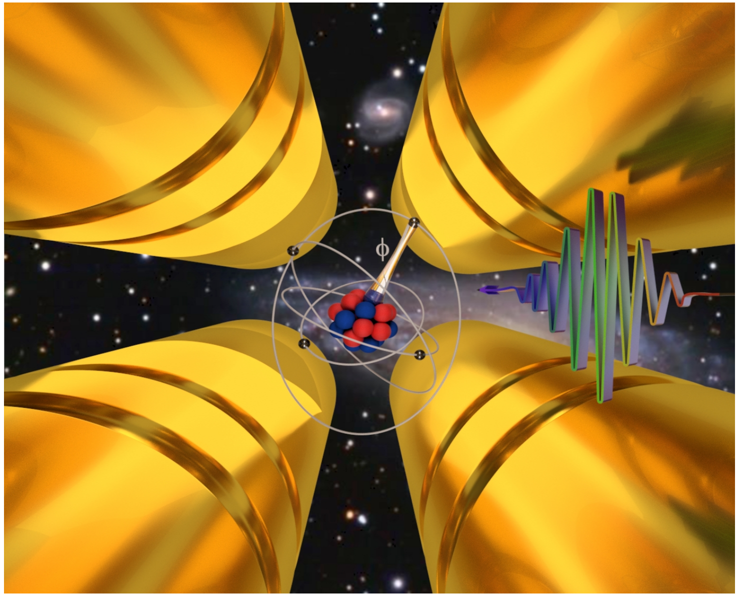
Atomic sensors for light new particles and high-frequency gravitational waves

Elina Fuchs
Leibniz Universität Hannover
& PTB Braunschweig



Light Dark World Forum
Karlsruhe, September 19th, 2023

Leibniz Universität Hannover

PTB

QuantumFrontiers

mat

Outline

2) Quantum Sensors

3) Atomic clocks for light new bosons

4) High-frequency GWs with optical photons

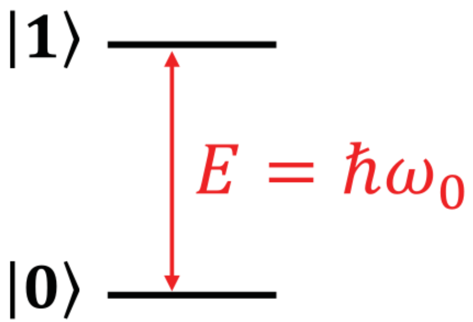
Quantum Sensors

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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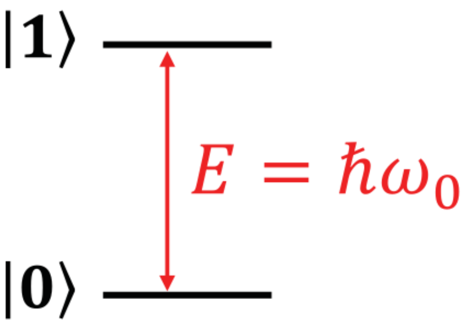

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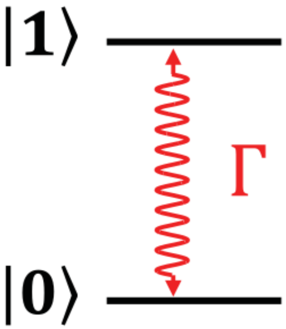

iv) interaction with external field
→ energy shift or transition between levels

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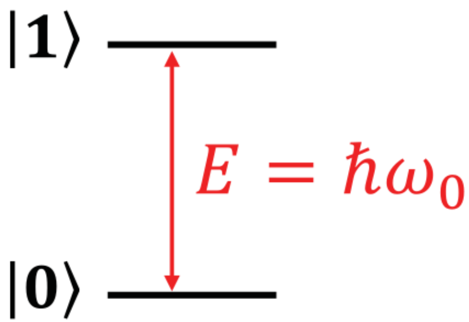

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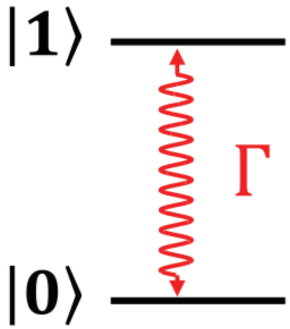
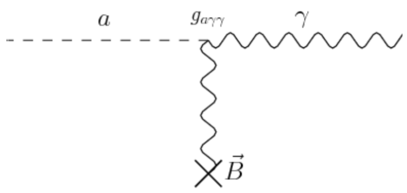


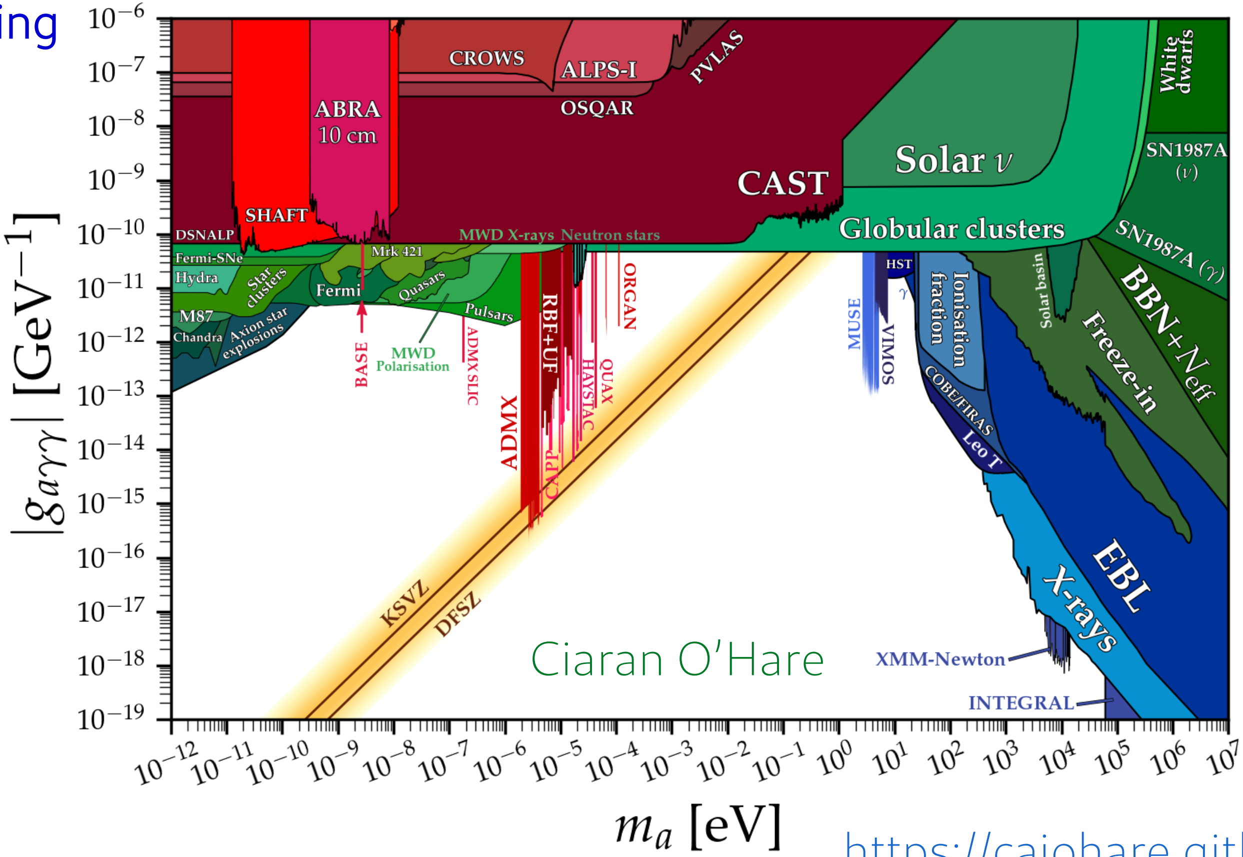
iv) interaction with external field
→ energy shift or transition between levels

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

Squeezing: e.g. in axion searches

axion-photon coupling





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

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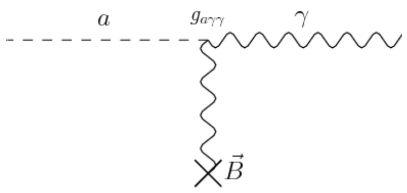
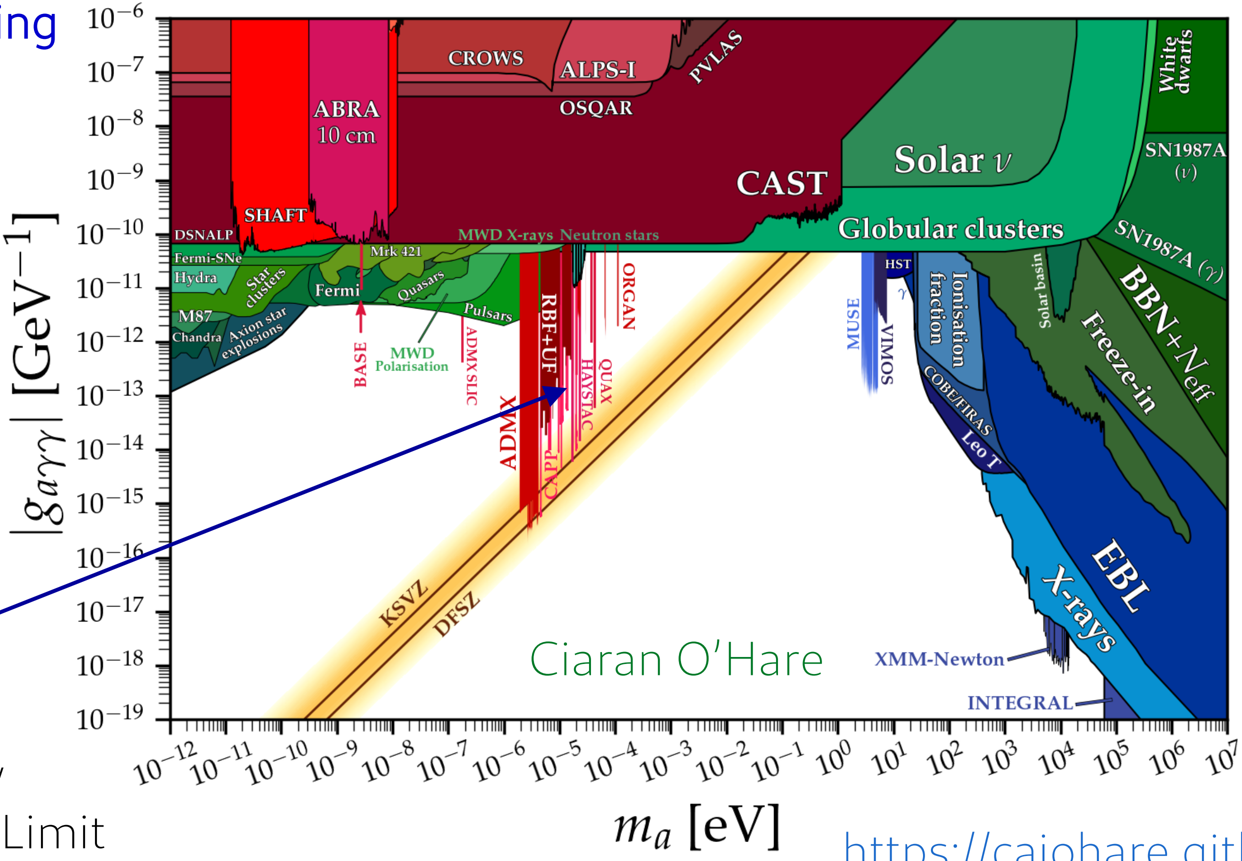
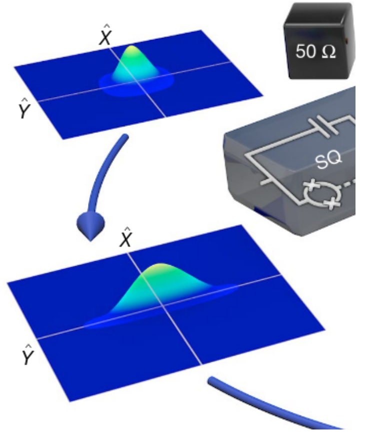




Haystac goes below Standard Quantum Limit

Squeezing HAYSTAC [Nature]



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

The virtue of frequency measurements

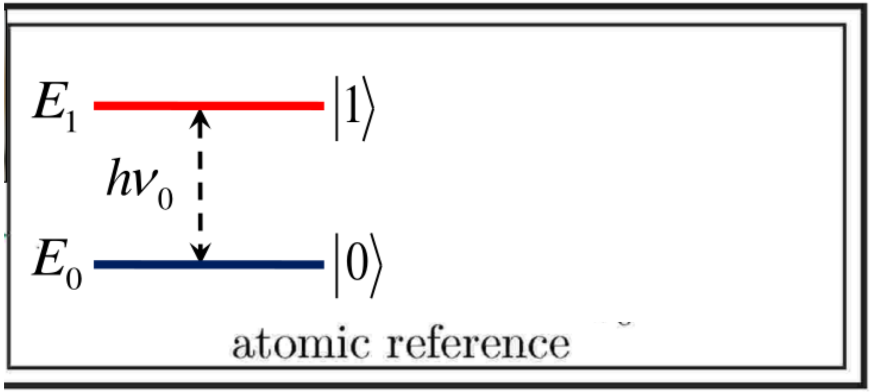
"Never measure anything but frequency!"

Arthur Schawlow,

Nobel Prize in physics 1981 for the co-development of the laser

Goal: Turn precise frequency measurements into a tool for particle physics

Atomic clocks as Quantum Sensor



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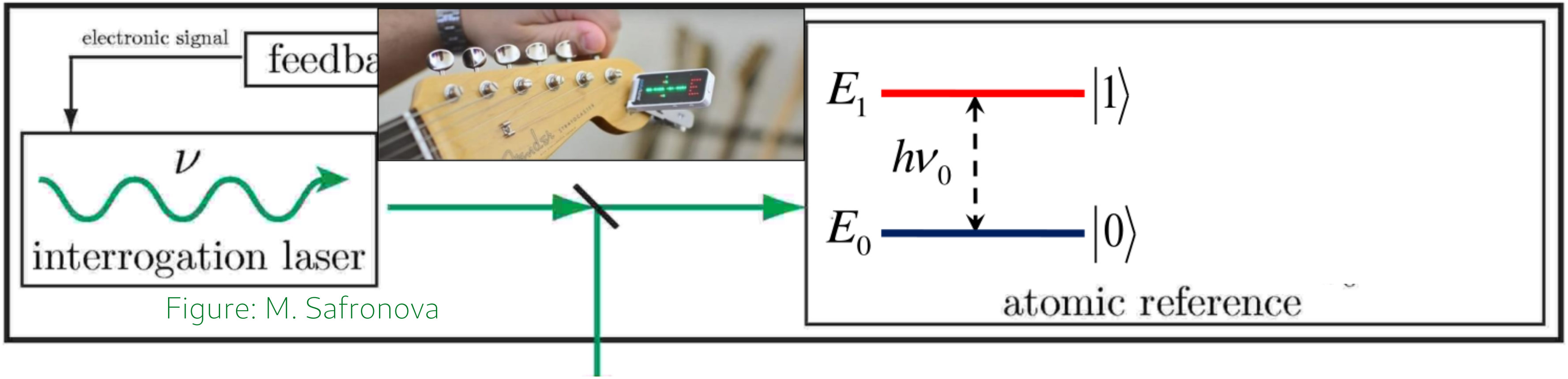

Figure: M. Safronova

Atomic clocks as Quantum Sensor

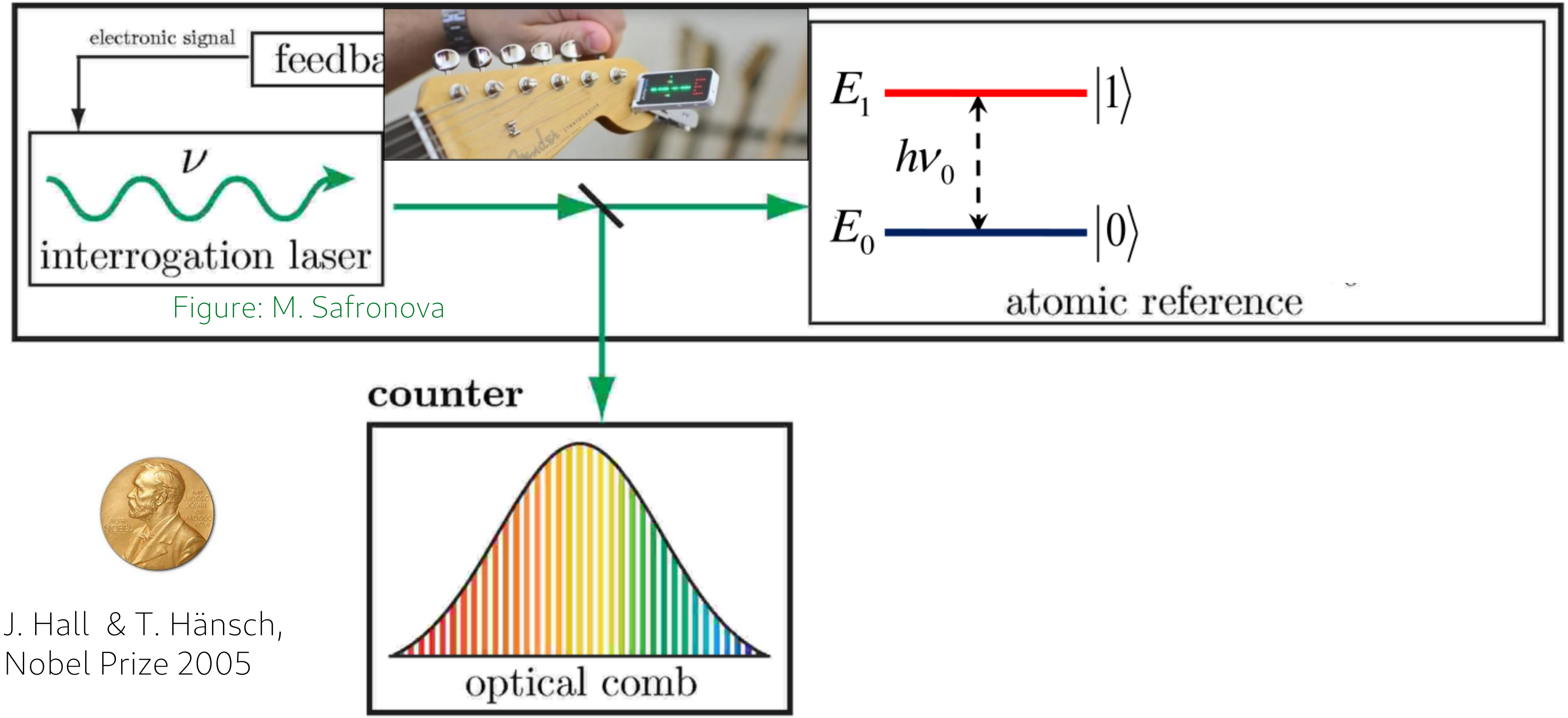

Figure: M. Safronova

J. Hall & T. Hänsch,
Nobel Prize 2005

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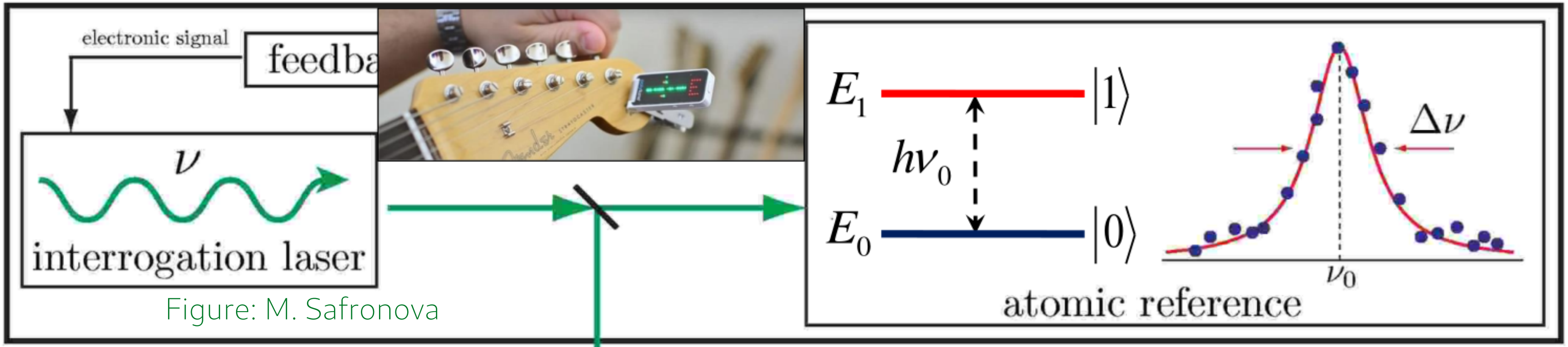

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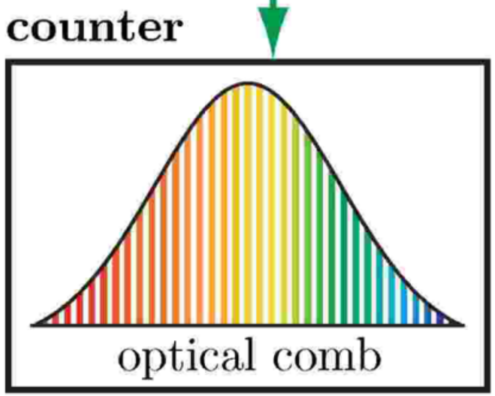

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Evolution of clock precision

