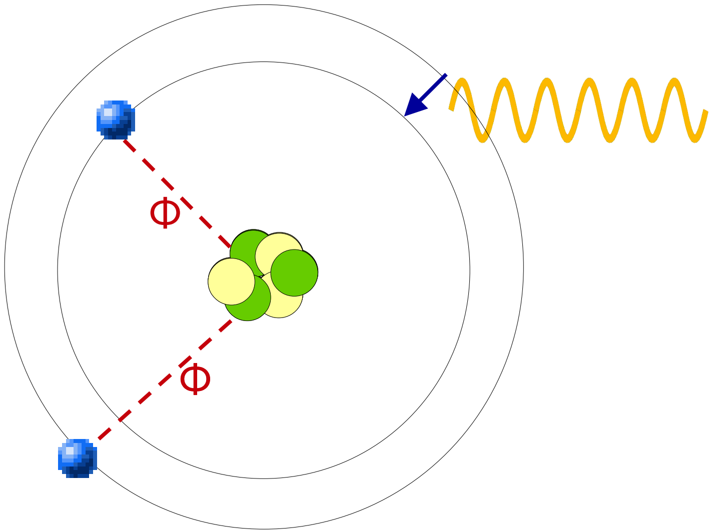

Challenge of theory-exp comparison

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- Challenge: theory, nuclear uncertainties >> uncertainties of frequency measurements

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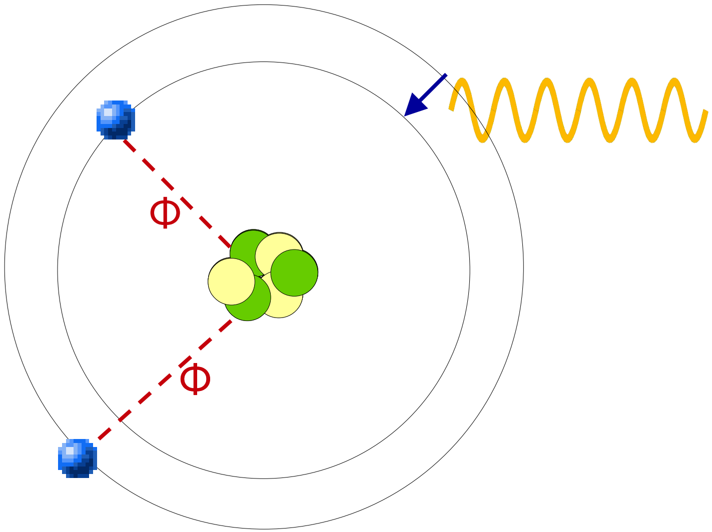
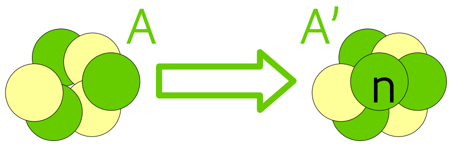
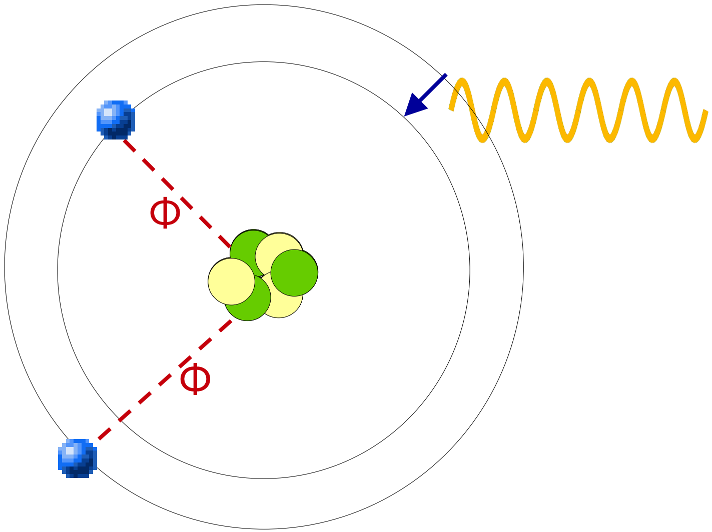


Data-driven atomic search for light scalar

- Motivation: search for light new boson Φ that couples to electrons and neutrons
- Φ perturbs electron levels → only tiny frequency change
- Challenge: theory, nuclear uncertainties >> uncertainties of frequency measurements
- Our method: Measure 2 transitions, 3 isotope pairs very precisely



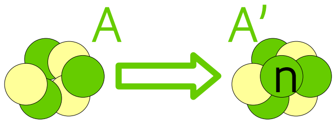


- Berengut, Budker, Delaunay, Flambaum, Frugiuele, EF, Grojean, Harnik, Ozeri, Perez, Soreq; PRL 120 (2018) 091801
- Solaro, Meyer, Fisher, Berengut, EF, Drewsen; PRL 125, 123003 (2020)

King plot of Isotope Shifts

Mass shift (MS) Field shift (FS)

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



electronic
nuclear

Poorly known nuclear charge radius

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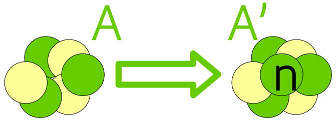

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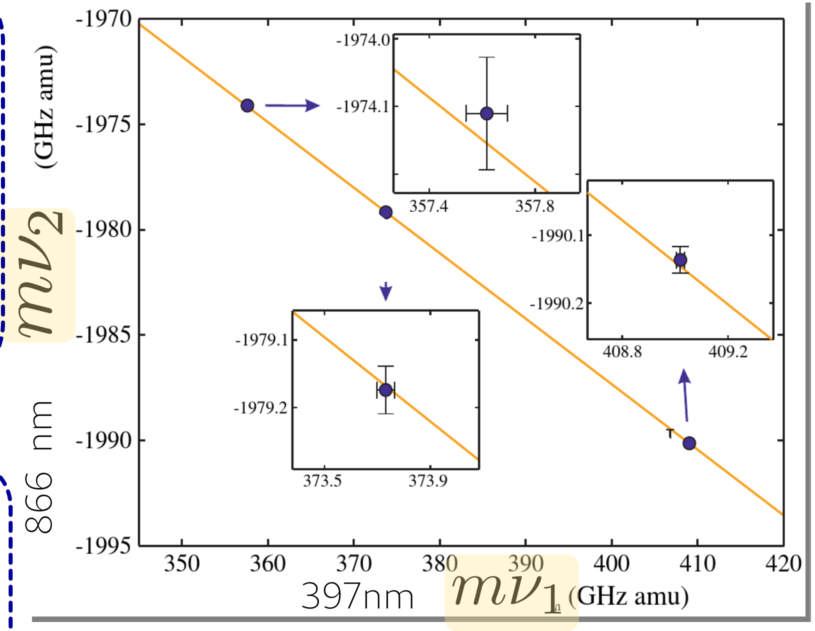
$i = 1, 2$

2nd transition to eliminate charge radius [King '63]

Linear King relation (at leading order):

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



[Gebert, Wan, Wolf, Angstmann, Berengut, Schmidt; PRL 115, 053003 (2015)]

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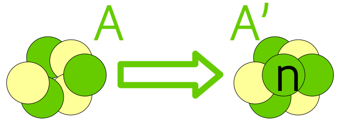

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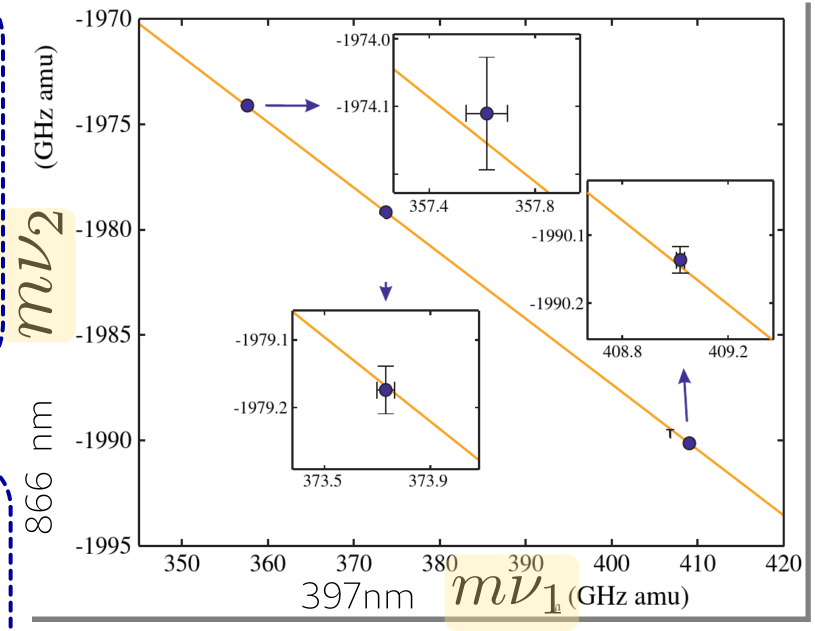

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A → A′ (n)

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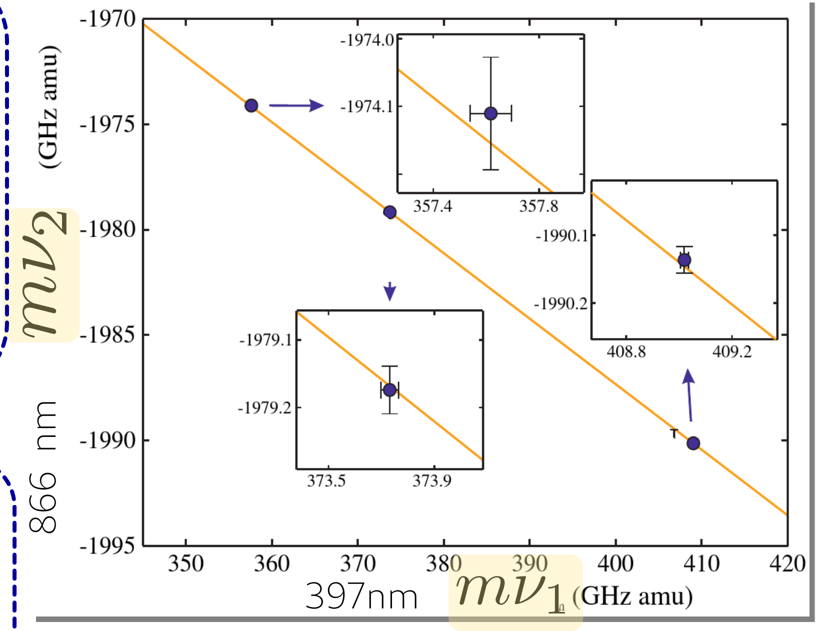


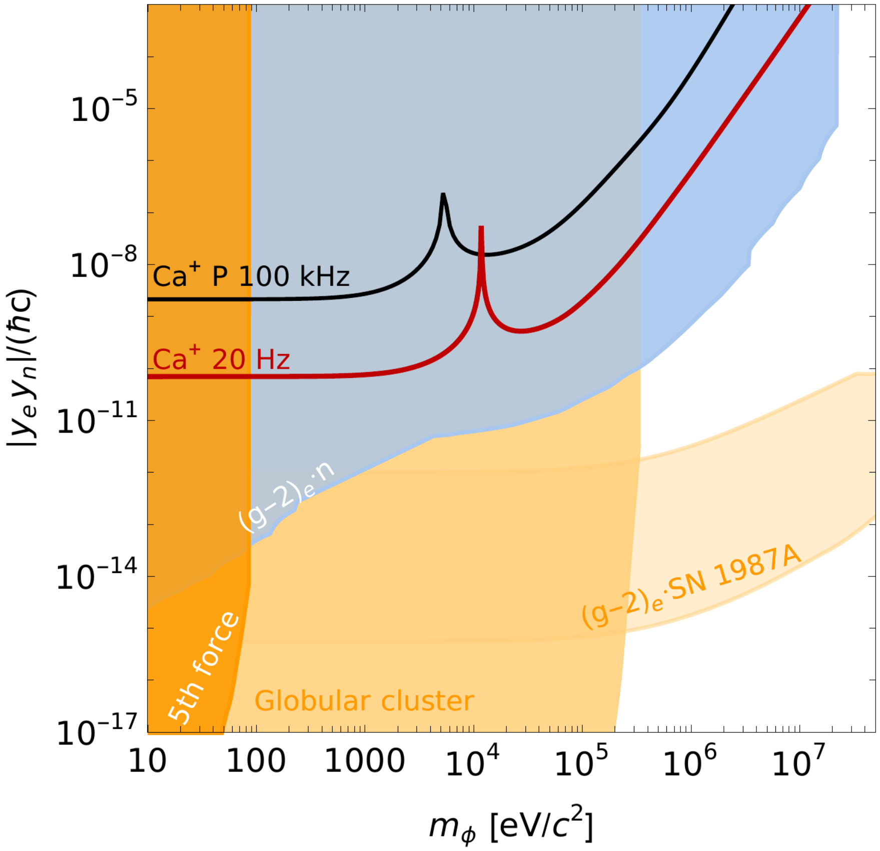
[Gebert, Wan, Wolf, Angstmann, Berengut, Schmidt; PRL 115, 053003 (2015)]

check if 3 points (= 3 isotope pairs) on straight line

Ca⁺ Isotope Shift Bounds on Φ

Berengut, Budker, Delaunay, Flambaum, Frugiuele, EF, Grojean, Harnik, Ozeri, Perez, Soreq; PRL 2018

Solaro, Meyer, Fisher, Berengut, EF, Drewsen; PRL 2020



- **Ca⁺ King plot:** D-fine splitting, 4 isotope pairs
- **Improvement** of former Ca bound by **factor 30**

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Berengut, Budker, Delaunay, Flambaum, Frugiuele, EF, Grojean, Harnik, Ozeri, Perez, Soreq; PRL 2018

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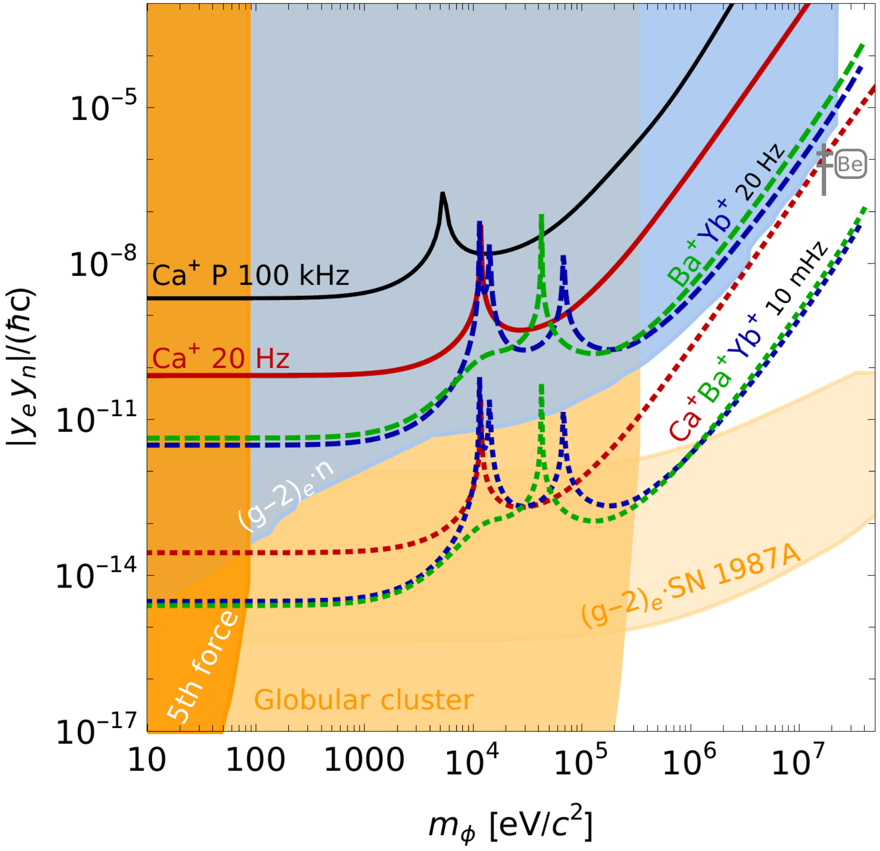

