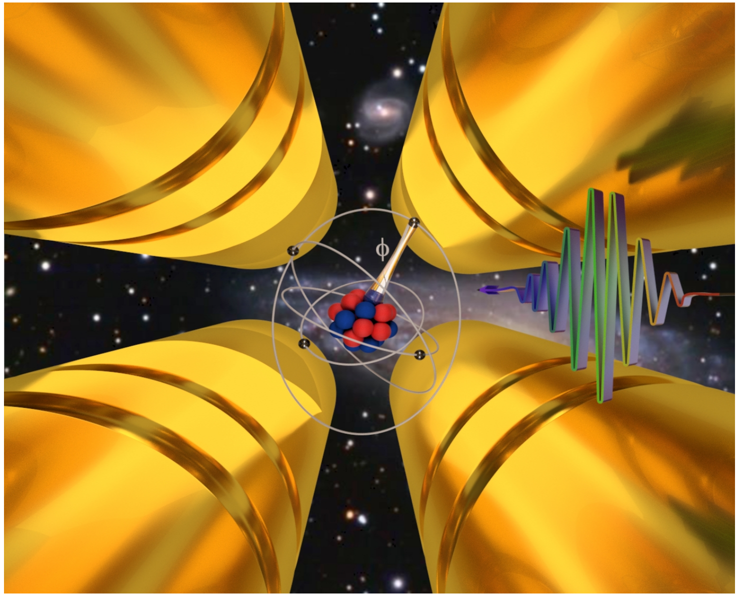
Quantum Sensing for light New Physics and Gravitational Waves

Elina Fuchs
CERN
& Leibniz Universität Hannover
& PTB Braunschweig

CERN Theory Colloquium
June 14th, 2023



QuantumFrontiers
QUANTUM TECHNOLOGY INITIATIVE

Outline

1) Motivation for light New Physics

2) Quantum Sensors

3) Atomic clocks for light new bosons

4) High-frequency GWs with optical photons

Particle questions Quantum sensing

Baryon Asymmetry

Dark Matter

Strong CP problem

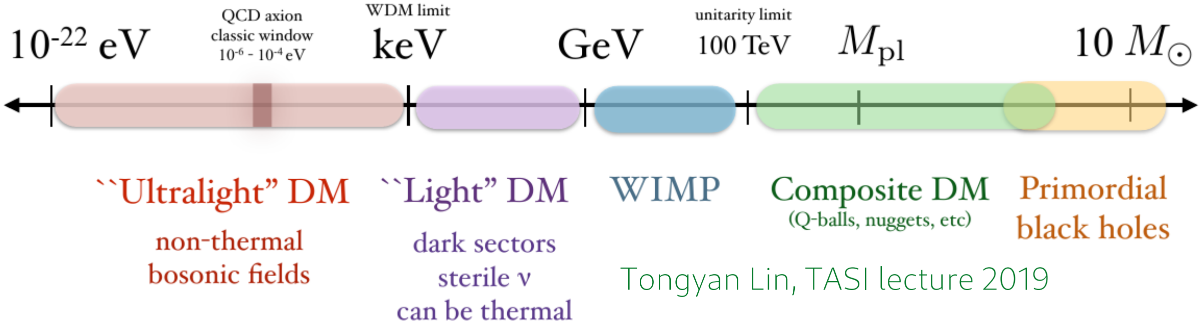
Hierarchy problem

Electroweak phase transition

Neutrino masses

Why light New Physics

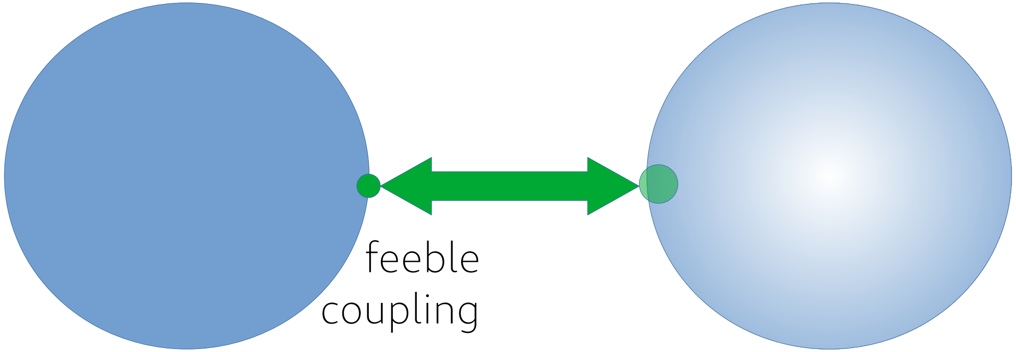
- Spontaneous breaking of exact symmetries → massless particles
    - Approximate symmetries broken → low-mass particles
- Small mixing with SM, e.g. dark photon, …
- Still a lot of unexplored model and parameter space
- DM options: mass scale



Tongyan Lin, TASI lecture 2019

- can address SM shortcomings, e.g. relaxion, axion, …
- interplay of cosmo/astro/precision/intensity/precision frontiers

Mediators to Dark Sector



→ Intensity, precision frontiers

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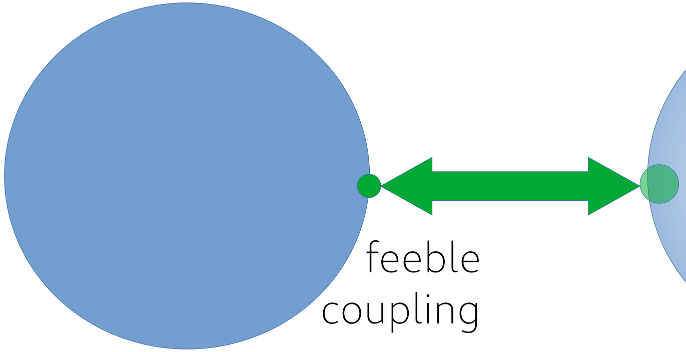
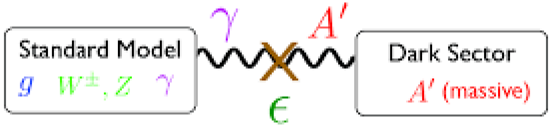


→ Intensity, precision frontiers

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



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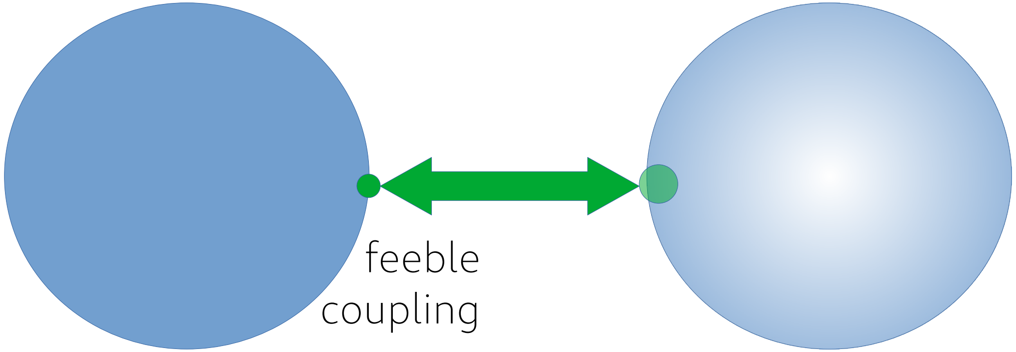

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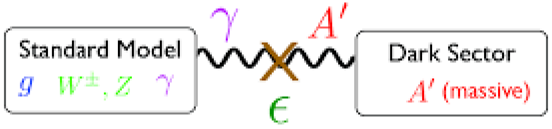
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N L H N$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$



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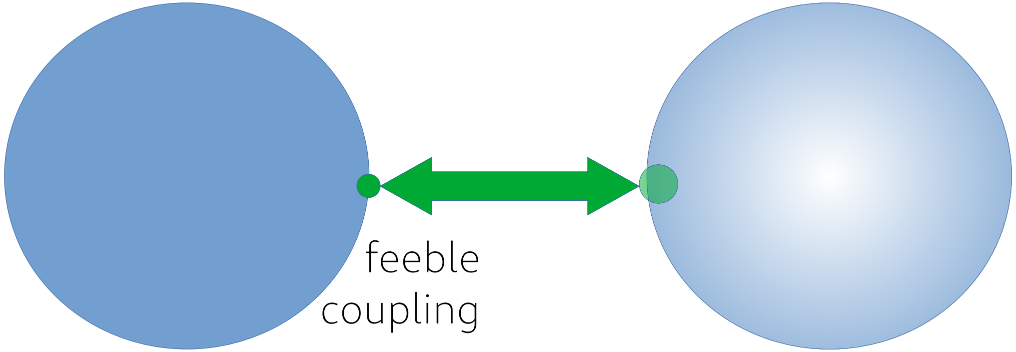

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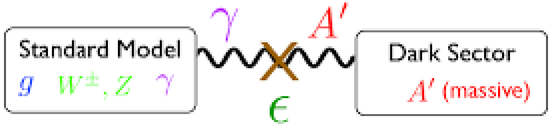


Motivation/need to search for light, feebly interacting particles

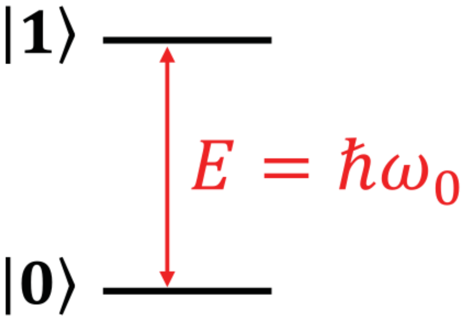
Quantum Sensors

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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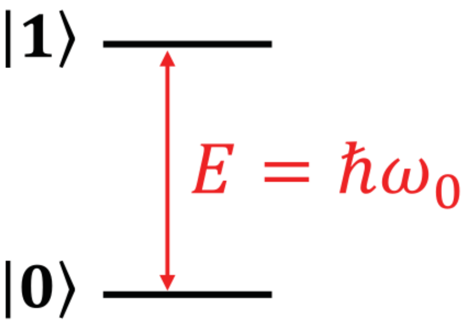
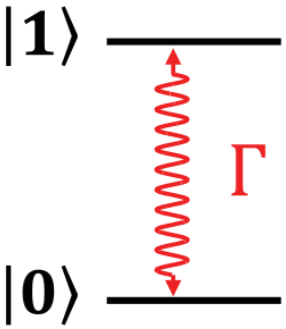


iii) quantum system can be coherently manipulated

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



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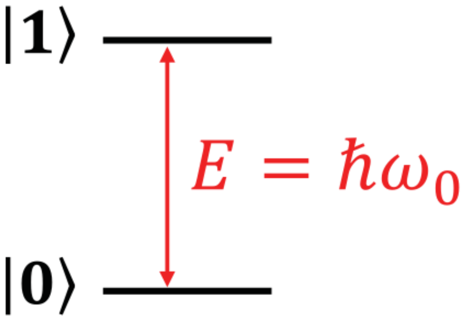

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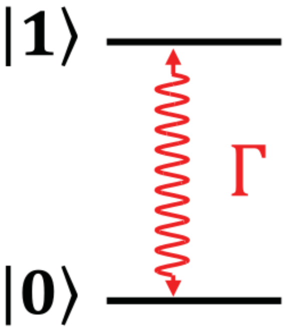

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e.g.: atoms, ions, Rydberg states, superconducting circuits, cavities, clocks, interferometers, …
&entanglement/squeezing → **well suited for light DM/NP, GWs, also for HEP detectors**

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 $\delta_{\mathrm{SQL}} \propto N_{\mathbf{atom}}^{-1/2}$

Heisenberg limit: fundamental limit

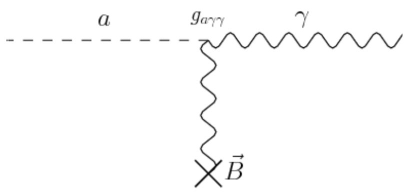
$$\delta_{\mathrm{Heisenberg}} \propto N_{\mathrm{entangled}}^{-1/2} N_{\mathrm{atom}}^{-1/2} \longrightarrow N_{\mathrm{atom}}^{-1}$$