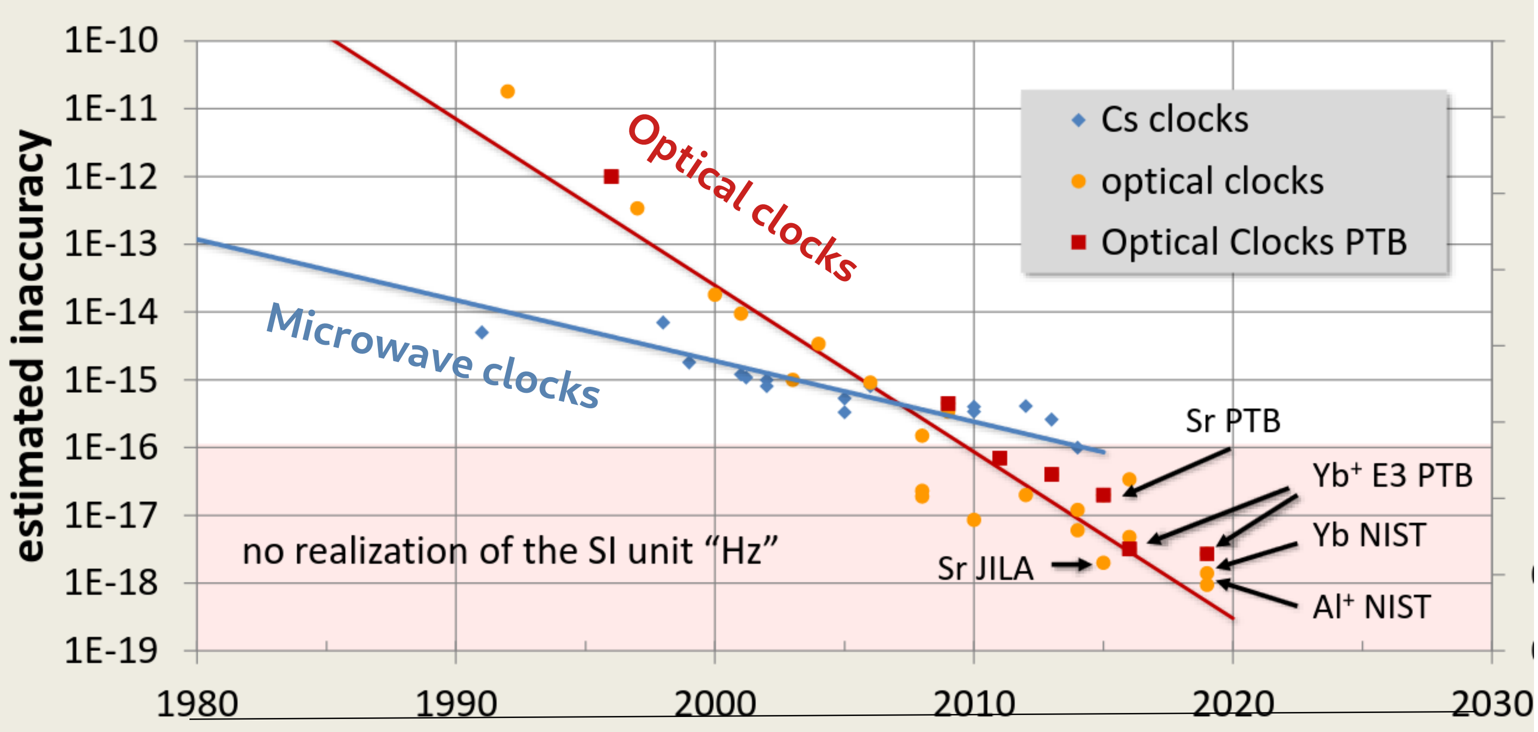
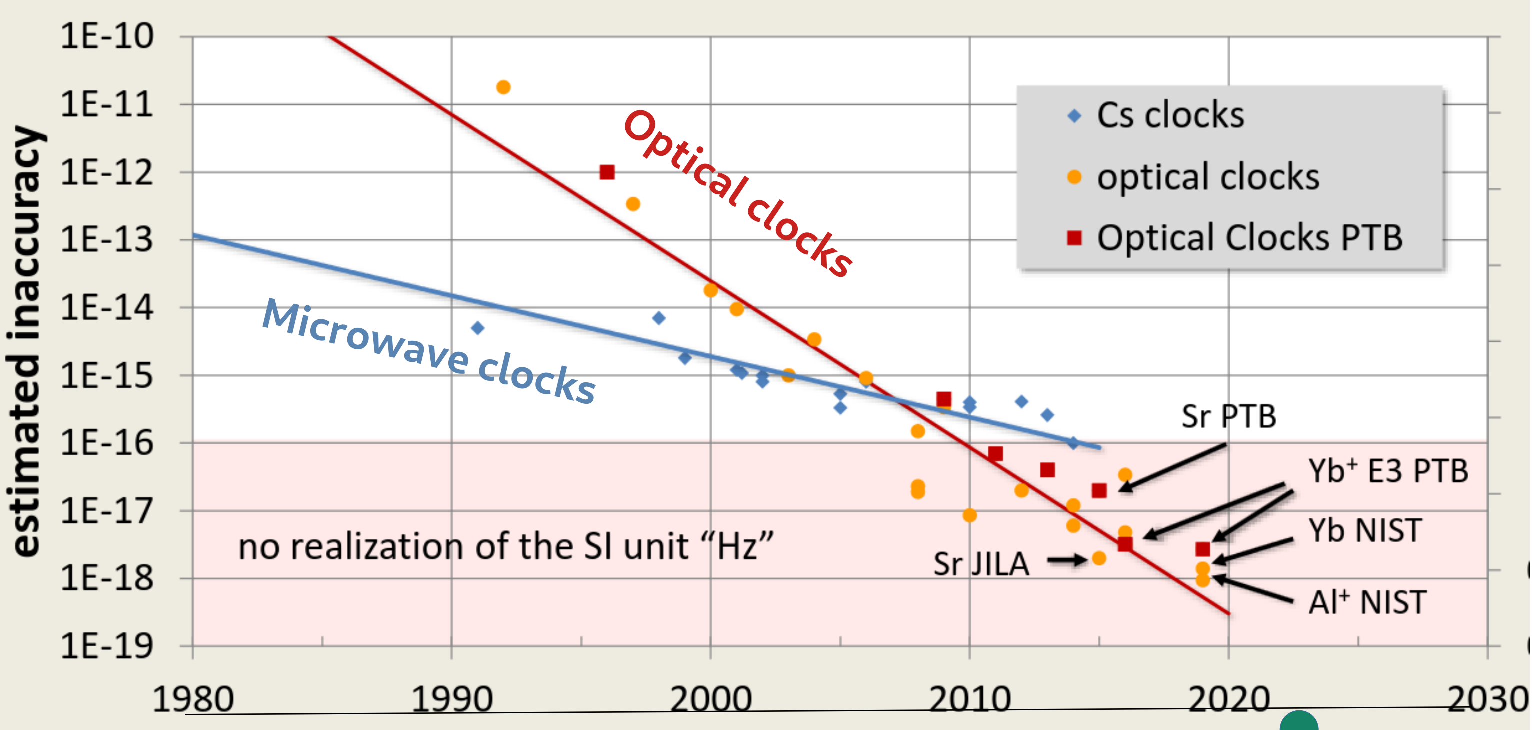


Figure adapted from P. Schmidt's talk at QT4HEP

Al$^+$ clock: S-P with 9.4×10^{-19} precision
Brewer et al PRL'19

Hz defined by #oscillations between 2 hyperfine levels of Cs

Evolution of clock precision



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Sr lattice clock with 100,000 atoms:
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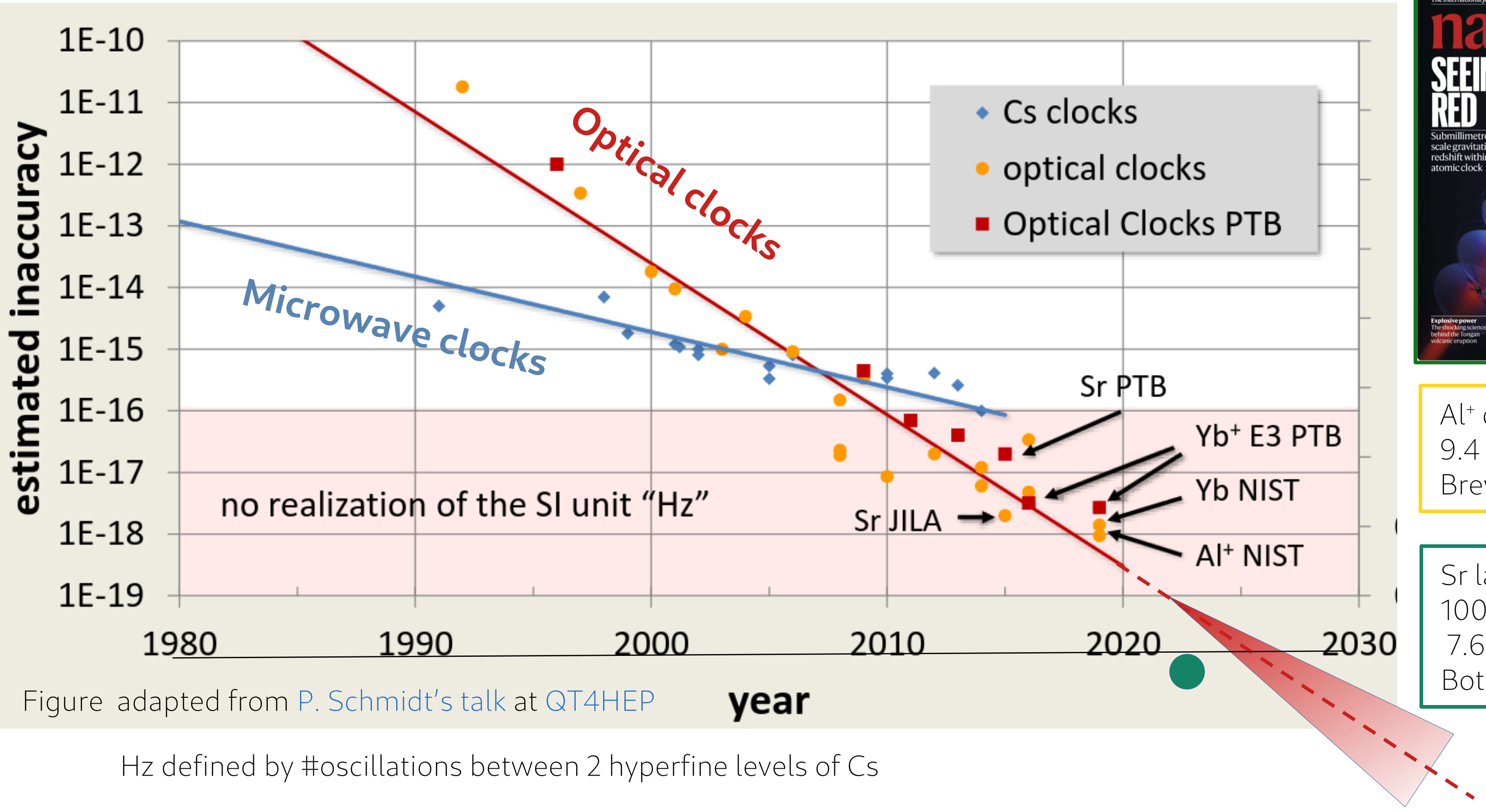

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Hz defined by #oscillations between 2 hyperfine levels of Cs

What does 10^{-18} mean?

See talk by P. Schmidt at QT4HEP 2022

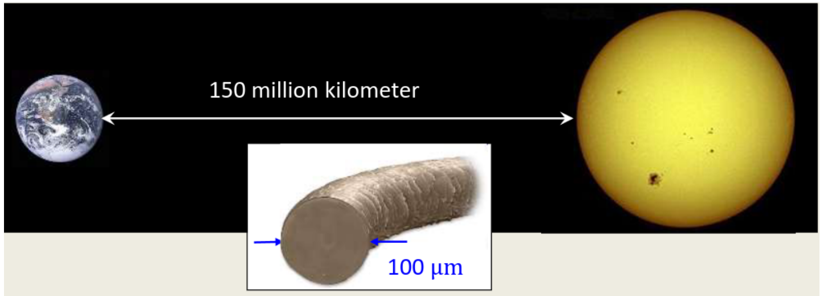
$$\frac{f_{\mathrm{Al}^+}}{f_{\mathrm{Yb}}} = 2.162887127516663703(13)$$

Frequency ratio of 2 precisely measured transitions

BACON collaboration, Nature 591, 564 (2021)

1 s deviation in
30 billion years

Distance earth – sun at the precision of 1/1000 of diameter of a hair

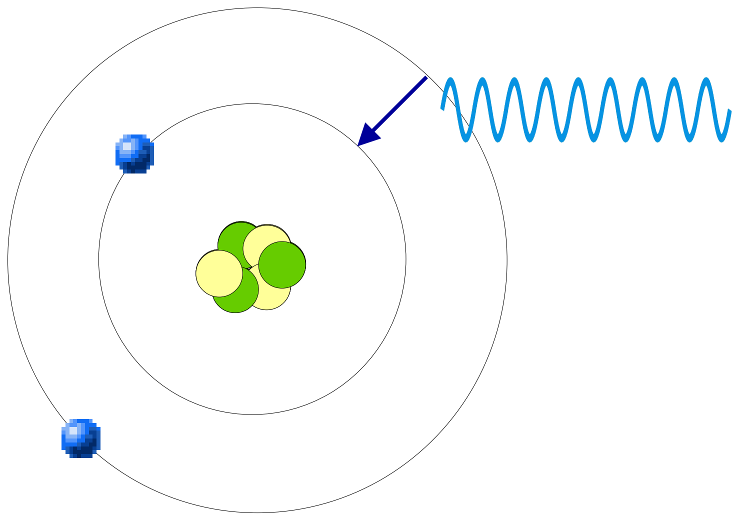


Outline

3) Atomic clocks for light new bosons

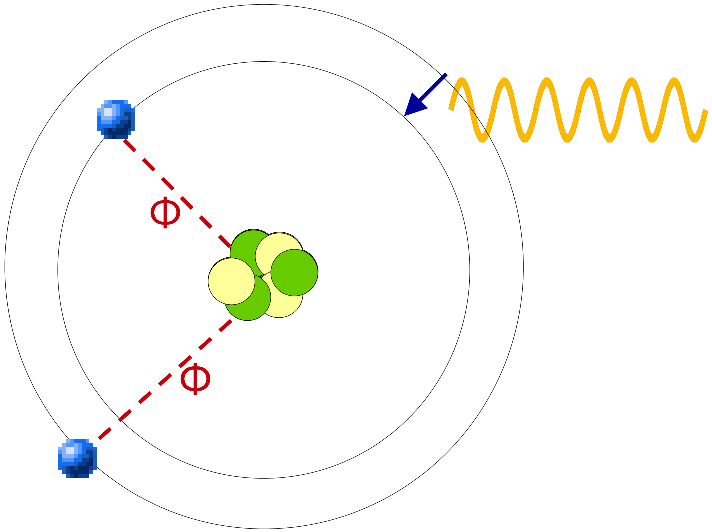
Light scalar in atomic spectrum?

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



Light scalar in atomic spectrum?

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



Can this change the rate of clocks?

Variation of fundamental constants

Antypas et al, Snowmass 2203.14915

Scalar ultralight DM ϕ

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

→ induces **oscillations** of couplings and fermion masses:

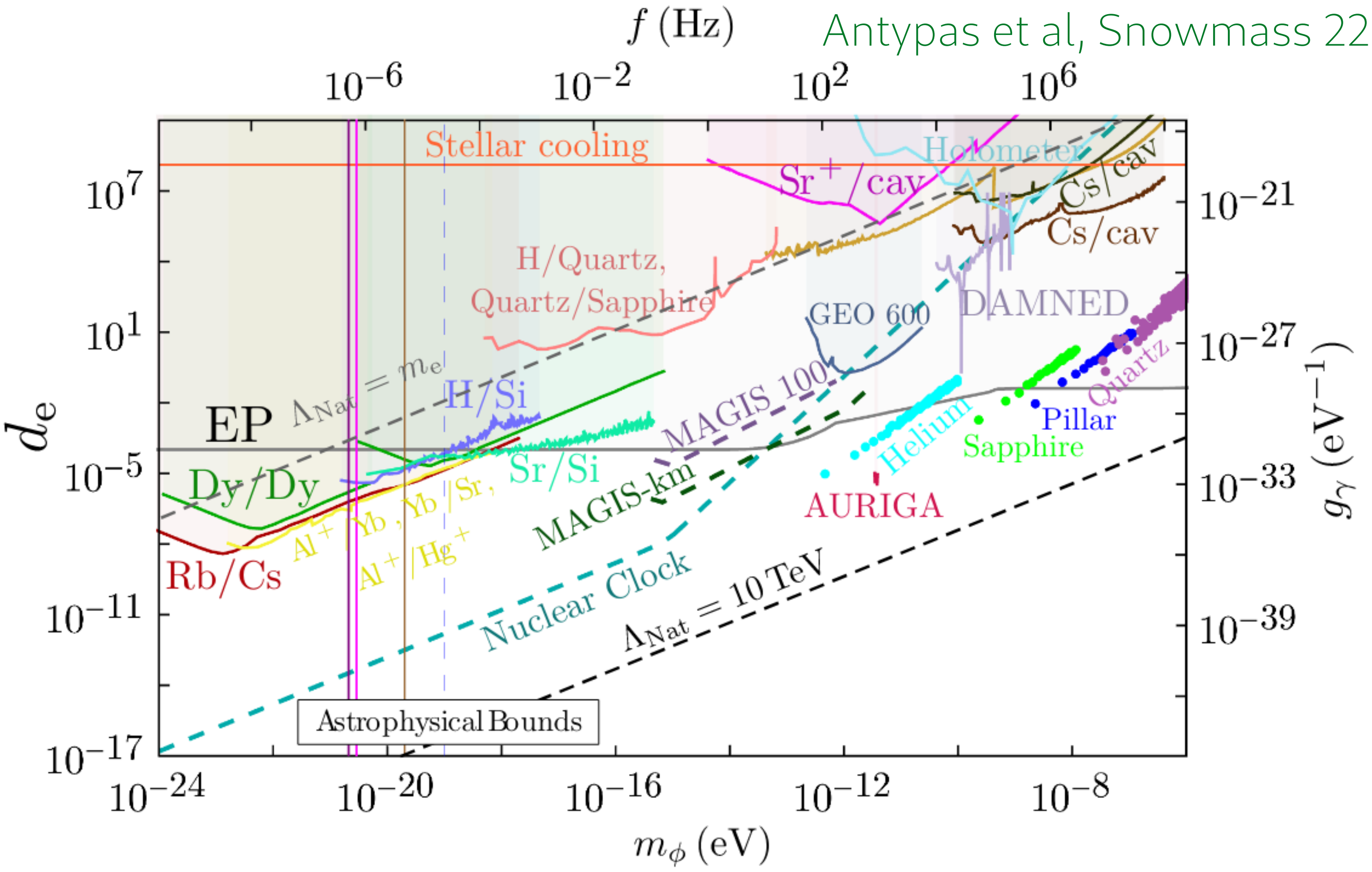
$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

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

Ultralight scalar DM-photon coupling

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

Antypas et al, Snowmass 2203.14915



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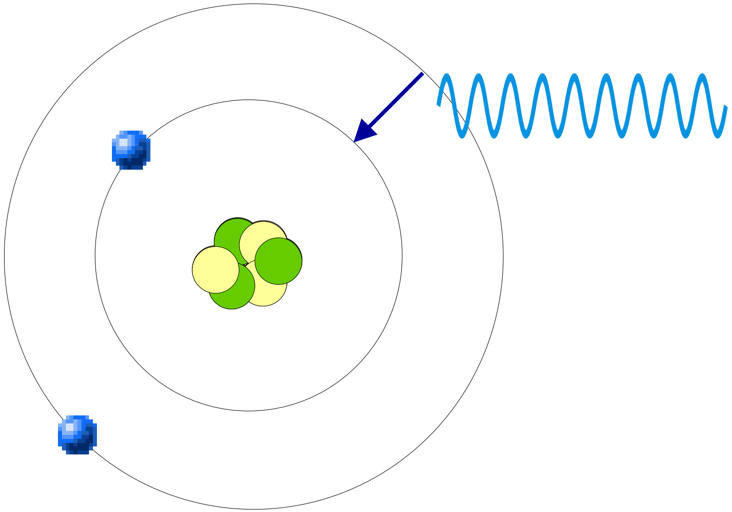

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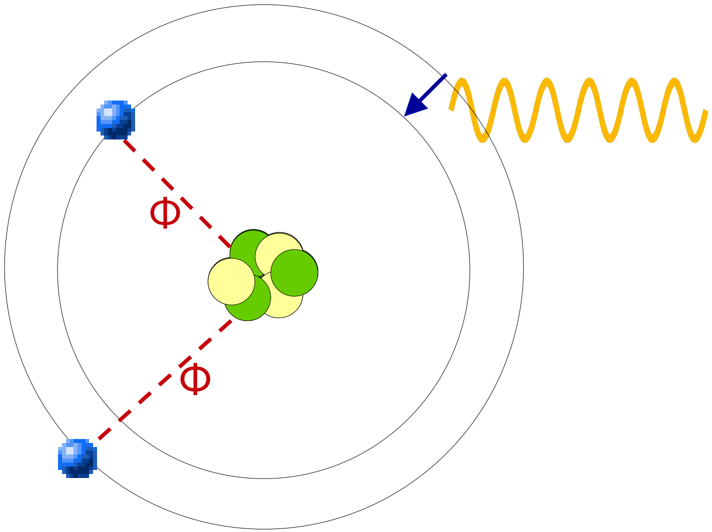
$$V_{\rm NP} = \frac{y_e y_n}{4\pi r} e^{-m_\phi r}$$



Challenge of theory-exp comparison

- Motivation: search for light new boson Φ that couples to electrons and neutrons
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- Challenge: theory, nuclear uncertainties >> uncertainties of frequency measurements

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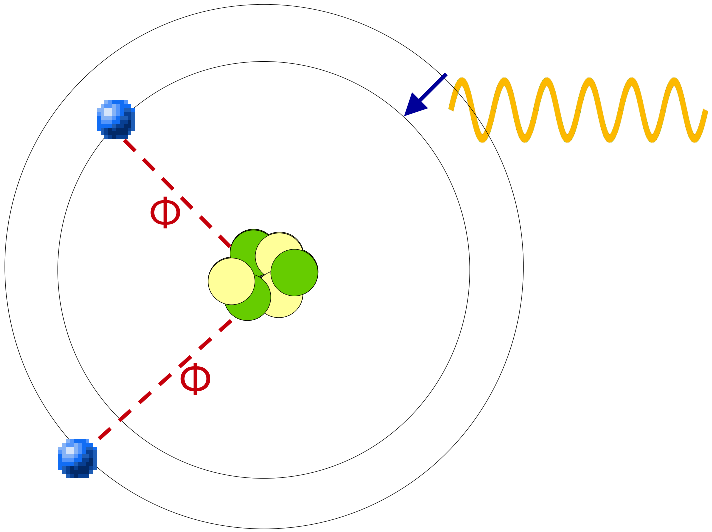
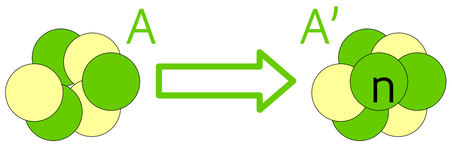
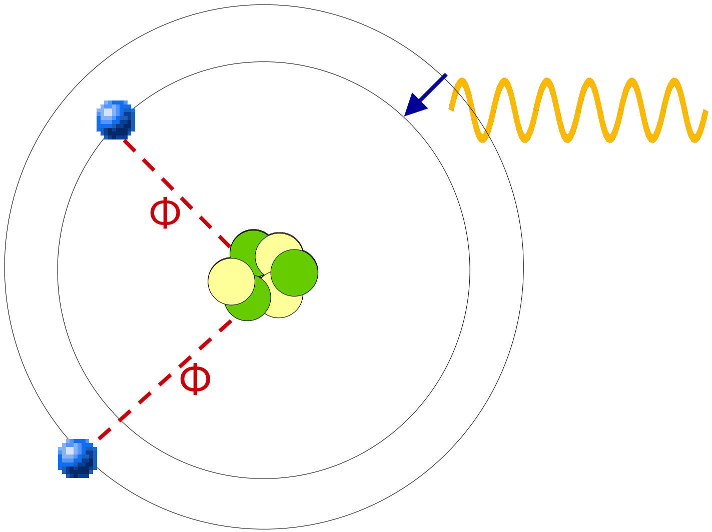


Data-driven atomic search for light scalar

- 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



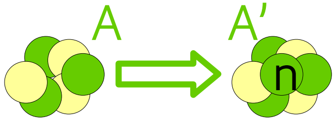


- Berengut, Budker, Delaunay, Flambaum, Frugiuele, EF, Grojean, Harnik, Ozeri, Perez, Soreq; PRL 120 (2018) 091801
- Solaro, Meyer, Fisher, Berengut, EF, Drewsen; PRL 125, 123003 (2020)

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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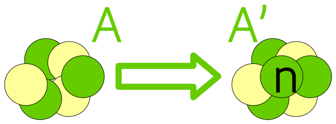

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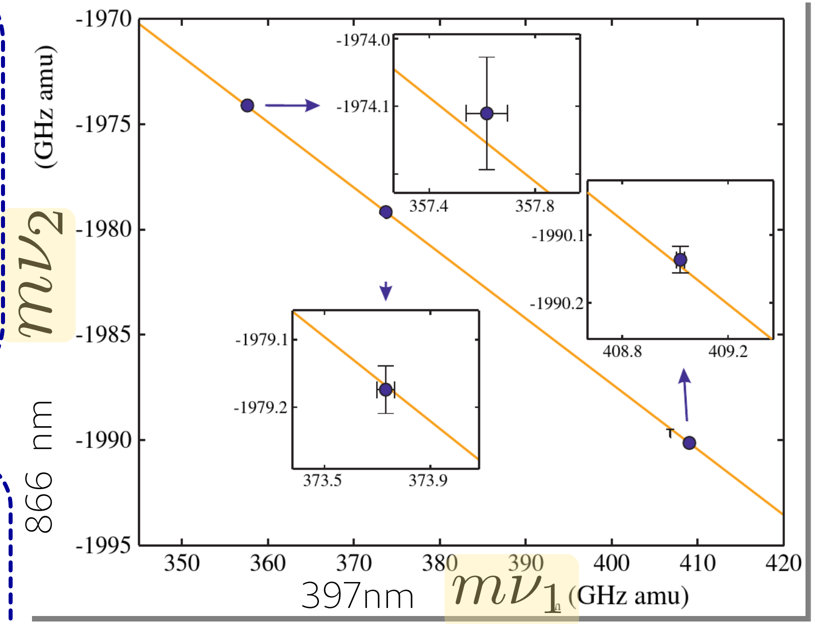
$i = 1, 2$

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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A → A' (n)