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- Realistic precision: **10 mHz**
  - Ca, Ba, Yb can probe untested parameter space

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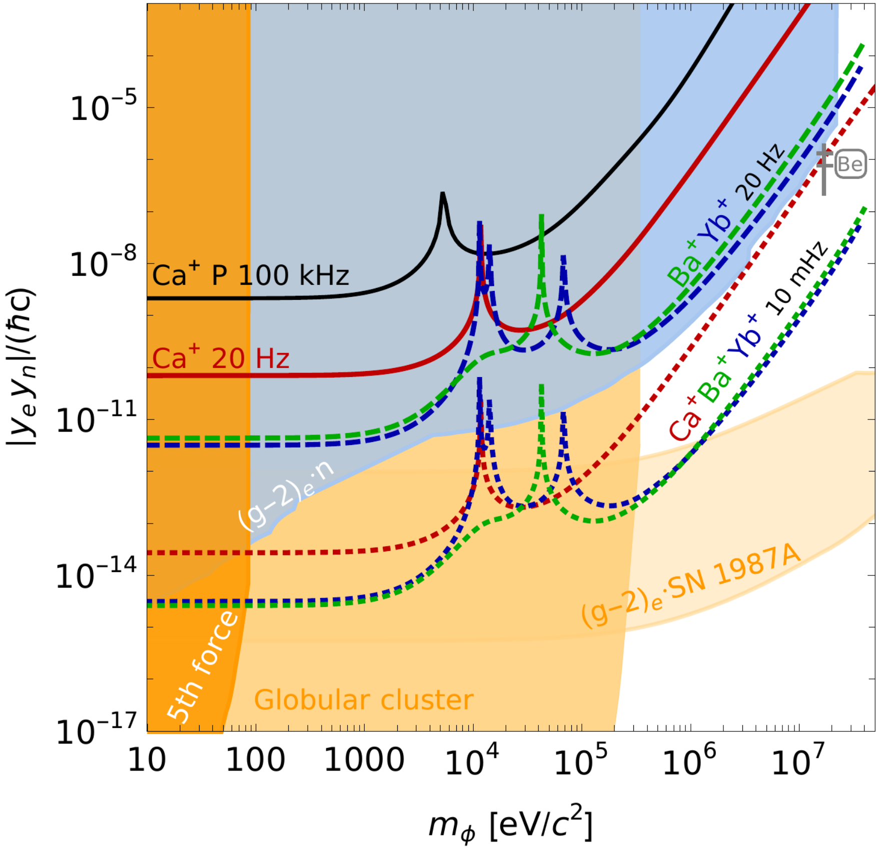

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Particle model applications: B-L, dark photon, chameleon
Frugiuele, **EF**, Perez, Schlaffer '16

few-electron systems: Delaunay, Frugiuele, **EF**, Soreq '17

Generalized King plot

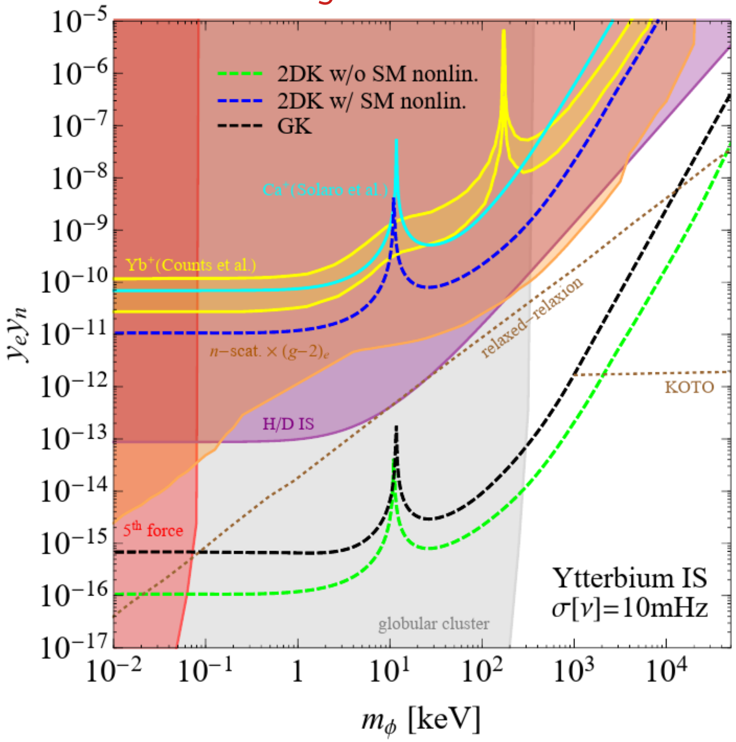
$$m\nu_i^a = K_i + \sum_{l=1}^{m-1} F_{il} m\lambda_{l,a} + \alpha_{\rm NP} X_i h_a$$

sum of higher-order SM terms (without calculating them)

- replace unknowns by additional isotope shifts
- Number of clock transitions, isotopes and higher-order terms has to match

[Berengut, Delaunay, Geddes, Soreq '20]

Higher-orders included



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sum of higher-order SM terms (without calculating them)

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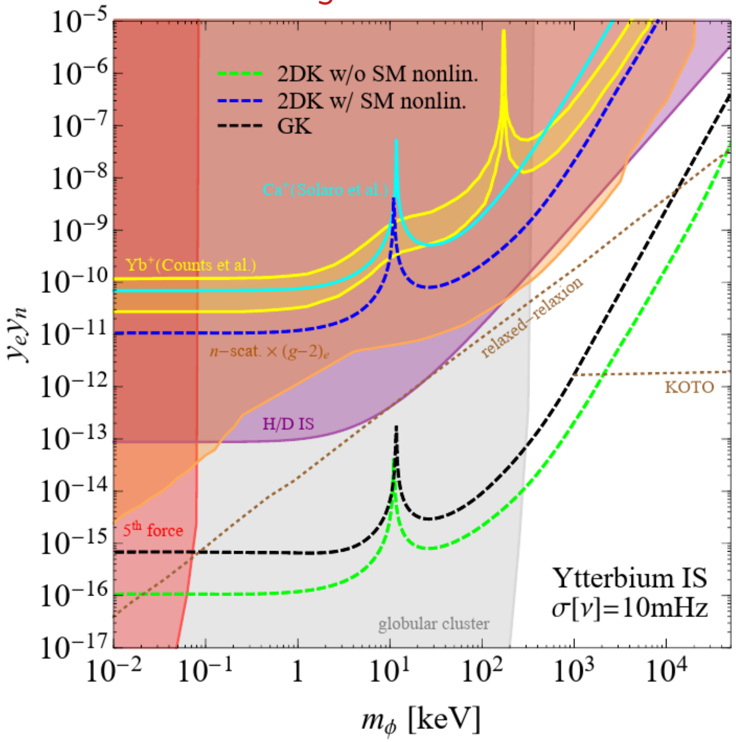
For any #transitions, isotope pairs and to combine elements:
Global fit to all King plots

[Delaunay, EF, Kirk, Mariotti; in progress]

[Berengut, Delaunay, Geddes, Soreq '20]

Higher-orders included



Further NP atomic precision probes

- Highly charged ions: clocks, isotope shifts
- Rydberg states
- Few-electron systems (H, He, D, Li,...)
- Frequency modulation by GWs
- Tests of Local Lorentz invariance violation

Variation of fundamental constants

Antypas et al, Snowmass 2203.14915

Scalar ultralight DM ϕ

$$\mathcal{L}_{\text{int}}^{\text{lin}} = \kappa\phi \left\{ \left[\frac{d_e F_{\mu\nu} F^{\mu\nu}}{4} - d_{m_e} m_e \bar{\psi}_e \psi_e \right] - \left[\frac{d_g \beta_3 G^a_{\mu\nu} G^{a\mu\nu}}{2 g_3} + \sum_{q=u,d,s} \left(d_{m_q} + \gamma_m d_g \right) m_q \bar{\psi}_q \psi_q \right] \right\}$$

→ induces **oscillations** of $\alpha_{\mathbf{em}}$ and fermion masses:

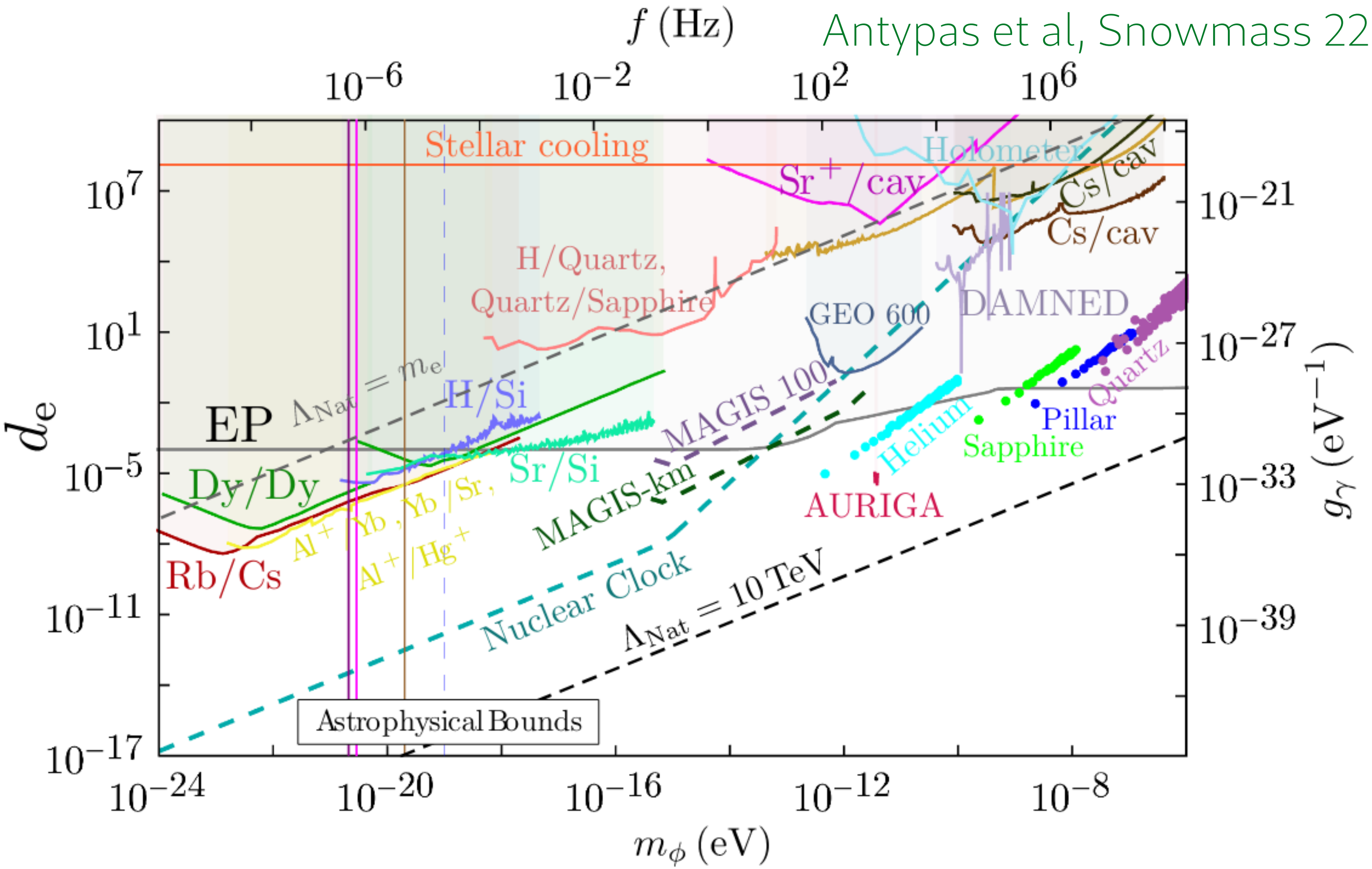
$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

$$\alpha \to \frac{\alpha}{1 - g_\gamma \phi} \approx \alpha(1 + g_\gamma \phi)\,, \quad m_\psi \to m_\psi + g_\psi \phi$$

Ultralight scalar DM-photon coupling

$$\kappa \frac{d_e}{4} \phi F_{\mu\nu} F^{\mu\nu}$$

Antypas et al, Snowmass 2203.14915



CERN Quantum Technology Initiative

QTI: https://quantum.cern/

Head: Alberto di Meglio

Branches:	Coordinators:
Quantum Sensing	Michael Doser
Quantum Computing	Sofia Vallecorsa
Quantum Theory & Simulation	Elina Fuchs
Quantum Communication & Networks	Edoardo Martelli

Collaboration between CERN and universities/institutes in the member (&non-member) states
Also collaboration with industry (e.g. IBM-Q)

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Now proposal for **QTI Phase 2** with experiments, qubits, theory.

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Stay tuned, get involved!

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QUANTUM TECHNOLOGY INITIATIVE

Summary: Light NP vibrant

→ Well-motivated scenarios with light NP

→ Axion searches with various techniques

→ Relaxion: exotic light pseudoscalar with implications across scales

→ Quantum sensors (e.g. atomic clocks) probe light NP

Exciting developments across frontiers over past few years and expected in the very near future!

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Thank you!

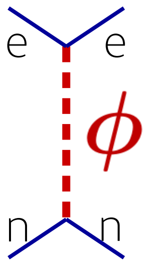
Exciting developments across frontiers over past few years and expected in the very near future!

APPENDIX

NP shifts of atomic spectra

Energy shift due to new long-range interaction

$$V_{\rm NP} = \frac{y_e y_n}{4\pi r} e^{-m_\phi r}$$



$$m\nu_2 = F_{21} m\nu_1 + K_{21} - y_e y_n A A' (X_2 - X_1 F_{21})$$

NP ϕ coupling to electrons and neutrons

theory input: NP electronic coefficients

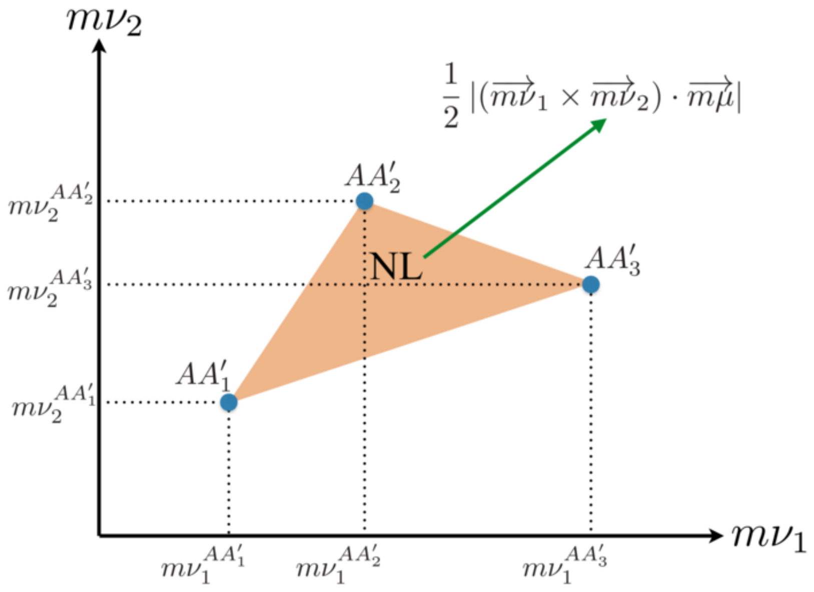
overlap of wavefunctions with NP potential