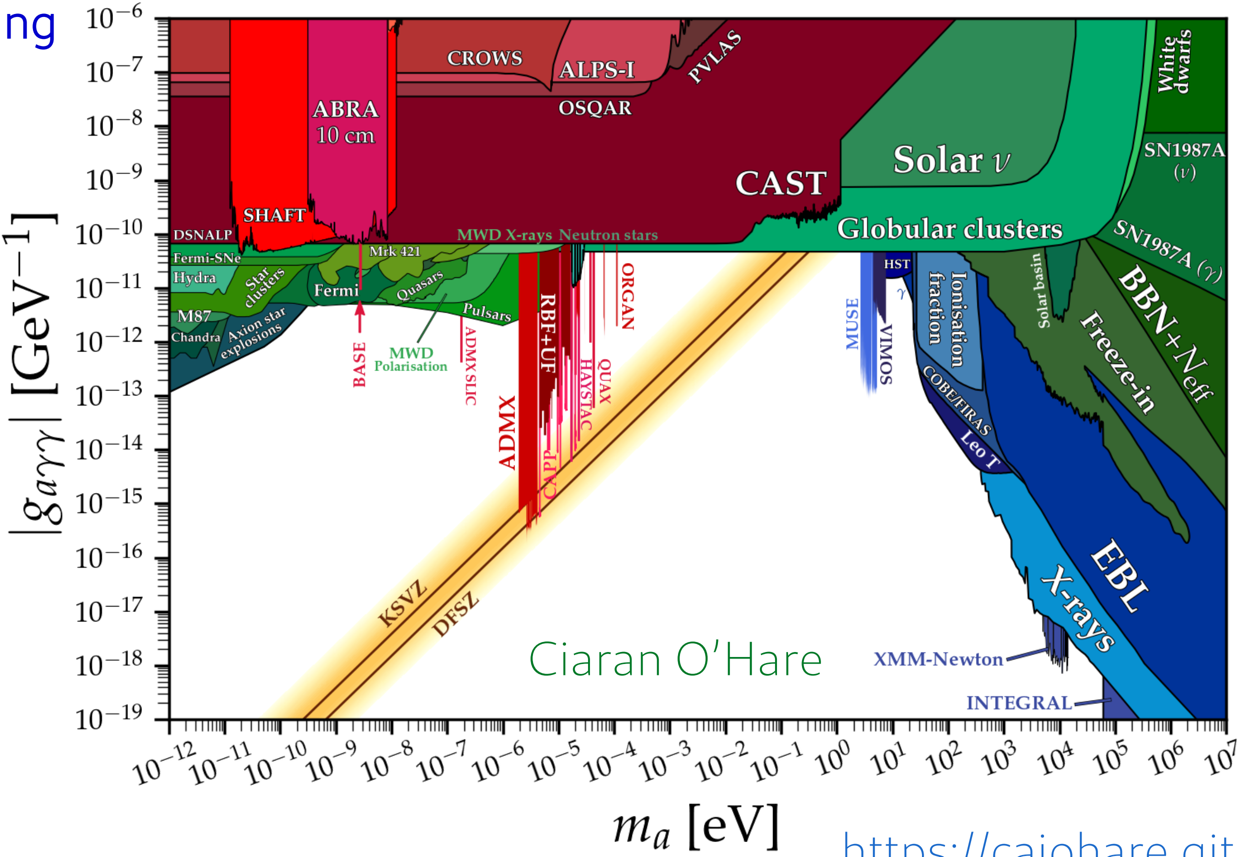
Best if all atoms entangled!

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

Squeezing: e.g. in axion searches

axion-photon coupling





Ciaran O'Hare

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

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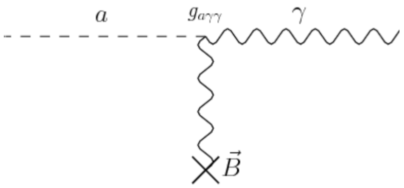
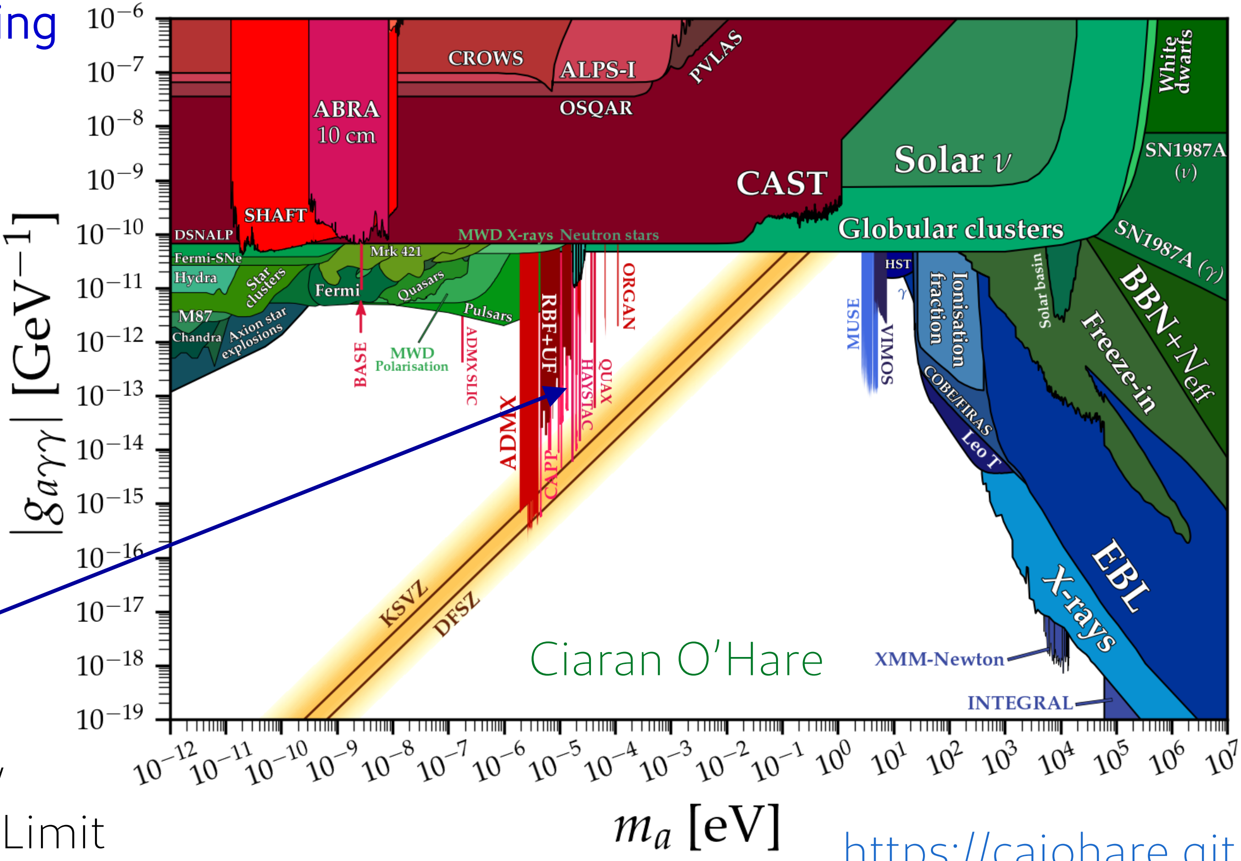
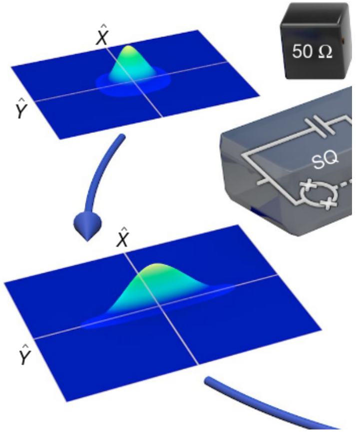




Ciaran O'Hare

Squeezing
HAYSTAC
[Nature]



Haystac goes below
Standard Quantum Limit

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

The virtue of frequency measurements

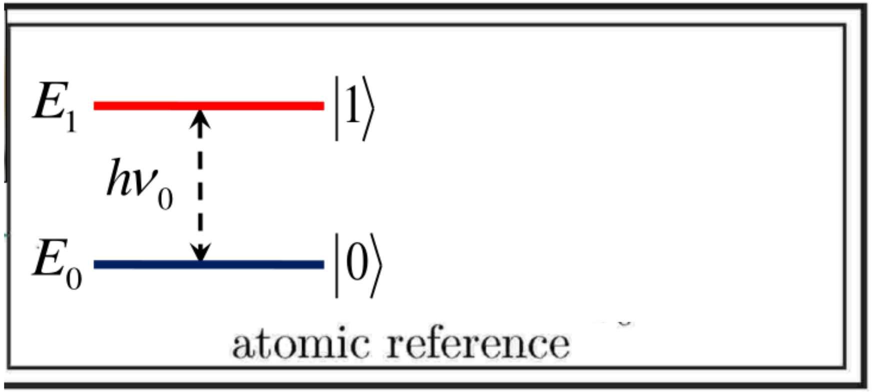
"Never measure anything but frequency!"

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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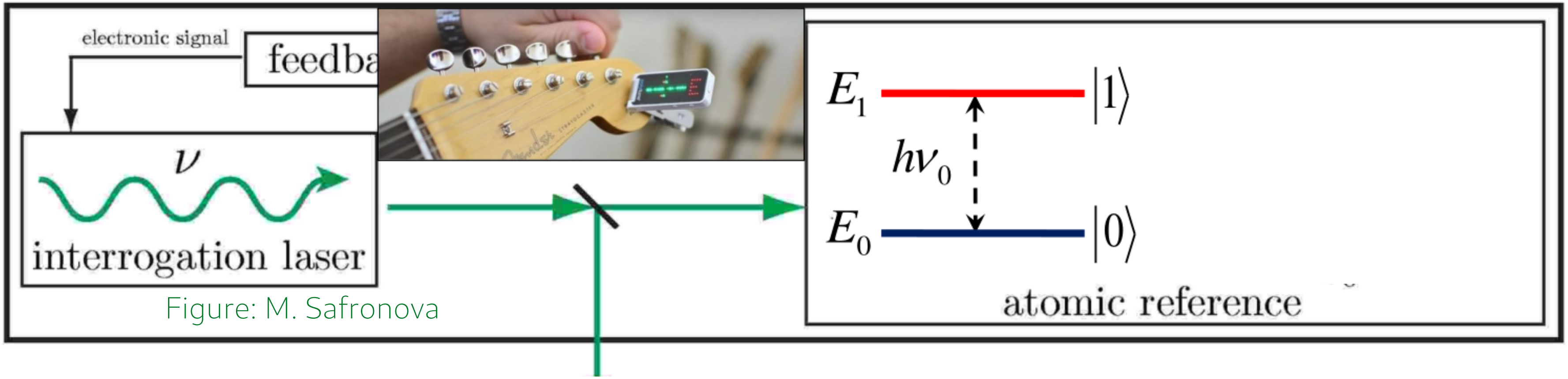

Figure: M. Safronova

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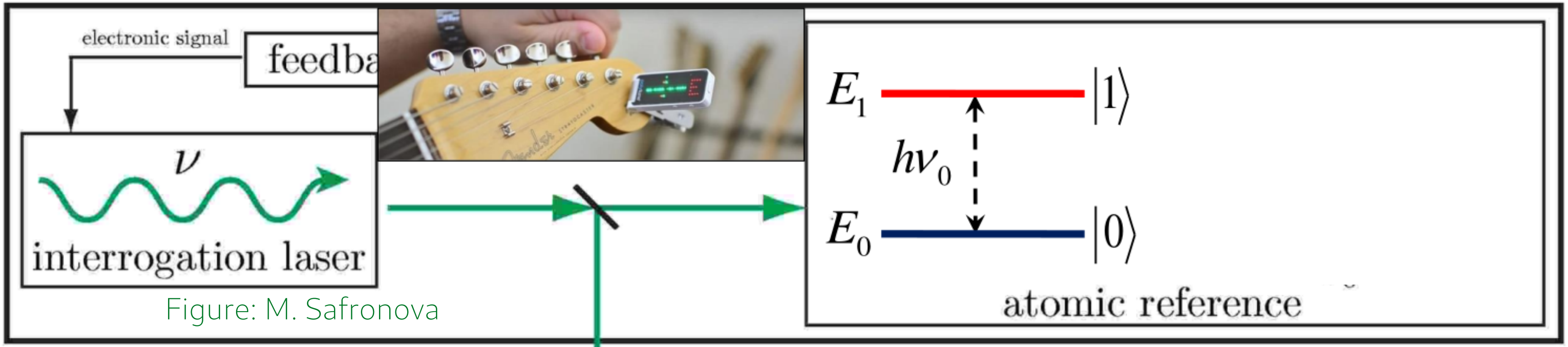