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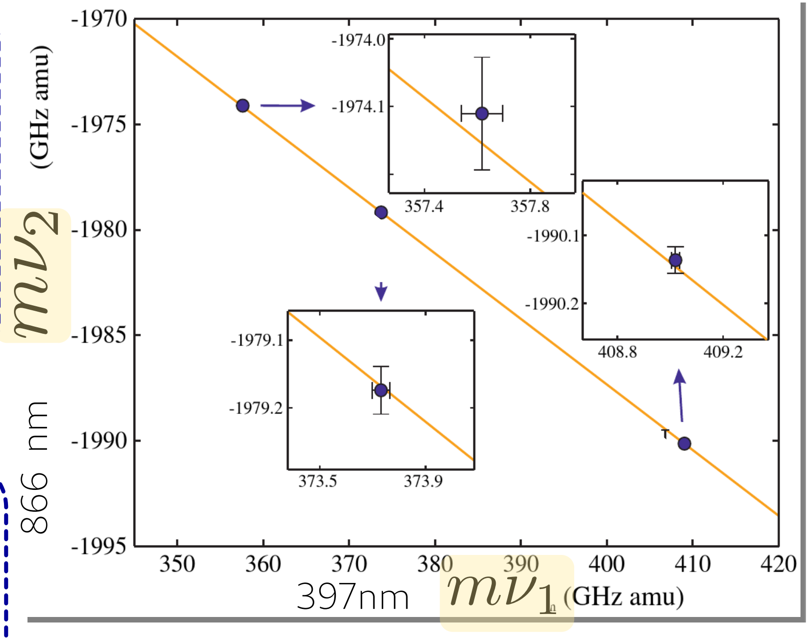

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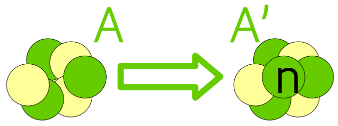

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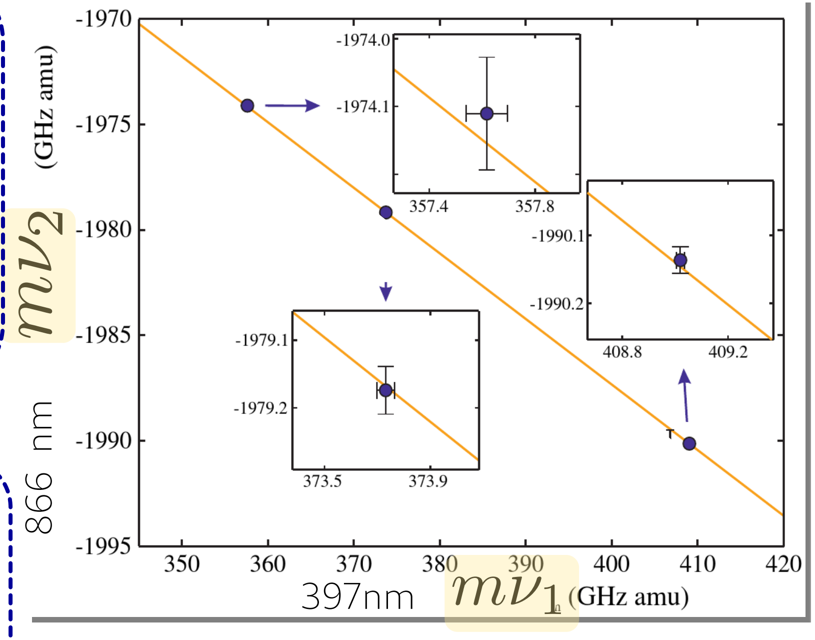


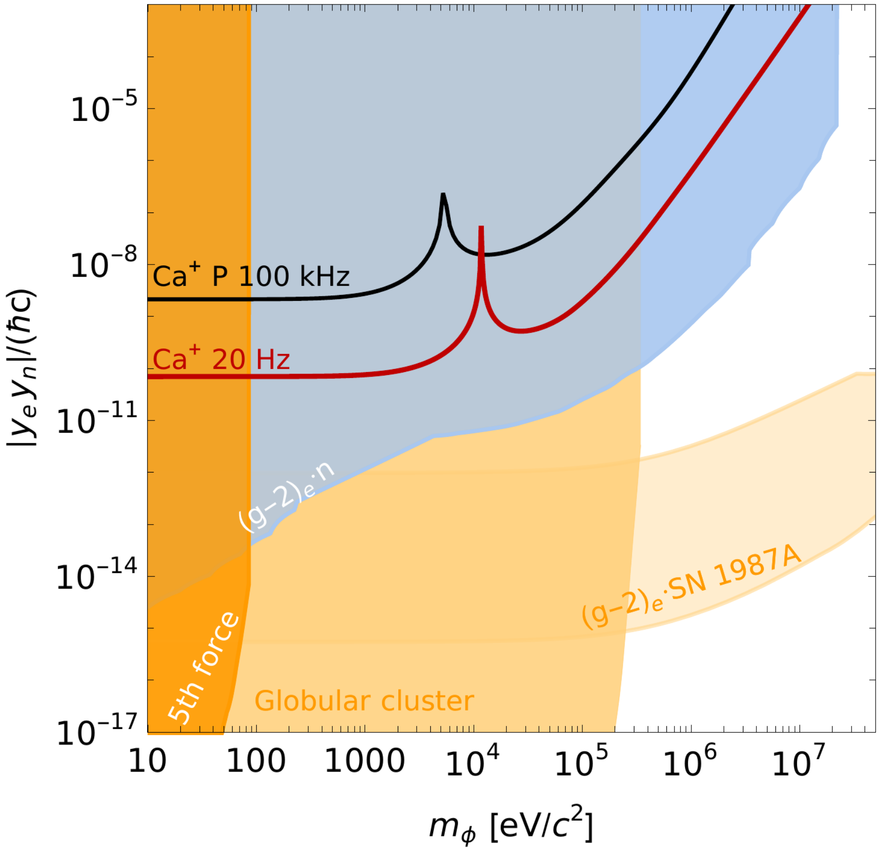
[Gebert, Wan, Wolf, Angstmann, Berengut, Schmidt; PRL 115, 053003 (2015)]

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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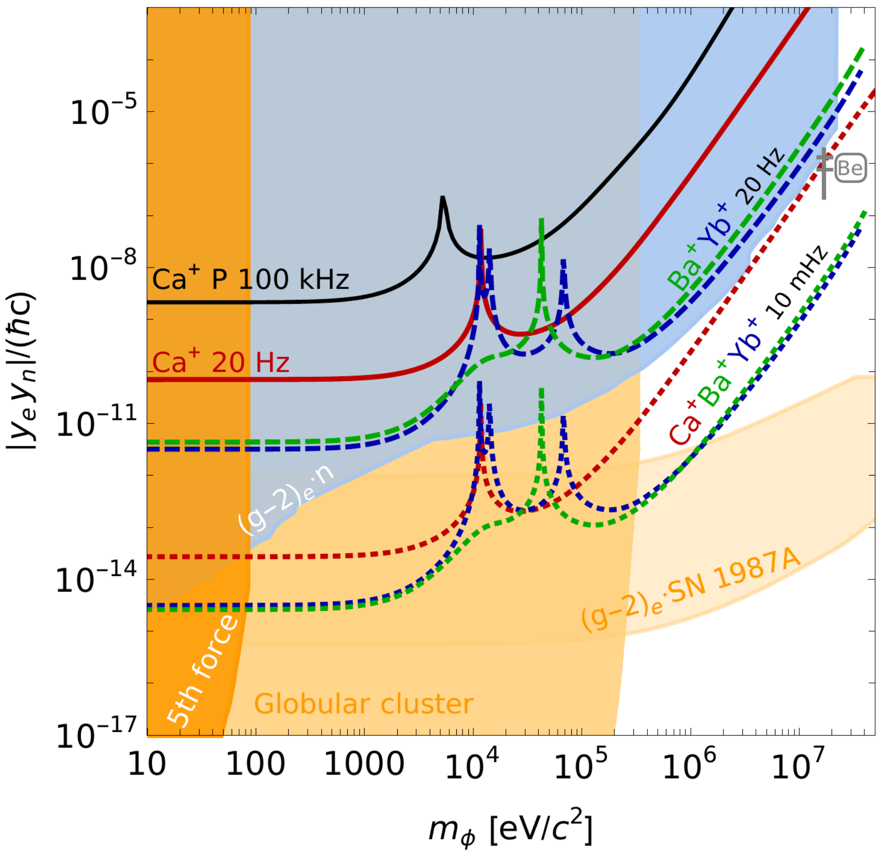

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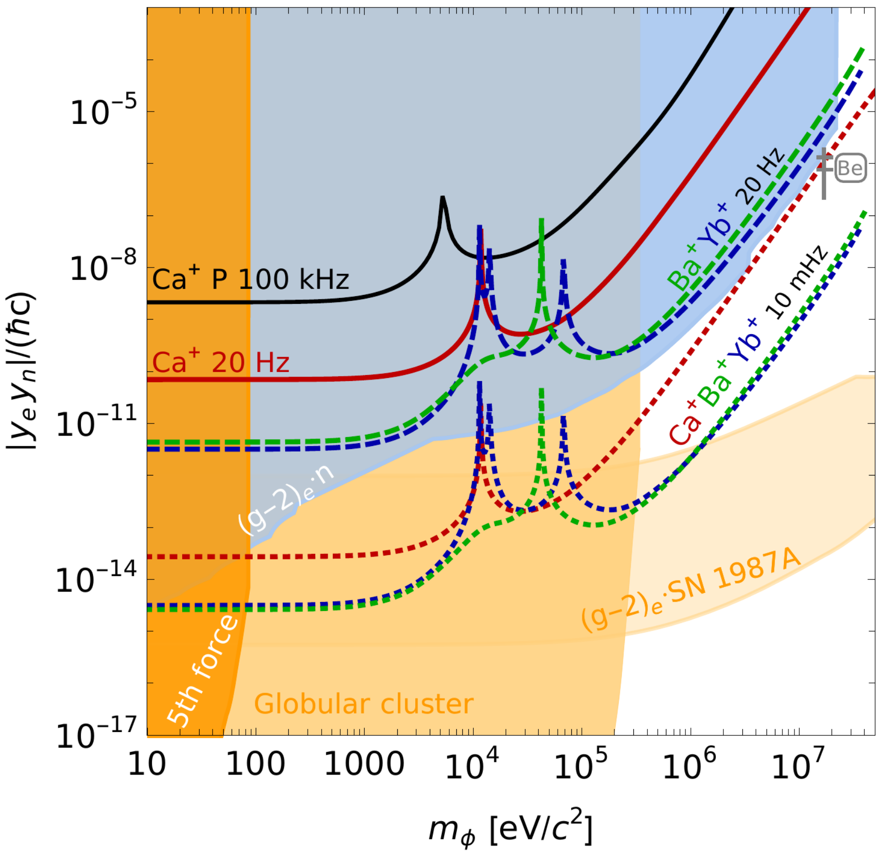

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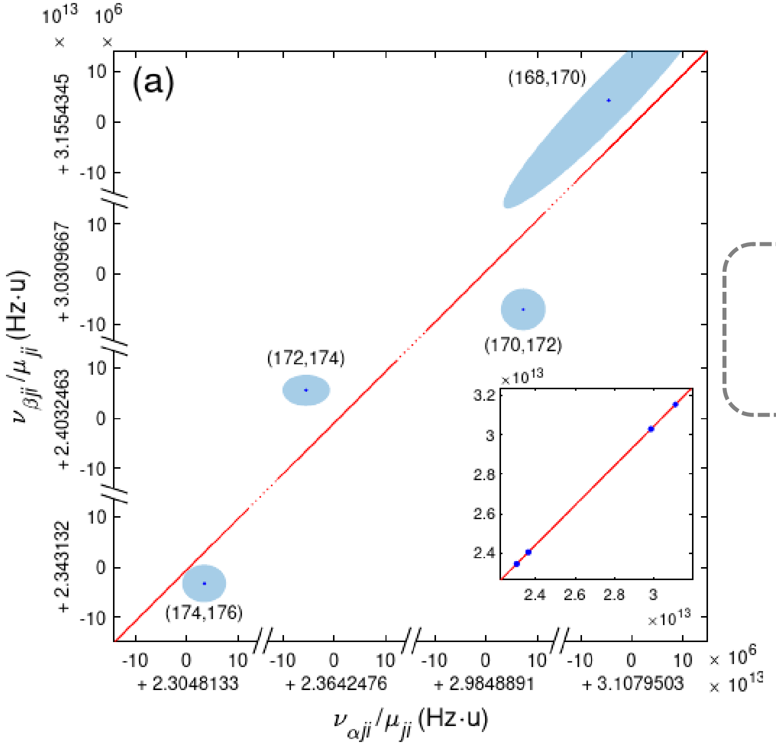
Particle model applications: B-L, dark photon, chameleon
Frugiuele, EF, Perez, Schlaffer '16

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

Nonlinearity in Yb$^+$ isotope shifts

[Counts, Hur, Craik, Jeon, Leung, Berengut, Geddes, Kawasaki, Jhe, Vuletić, PRL 125, 123003 (2020)]
+updates MIT '22, Mainz '22, PTB/Heidelberg/Hannover in prep.



- 3σ nonlinearity
- SM nuclear effect?

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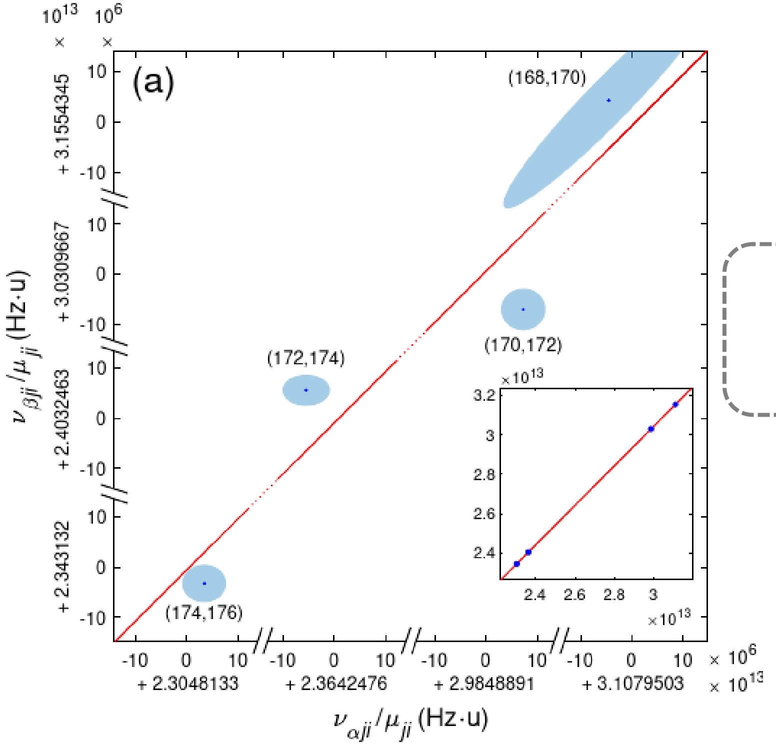


- 3σ nonlinearity
- SM nuclear effect?

BSM or nuclear physics?

Strategy: consider predicted SM NL and constrain residual NL

Generalized King plot

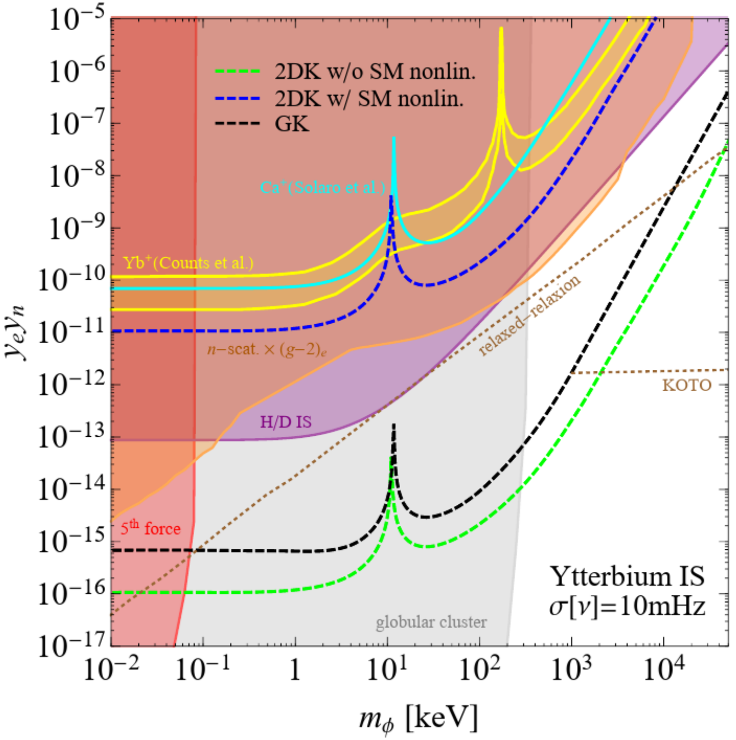
$$m\nu_i^a = K_i + \sum_{l=1}^{m-1} F_{il} m\lambda_{l,a} + \alpha_{\rm NP} X_i h_a$$

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]

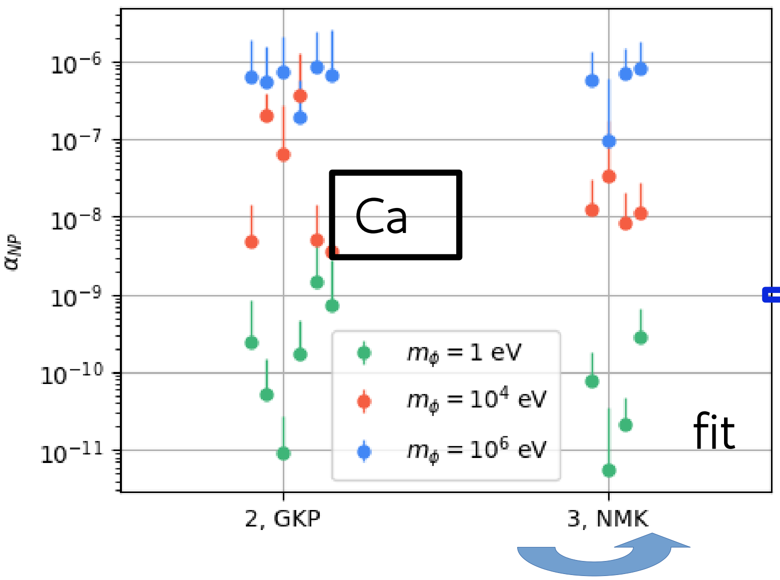
Higher-orders included



Global fit to all atomic data

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

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



Yb | Ba | Sr | ...

Delaunay, Karr, Kitahara, Koelemeij, Soreq, Zupan [PRL 2022]
Bounds from CODATA

- Different systematics (nuclei…)
- Compatible with same New Physics hypothesis?

Overall spectroscopy bound

Highly Charged Ions (HCI)

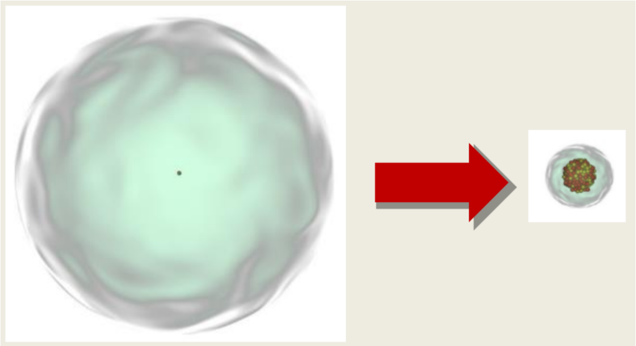


Figure: P. Schmidt

- Electrons removed → less multi-body effects
- QED effects amplified ~Z^4
- Systematic shifts reduced, Stark shifts ~Z^{-6}
  → high accuracy in traps

- electrons more closely bound
  → test shorter interaction range?

- ✓ Very sensitive to time-variation of fundamental constants test ultralight DM
- ✓ Precise optical clock, e.g. Ar^{13+} (2×10^{-17}) [PTB&MPIK, King et al Nature '22]
- ✓ Precise isotope shift measurements possible test light mediators

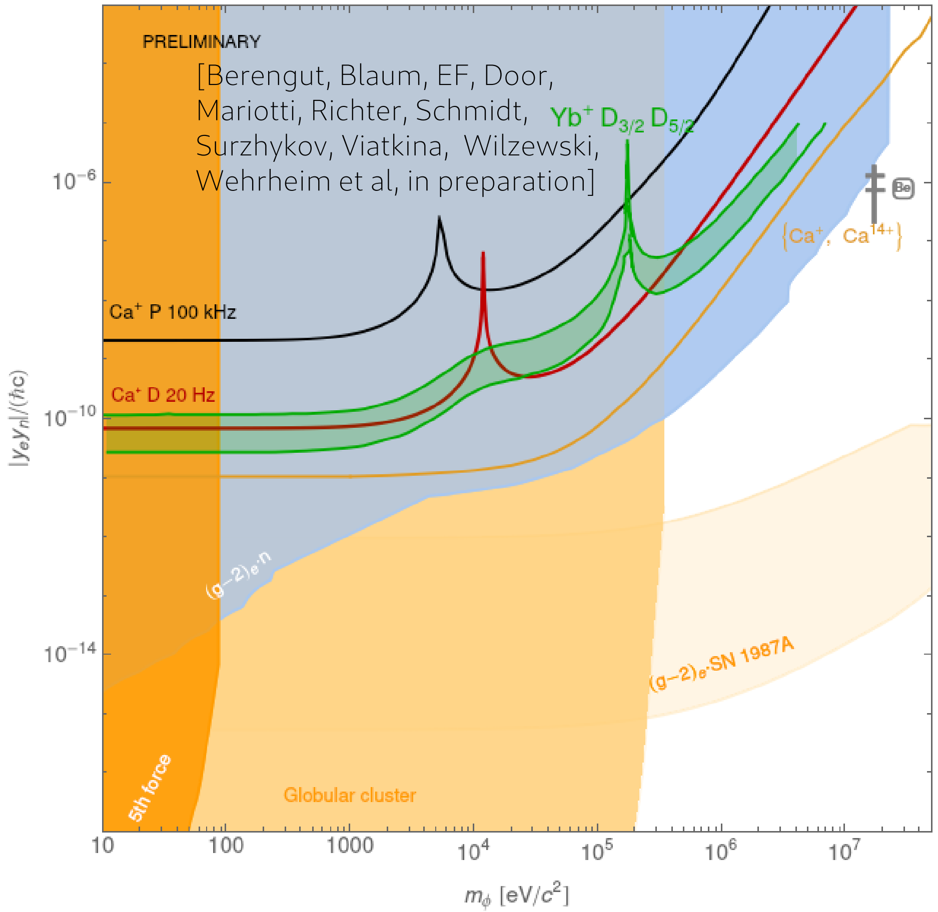
HCI clock: New Physics bound

- PTB: Ca^{14+} $P_0 \rightarrow P_1$ @1Hz

  A. Wilzewski, M. Wehrheim, P. Schmidt et al [preliminary]

- Combined with Ca^{+} $S \rightarrow D_{5/2}$ @10 /20Hz

  Knollmann et al PRA '19, Solaro, EF et al PRL '20



HCI clock: New Physics bound

- PTB: Ca^{14+} $P_0 \to P_1$ @1Hz

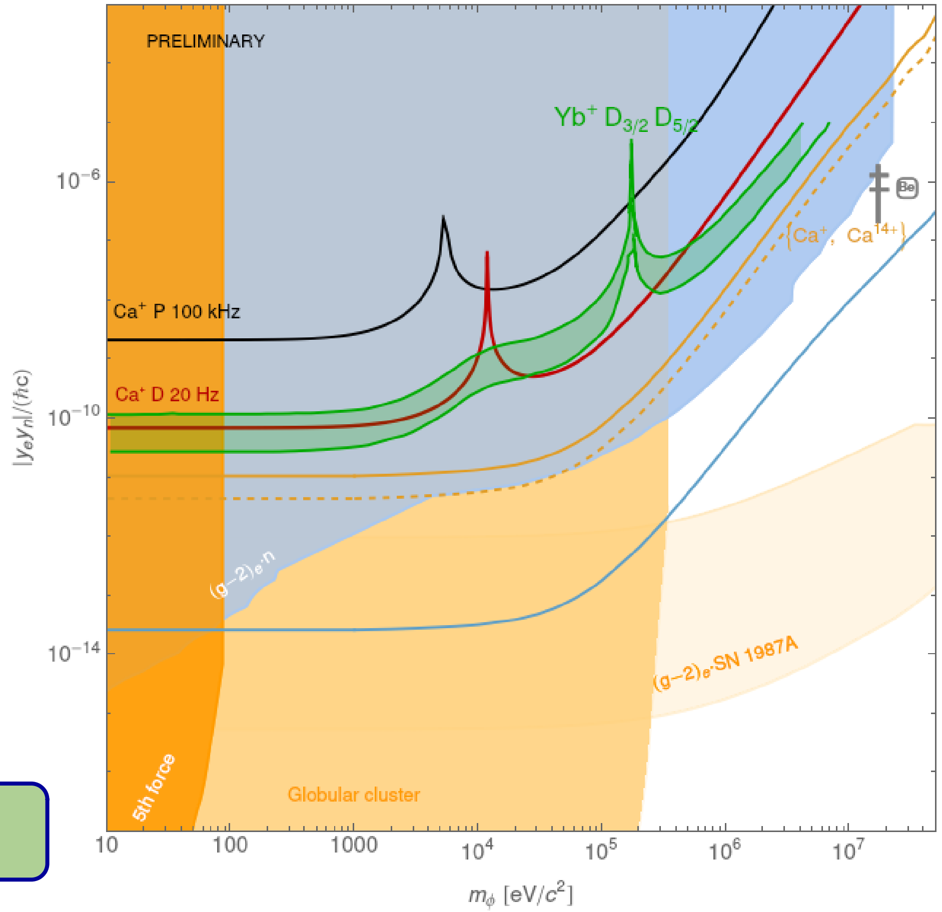
  A. Wilzewski, M. Wehrheim, P. Schmidt et al [preliminary]
- Combined with Ca^{+} $S \to D_{5/2}$ @10 /20Hz