$X_i = X_i(m_\phi)$

Goal: bound on $y_e y_n$ and m_ϕ in **data-driven** approach

Nonlinearity as data-driven NP measure

- Deviations from straight line → triangle
- Area = measure of NL



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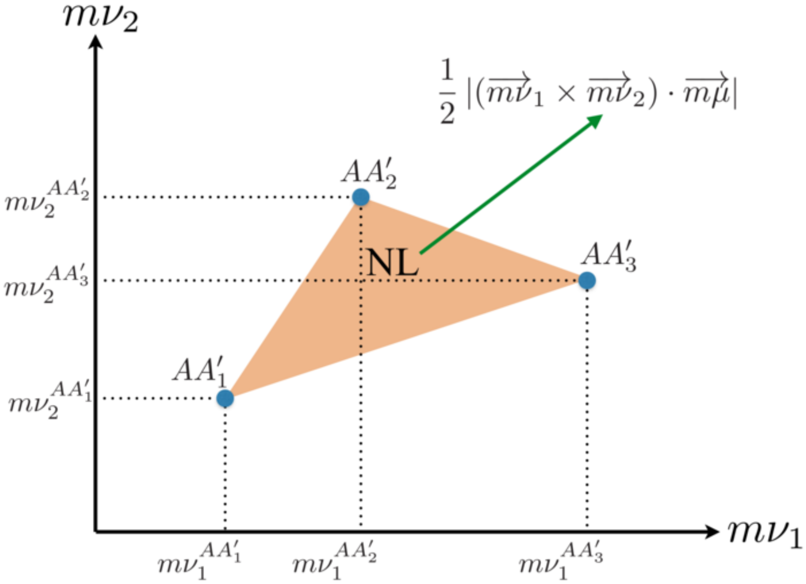
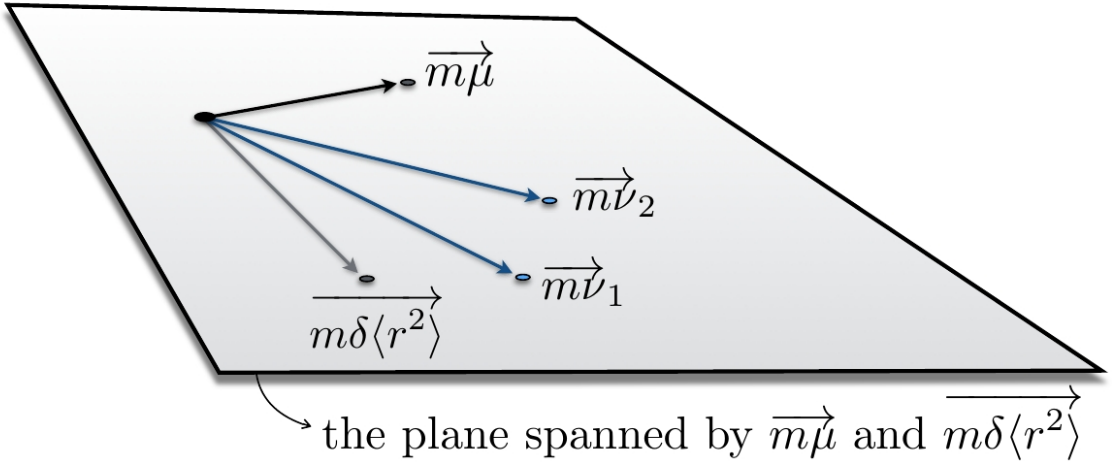


- Linearity plane: linear combinations of FS+MS
- Volume of parallelepiped = measure of NL



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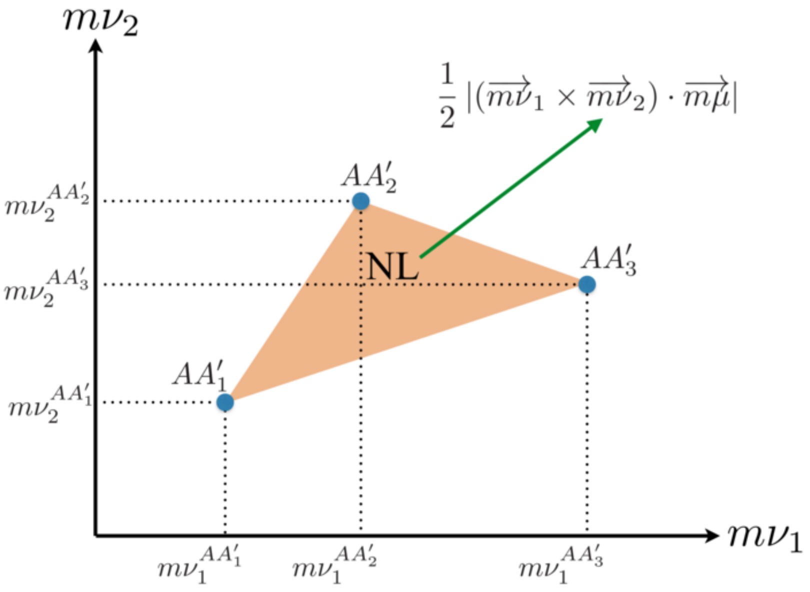

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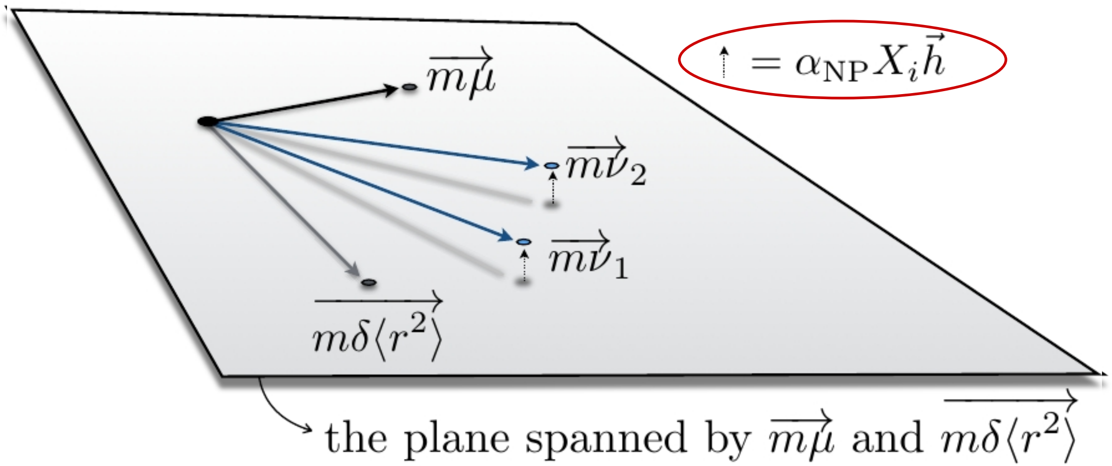

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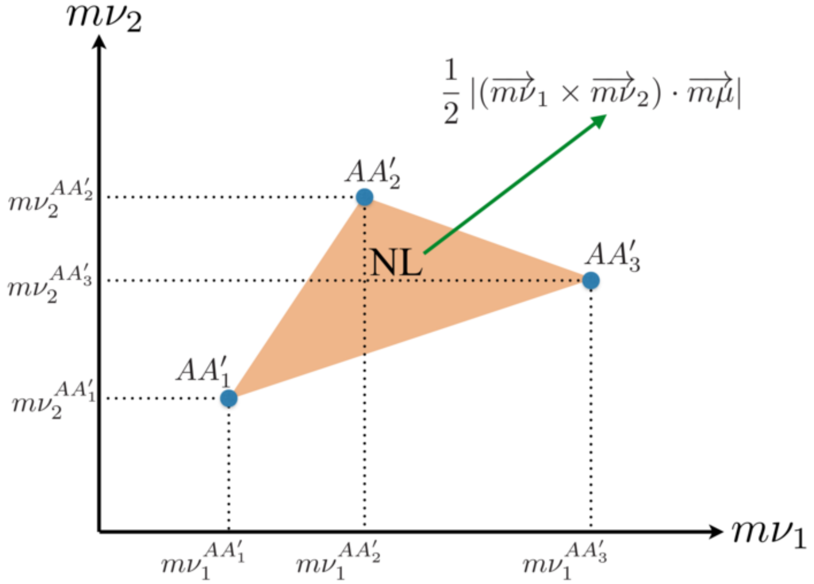

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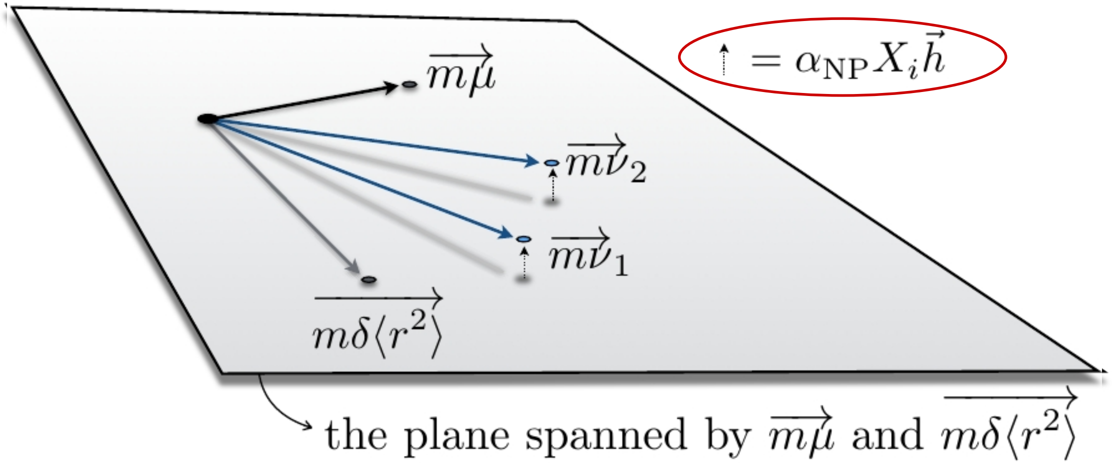

quantify NL → if within uncertainty → bound NP

NP King linearity violation (KLV)

- NP isotope dependence: $\vec{h} \simeq -A\vec{A}'$ amu (for linear $\phi - N$ coupling)

new term in King relation

[Berengut, Budker, Delaunay, Flambaum, Frugiuele, EF, Grojean, Harnik, Ozeri, Perez, Soreq, PRL 2018]

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Developed isotope vector space

NP can break linearity: non-linearity measure $\mathrm{NL_{NP}}$

$$\mathrm{NL_{NP}} = [\overrightarrow{m\mu} \times (X_2 - F_{21}X_1)\ \overrightarrow{m\nu}_1] \cdot \vec{h}$$

$\mathrm{NL_{NP}} = 0$ if

(i) $X_i \propto F_i$ (heavy m_ϕ)

(ii) $\vec{h} || \overrightarrow{m\mu}$ or $\overrightarrow{m\delta\langle r^2\rangle}$

MS FS

[Berengut, Budker, Delaunay, Flambaum, Frugiuele, EF, Grojean, Harnik, Ozeri, Perez, Soreq, PRL 2018]

Constraint on mass and couplings

[Berengut, Budker, Delaunay, Flambaum, Frugiuele, EF, Grojean, Harnik
Ozeri, Perez, Soreq] PRL 120 (2018) 091801

<u>Data-driven bound:</u>

data

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

Mild NP assumption: ϕ couples linearly to nucleus

Theory input

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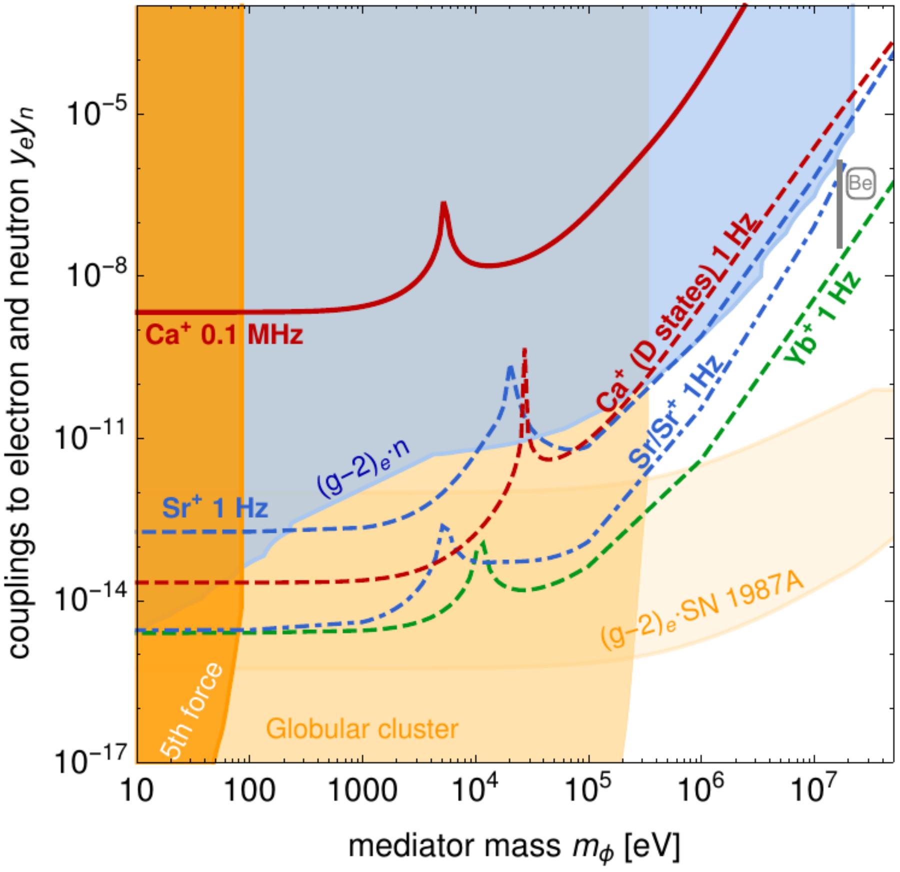

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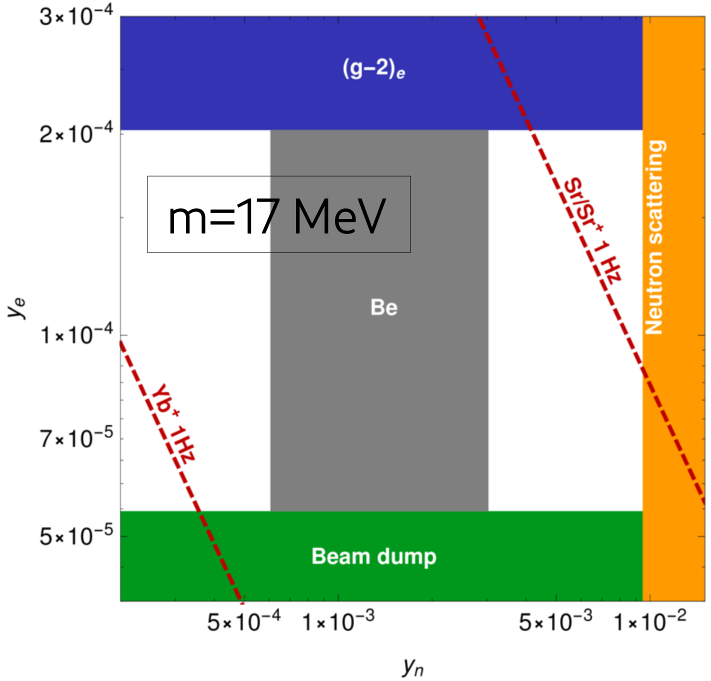
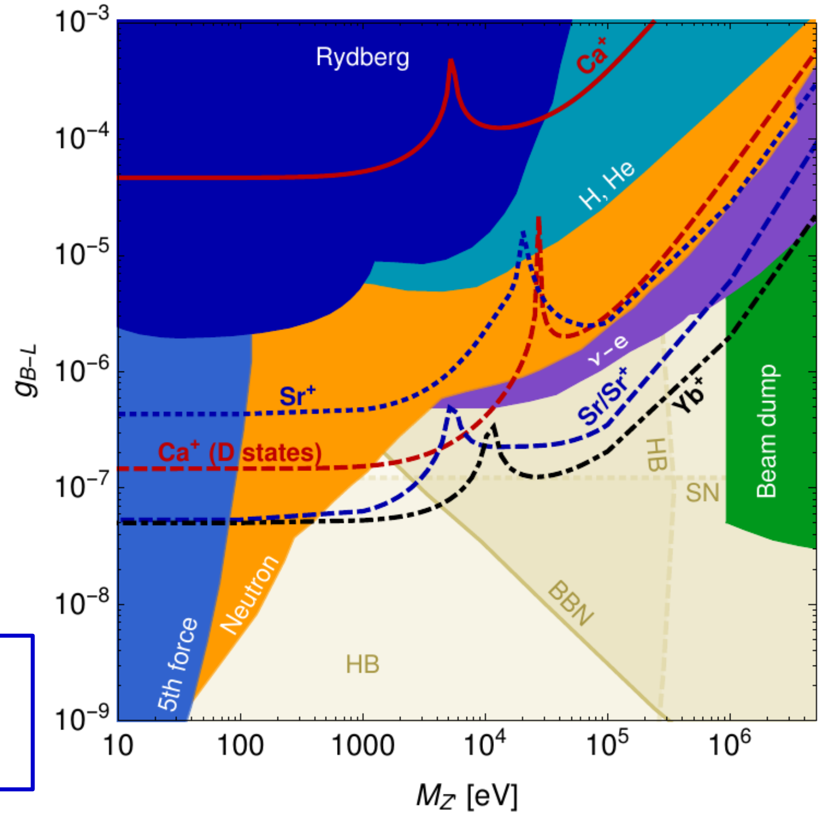
Implications for NP models