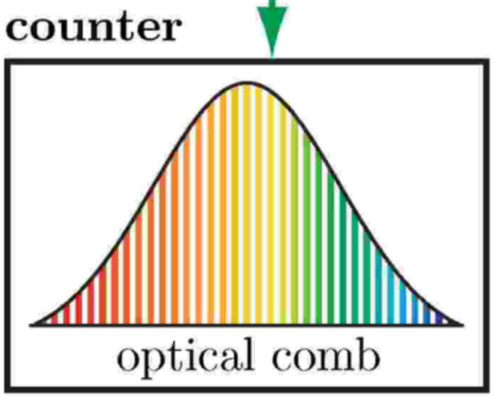

Figure: M. Safronova

J. Hall & T. Hänsch,
Nobel Prize 2005

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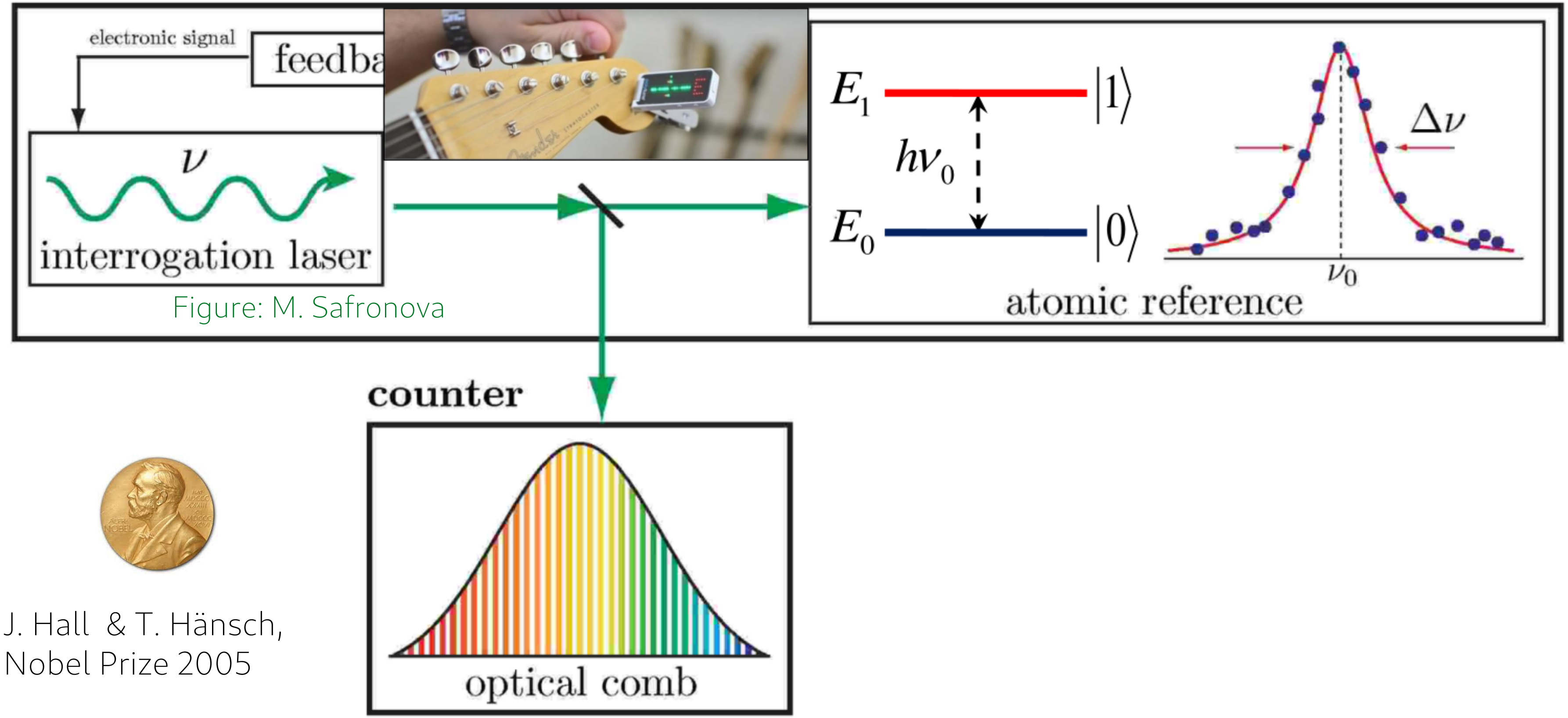

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Evolution of clock precision

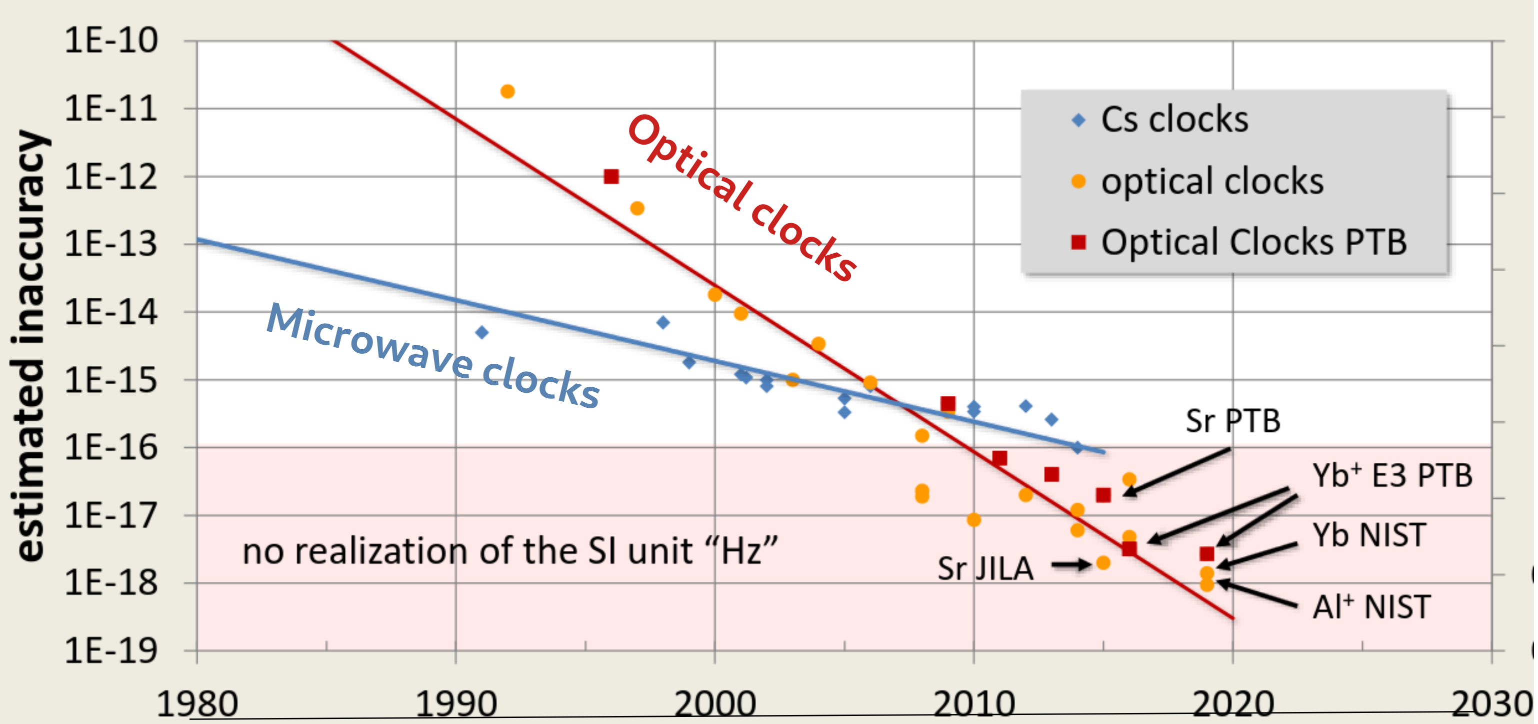

Figure adapted from P. Schmidt's talk at QT4HEP

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

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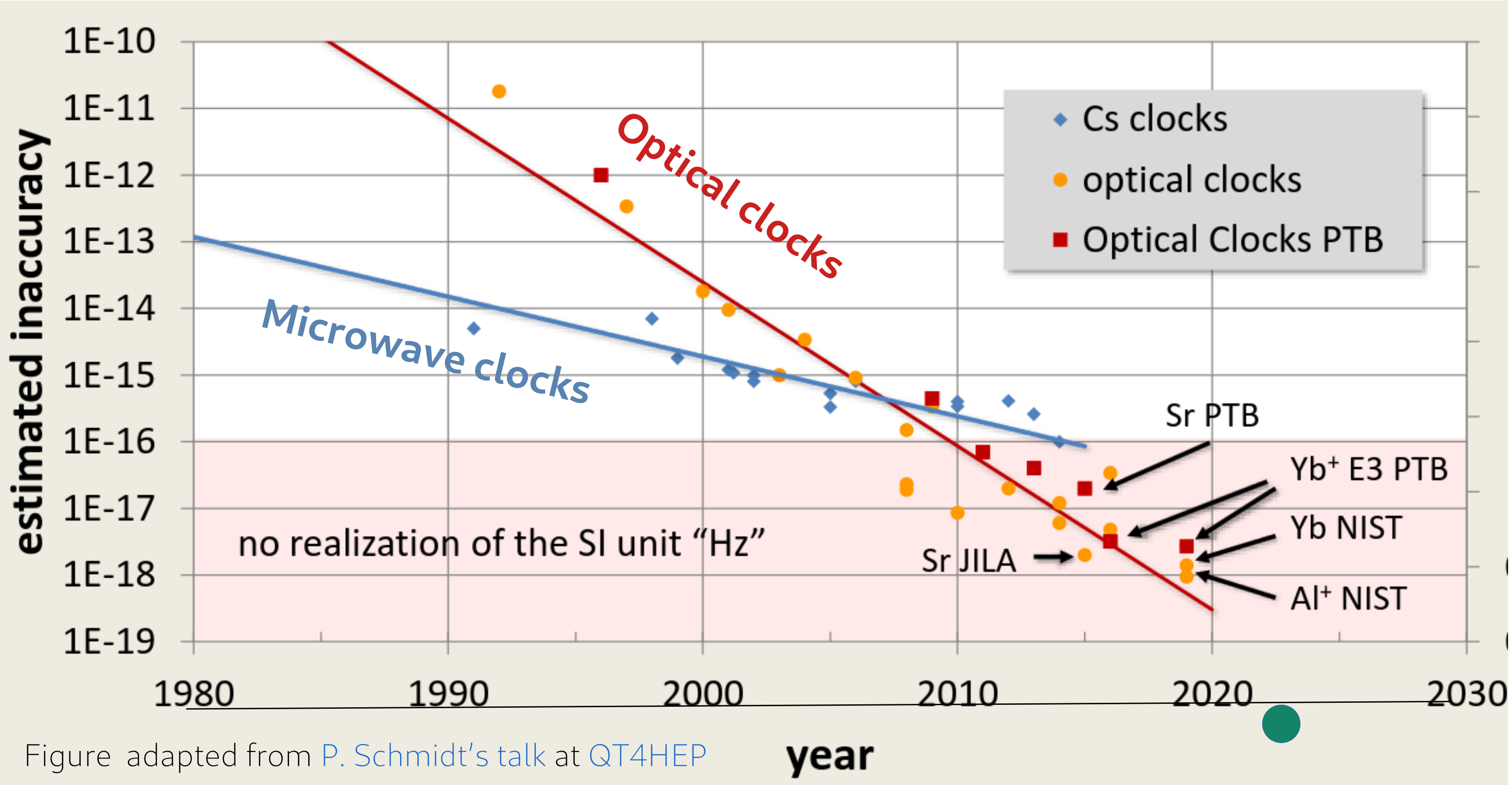

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The international journal of science / 17 February 2022

nature

SEEING RED

Submillimetre-scale gravitational redshift within an atomic clock

Explosive power The shocking science behind the Tongan volcanic eruption

Coronavirus Why has disability been left out of COVID discussions?