  Knollmann et al PRA '19, Solaro, EF et al PRL '20

NP sensitivity limited by isotope masses

→ MPIK Heidelberg improving the precision

→trade isotope masses 3rd frequency
→ "no-mass King plot"



Isotope shifts about to test new parameter space

Outline

Domcke, Kopp, EF, Bringmann 2304.10579, to appear (PRD Letter)

4) High-frequency GWs with optical photons

GW sources and detectors

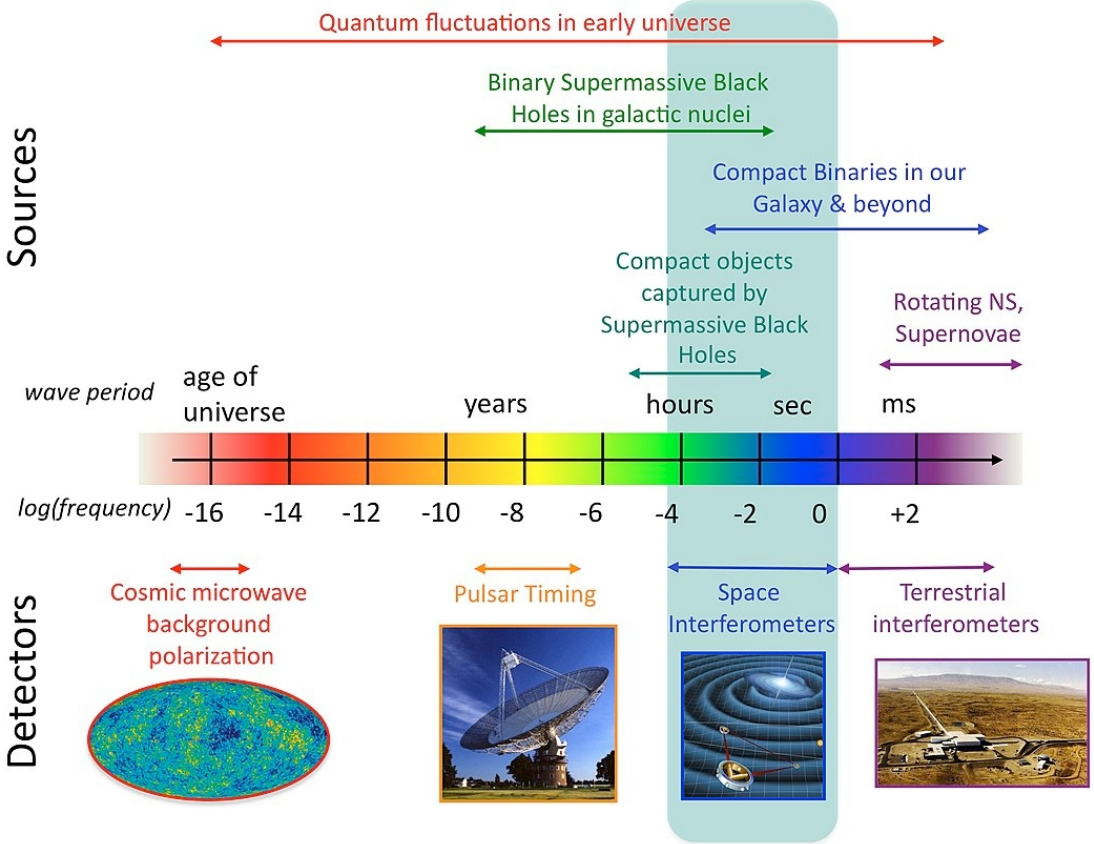


Image: NASA

Sensitivity to GW sources

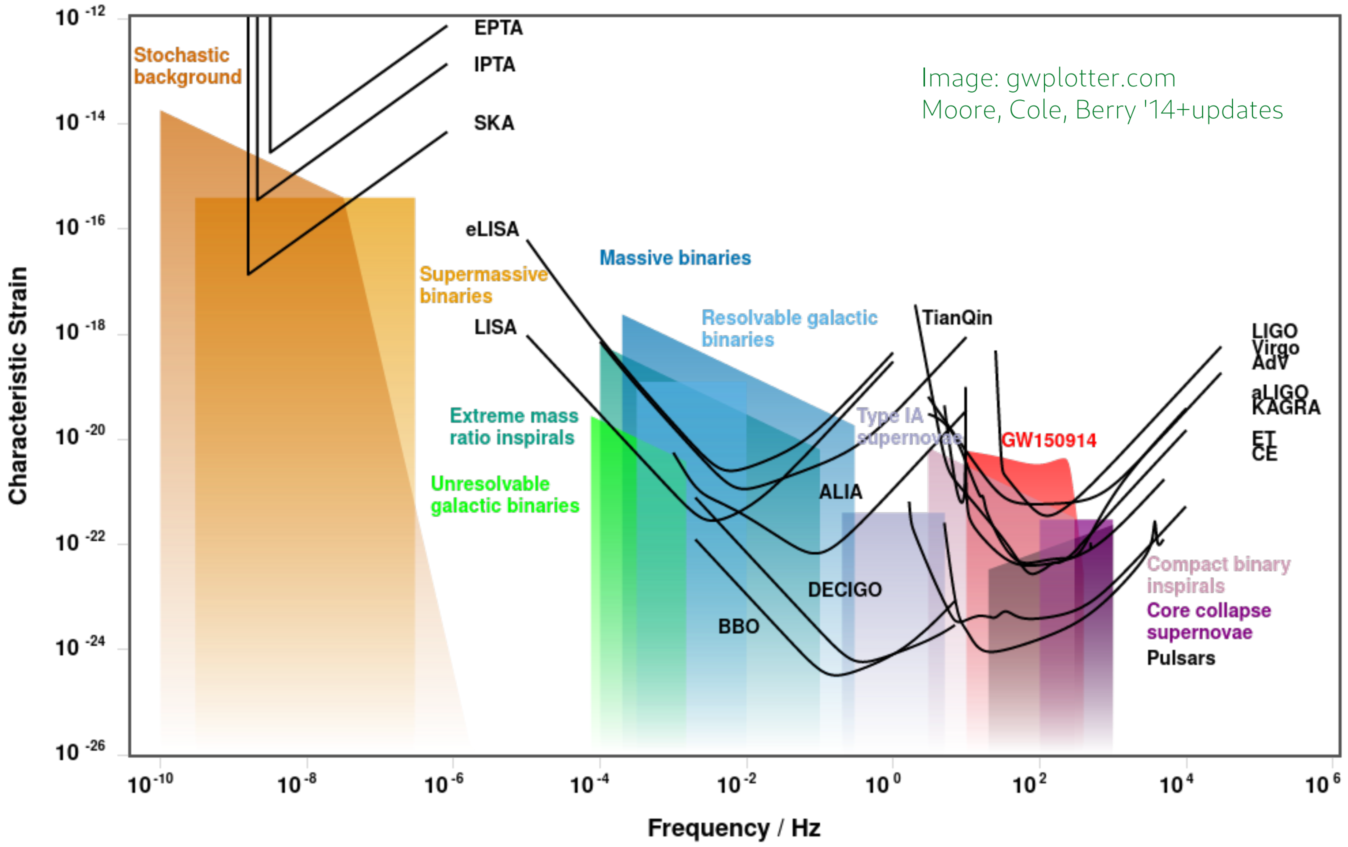


Image: gwplotter.com
Moore, Cole, Berry '14+updates

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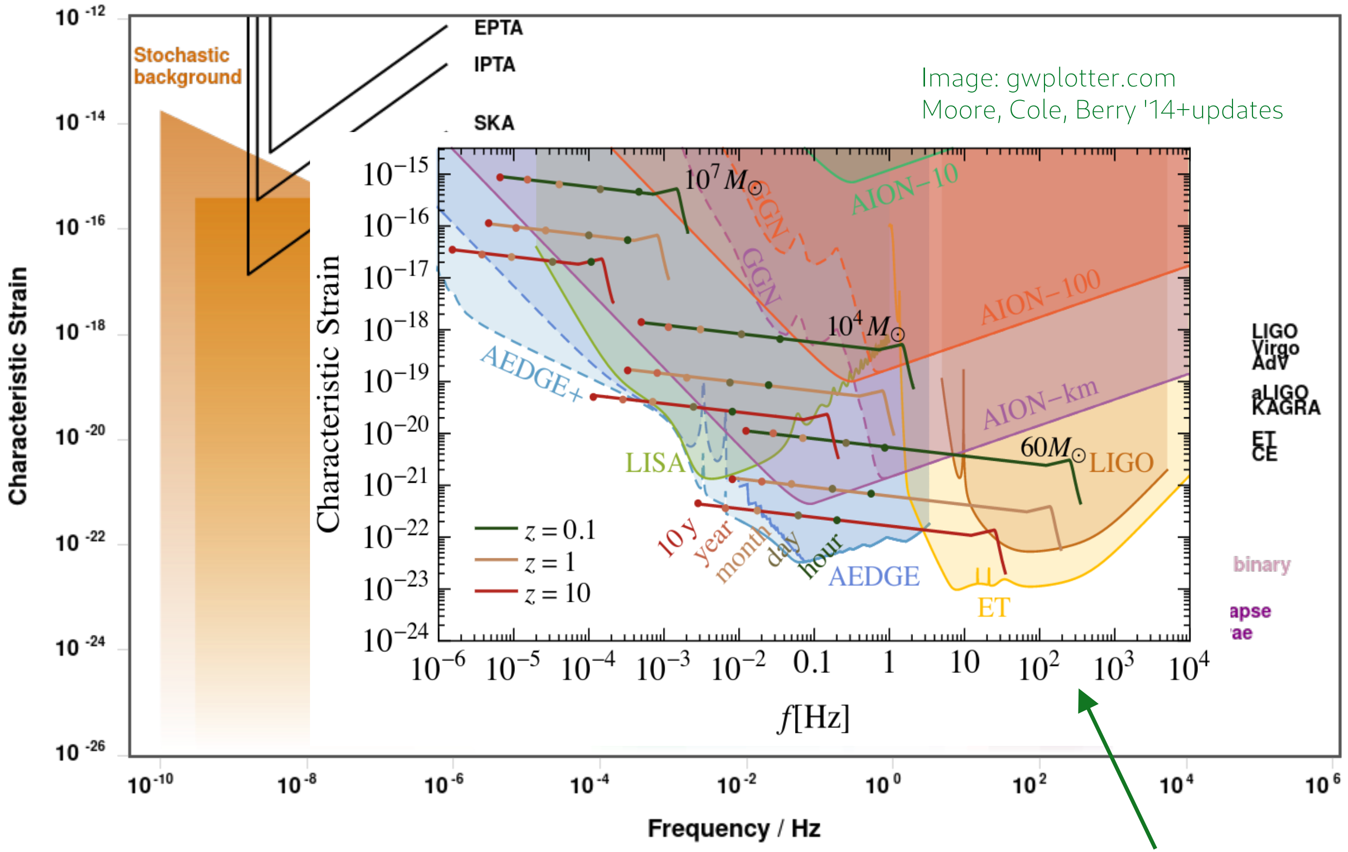


Image: gwplotter.com
Moore, Cole, Berry '14+updates

Badurina, Buchmueller, Ellis, Lewicki, McCabe, Vaskonen '21

Atom Interferometers sensitive to mid-frequency GWs

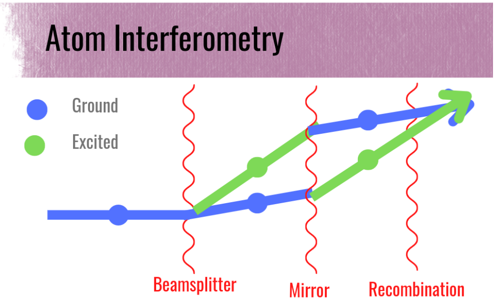


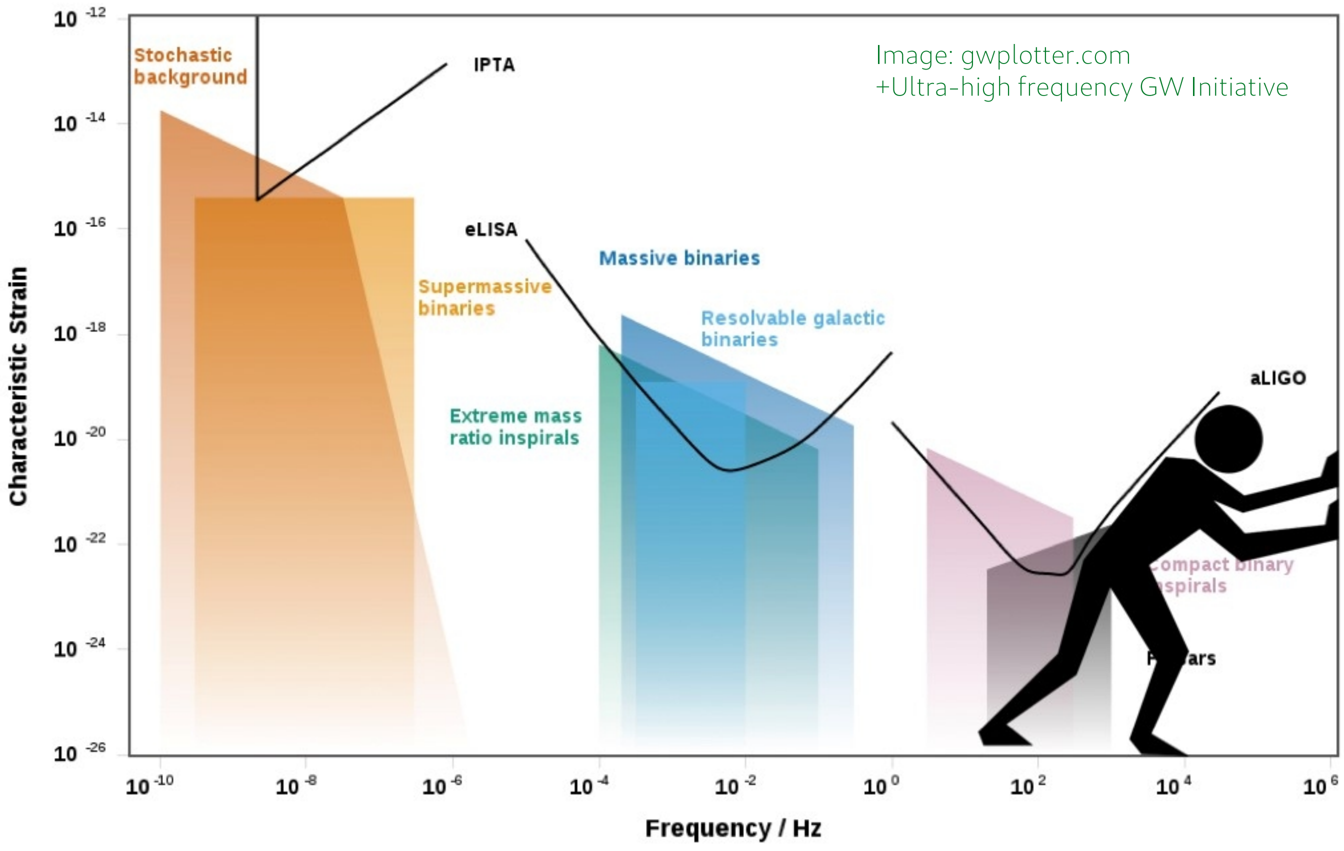
Image:
H. Banks

Measure phase difference between matter waves

As a GW Detector:

GW modifies distance between 2 atom interferometers → phase shift

Pushing towards high frequencies



GW sources and detectors

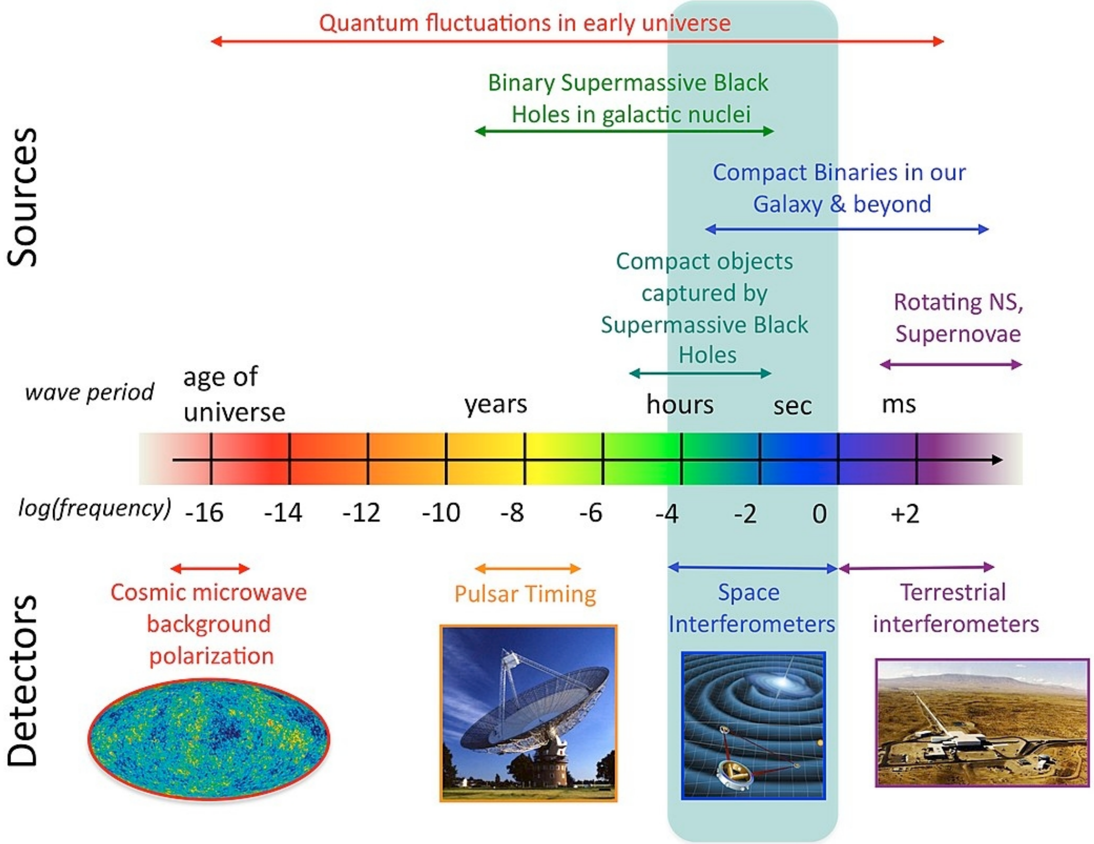


Image: NASA

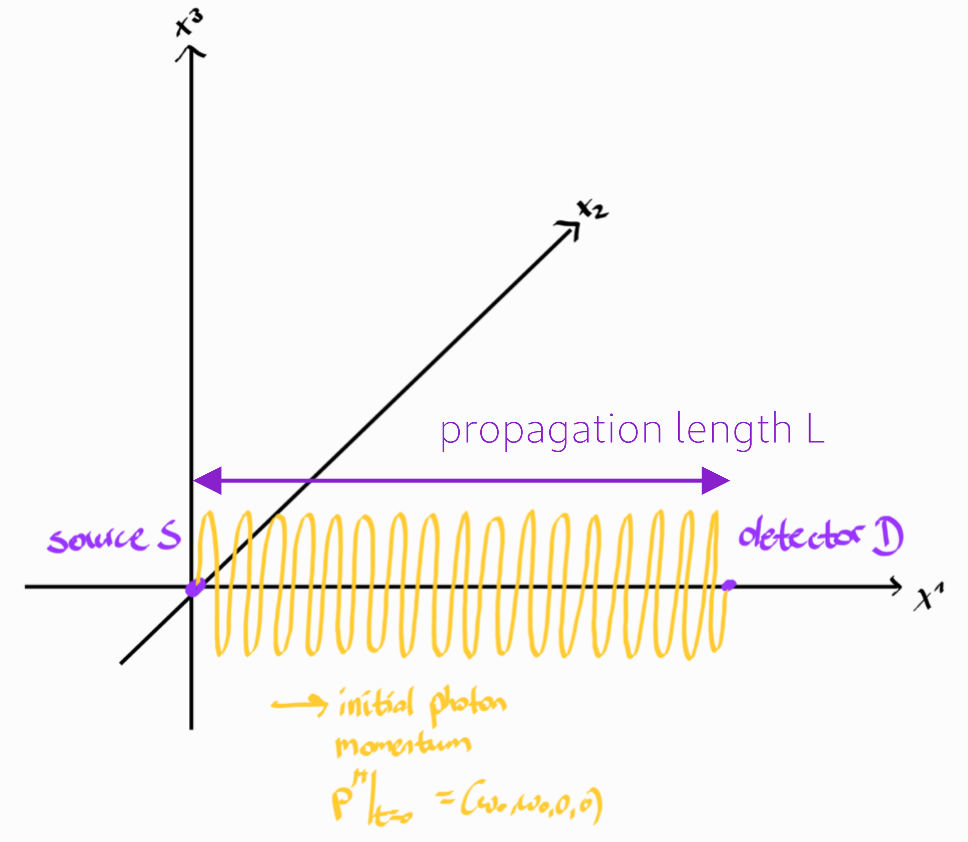
sources for high-frequency GWs expected?

If yes, how can one detect them?