[Frugiuele, EF, Perez, Schlaffer '17]

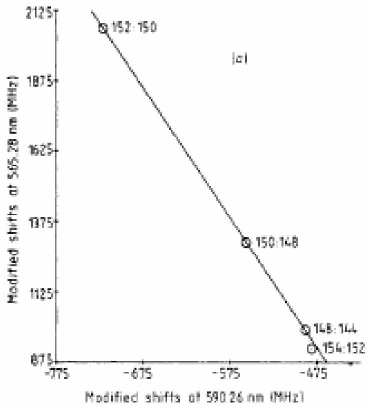


Yb+ 1Hz potential to rule out protophobic explanation of Atomki ^{8}Be anomaly

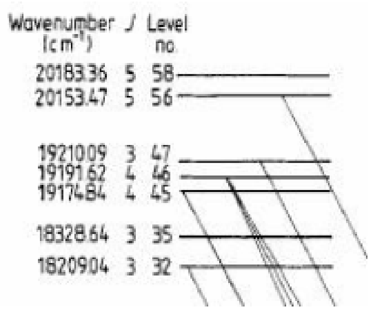
$U(1)_{B-L}$
New Z' boson

Caveat: Linearity breaking in SM

- SM nonlinearity
  - Mixing of degenerate energy levels [Griffith, Isaak, New, Rall '81]
  - **NLO field shift** [Palmer, Stacey '81]
  - Nuclear **polarization** [Seltzer '69] [Blundell, Baird, Palmer, Stacey, Woodgate '87]
  - Nuclear **deformation** [Flambaum, Samsonov, Tan, Viatkina '21]



Samarium (Sm)



- Standard Model contribution to King nonlinearity calculated: for some transitions in Ca^+, Sr^+, Ba^+, Yb^+, Hg^+ [Flambaum, Geddes, Viatkina '18]
- SM nonlinearities: dependence on nuclear radii [Müller, Yerokhin, Artemyev, Surzhykov '21]
- Few-electron ions [Debierre, Oreshkina, Valuev, Harman, Keitel '22]

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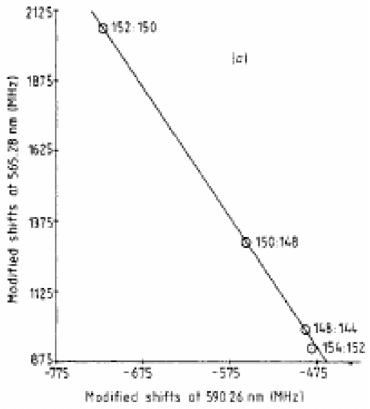
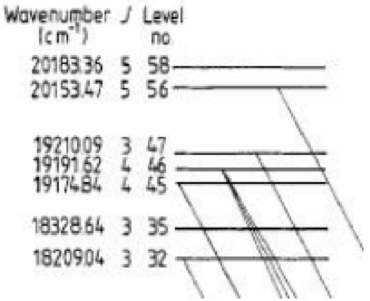


Samarium (Sm)

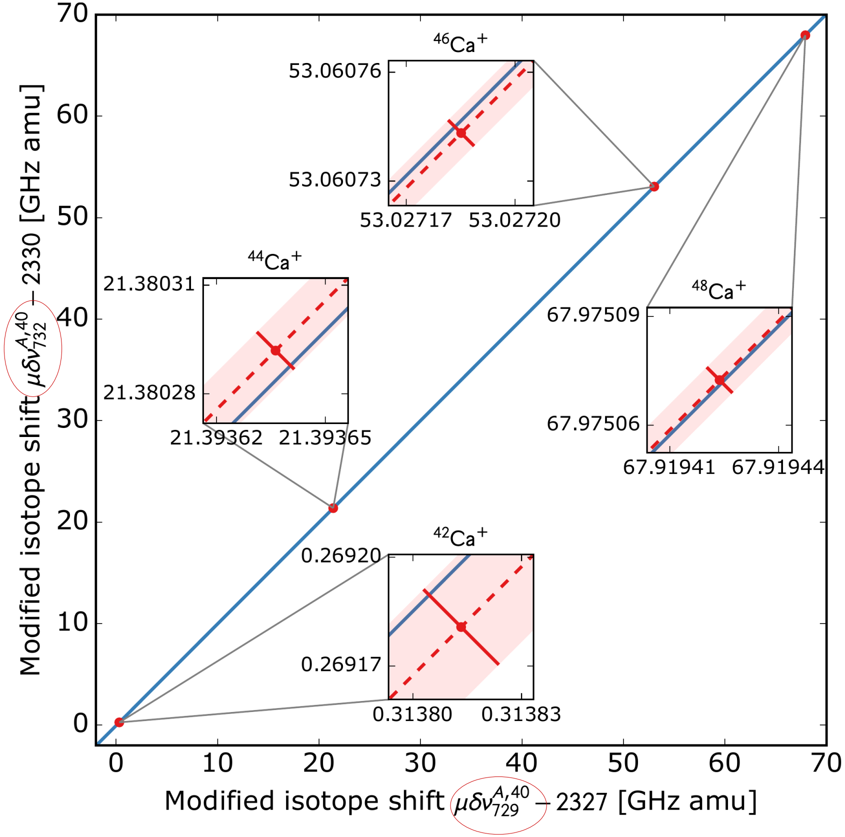


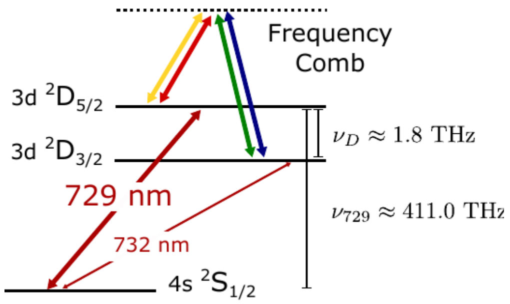
- Standard Model contribution to King nonlinearity calculated: for some transitions [Flambaum, Geddes, Viatkina '18] in Ca^+, Sr^+, Ba^+, Yb^+, Hg^+
- SM nonlinearities: dependence on nuclear radii [Müller, Yerokhin, Artemyev, Surzhykov '21]
- Few-electron ions [Debierre, Oreshkina, Valuev, Harman, Keitel '22]

Strategy: consider predicted SM NL and constrain residual NL

Very precise Ca^+ King Plot

[Solaro, Meyer, Fisher, Berengut, EF, Drewsen, PRL 125, 123003 (2020)]





[Solaro, Meyer, Fisher, DePalatis, Drewsen, PRL.120.253601]

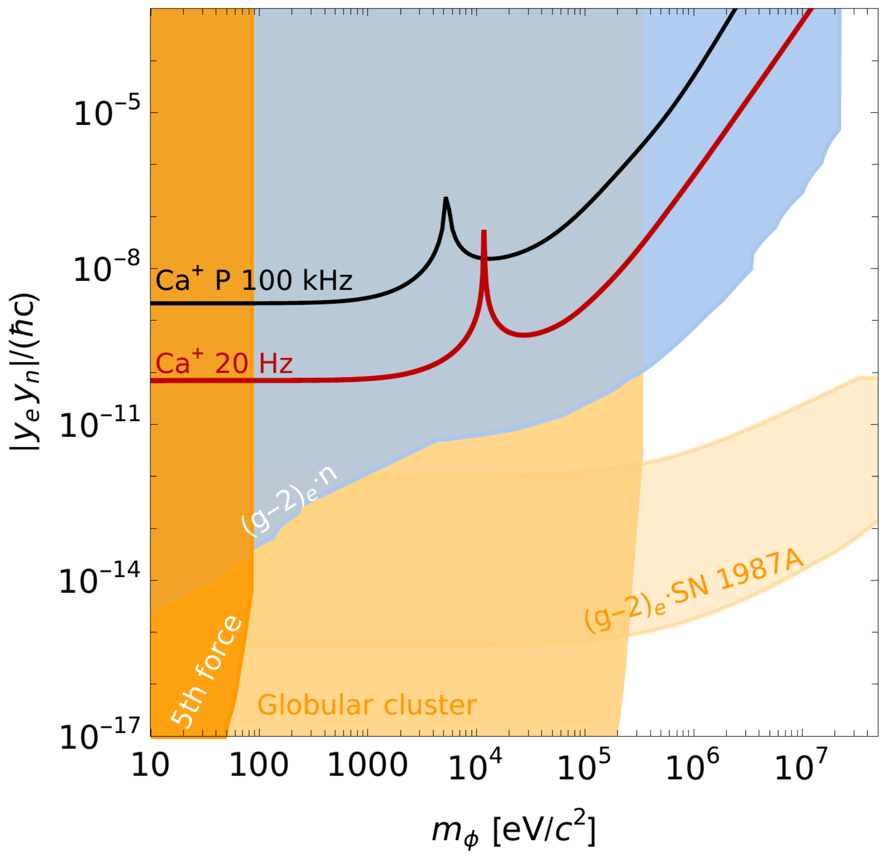
Aarhus: $D_{3/2}$-$D_{5/2}$ at **20 Hz**

Ca 40, 42, 44, 46, 48

King plot linear at ~1σ, χ^2=0.9

New Ca⁺ Isotope Shift Bounds on Φ

[Solaro, Meyer, Fisher, Berengut, EF, Drewsen, PRL 125, 123003 (2020)]



- **New 4D** projection method for 4 isotope pairs
- **Improvement** of former Ca bound by factor 30
- Limited by D-fine precision
- Same transitions in Ba, Yb with 20 Hz comparable to $(g\text{-}2)_e$*n-scatt
- Anticipated precision: **10 mHz**
  - Ca, Ba, Yb can probe untested parameter space

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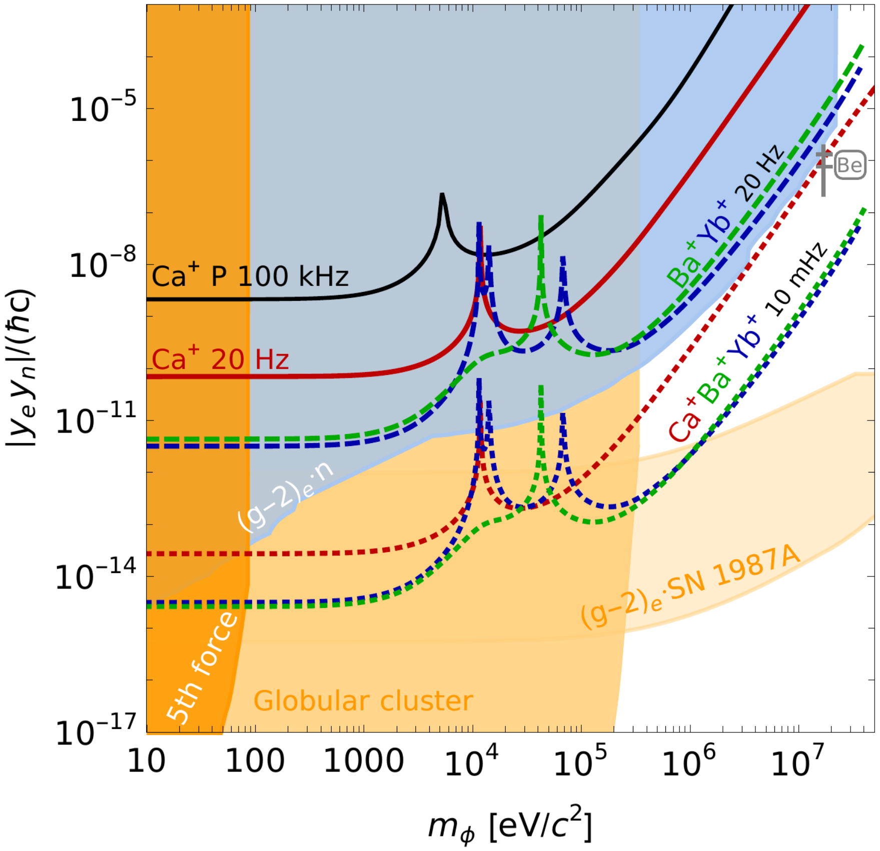

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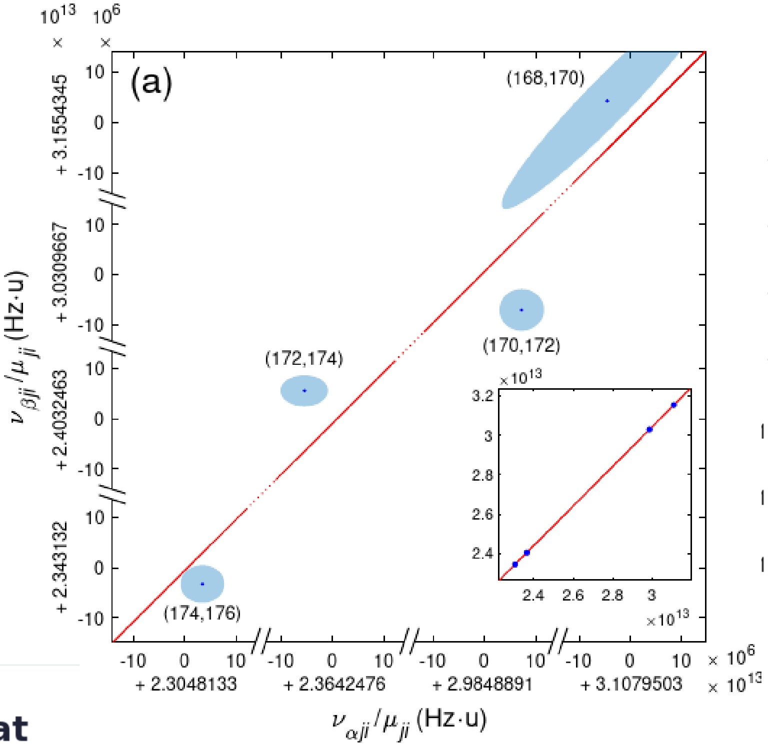
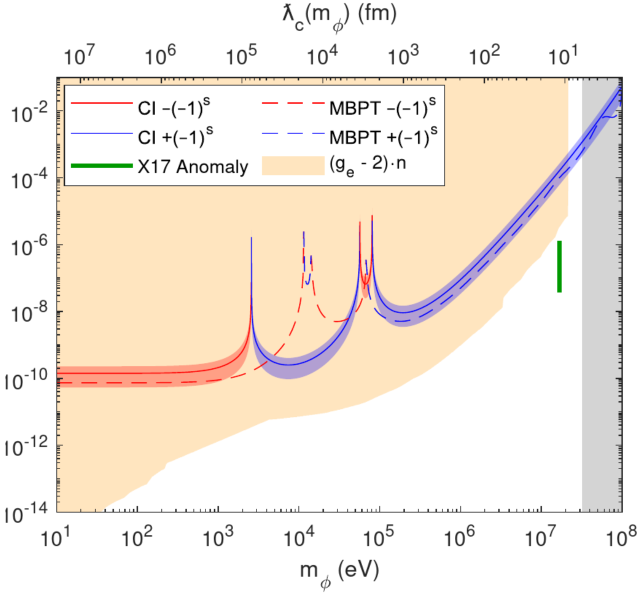
Nonlinearity in Yb^+ isotope shifts

[Counts, Hur, Craik, Jeon, Leung, Berengut, Geddes, Kawasaki, Jhe, Vuletić, PRL 125, 123003 (2020)]

- Same transitions:
  - $S\text{-}D_{3/2}$, $S\text{-}D_{5/2}$
  - Precision 300 Hz
- Also 4 isotope pairs
- **3σ nonlinearity**
- Nuclear deformation?