Sound connections Inner-ear anatomy affirms evolutionary tree of bats

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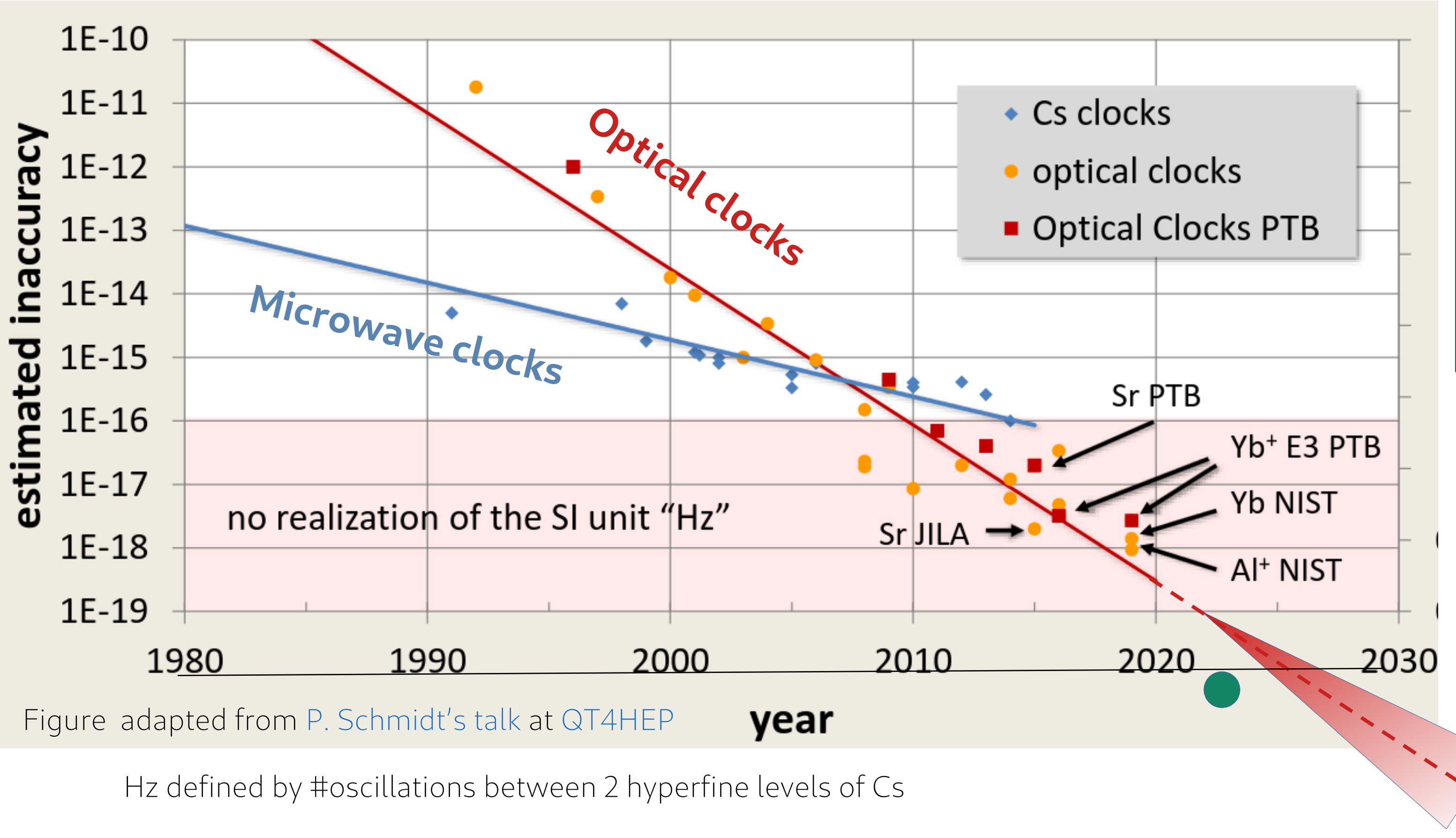

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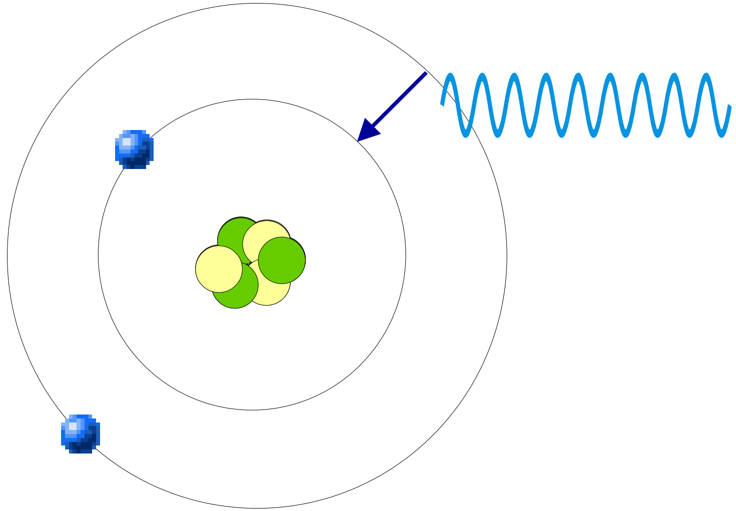
Outline

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



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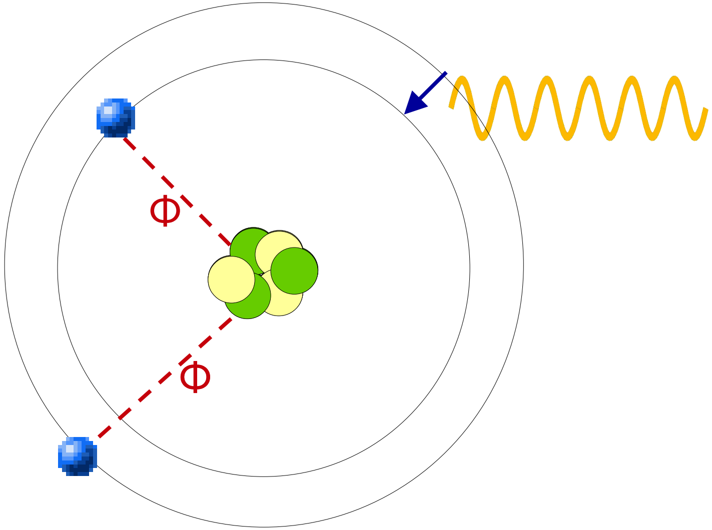

Challenge of theory-exp comparison

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

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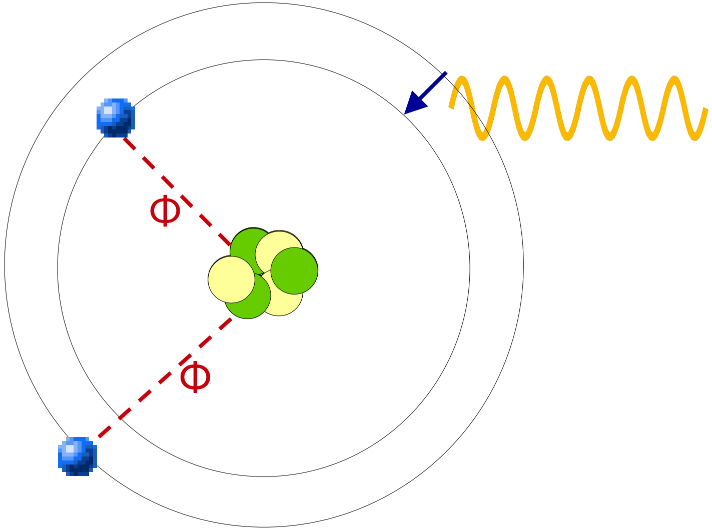

Data-driven atomic search for light scalar

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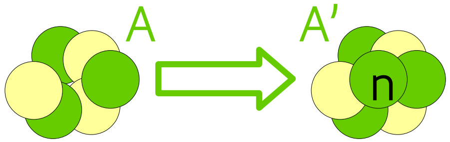
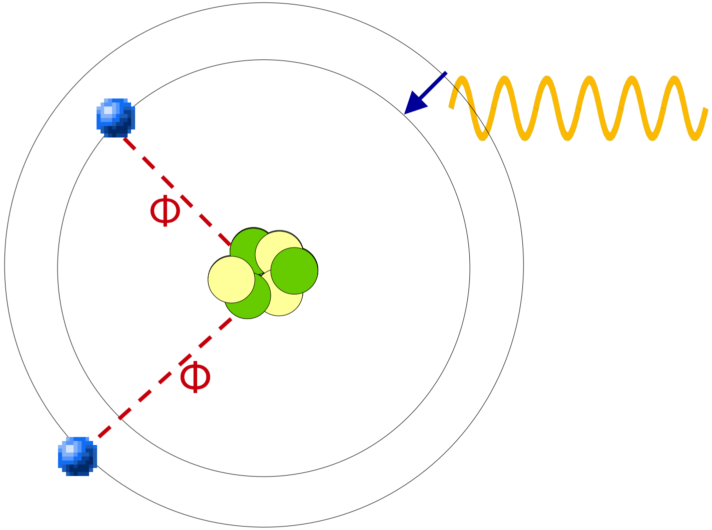
- Challenge: theory, nuclear uncertainties >> uncertainties of frequency measurements
- Our method: Measure 2 transitions, 3 isotope pairs very precisely



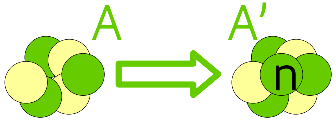


- Berengut, Budker, Delaunay, Flambaum, Frugiuele, EF, Grojean, Harnik, Ozeri, Perez, Soreq; PRL 120 (2018) 091801
- Solaro, Meyer, Fisher, Berengut, EF, Drewsen; PRL 125, 123003 (2020)

King plot of Isotope Shifts

Mass shift (MS) Field shift (FS)

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



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nuclear

Poorly known nuclear charge radius

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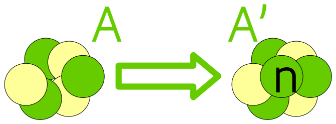

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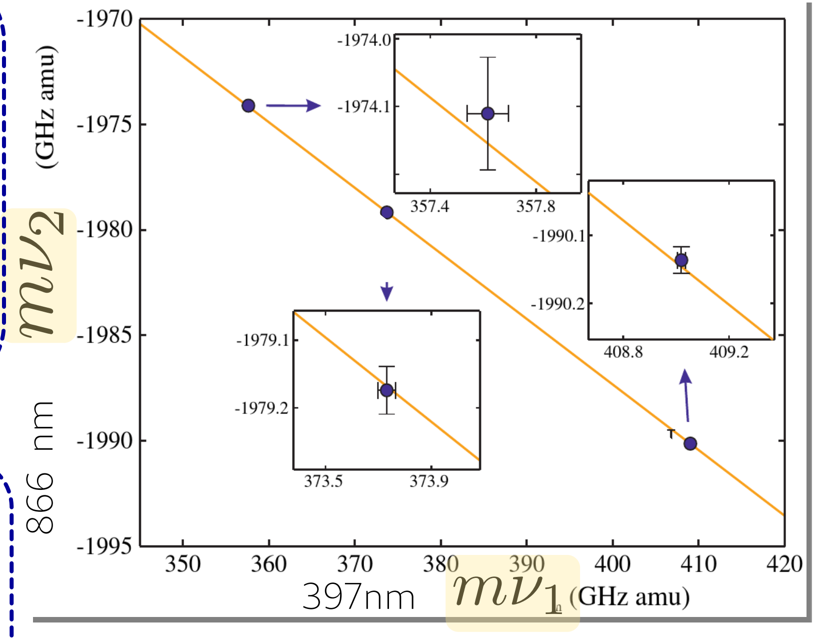
$i = 1, 2$

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

Linear King relation (at leading order):

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



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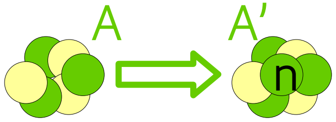

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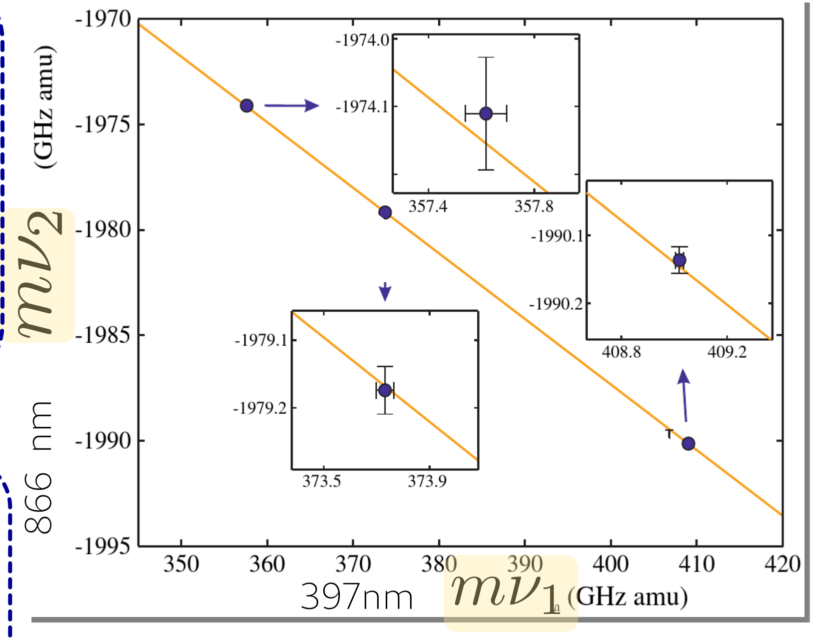