Searches and proposals:

- Interferometers
- Levitated sensors
- Radio cavities

Photon in gravitational field

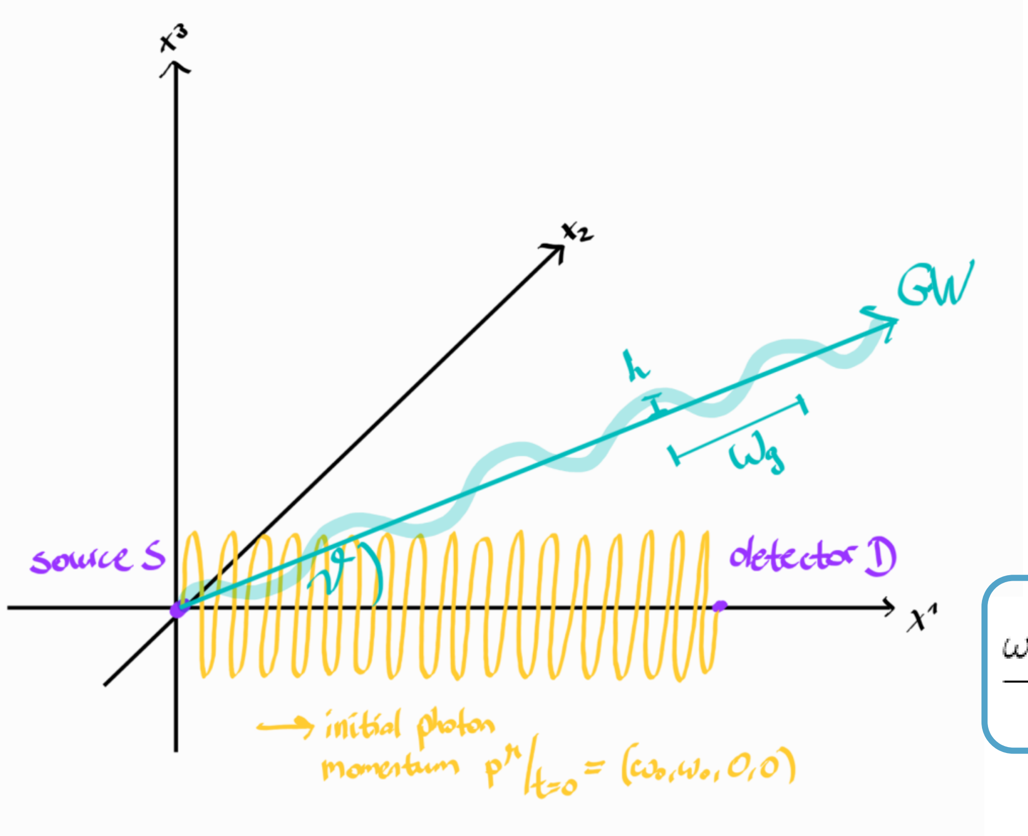


Goal: compare frequency of photon measured by S and D

Free-falling observer moving with 4-velocity u^μ measures at D

$$\omega_\gamma = -g_{\mu\nu} p^\mu u^\nu$$

Photon in gravitational field



Goal: compare frequency of photon measured by S and D

Gravitational Wave: perturbs metric

$$
\begin{aligned}
g_{\mu\nu} &= \eta_{\mu\nu} + h_{\mu\nu} \\
p^\mu &= (\omega_0, \omega_0, 0, 0) + \delta p^\mu \\
u^\mu &= (1, 0, 0, 0) + \delta u^\mu ,
\end{aligned}
$$

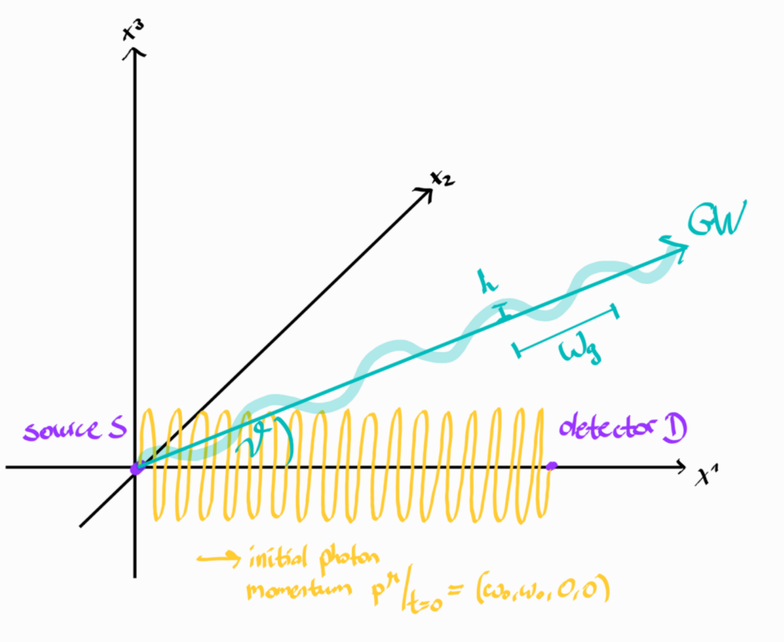
~h (GW strain)

Geodesic equation →…→ master formula for frequency change at O(h):

$$
\frac{\omega_\gamma^D - \omega_\gamma^S}{\omega_\gamma^D} = -\frac{\omega_0}{2} \int_0^{\lambda_D} d\lambda' \, \partial_0 \left[h_{00} + 2h_{10} + h_{11} \right]_{x^\mu = x^\mu_{\lambda', 0}} + \left[\delta u^0 - \delta u^1 \right](\lambda_D) - \left[\delta u^0 - \delta u^1 \right](\lambda_S) .
$$

Free-falling detectors – TT frame

- S and D in free fall (move freely at least in direction of photon propagation)
  → most convenient in **transverse traceless (TT) gauge** $h^{TT}_{\mu 0} = 0\,, \quad \partial^i h^{TT}_{ij} = 0\,, \quad \eta^{ij} h^{TT}_{ij} = 0$
  where observers at rest remain at rest



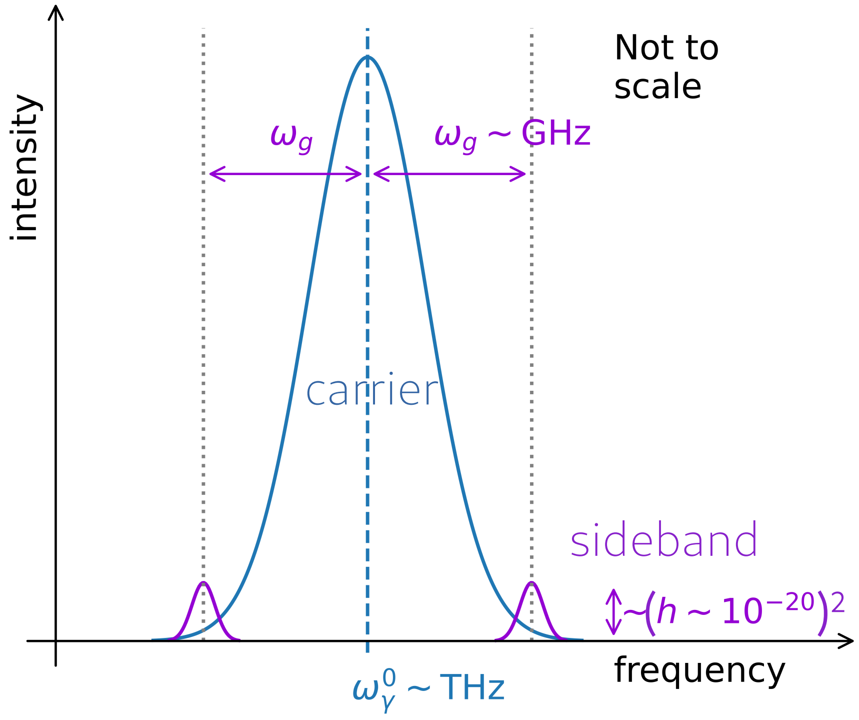
$$h^{TT}_{11}(x^\mu) = h_+ s^2_\vartheta \cos\left[\omega_g(x^0 - c_\vartheta x^1 - s_\vartheta x^3) + \varphi_0\right]$$

Plane wave

Frequency shift by GW (in + polarization)

$$\frac{\omega^D_\gamma - \omega^S_\gamma}{\omega^D_\gamma} = h_+ c^2_{\vartheta/2}\left\{\cos\varphi_0 - \cos\left[\omega_g L(1 - c_\vartheta) + \varphi_0\right]\right\},$$

Detection: 1) Sidebands

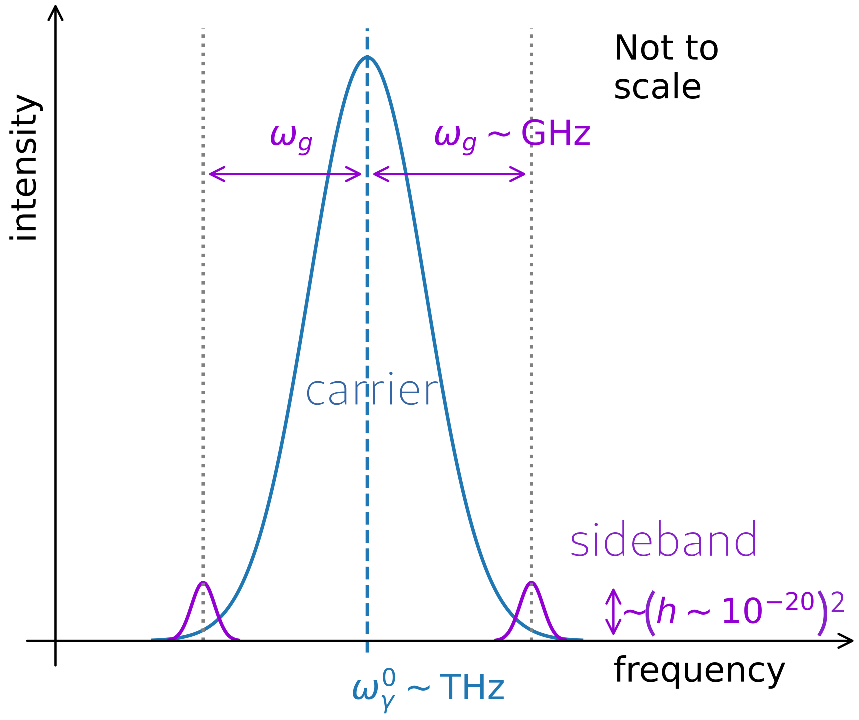


- tiny sidebands
  - separated from carrier (original photon frequency) by GW frequency ω_g
  - suppressed by the GW amplitude $h^2 \sim 10^{-40}$

⇨ Advantage for high-frequency GWs

Still: tails from intense carrier line can hide the sidebands

Detection: 1) Sidebands



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⇨ Advantage for high-frequency GWs

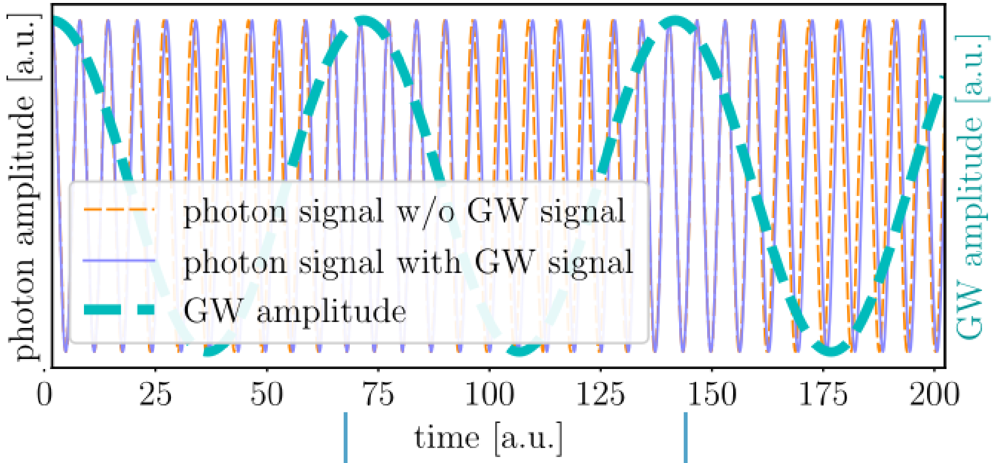
Still: tails from intense carrier line can hide the sidebands

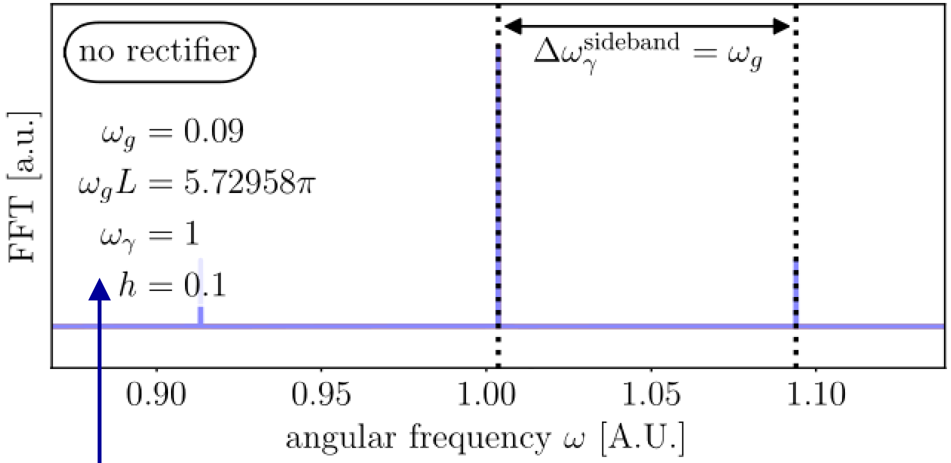
⇨ How to make the sidebands detectable?

→ Cavities, fiber Bragg grating, optical rectifier,…?

Detection: 2) Optical clocks

Original setup:



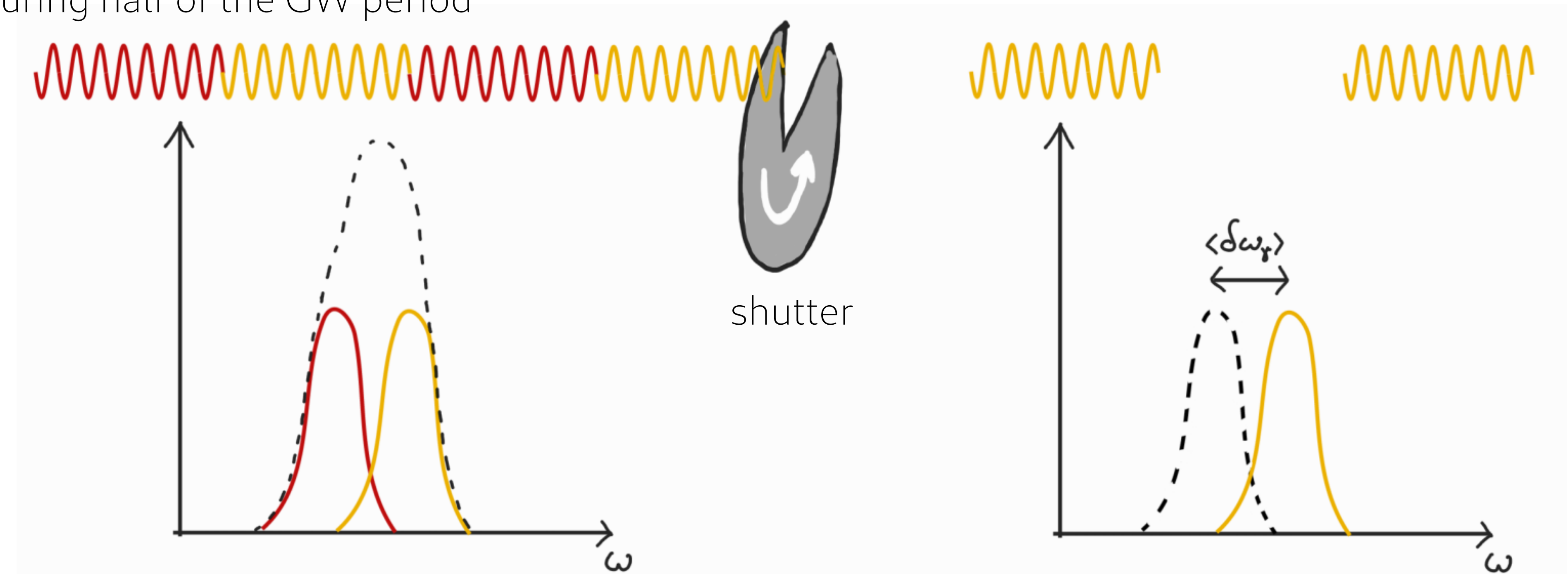


Parameters chosen for illustration purposes only

Phase modulation is averaged out during GW period ⇒ Only sidebands, no net frequency shift of γ

Detection: 2) Optical rectifier

Idea: block the photon propagation during half of the GW period ⟹ Shift does *not* average out

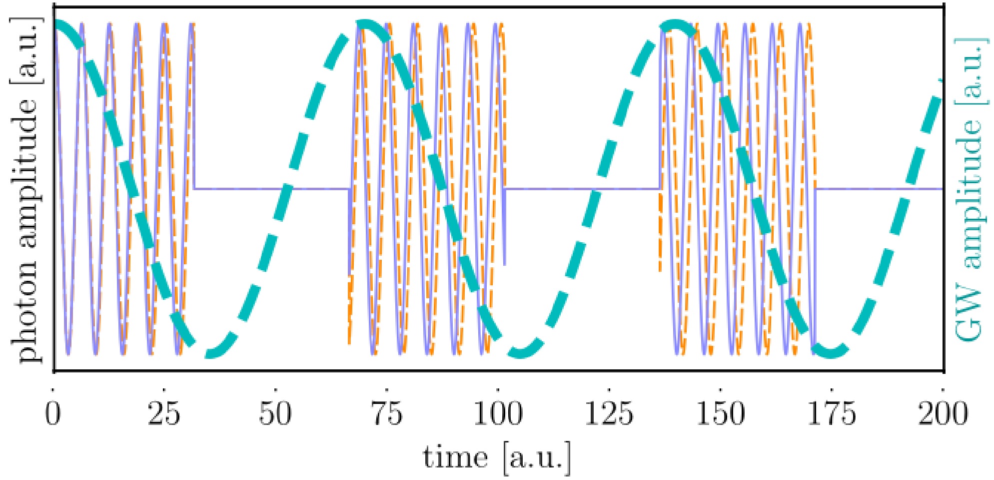


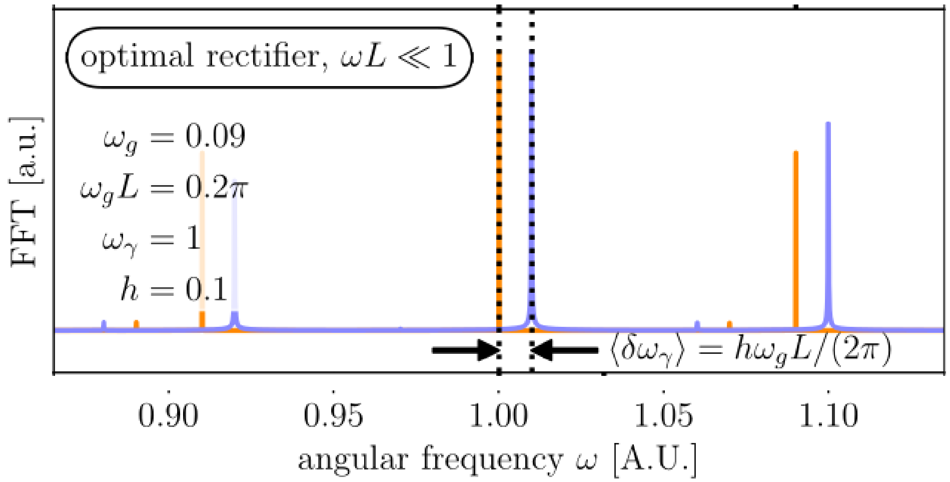
Photon net frequency shift detectable by Ramsey spectroscopy

Rectifier: small ωL

Pass if $\sin\varphi_0 = \sin\omega_g t > 0$

$$\langle\delta\omega_\gamma\rangle = h\omega_g L/(2\pi) \quad (\theta = \pi/2)$$





Orange sideband: effect of shutter

Not only sideband, but also frequency shift of photon carrier line

Sensitivity

Assumptions in the limits:

$\tau = 1\,\mathrm{s},\ L = 1\,\mathrm{m},\ \omega_\gamma^S/2\pi = 2\times 10^{14}\,\mathrm{Hz}$

Integration time — optical

$P = \mathrm{mW}$ Laser power: need high #photons

transmission — Thermal noise

$$(\alpha_T, \alpha_{th}) = \{(10^{-10}, 10^{-15}), (10^{-15}, 10^{-17}), (10^{-20}, 10^{-19})\}$$