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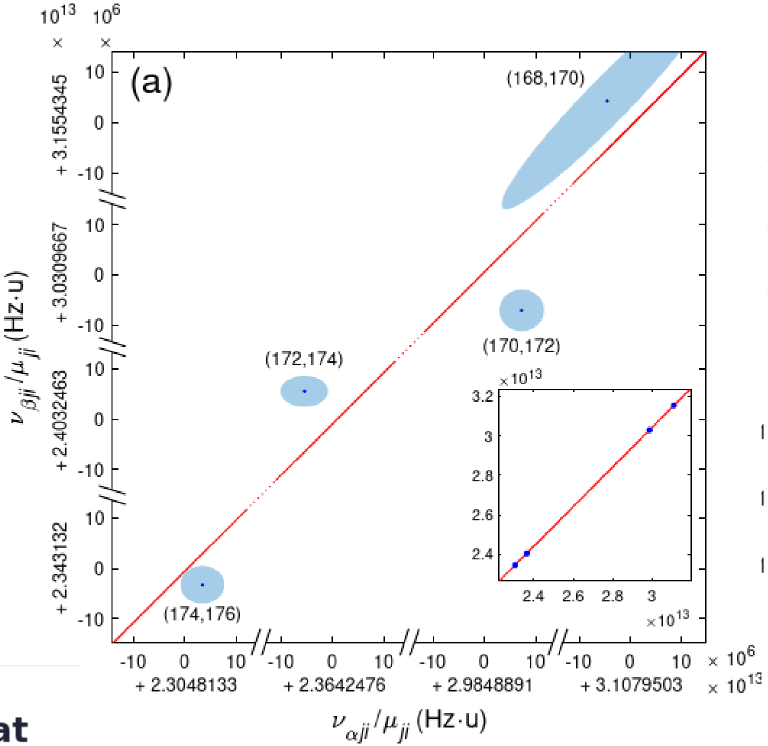
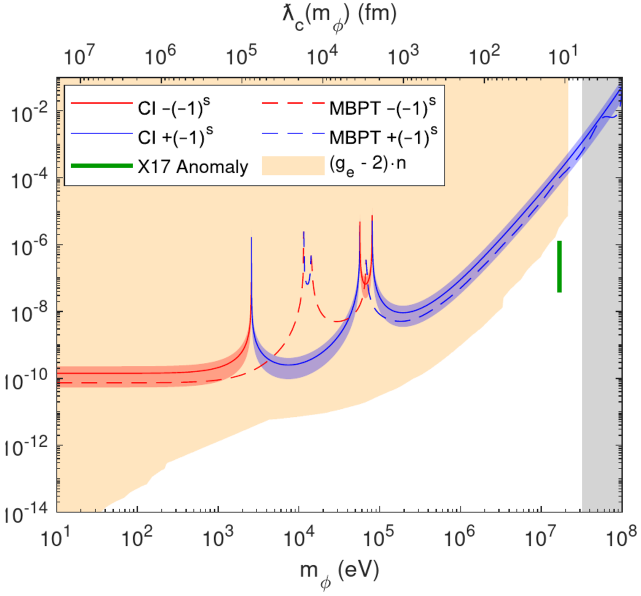




BSM or nuclear physics?

Scrutinizing the Yb anomaly

Figueroa, Berengut, Dzuba, Flambaum, Budker, Antypas, PRL 2022

New Yb/Yb+ King plot: reduced nonlinearity could be explained by **nuclear deformation**

Hur, Craik, Counts, Berengut, Vuletic et al, '22

S→ F octupole transition of Yb+ combined with previous Yb+ and Yb IS:

- 4.3 sigma for **2nd source**
- future: 4 orders improvement of exp. uncertainty to sub-Hz level as in simultaneously trapped Sr^+

Flambaum, Samsonov, Tan, Viatkina '21

Nuclear polarization effects in atoms and ions

Fürst, Zeh, Dreissen, Kulosa, Kalincev, Lange, Benkler, Huntemann, Peik, Mehlstäubler PRL 2020

- **Improved measurement** of 411nm E2 and 467nm E3 transitions at few Hz
- further with sub-10-Hz precision, update coming soon

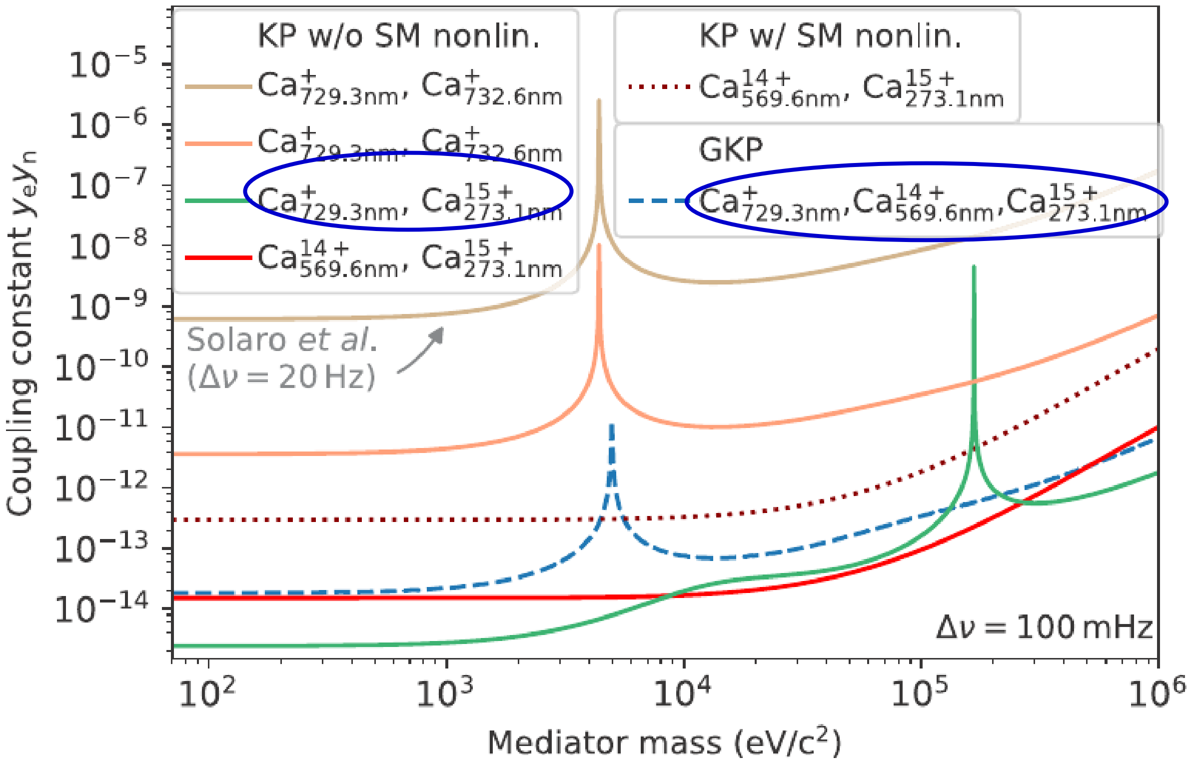
Highly charged ion (HCI) King plot

[Rehbehn, Rosner, Bekker, Berengut, Schmidt, King, Micke, Gu, Müller, Suryhzkov, Crespo Lopez-Urrutia '21]

[King, Spieß, Micke, Wilzewski, Leopold, Benkler, Lange, Huntemann, Suryhzkov, Zerokhin, Crespo, Schmidt; Nature 611 (2022)]

- HCIs: less electrons
- Generalized King plot
- Projected bounds assuming no isotope mass uncertainties

Very promising combination of singly and highly charged Ca ions



→ find optimal combination

→ ongoing: replacement of isotope masses AND higher-order mass shift

[Berengut, EF, Mariotti, Richter, Surzhykov, Viatkina; work in progess]

See also Hydrogen-like ions [Debierre, Keitel, Harman '22]

Direct comparison of theory and data

Few-electron systems

- Data *and* theory very precise
- Need only ≥1transition, ≥1 isotope
  - Isotope shifts: need p-radius
  - Direct frequency: combine with (g-2), Rydberg or 2nd transition

cf [Karshenboim '01, '10]
[Jaeckel, Roy '10]
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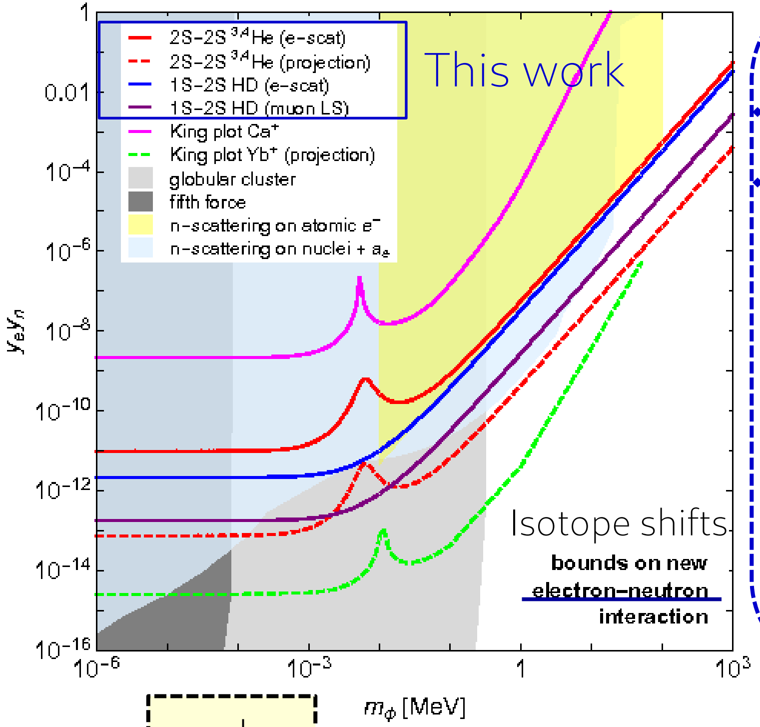
Direct comparison of theory and data

[Delaunay, Frugiuele, EF, Soreq '17]



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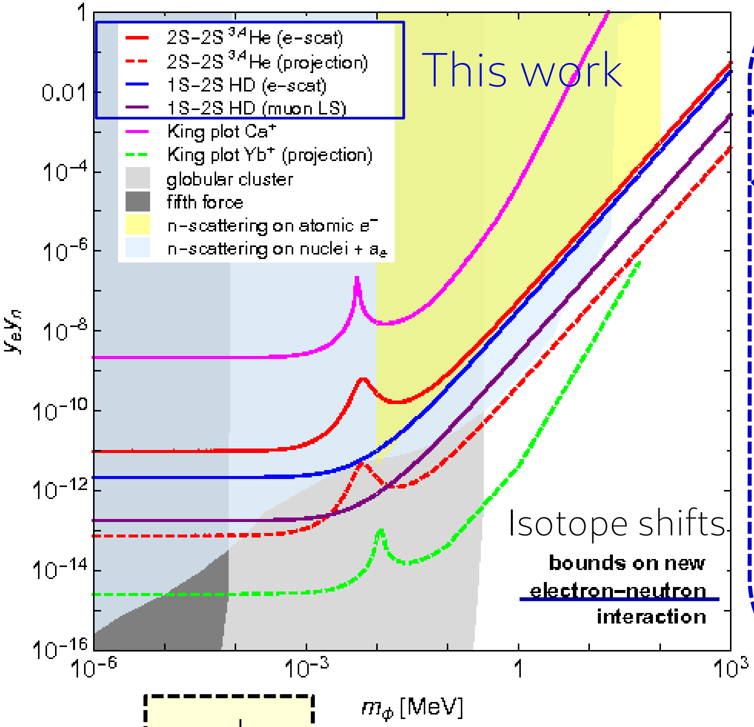

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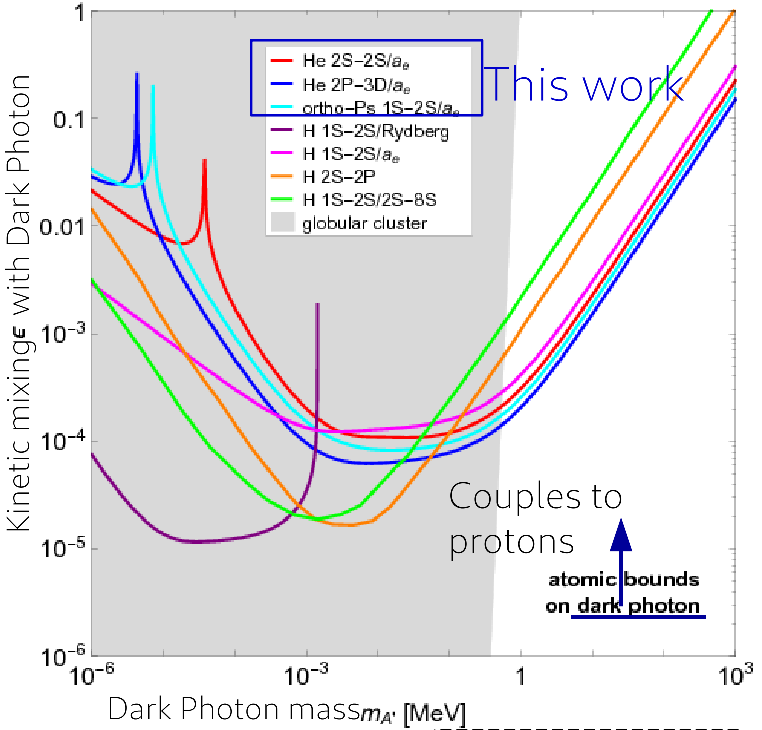

Dark photon

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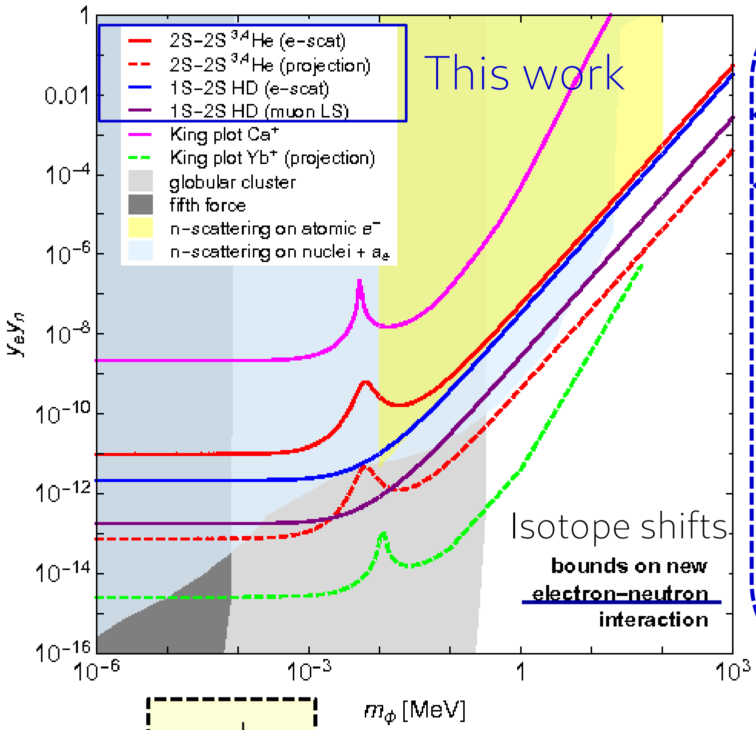