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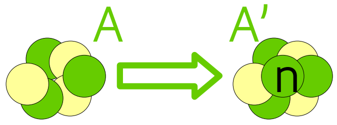

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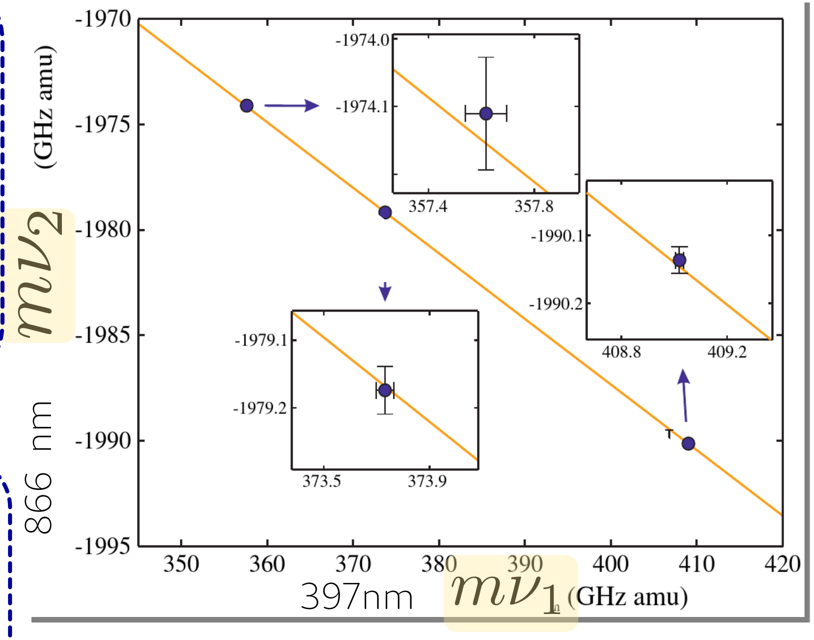

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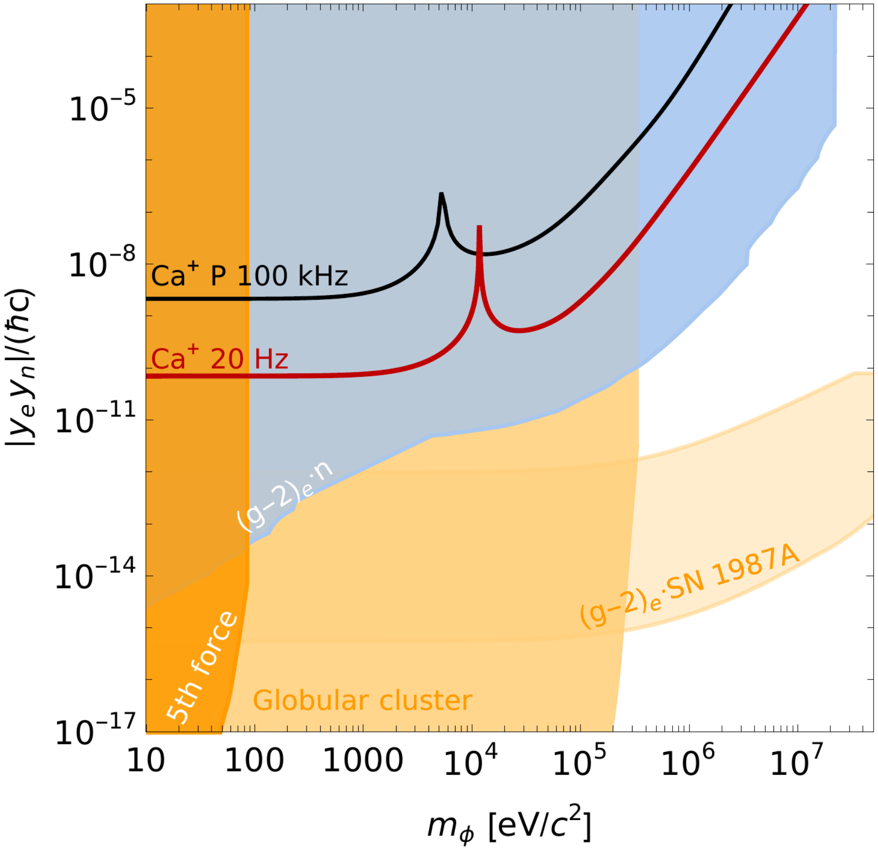
check if 3 points (= 3 isotope pairs) on straight line

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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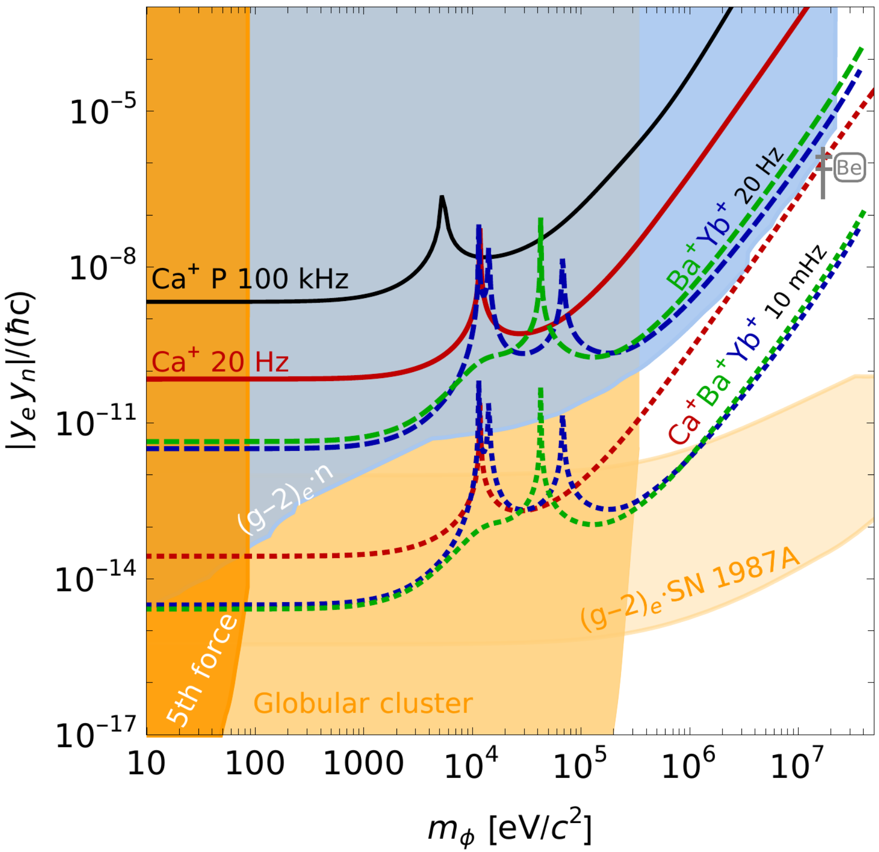

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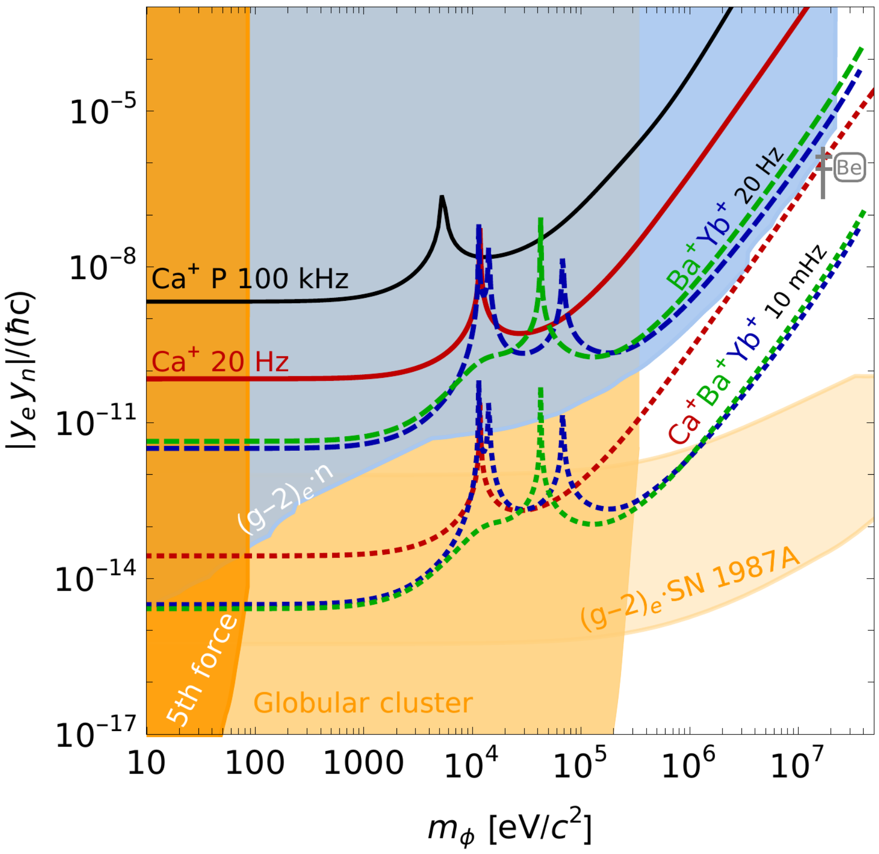

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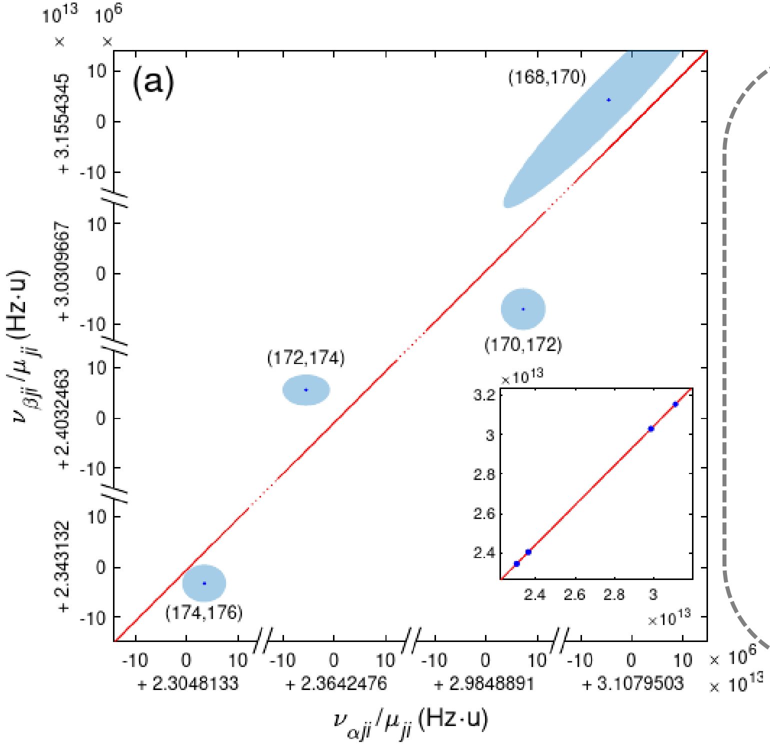
Particle model applications: B-L, dark photon, chameleon
Frugiuele, EF, Perez, Schlaffer '16

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, Mainz, PTB



- **3σ nonlinearity**
- Nuclear deformation?
- SM can induce nonlinearity at higher order
    - 2nd order mass & field shift
    - Nuclear polarizability, deformation

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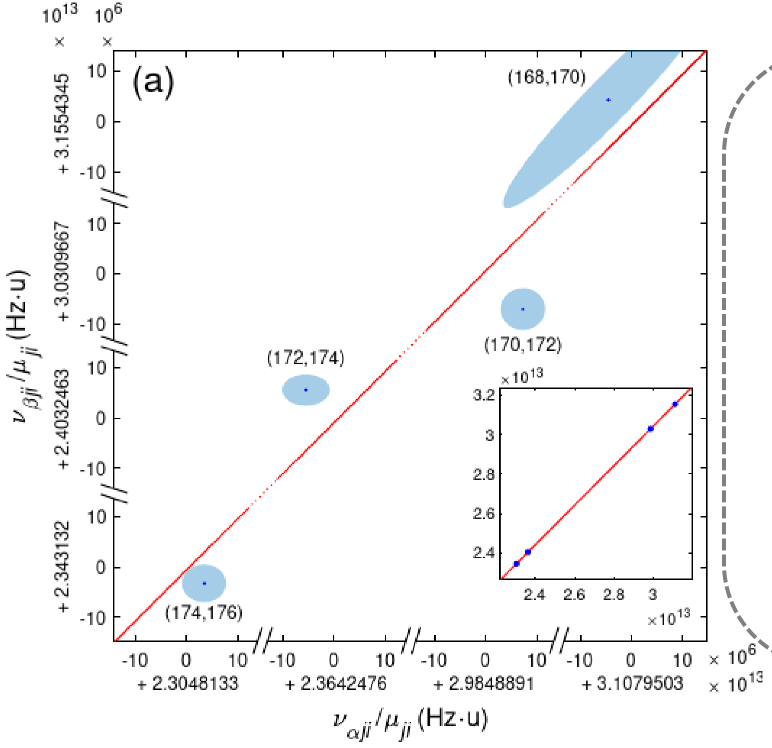


- 3σ nonlinearity
- Nuclear deformation?
- SM can induce nonlinearity at higher order
    - 2nd order mass & field shift
    - Nuclear polarizability, deformation

DECEMBER 4, 2020 FEATURE

Researchers observe what could be the first hints of dark bosons

by Ingrid Fadelli , Phys.org

BSM or nuclear physics?