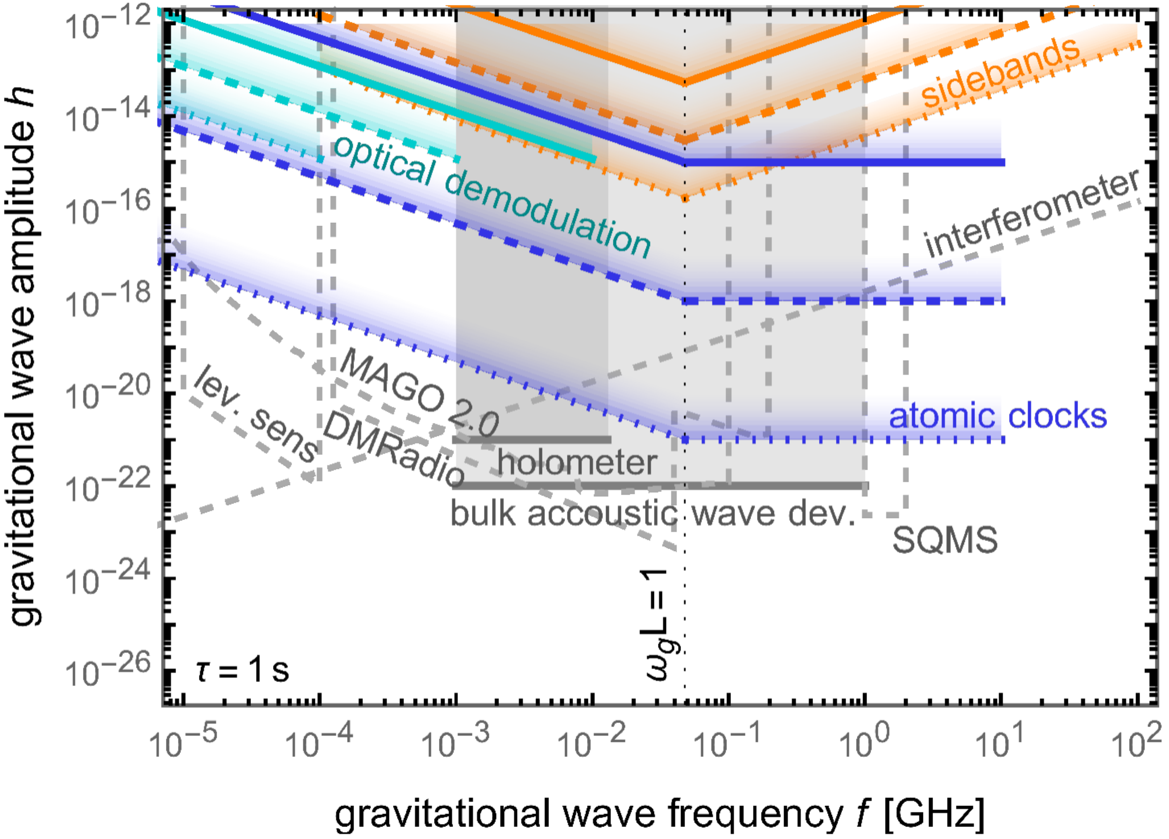
conservative

realistic

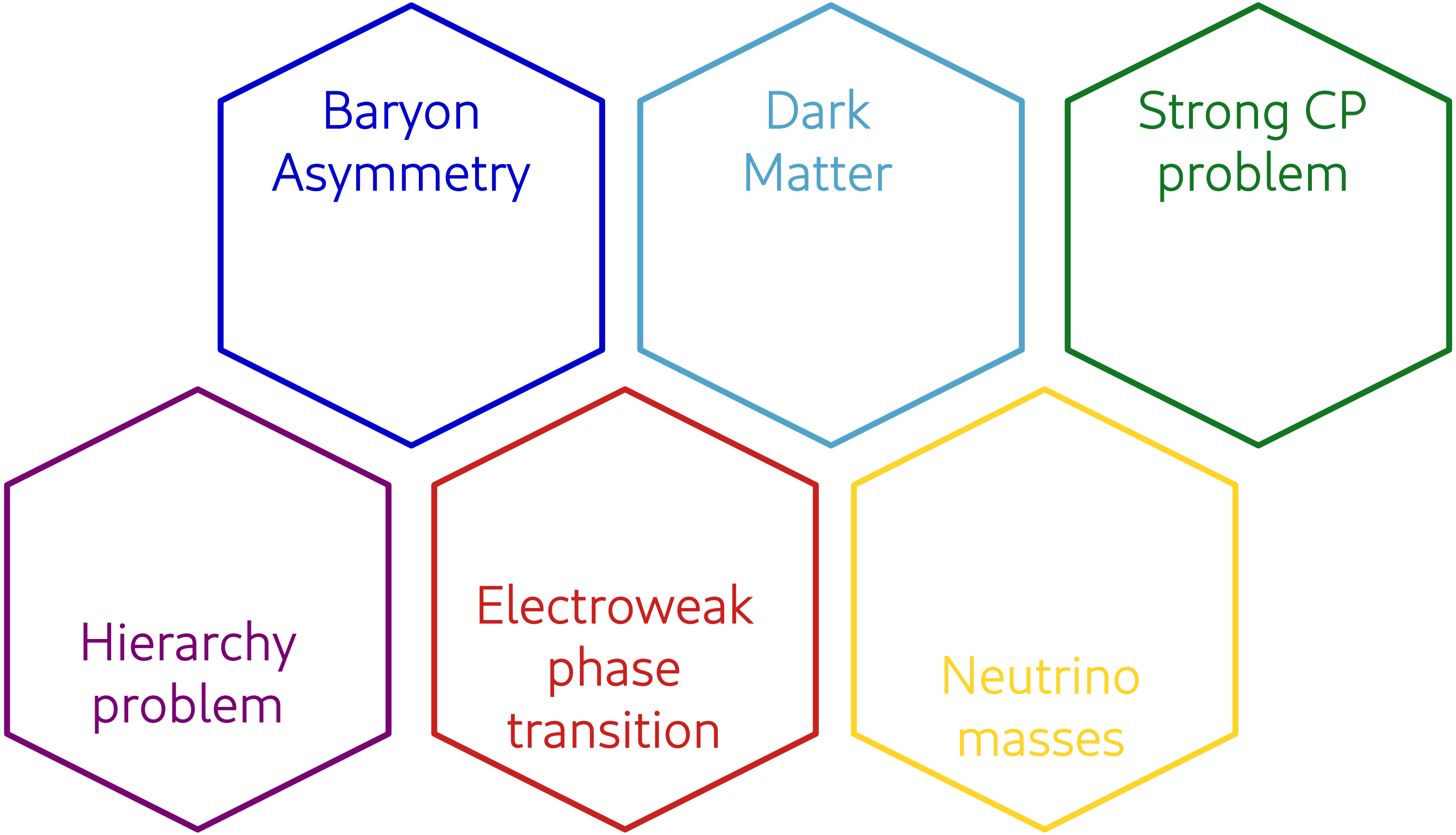
optimistic

Promising approach over broad frequency range

Bringmann Domcke Fuchs Kopp 2023



Particle questions Quantum sensing



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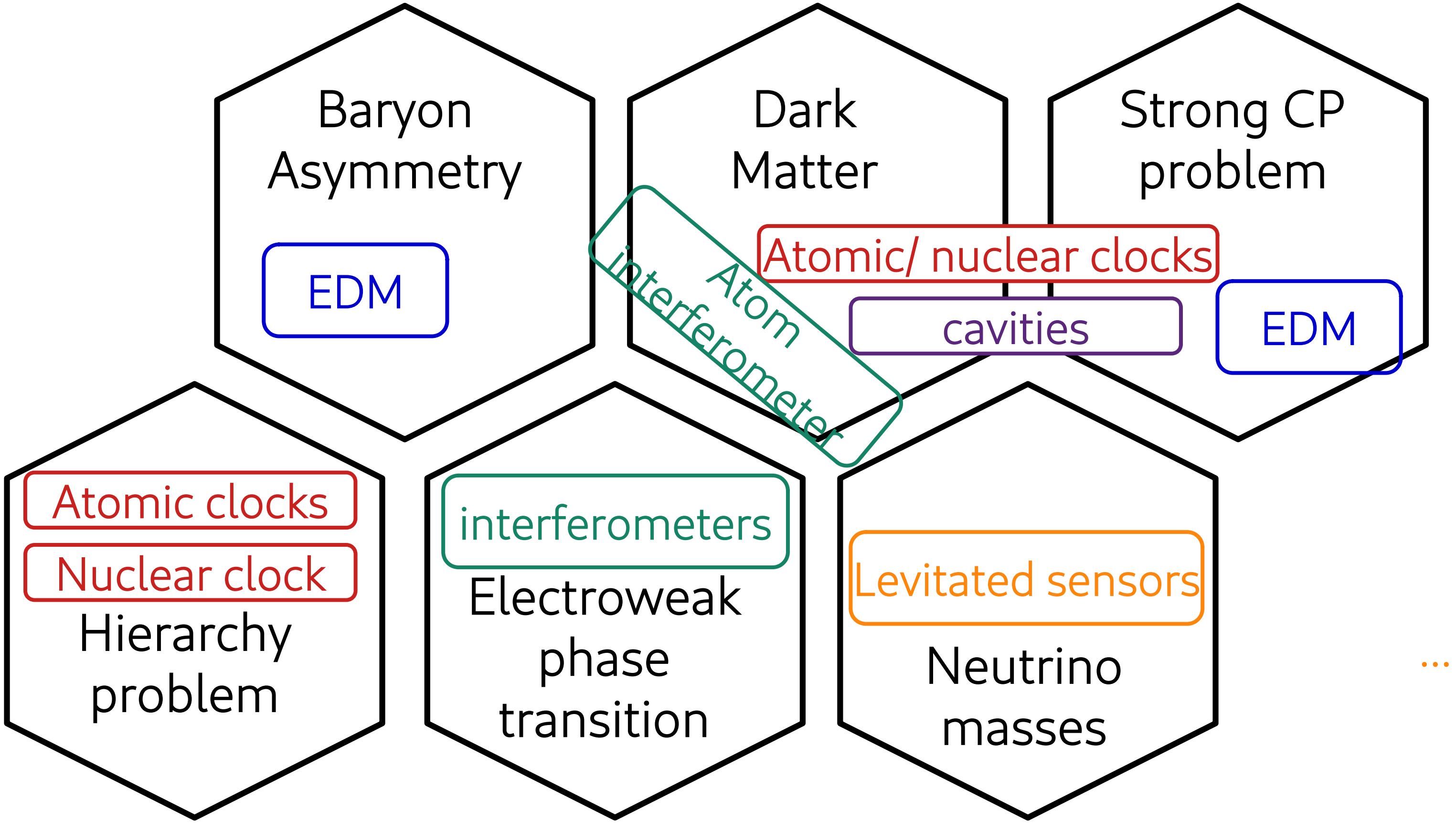

Summary: powerful atomic sensors

→ Well-motivated scenarios with light, feeble NP require novel searches

→ Quantum sensors e.g. clocks can enable measurement & enhance the sensitivity

→ Time variation, isotope shifts, highly charged ions, Rydberg states, nuclear clock,...

→ High-frequency GWs: proposal to look for sidebands and enable frequency shift

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

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Many regional/ national clusters, now also at CERN

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QUANTUM TECHNOLOGY INITIATIVE

Summary: powerful atomic sensors

Thank you!

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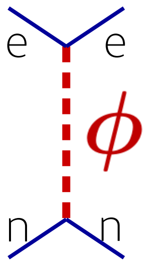
QUANTUM TECHNOLOGY INITIATIVE

APPENDIX

NP shifts of atomic spectra

Energy shift due to new long-range interaction

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



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

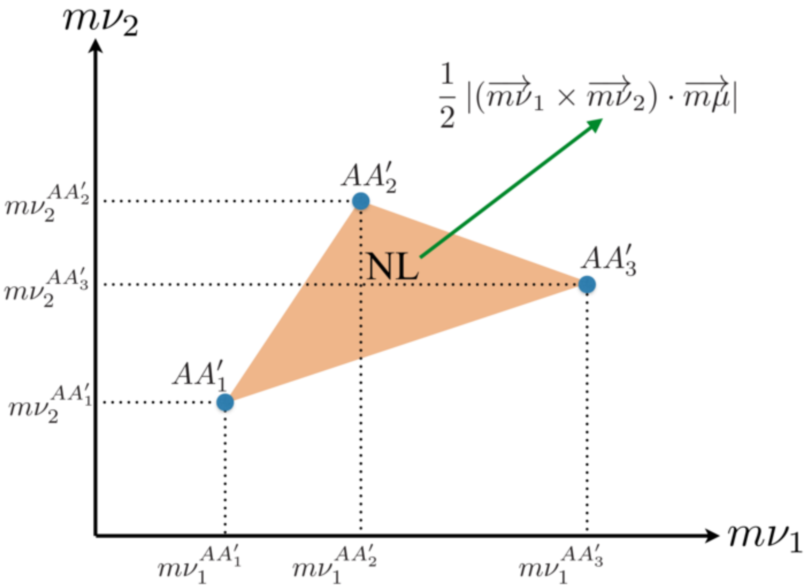
NP ϕ coupling to electrons and neutrons

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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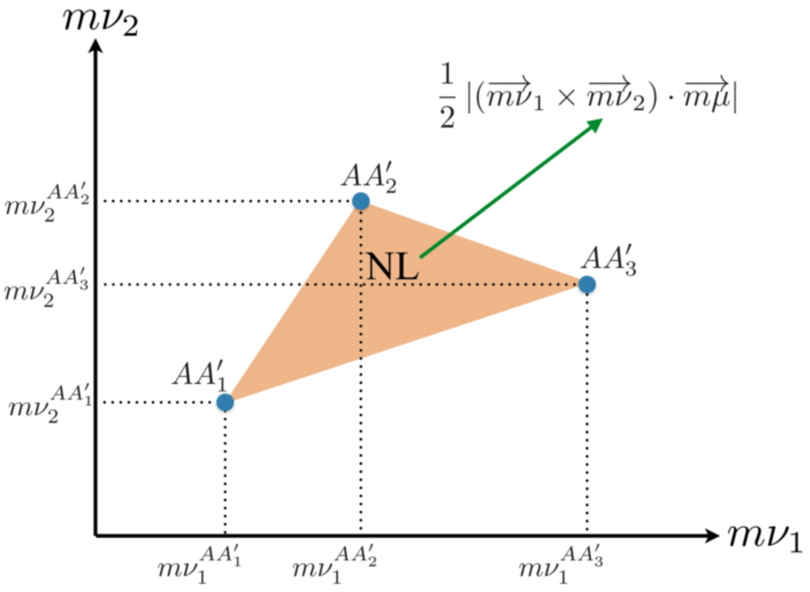
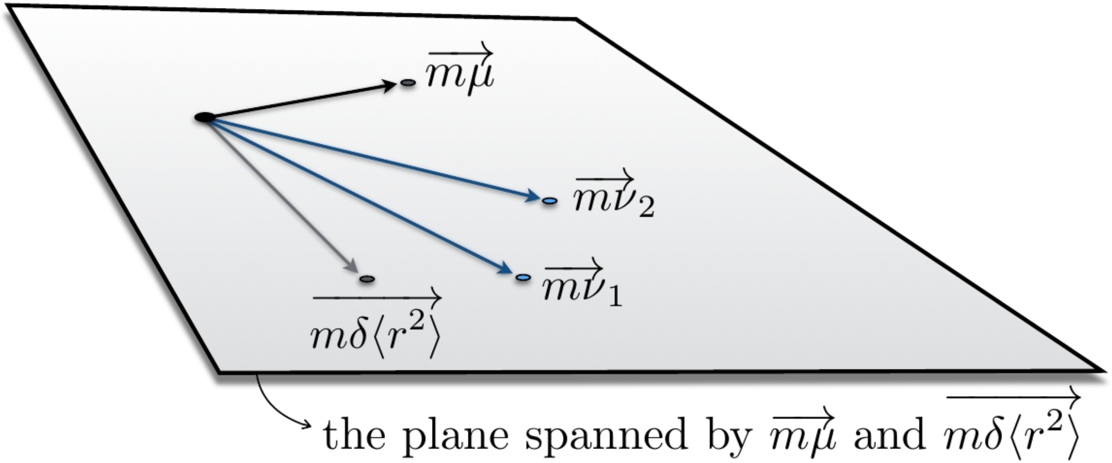


- Linearity plane: linear combinations of FS+MS
- Volume of parallelepiped = measure of NL



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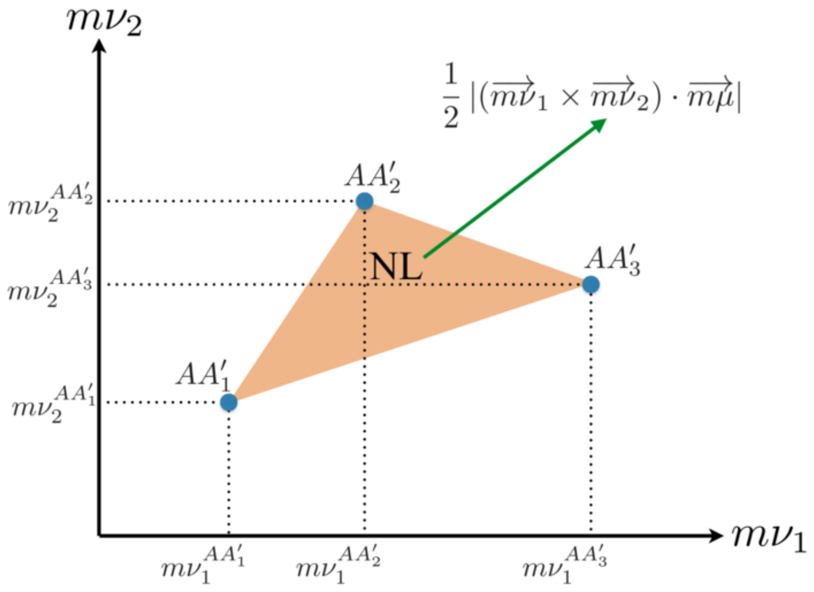

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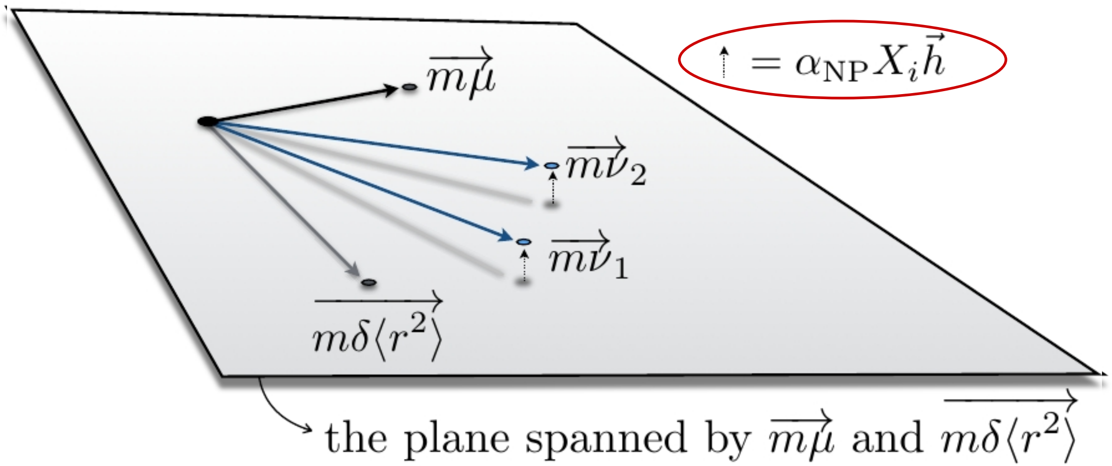

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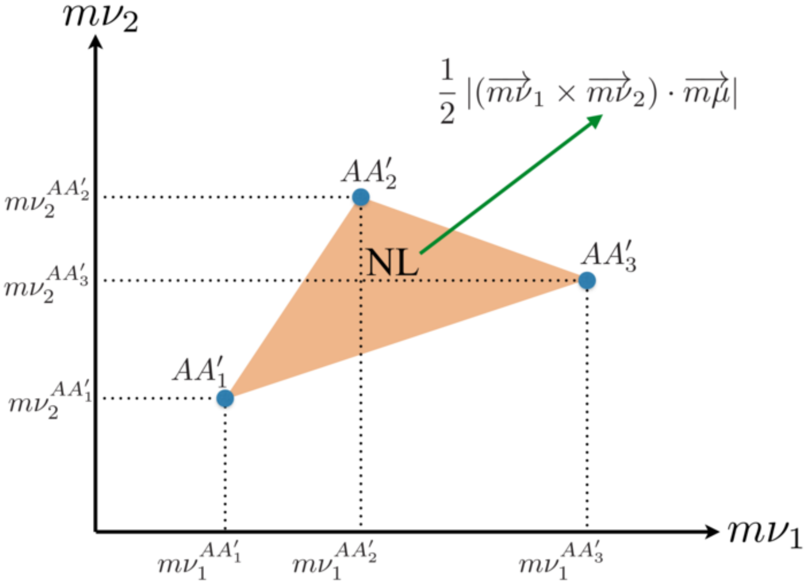

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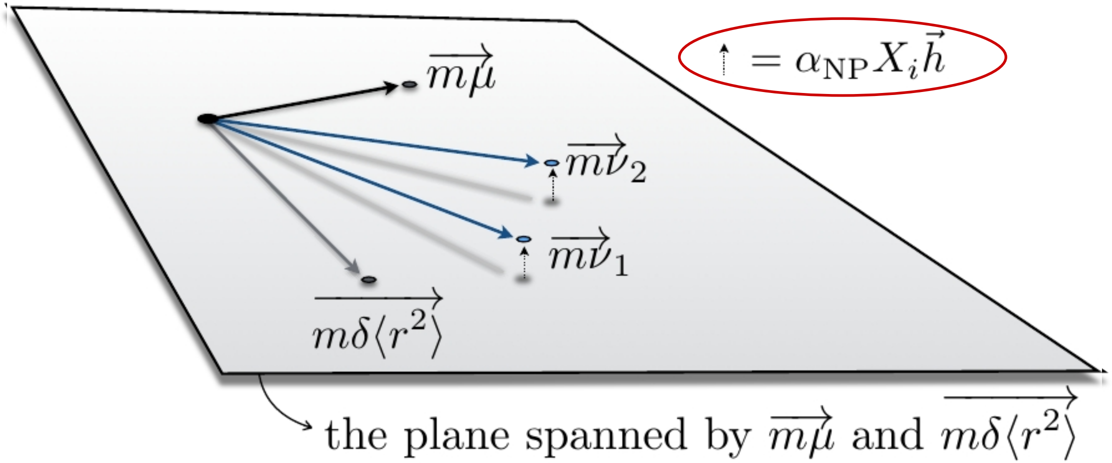

quantify NL → if within uncertainty → bound NP

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

Constraint on mass and couplings

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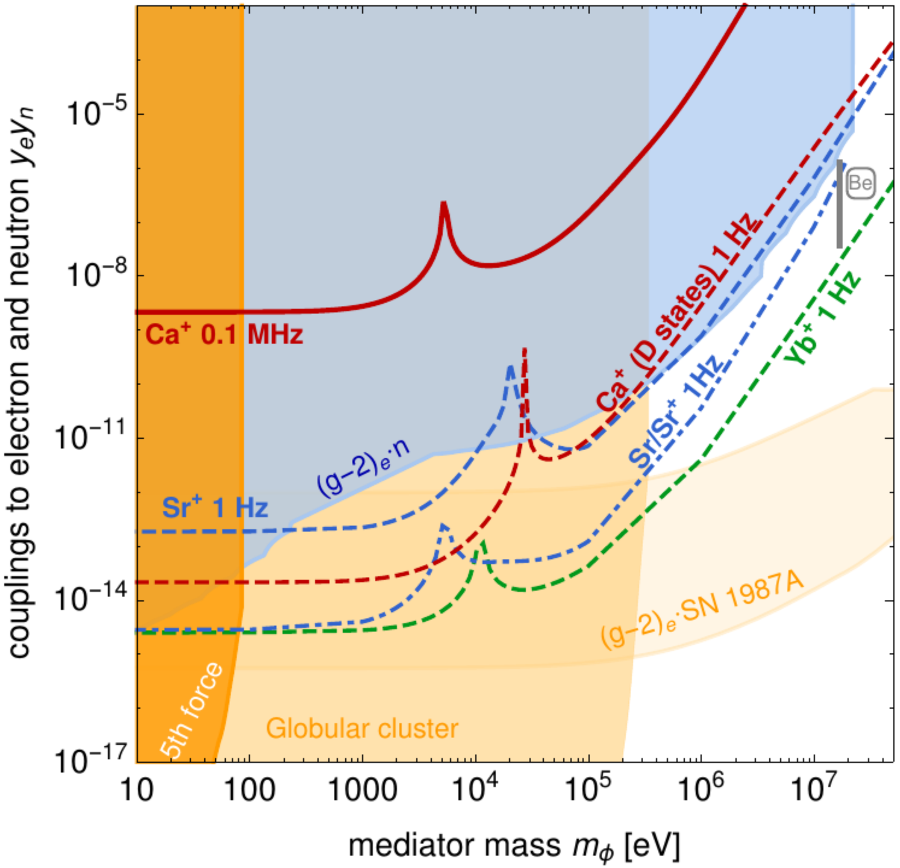

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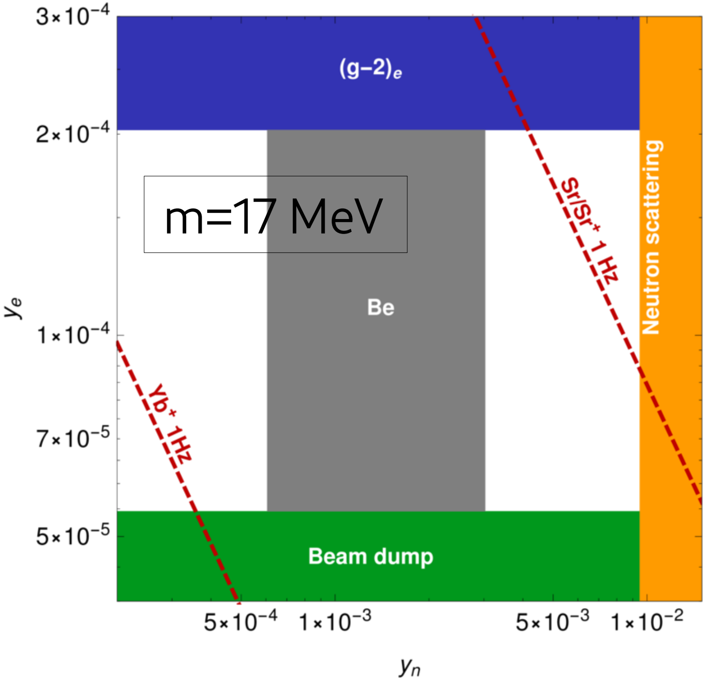
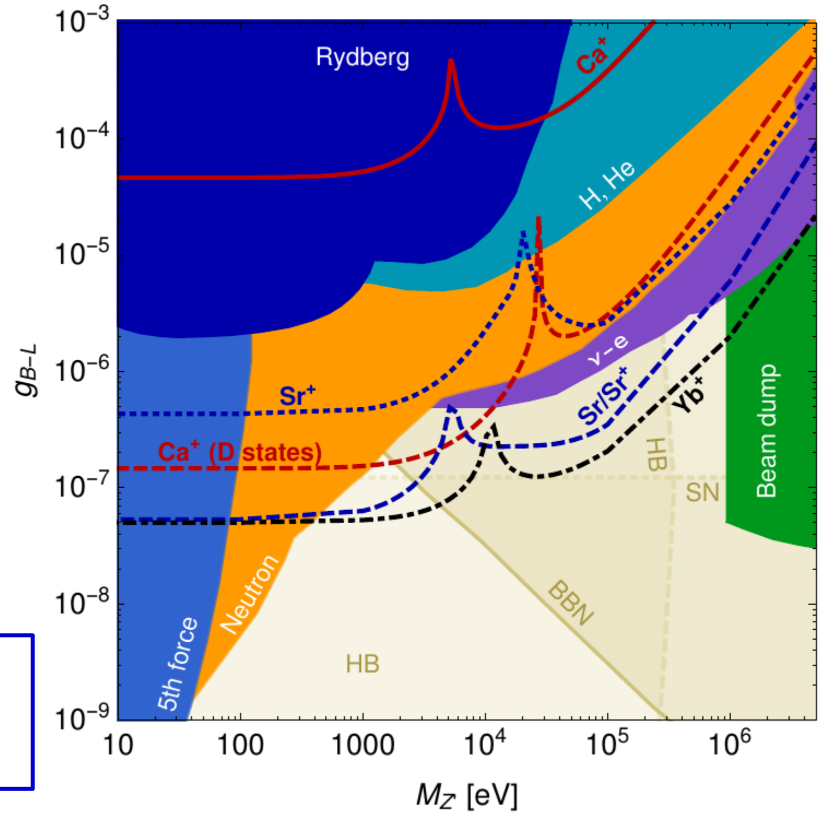
Implications for NP models



Yb+ 1Hz potential to rule out protophobic explanation of Atomki [8]Be anomaly

[Frugiuele, EF, Perez, Schlaffer '17]

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



Caveat: Linearity breaking in SM

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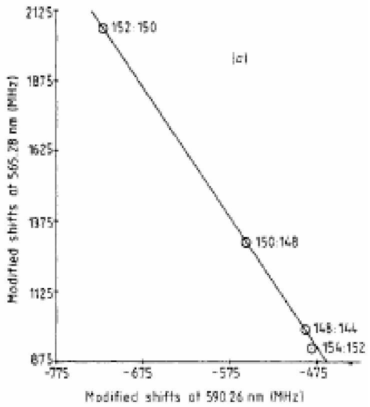
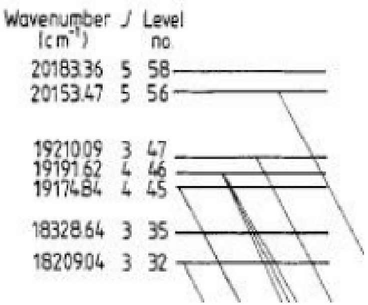


Samarium (Sm)



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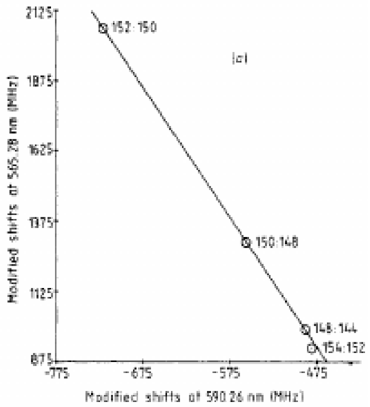
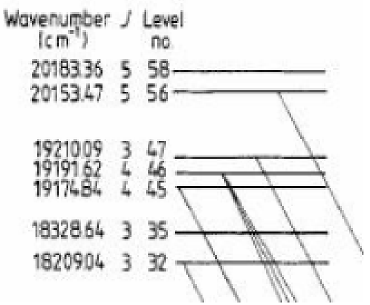