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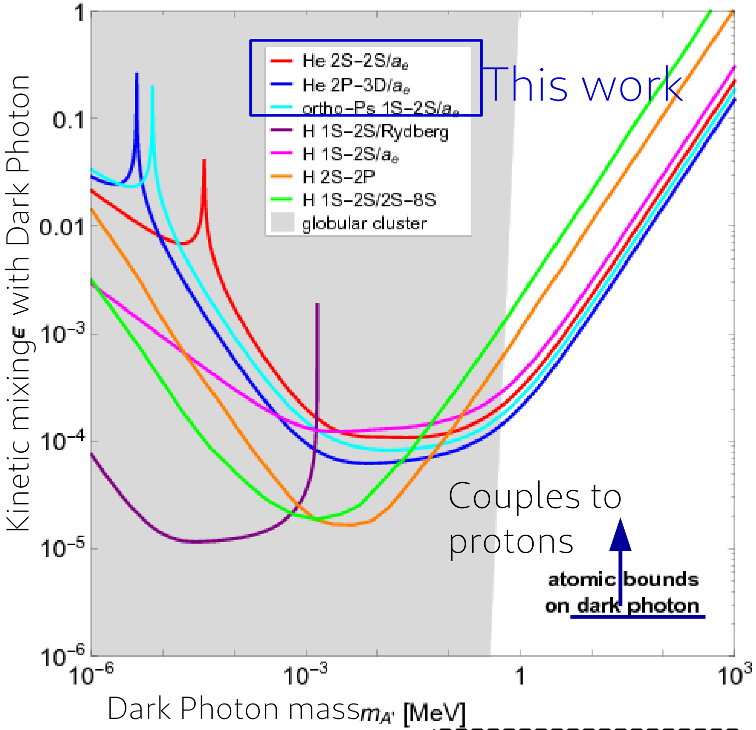

Dark photon

Precise frequencies and isotope shifts
→ complementary to King plot

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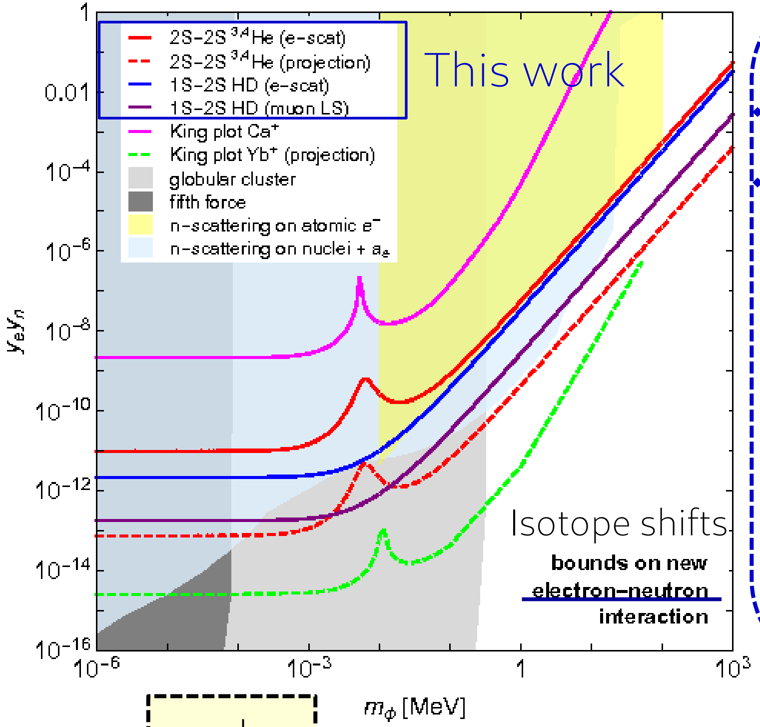

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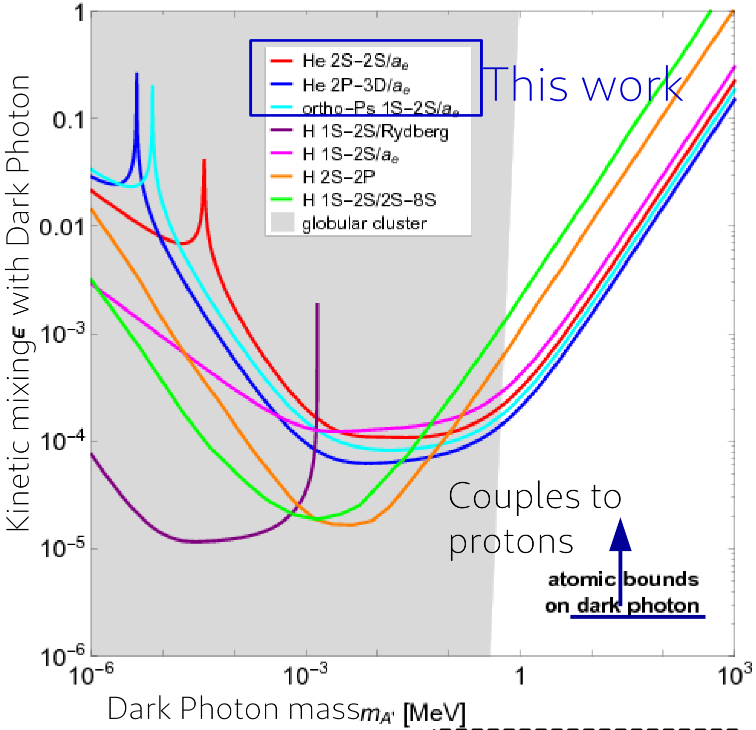


Dark photon

Precise frequencies and isotope shifts → complementary to King plot

New Ca^+ Isotope Shift Measurements

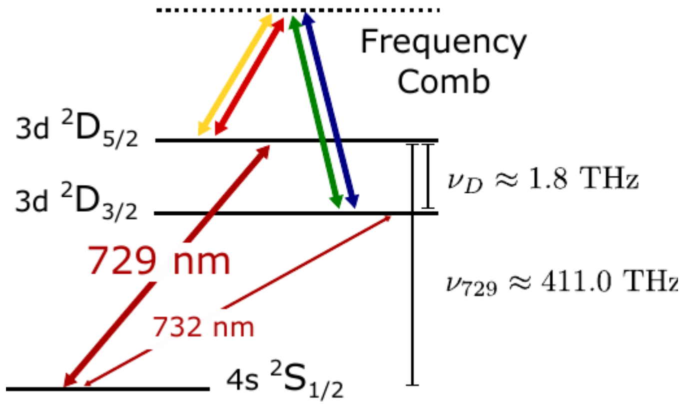
[Solaro, Meyer, Fisher, Berengut, EF, Drewsen, PRL 125, 123003 (2020)]

- Very precise measurement of **D-fine splitting** of Ca^+ at Aarhus (Denmark)

  $D_{3/2}$-$D_{5/2}$ at **20 Hz** → precision ~10^{-6}

- S-$D_{5/2}$ at 2 kHz → precision ~10^{-7}

  [Knollmann, Patel, Doret, PRA 2019] ~10^{-9}



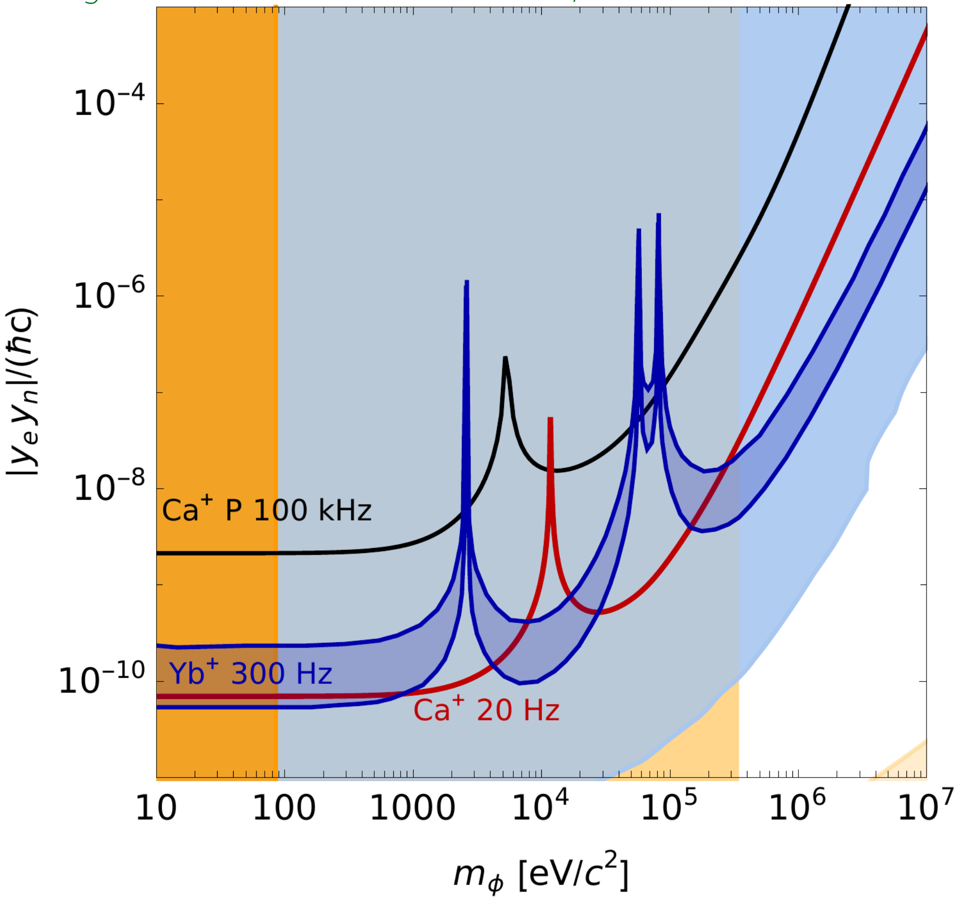
[Solaro, Meyer, Fisher, DePalatis, Drewsen (Aarhus University), PhysRevLett.120.253601]

5 isotopes measured: Ca 40, 42, 44, 46, 48
→ **4 pairs**, i.e. 1 more than required

Ca vs Yb King plots – compatibility

- Reach same sensitivity
  - Yb 10x more susceptible to NP
  - Ca 10x more precisely measured
- non/linearity no contradiction
  - different nuclear physics

[Yb digitalized from Counts et al '20; Ca from Solaro et al '20]



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if Yb-NL assumed as *purely* New Physics:
→ necessary coupling range is
- partly excluded by Ca
- excluded by $(g-2)_e$*n-scattering

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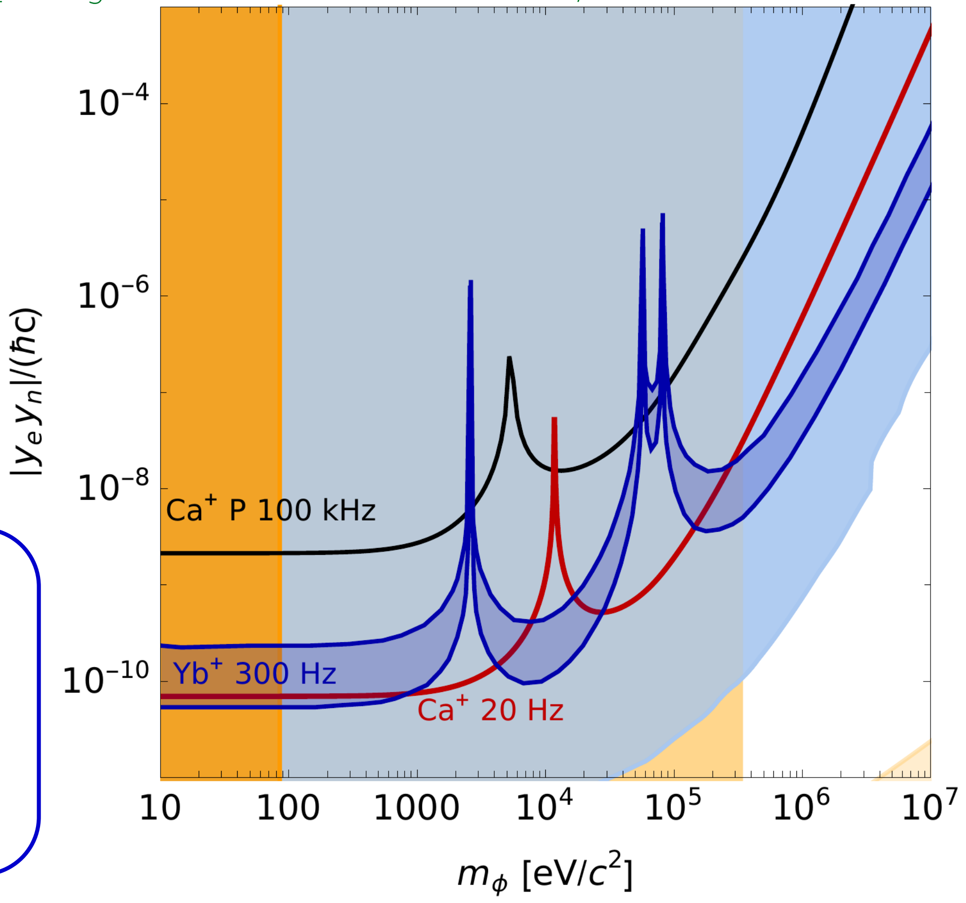
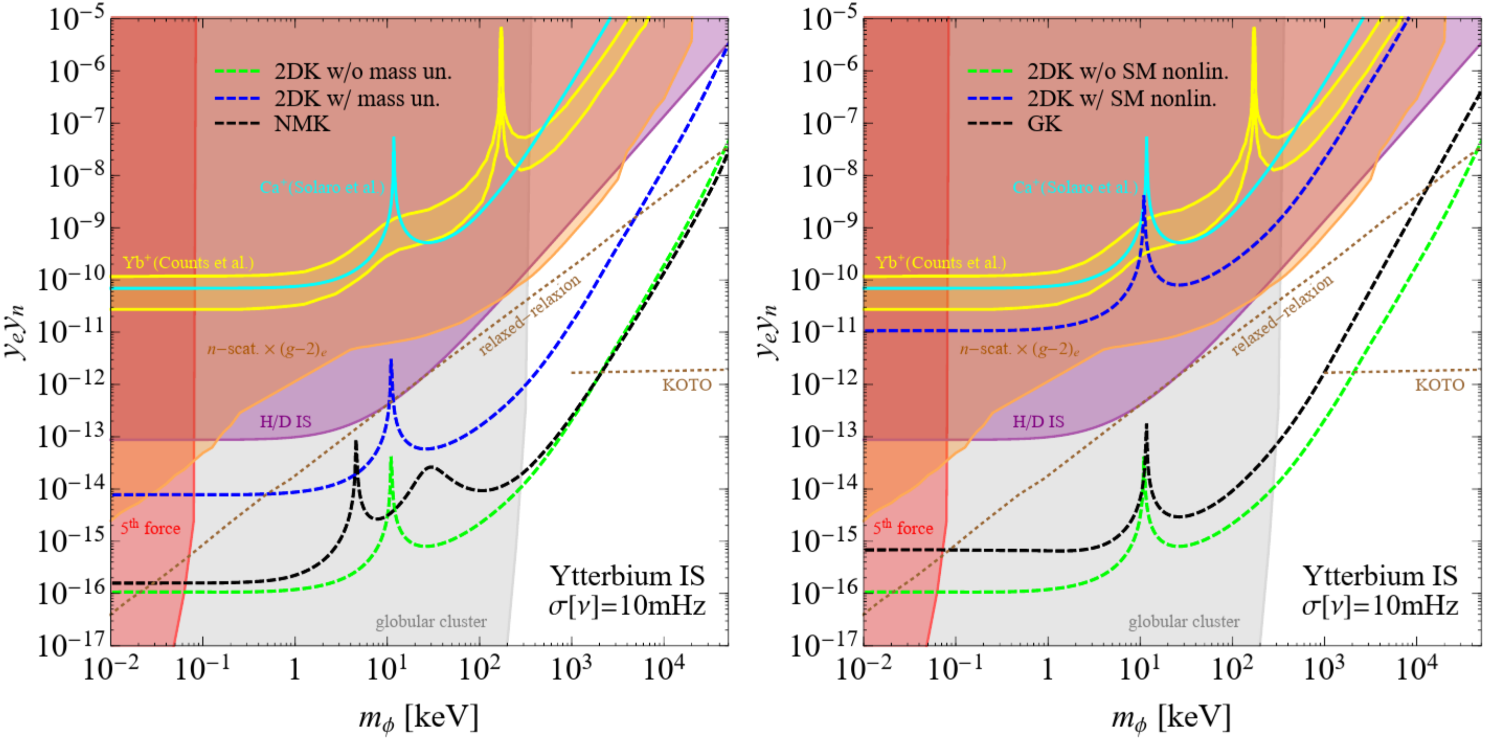