Strategy: consider predicted SM NL and constrain residual NL

Generalized King plot

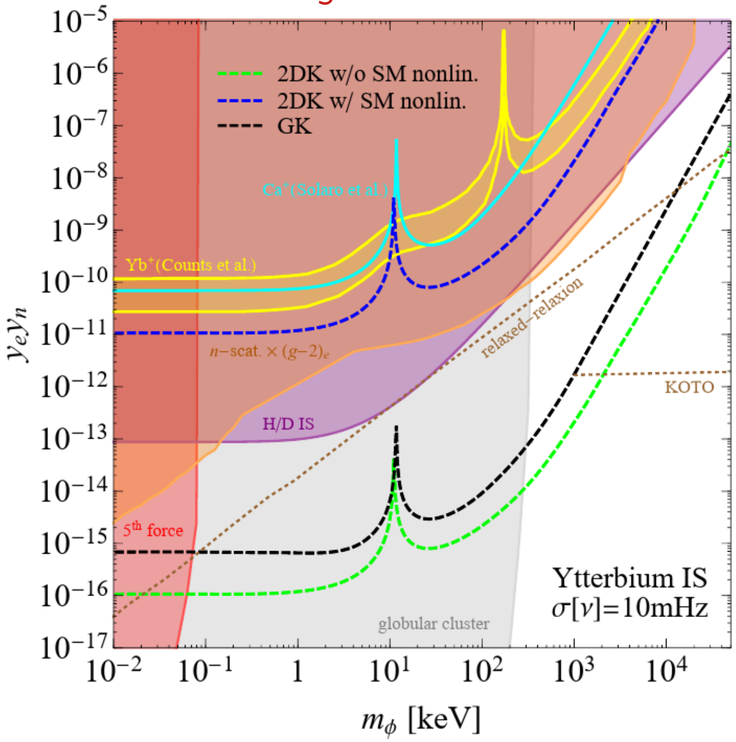
$$m\nu_i^a = K_i + \sum_{l=1}^{m-1} F_{il}\, m\lambda_{l,a} + \alpha_{\mathrm{NP}} X_i h_a$$

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



→ see also C. Delaunay's QTI talk

Generalized King plot

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

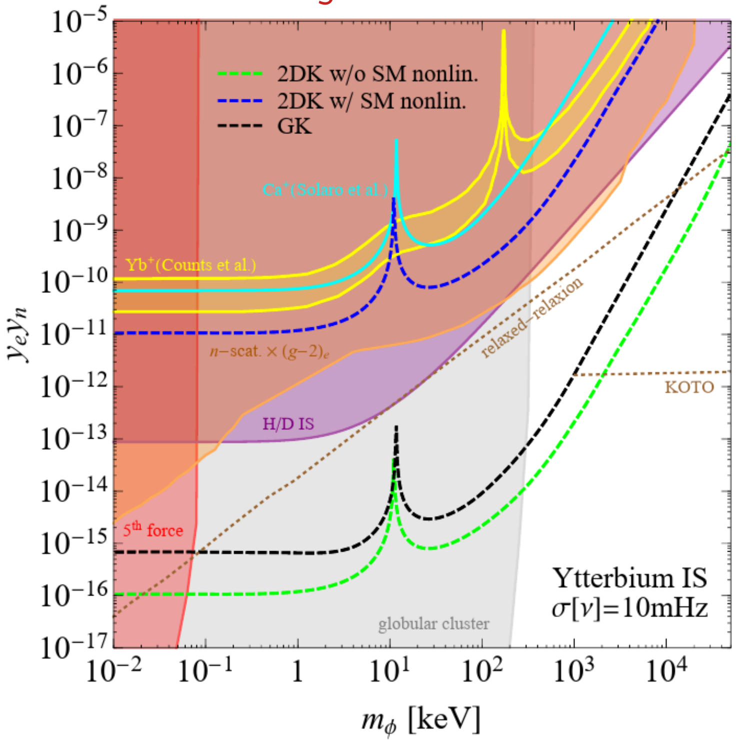
- replace unknowns by additional isotope shifts
- Number of clock transitions, isotopes and higher-order terms has to match

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

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

[Berengut, Delaunay, Geddes, Soreq '20]

Higher-orders included



→ see also C. Delaunay's QTI talk

Highly Charged Ions (HCI)

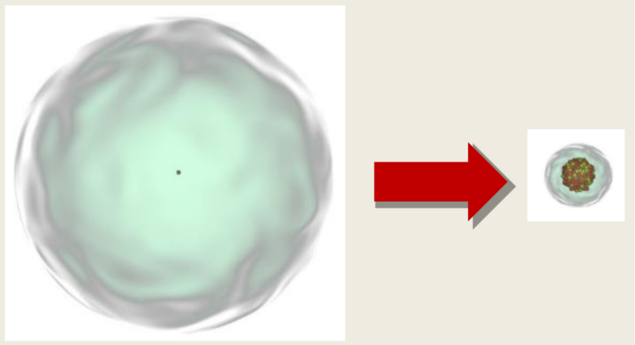


Figure: P. Schmidt

- 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

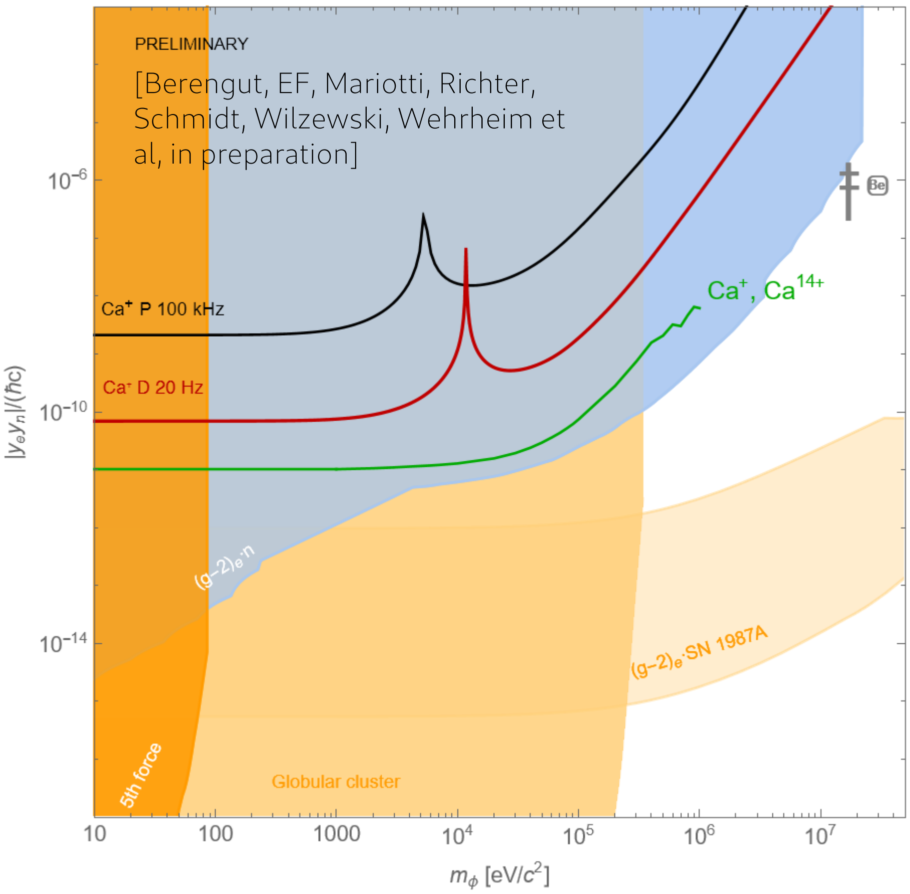
HCI clock: New Physics bound

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

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

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

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


PRELIMINARY

[Berengut, EF, Mariotti, Richter, Schmidt, Wilzewski, Wehrheim et al, in preparation]

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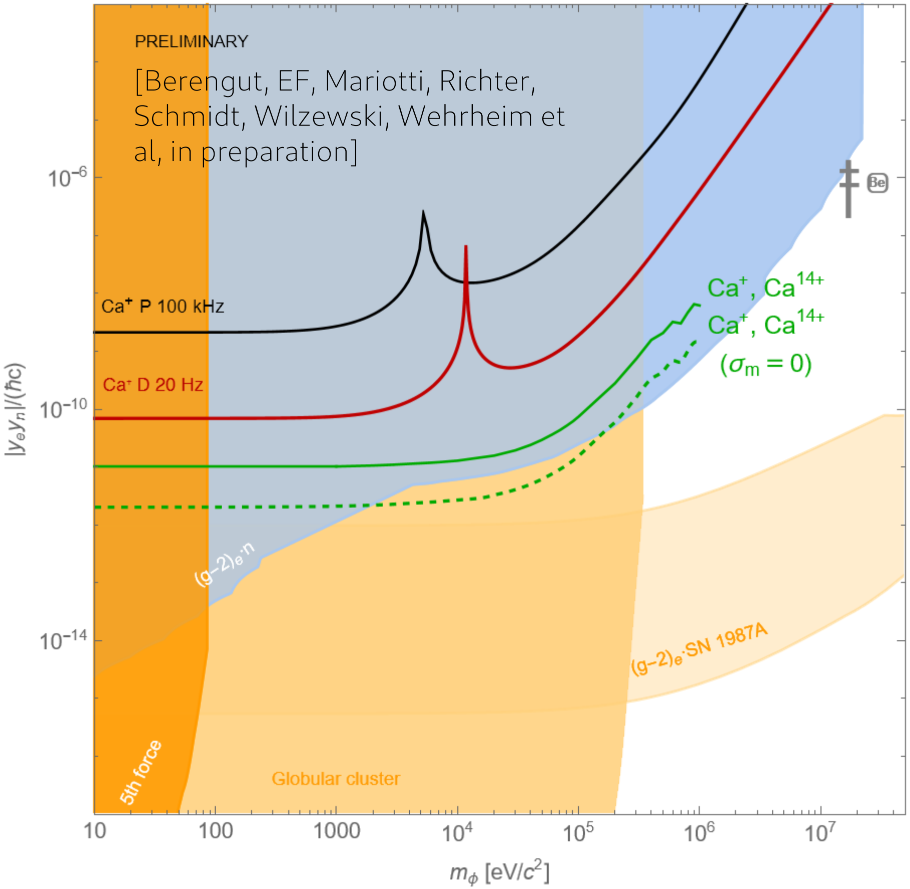
NP sensitivity limited by isotope masses

→ MPIK Heidelberg (K. Blaum's group) will improve precision

→trade isotope masses 3rd frequency

→ A. Mariotti's & J. Richter's QTI talk tomorrow



PRELIMINARY

[Berengut, EF, Mariotti, Richter, Schmidt, Wilzewski, Wehrheim et al, in preparation]