Samarium (Sm)



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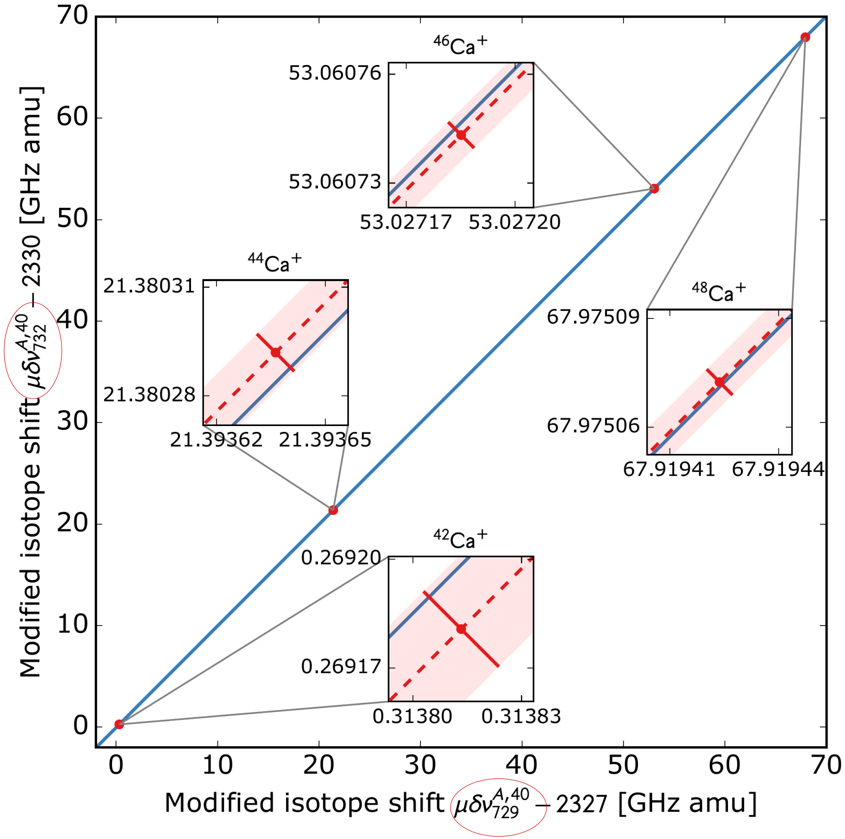
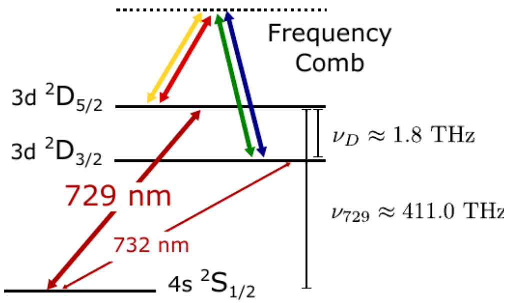
Strategy: consider predicted SM NL and constrain residual NL

Very precise Ca^+ King Plot

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





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

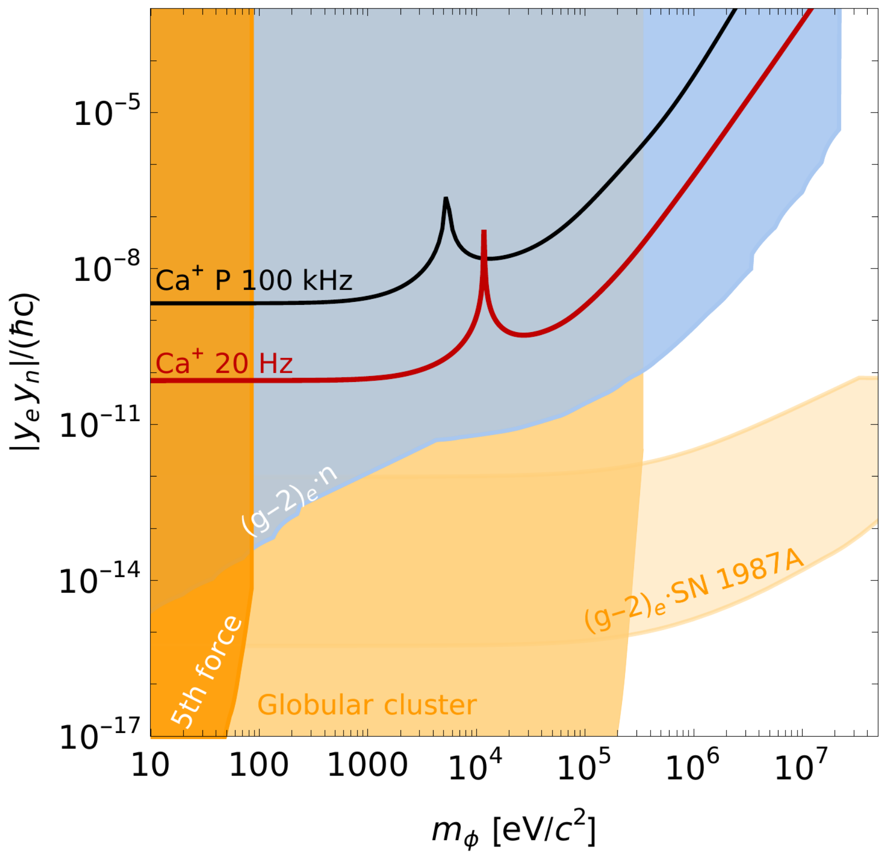
Aarhus: $D_{3/2}$-$D_{5/2}$ at **20 Hz**

Ca 40, 42, 44, 46, 48

King plot linear at ~1σ, χ^2=0.9

New Ca^+ Isotope Shift Bounds on Φ

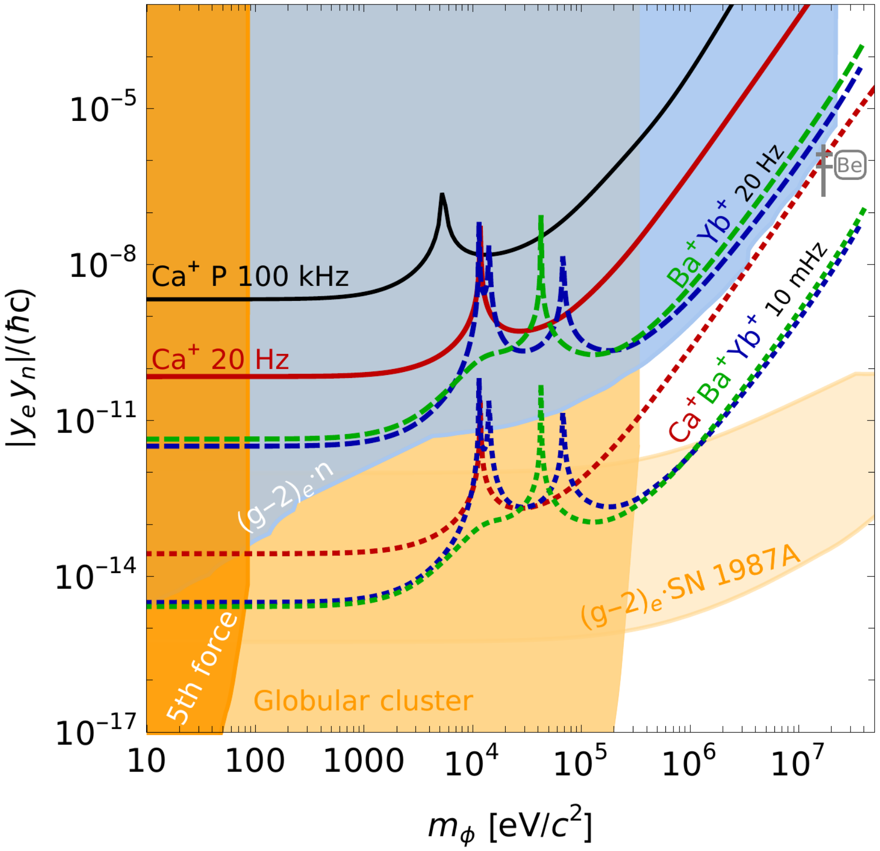
[Solaro, Meyer, Fisher, Berengut, EF, Drewsen, PRL 125, 123003 (2020)]



- 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

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 $(g-2)_e$*n-scatt
- Anticipated precision: **10 mHz**
  - Ca, Ba, Yb can probe untested parameter space

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 in $^{172}Yb^+$ at few Hz
- further with isotope shifts of S-D, S-F at sub-10-Hz precision → update coming soon

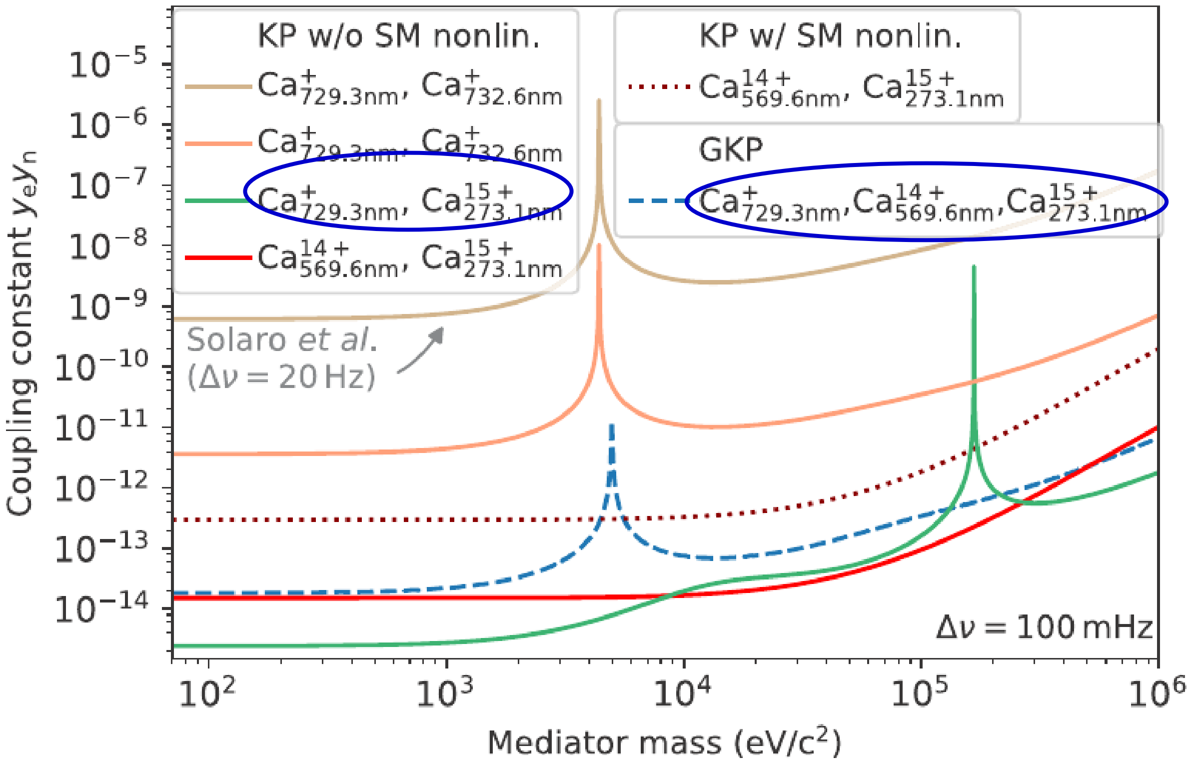
Highly charged ion (HCI) King plot

[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]
[Pachucki, Patkos, Yerokhin ‘17]

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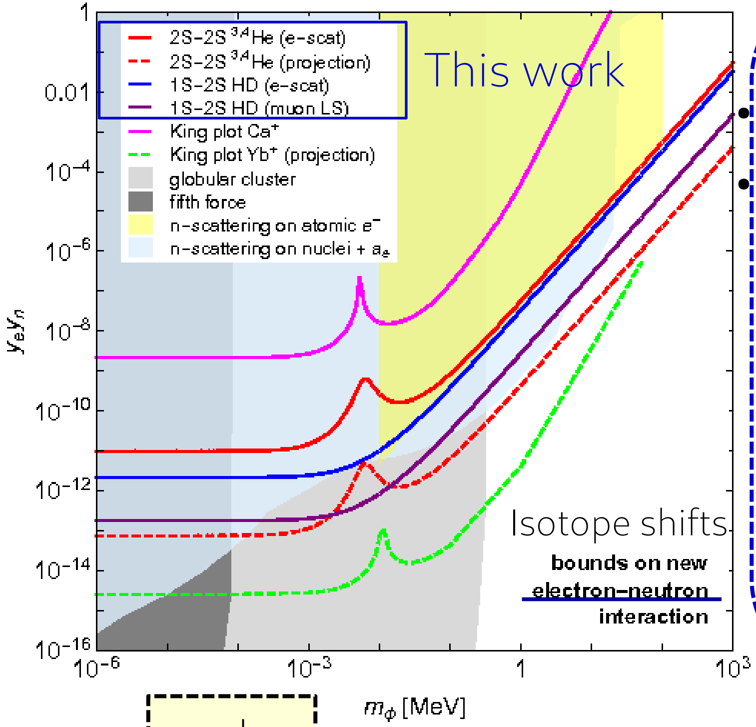

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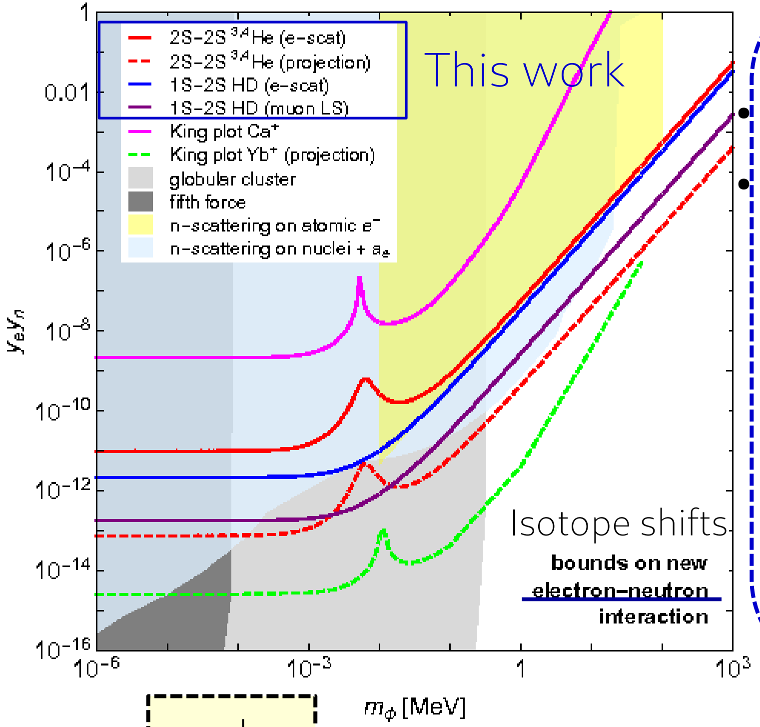

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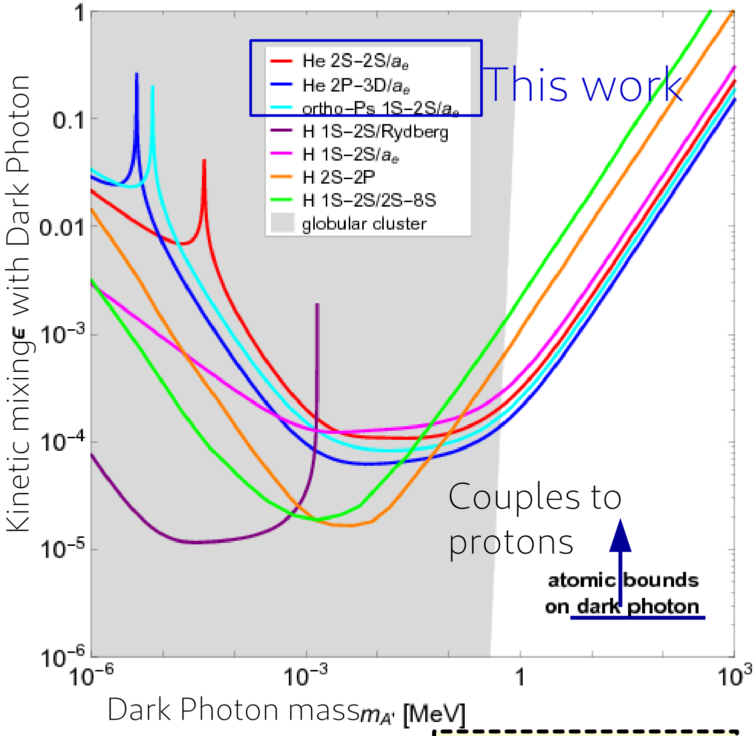

Dark photon

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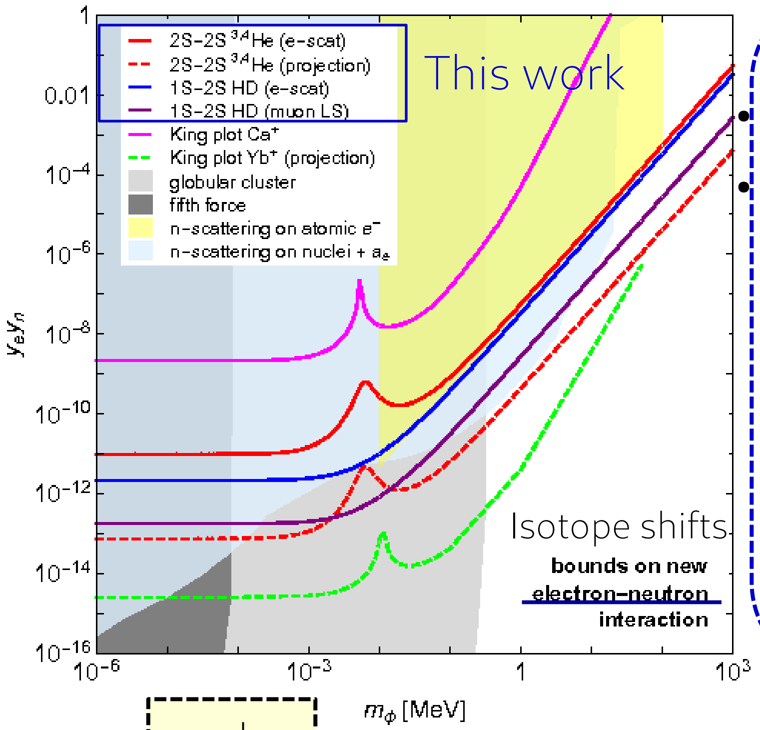

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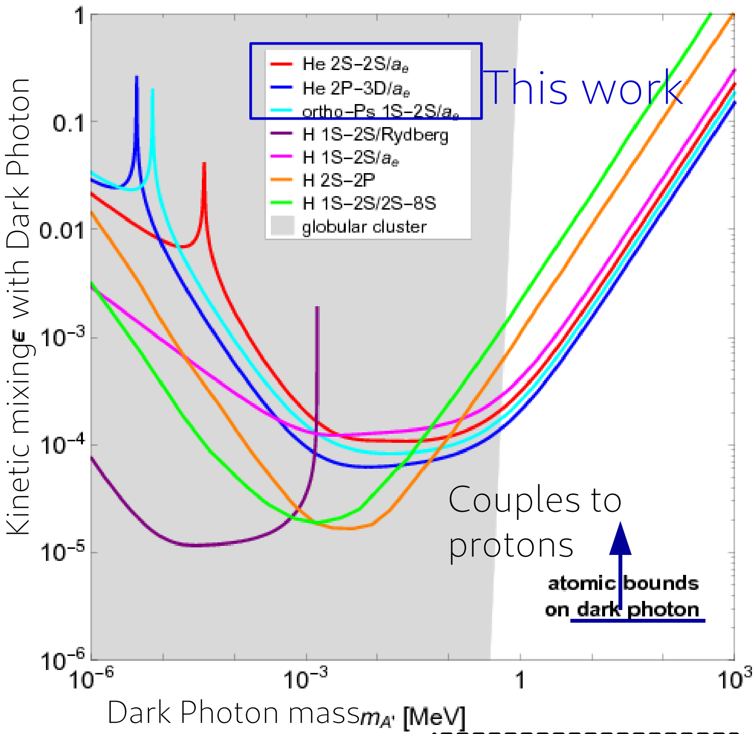

Dark photon

Precise frequencies and isotope shifts
→ complementary to King plot

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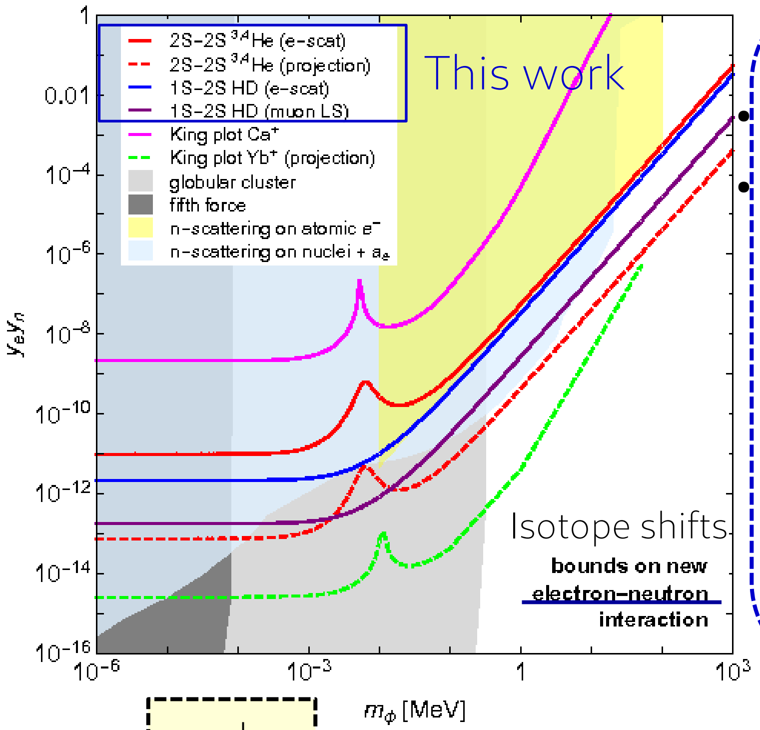

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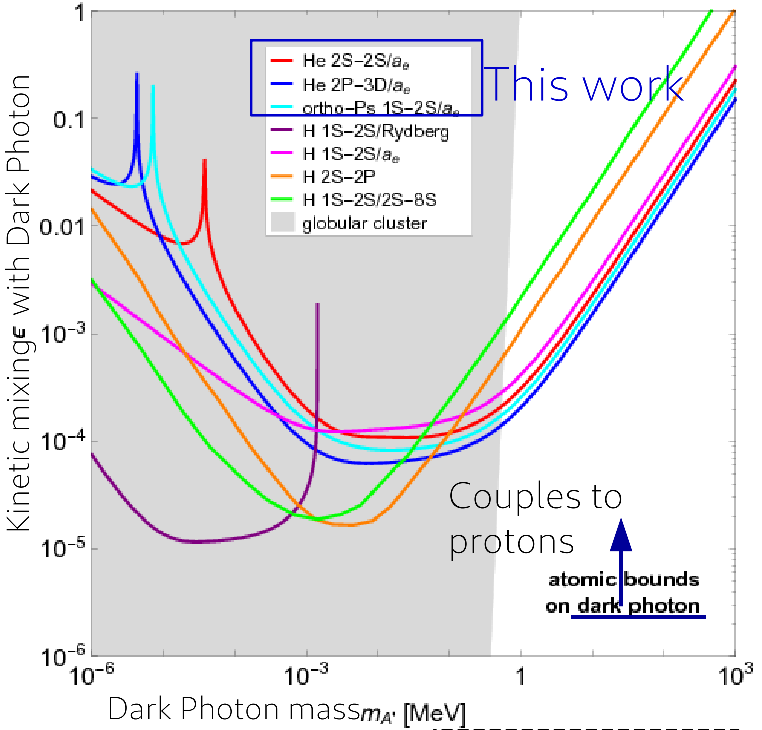