Generalised King Plot



NP electronic overlap

Electronic NP coefficient: overlap of wavefunctions of initial and final states (a, b) with the NP (Yukawa) potential

Perturbative approximation:

$$X_i = \int d^3r \frac{e^{-m_\phi r}}{4\pi r} \left[|\Psi_b(r)|^2 - |\Psi_a(r)|^2 \right]$$

Contact-Interaction + Multibody Perturbation Theory (CI+MBPT)

$$X_i = \frac{1}{A-Z} \frac{d\epsilon_{ab}}{d\alpha_{\mathrm{NP}}}\bigg|_{\alpha_{\mathrm{NP}}=0}$$

Difference of energy levels as a function of α_{NP}

Chameleon search with King plot

Dark Energy

Matter density

[Khoury, Weltman '04, '04]
[Brax, Burrage '10, '11]
[Frugiuele, EF, Perez, Schlaffer '17]

$$V_{\text{eff}} = V(\phi) + \frac{\phi\rho}{M}$$

Energy scale/coupling

Chameleon mass is density dependent:
→ Heavy in dense environment
→ screening in test masses
→ mediating a long-range interaction

$$\delta H\Big|_n = -\frac{m_e m_N}{4\pi r M^2}$$

Change in Hamiltonian
→ change in energy level of e

Match to V_{NP}

$$M > \sqrt{\frac{m_e m_n}{y_e y_n\big|_{\text{min}}}} \approx 500\ \text{TeV} \approx 2.5 \cdot 10^{-13}\, M_{\text{Pl}}$$

Sensitivity projection with future Yb^+ King plot with 1Hz precision

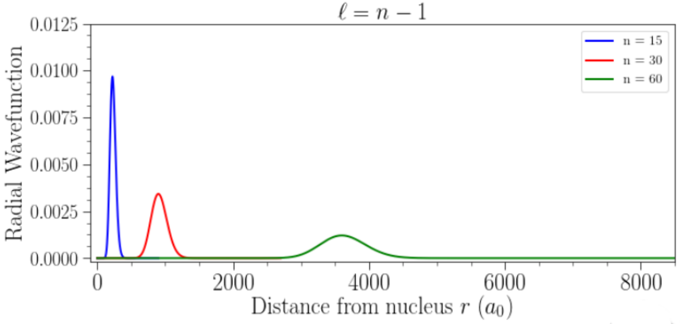
Rydberg states: reduce nucl. uncertainty

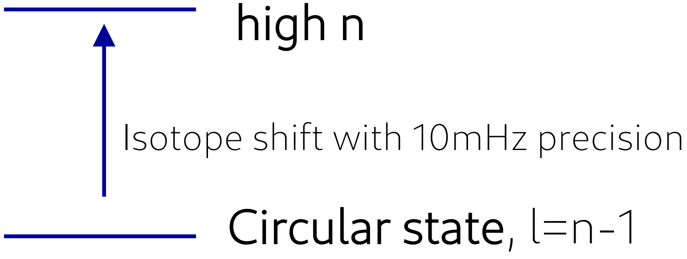
[Duque-Mesa, Firstenberg, EF, Geller, Ozeri, Perez, Shpilman; work in progress]

Highly excited states

→ less overlap with nucleus

→ but also with NP





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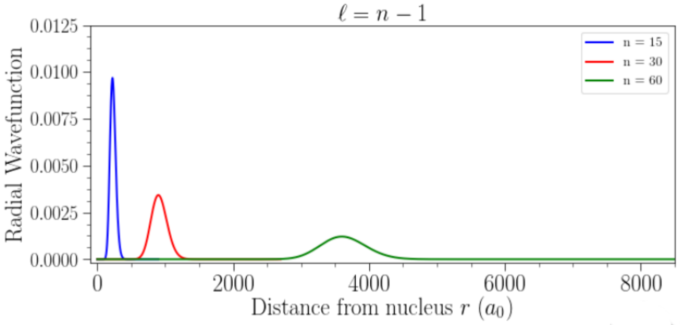
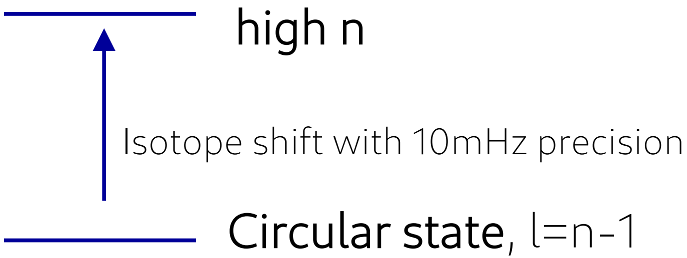
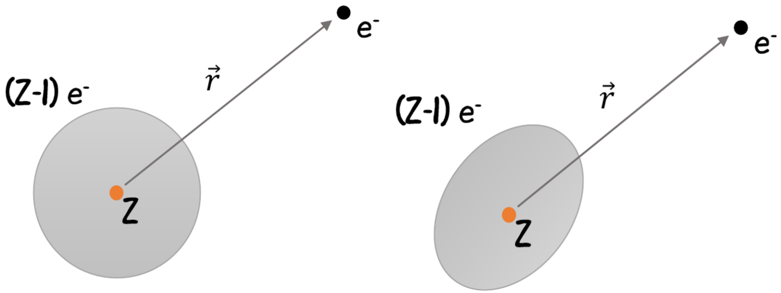
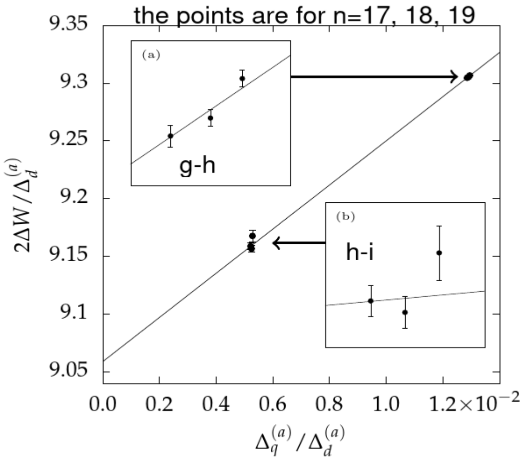




Bottleneck: Core polarizability



[image: MSc thesis, S. Duque-Mesa]



Rb data in polarizability plot:
[Berl, Sackett, Gallagher, Nunkaew '20]

Trick: Measure many transitions

Rydberg states: reduce nucl. uncertainty

[Duque-Mesa, Firstenberg, EF, Geller, Ozeri, Perez, Shpilman; work in progress]

Expect points in plane

$$\frac{f_{AB}}{\delta_Y} = -\left(\alpha^d_A m_e \mu^{-1}_{AB} + \frac{1}{2}\Delta\alpha^d_{AB}\right)\frac{\delta_{r^{-4}}}{\delta_Y} - \left(3\alpha^q_A m_e \mu^{-1}_{AB} + \frac{1}{2}\Delta\alpha^q_{AB}\right)\frac{\delta_{r^{-6}}}{\delta_Y} + 2\pi R_\infty m_e \mu^{-1}_{AB}\frac{\delta_{r^{-1}}}{\delta_Y} + \alpha_{NP}$$

dipole ($\vec{x}$) — quadrupole ($\vec{y}$)

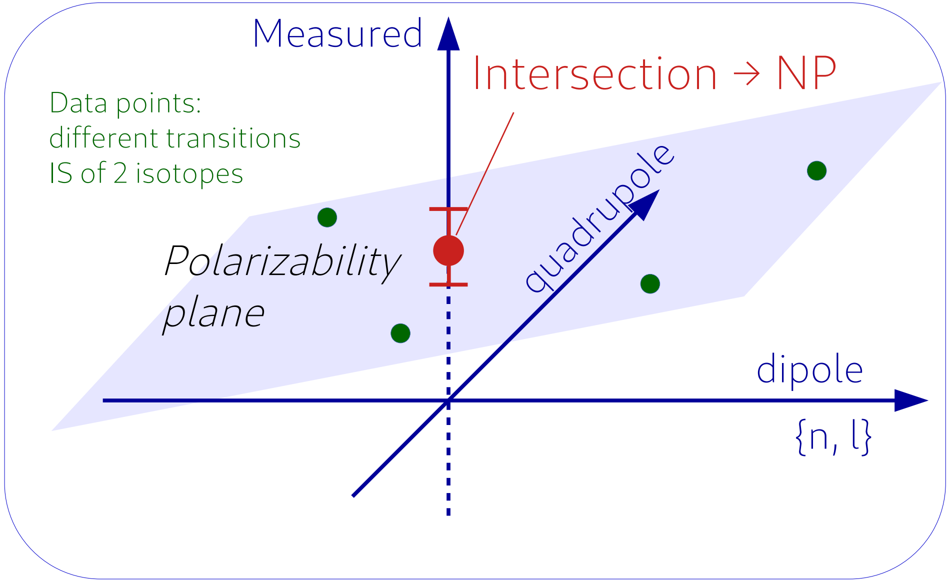
$$\delta_{r^q} = \langle r^q \rangle_{n_2 l_2} - \langle r^q \rangle_{n_1 l_1}$$

$$\delta_Y = \left\langle \frac{e^{-m_\phi r}}{r} \right\rangle_{n_2 l_2} - \left\langle \frac{e^{-m_\phi r}}{r} \right\rangle_{n_1 l_1}$$

Vector: Many n, l

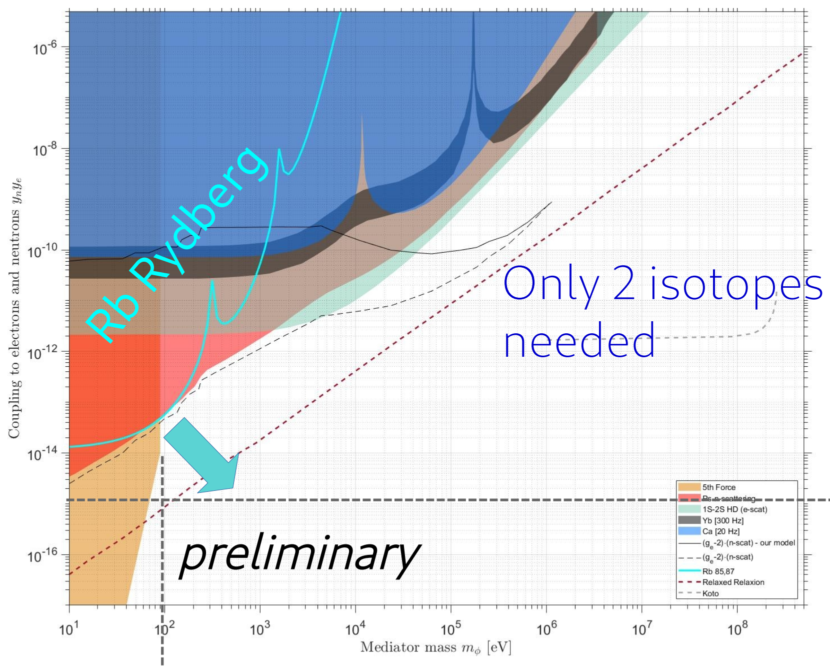
$$\vec{z} = C + A\vec{x} + B\vec{y}$$

$$C = \frac{(\vec{x}\times\vec{y})\cdot\vec{z}}{(\vec{x}\times\vec{y})\cdot\vec{1}} \rightarrow \alpha_{NP}$$

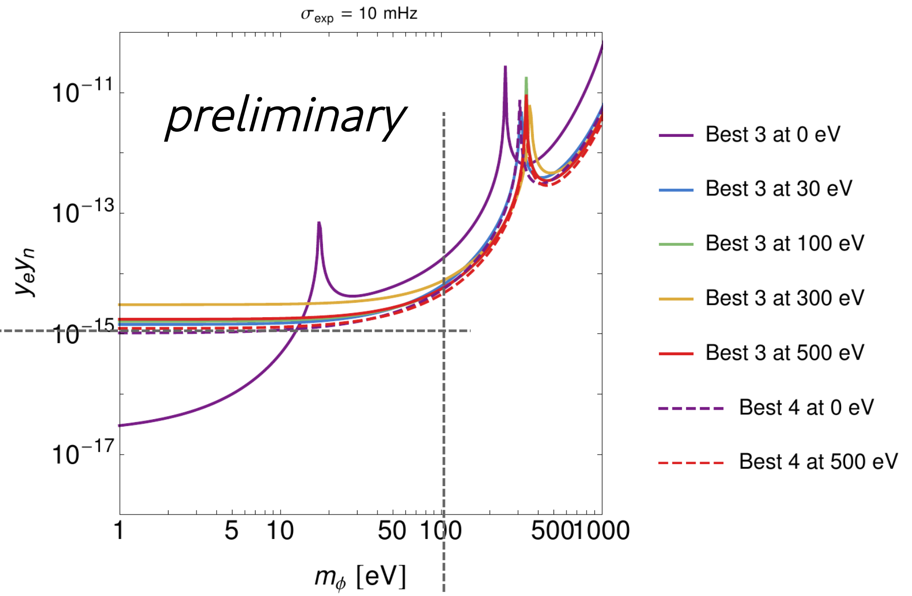


Rydberg states: reduce nucl. uncertainty

[Duque-Mesa, Firstenberg, EF, Geller, Ozeri, Perez, Shpilman; work in progress]



Choose best transitions for a mass range
4 or 3 transitions? only small improvement

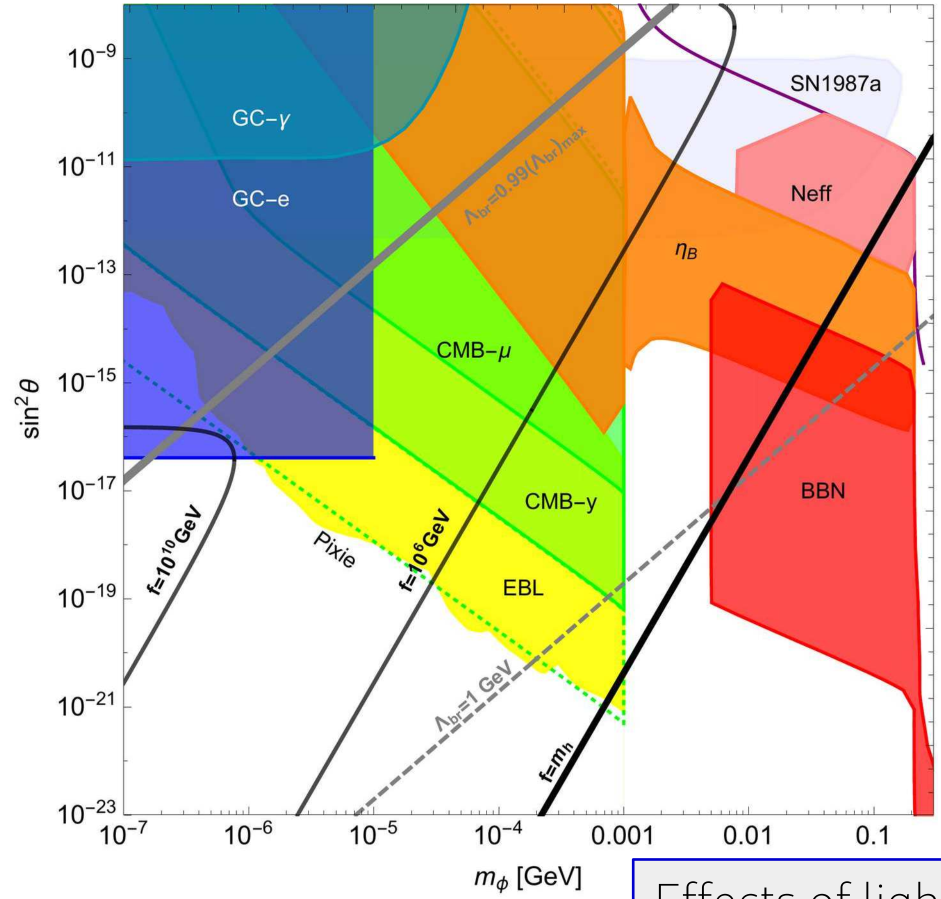


Possibly test new parameter space

See also Rydberg hydrogen [Jones, Potvliege, Spannowsky '19]