Isotope shifts about to test new parameter space

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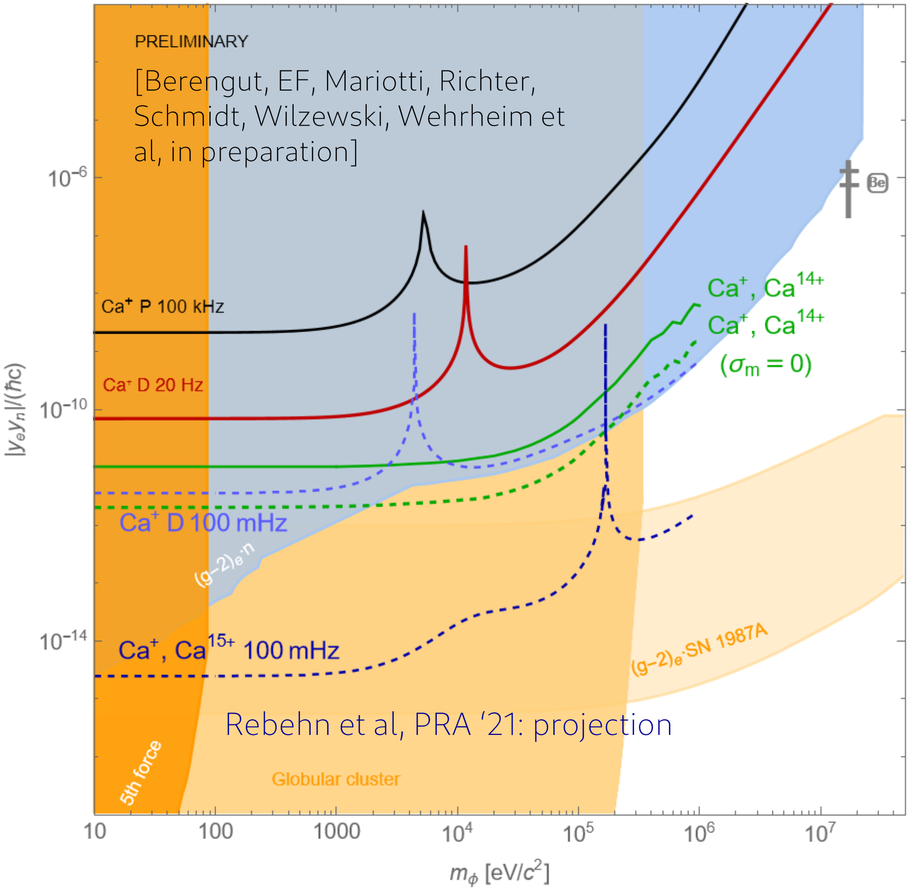


PRELIMINARY

[Berengut, EF, Mariotti, Richter, Schmidt, Wilzewski, Wehrheim et al, in preparation]

Rebehn et al, PRA '21: projection

Variation of fundamental constants

Antypas et al, Snowmass 2203.14915

Scalar ultralight DM ϕ

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

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

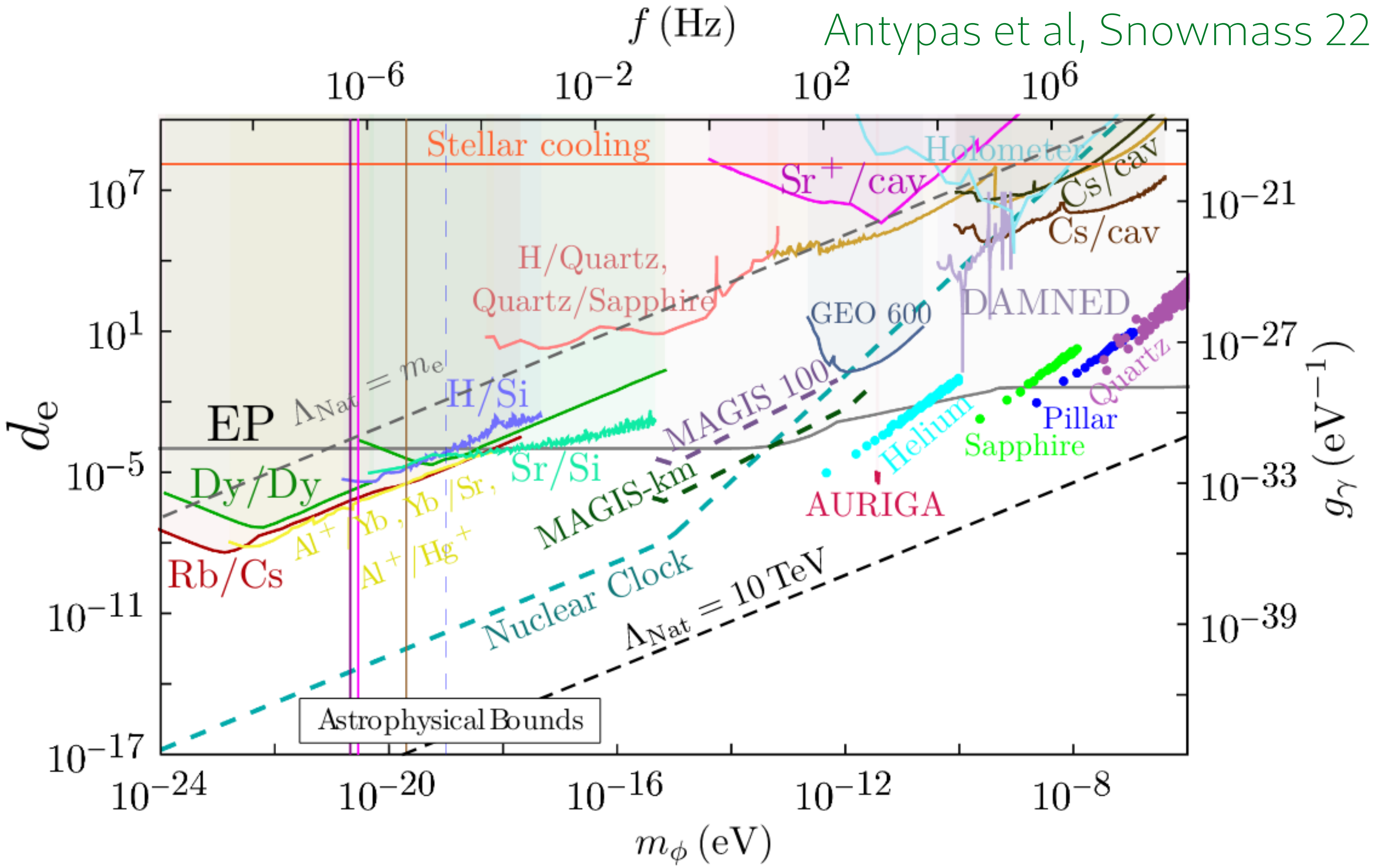
$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