Dark photon

Precise frequencies and isotope shifts
→ complementary to King plot

New Ca^+ Isotope Shift Measurements

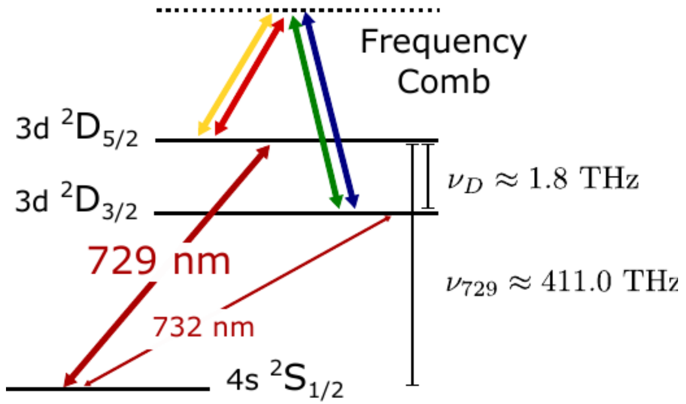
[Solaro, Meyer, Fisher, Berengut, EF, Drewsen, PRL 125, 123003 (2020)]

- 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}



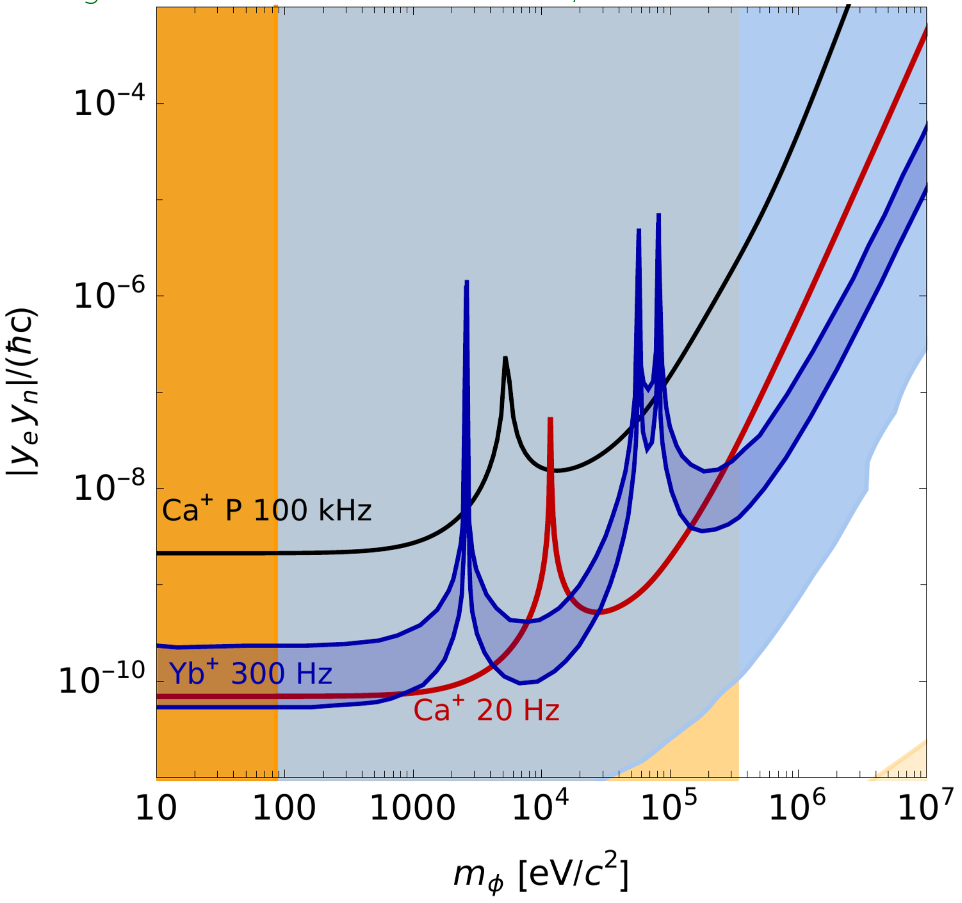
[Solaro, Meyer, Fisher, DePalatis, Drewsen (Aarhus University), PhysRevLett.120.253601]

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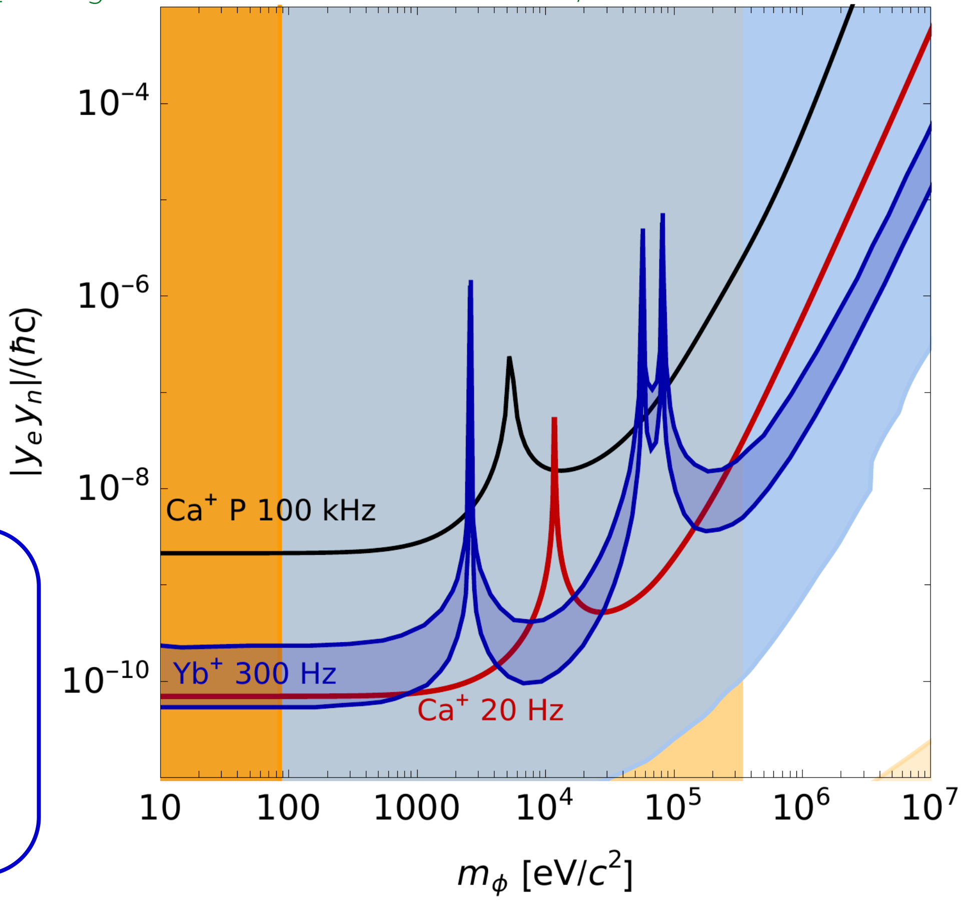
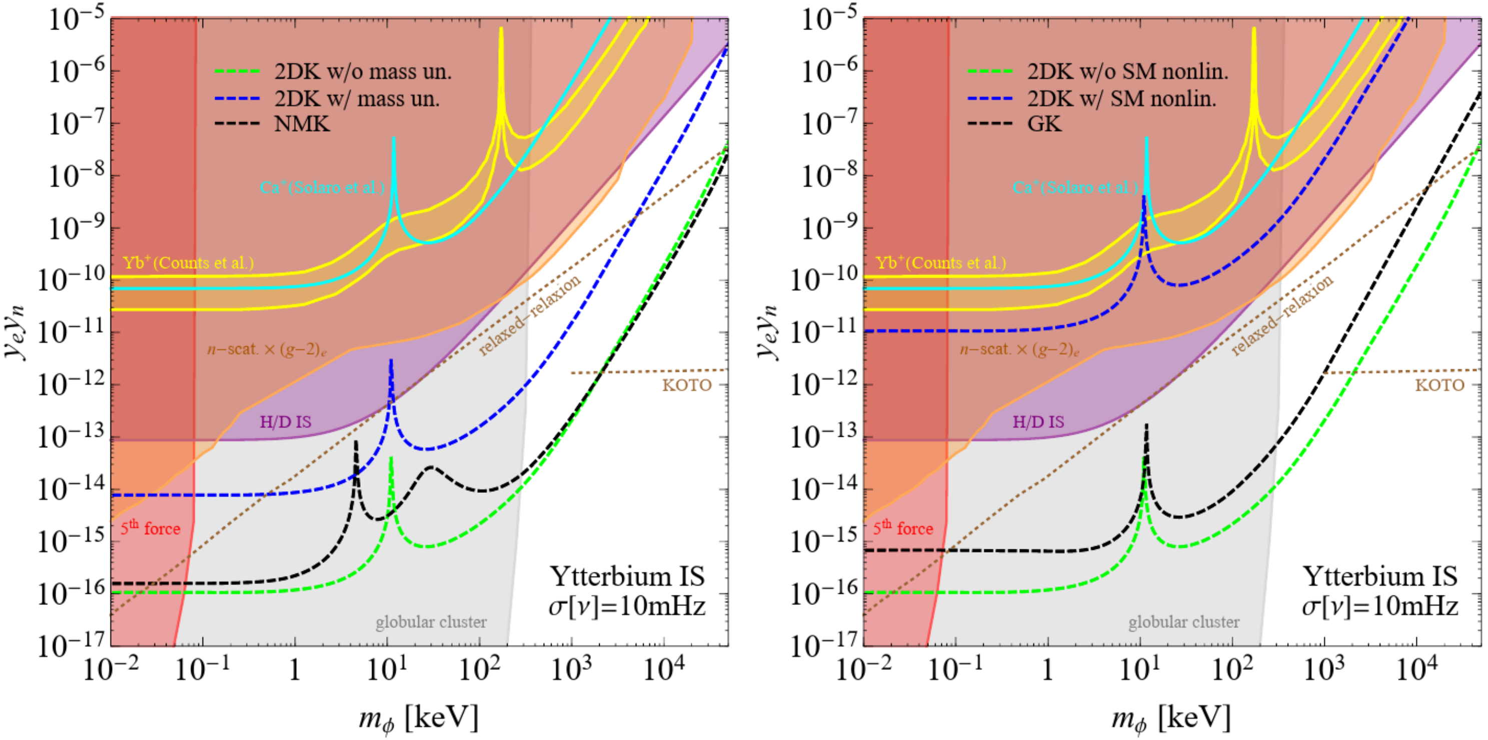
if Yb-NL assumed as *purely* New Physics:
→ necessary coupling range is
- partly excluded by Ca
- excluded by $(g-2)_e$*n-scattering

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



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)

$$X_i = \frac{1}{A-Z} \left. \frac{d\epsilon_{ab}}{d\alpha_{\rm NP}} \right|_{\alpha_{\rm NP}=0}$$

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

Atomic clock key figures

Characterize the performance of a clock by its relative frequency change
Goals: stable and accurate clock

$$f(t)/f_0 = 1 + \epsilon + y(t)$$

Accuracy

- Systematic uncertainty in clock frequency.
- Two types of shifts
  1. **Field shifts** e.g. Zeeman shift and black body shift
  2. **Motional shifts** e.g. Relativistic Doppler

$$\frac{\Delta f}{f} = \frac{\langle \vec{v} \cdot \hat{k} \rangle}{c} - \frac{\langle v^2 \rangle}{2c^2} - \frac{\langle \vec{v} \cdot \hat{k} \rangle^2}{2c^2} + \cdots$$

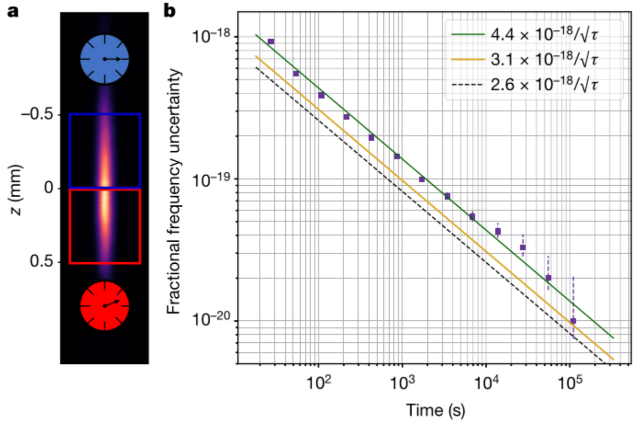
Stability

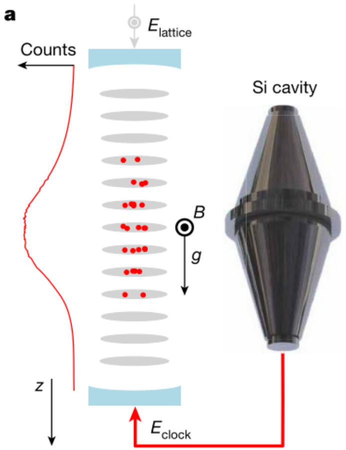
- Average fractional frequency variations
- Typically characterized by the *Allan deviation:*

$$\sigma_y(\tau) \cong \frac{1}{Q} \frac{1}{SNR} \sqrt{\frac{T_C}{\tau}}$$

See D. Hume's talk at ECFA workhop '21

Sr lattice clock





- 1-dimensional Sr optical lattice clock: measured linear frequency gradient inside a single atomic sample to a relative uncertainty of phenomenal 7.6×10^{-21}
- 100,000 ultracold Sr atoms in an optical lattice
- narrow $S_0 \rightarrow P_0$ transition
- magic trap depth → suppress collisional shifts
- fundamental to achieve this precision: the record coherence time of 37s
- frequency comparison within one sample: 2 uncorrelated subregions separated by a mm
- Test gravitational time dilation at mm scale.

Noise

- Quantum projection noise:
  - Discrete measurement outcomes 0,1 with probabilities p, (1-p)
  - Experiment repeated N times → $p = \frac{N_1}{N}$
  - Variance of binomial distribution $\sigma^2_{p,\text{quantum}} = \frac{1}{N} p(1-p).$

- Decoherence
  - Decoherence & relaxation → random transitions
  - → reduced probability $\delta p_{\text{obs}}(t) = \delta p(t) e^{-\chi(t)},$

$$\chi(t) = (\Gamma t)^a,$$

  - Decoherence time/ decay rate $\Gamma = T_\chi^{-1}$ → max. sensing time

Entanglement

Goal: enhance the measurement precision by quantum properties

Standard Quantum Limit: measurement uncertainty from the Heisenberg principle
→ reduced for large number of atoms as $\delta_{\mathrm{SQL}} \propto N_{\mathrm{atom}}^{-1/2}$

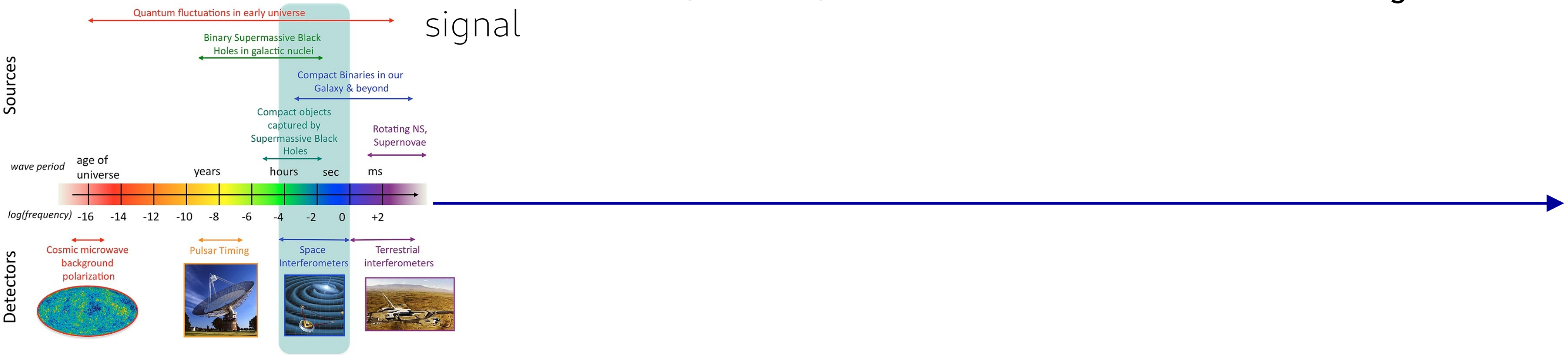
Heisenberg limit: fundamental limit

$$\delta_{\mathrm{Heisenberg}} \propto N_{\mathrm{entangled}}^{-1/2} N_{\mathrm{atom}}^{-1/2} \longrightarrow N_{\mathrm{atom}}^{-1}$$

Best if all atoms entangled!

Already used:
e.g. spectroscopy of entangled Sr isotopes [Ozeri et al, PRL '19]

GW sources: high frequency



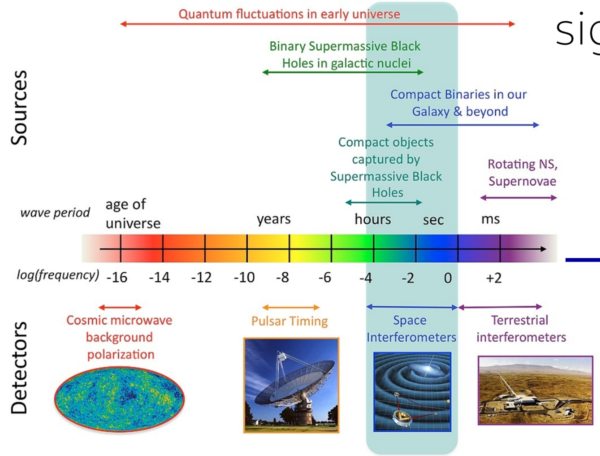
Ultrahigh frequency >10kHz:
no known astrophysical sources with large enough signal

Potential sources:

- **1st order phase transition** in Early Universe at T>> 100 GeV
- Primordial Black Hole mergers

Image: NASA

GW sources: high frequency



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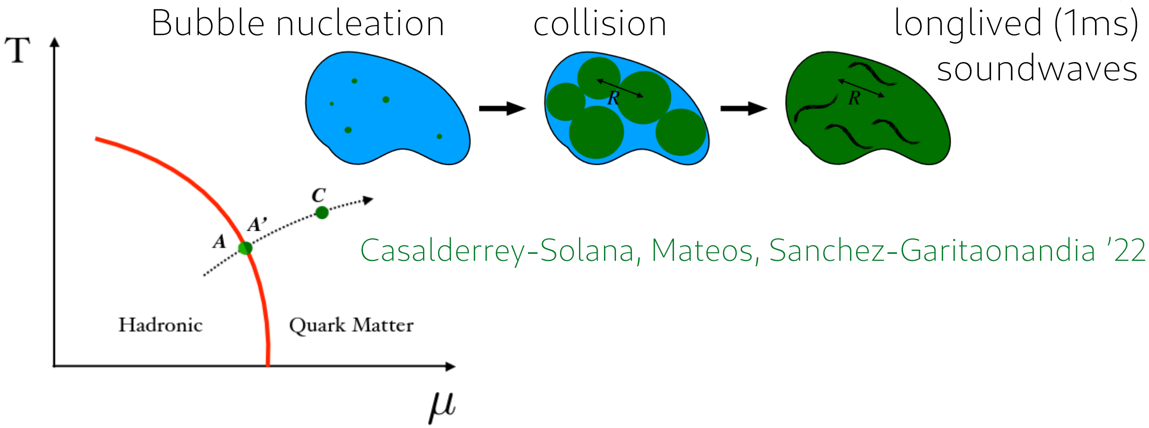

Casalderrey-Solana, Mateos, Sanchez-Garitaonandia '22

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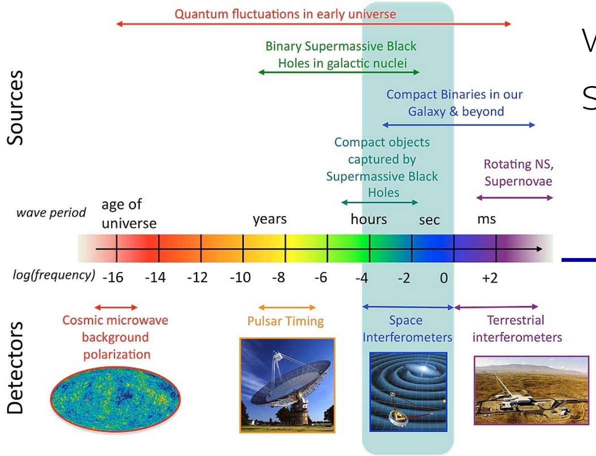

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Searches and proposals:

- Interferometers
- Levitated sensors
- Radio cavities

Rigid ruler – PD frame

- **Proper-detector (PD) frame:** distances an observer with a rigid ruler would measure

$$\frac{\omega_\gamma^D - \omega_\gamma^S}{\omega_\gamma^D} = \frac{h_+}{2}\left\{\cos\varphi_0 - \omega_g L \sin(\omega_g L + \varphi_0) + \left(\frac{1}{2}\omega_g^2 L^2 - 1\right)\cos(\omega_g L + \varphi_0)\right\}$$

Enhanced sensitivity for large $\omega_g L \gg 1$?

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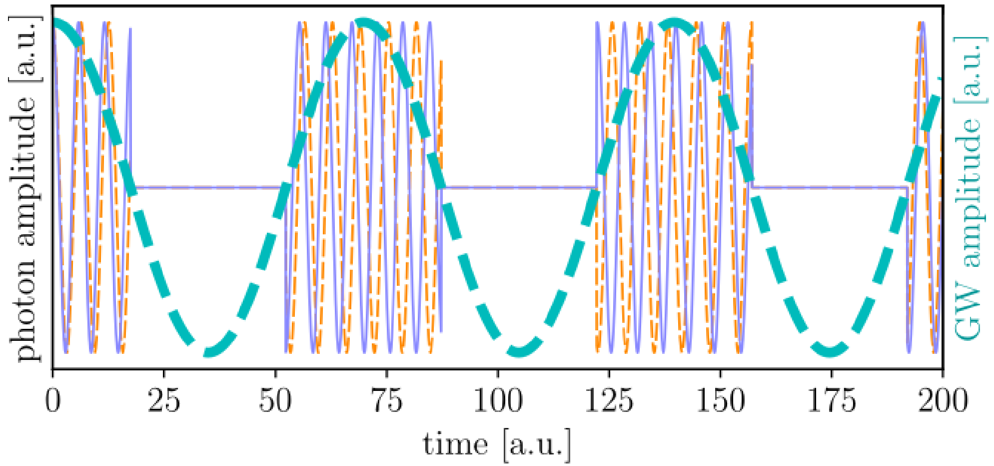
❌ no material is perfectly rigid at high frequencies!

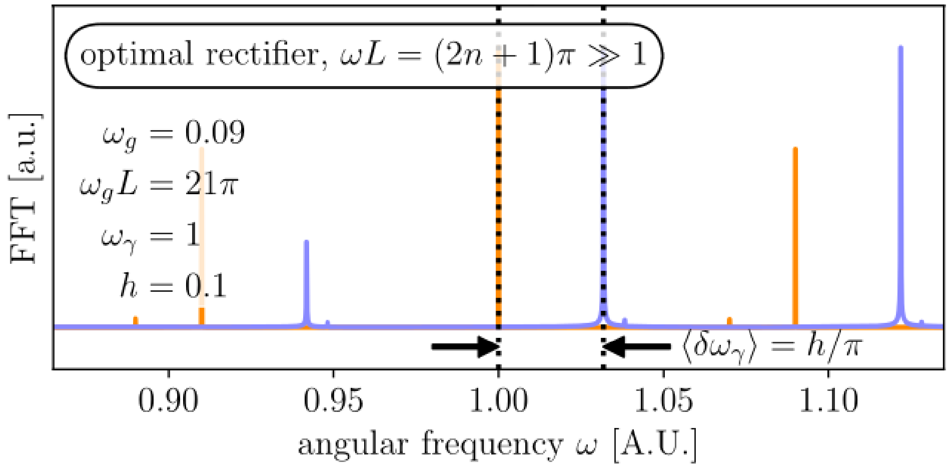
→ generic implication for detector design:
this equation is not directly applicable for $\omega_g L \gg v_s$

Rectifier: large ωL

Pass if $\sin[\varphi_0 + \pi/2] > 0$

$\langle \delta\omega_\gamma \rangle = h/\pi$





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	D. Grabowska→ EF→ J. Kopp
Quantum Communication & Networks	Edoardo Martelli

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

Nov 2022: Quantum Technologies for High Energy Physics (QT4HEP)
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QUANTUM TECHNOLOGY INITIATIVE

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Stay tuned, get involved!

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QUANTUM TECHNOLOGY INITIATIVE

QTI Phase 2 Vision