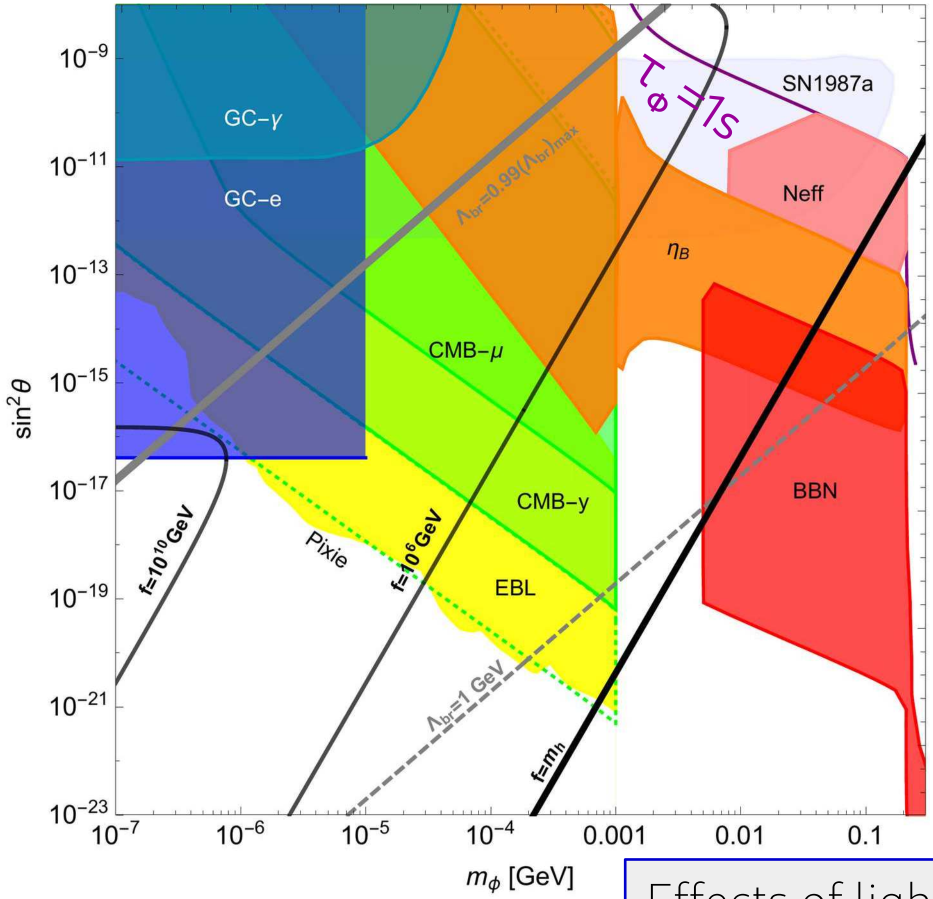
Relaxion Cosmology

Flacke, Frugiuele, EF, Gupta, Perez '16



Effects of light new scalar on the Universe

Relaxion Cosmology



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Late decays after **ν** decoupling

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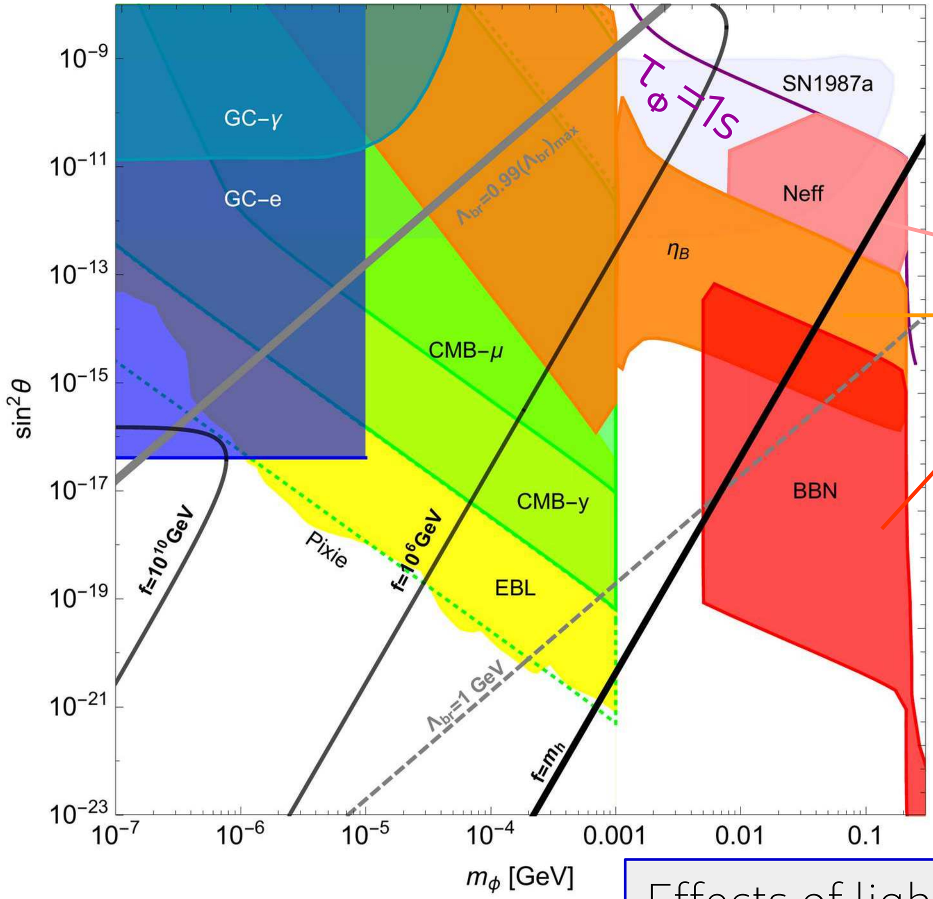

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Entropy injection between BBN and CMB

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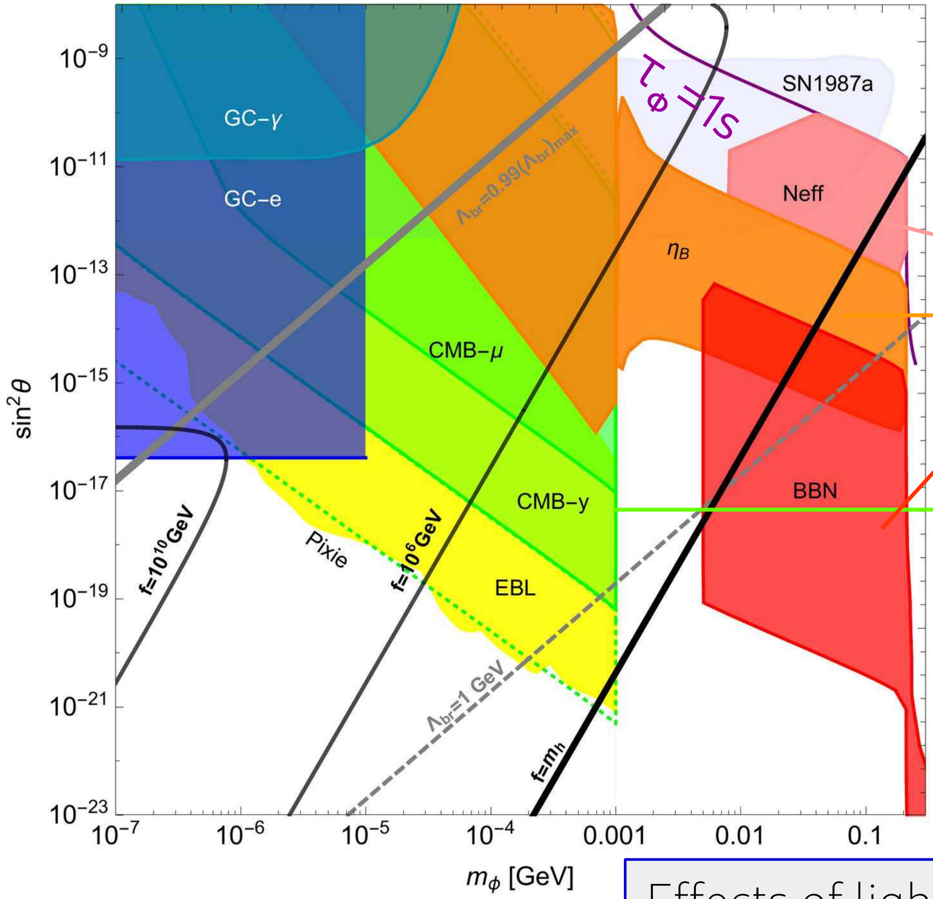

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- photon thermalization

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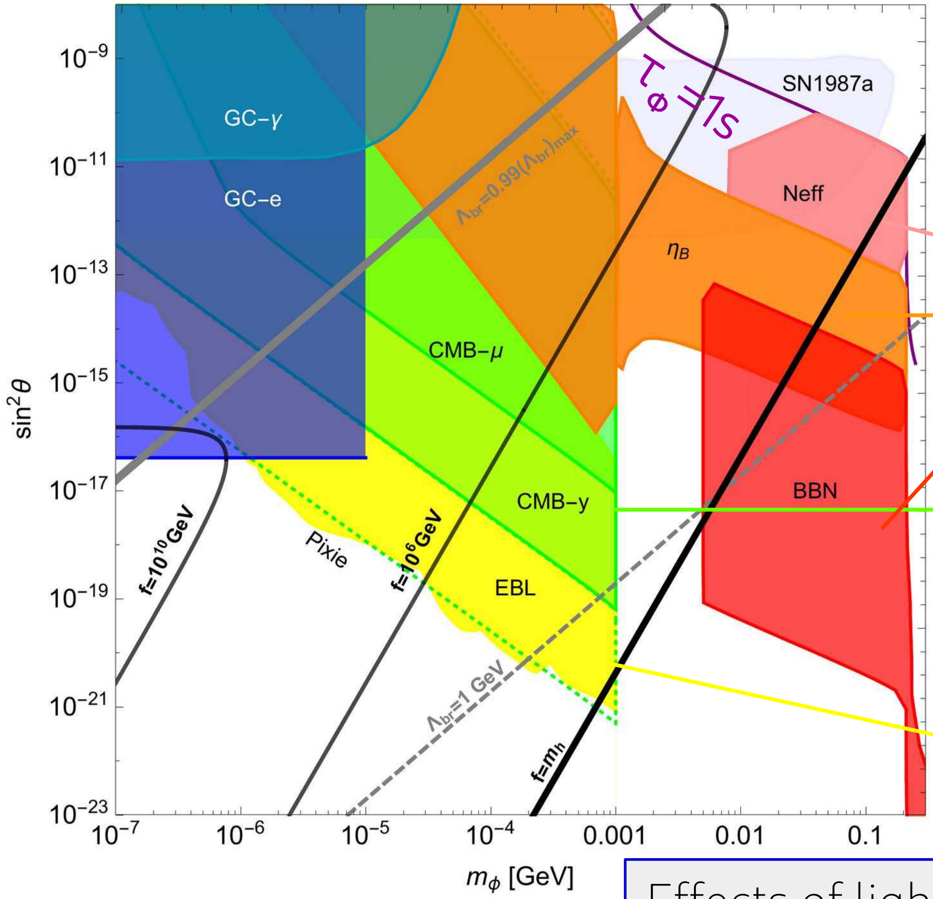

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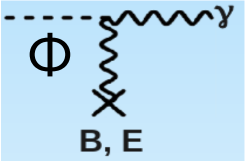
Diffuse extragalactic background light

Effects of light new scalar on the Universe

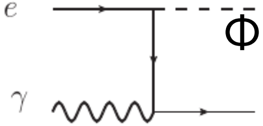
Relaxion Cosmology

Globular cluster cooling

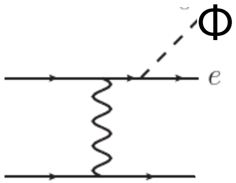
Primakoff process

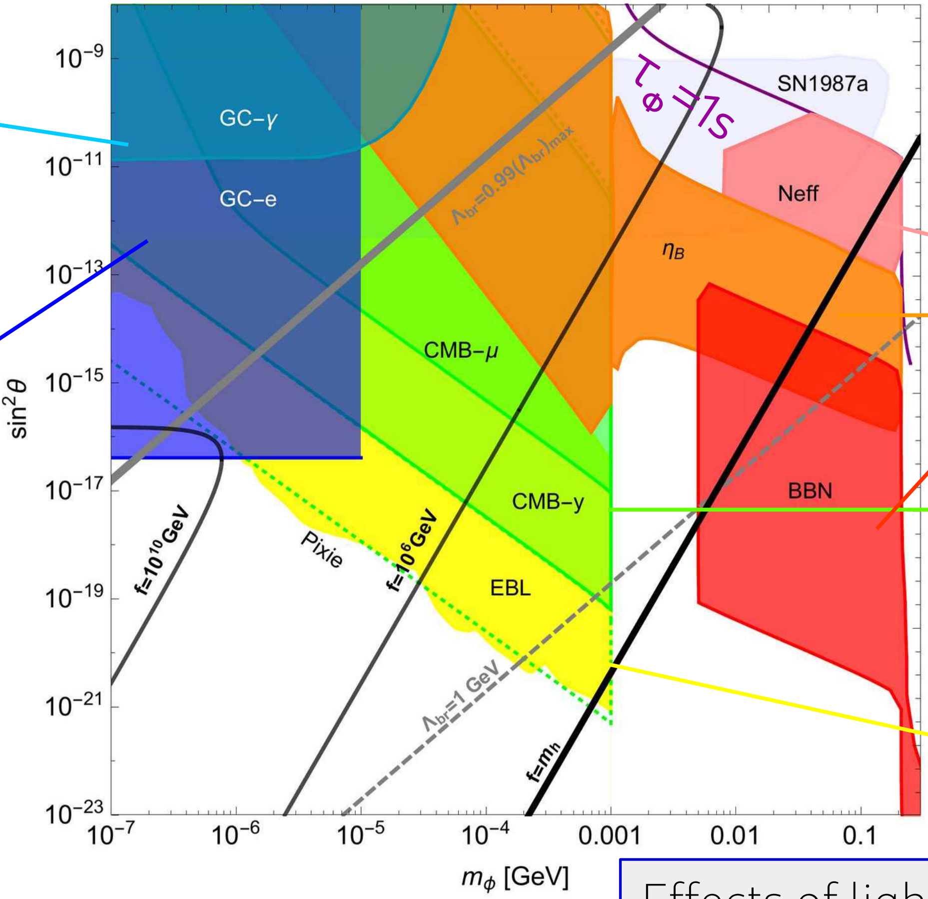


Compton



Bremsstrahlung





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