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

Ultralight scalar DM-photon coupling

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

Antypas et al, Snowmass 2203.14915

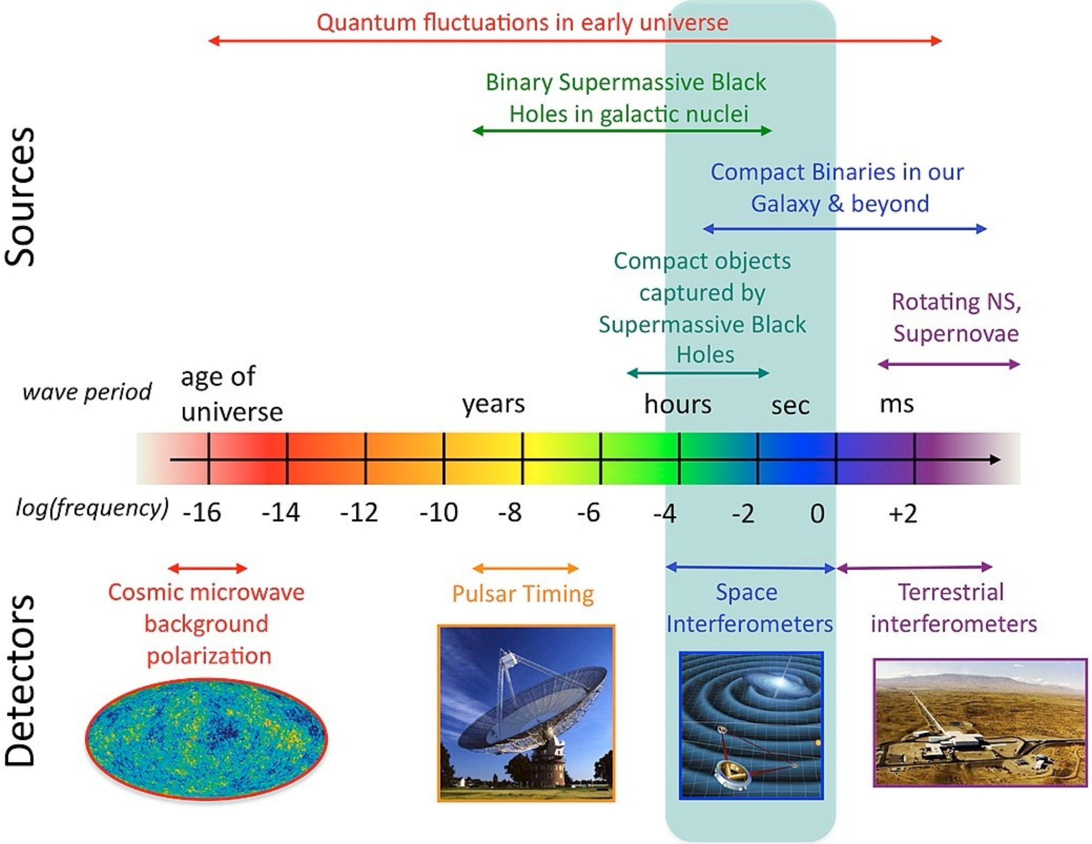


Outline

Domcke, Kopp, EF, Bringmann 2304.10579

4) High-frequency GWs with optical photons

GW sources and detectors



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

wave period: age of universe, years, hours, sec, ms

log(frequency): -16, -14, -12, -10, -8, -6, -4, -2, 0, +2

Detectors

Cosmic microwave background polarization

Pulsar Timing

Space Interferometers

Terrestrial interferometers

Image: NASA

Sensitivity to GW sources

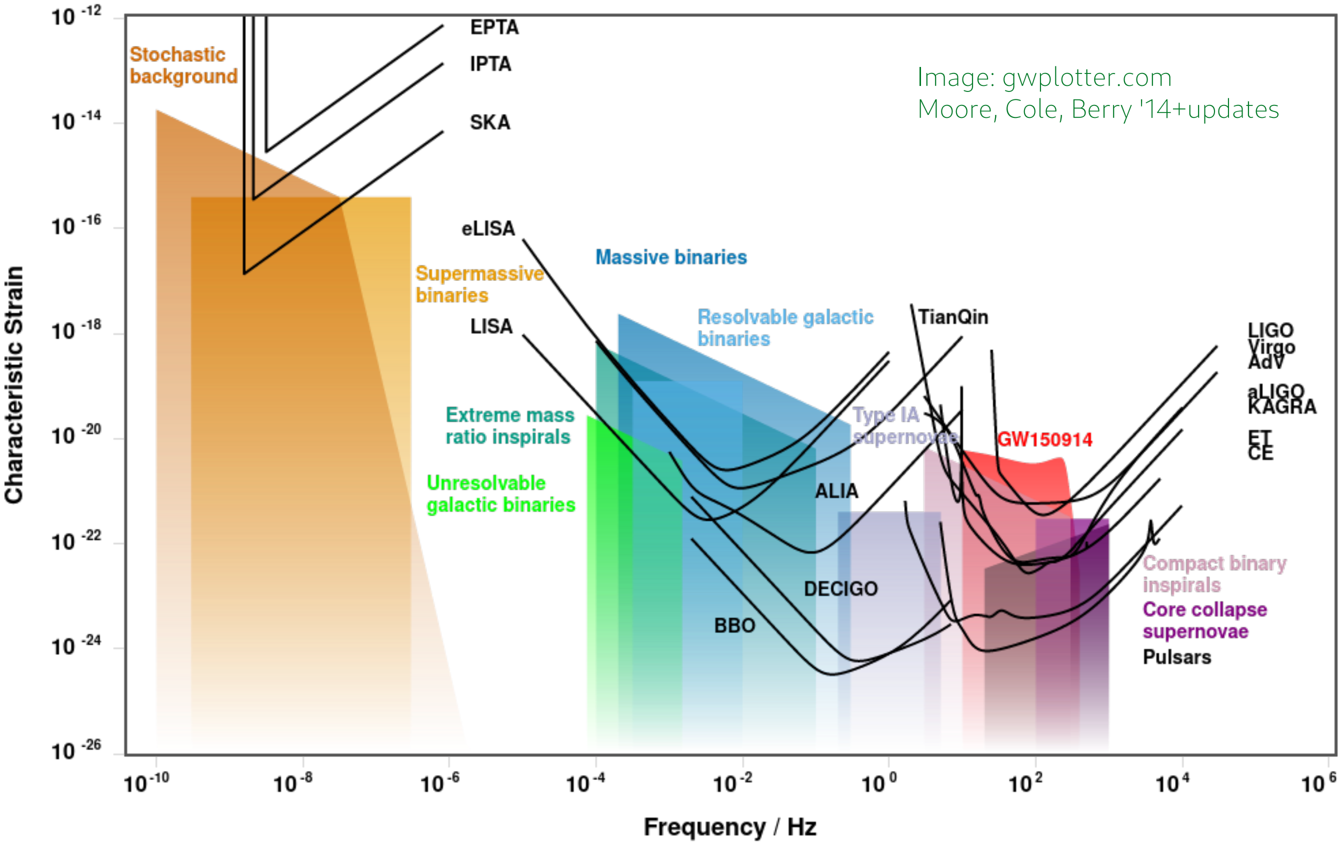


Image: gwplotter.com
Moore, Cole, Berry '14+updates

Sensitivity to GW sources

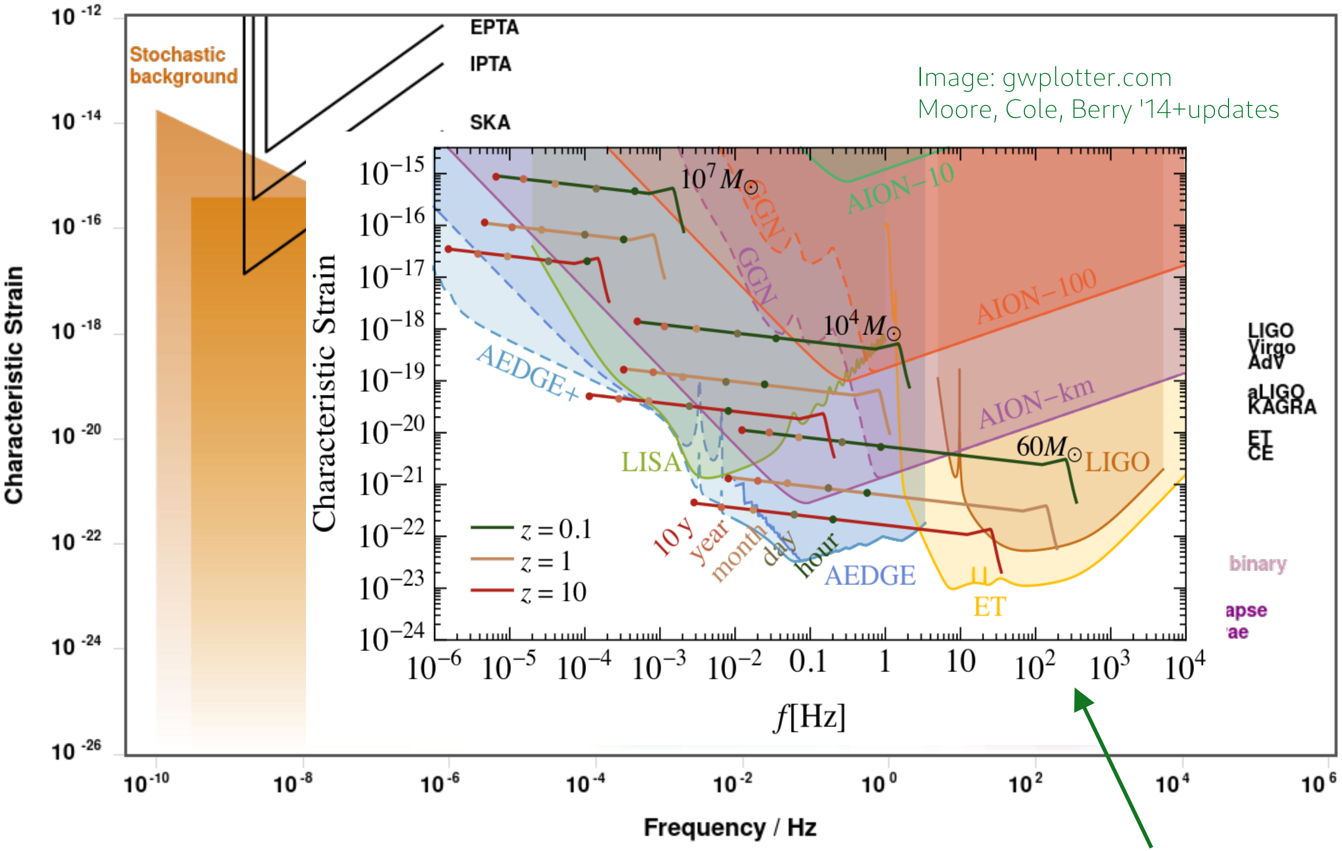


Image: gwplotter.com
Moore, Cole, Berry '14+updates

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

Atom Interferometers sensitive to mid-frequency GWs

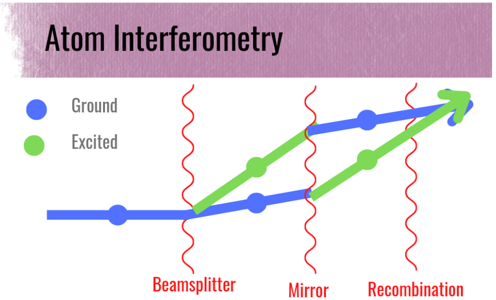


Image:
H. Banks

Measure phase difference between matter waves

As a GW Detector:

GW modifies distance between 2 atom interferometers → phase shift

Pushing towards high frequencies

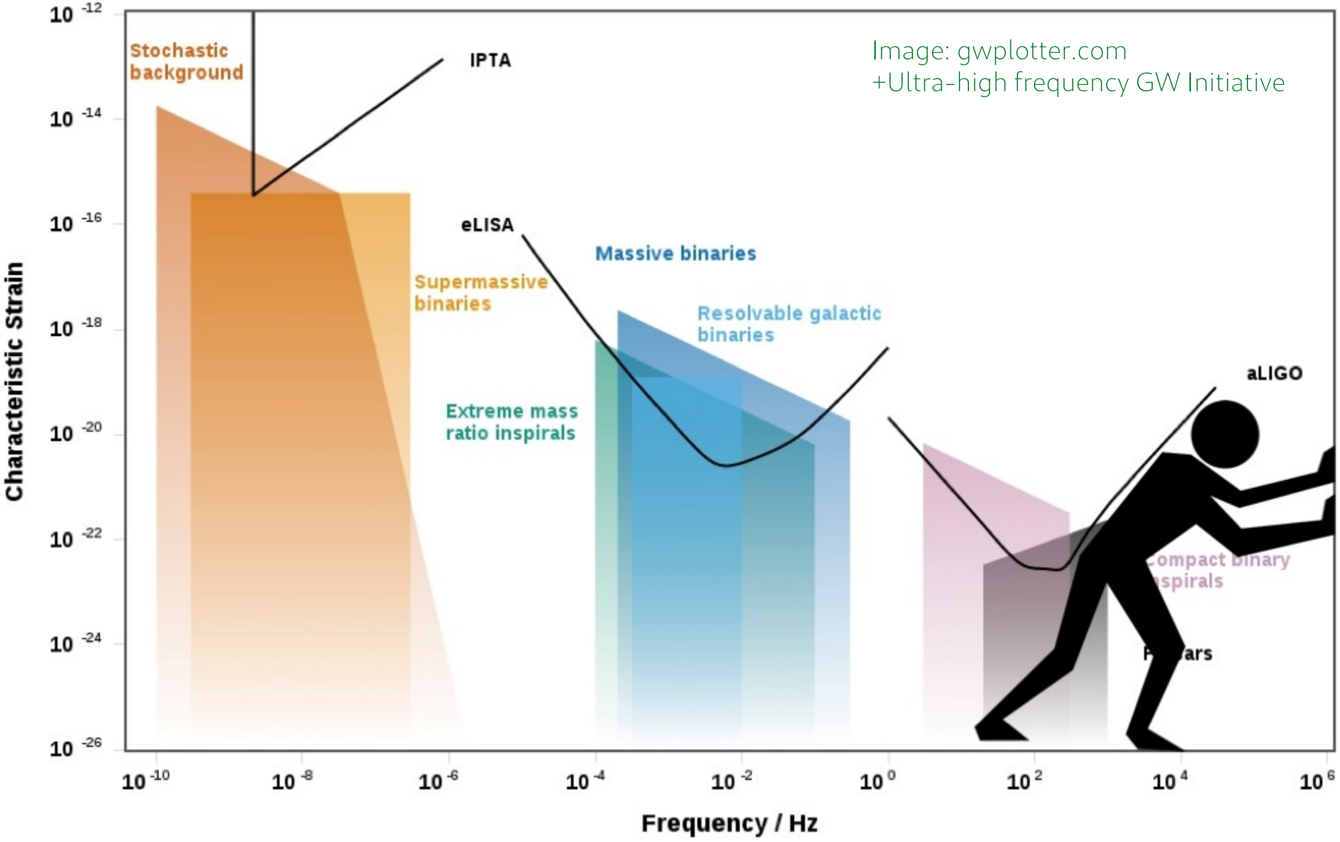


Image: gwplotter.com
+Ultra-high frequency GW Initiative

GW sources and detectors

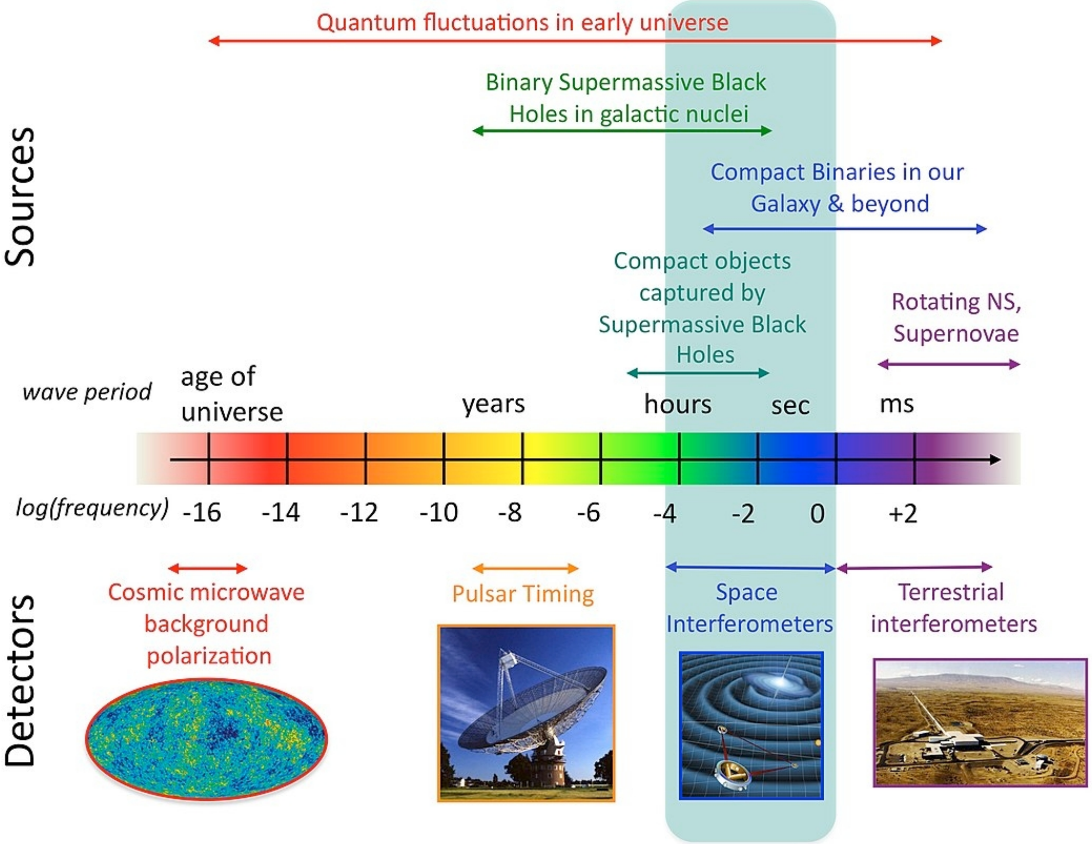


Image: NASA

Any sources for high-frequency GWs expected?

If yes, how can one detect them?

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**

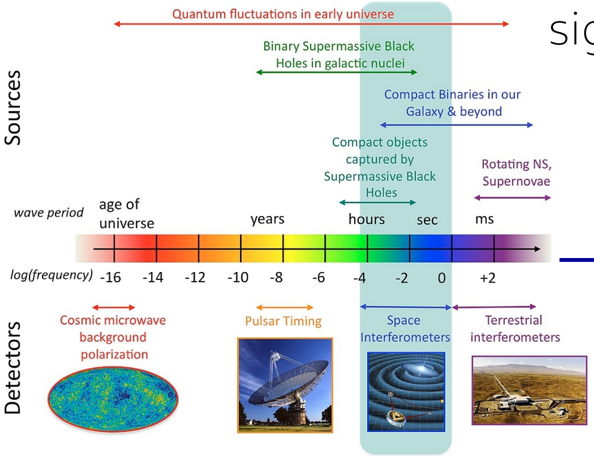


Image: NASA

GW sources: high frequency

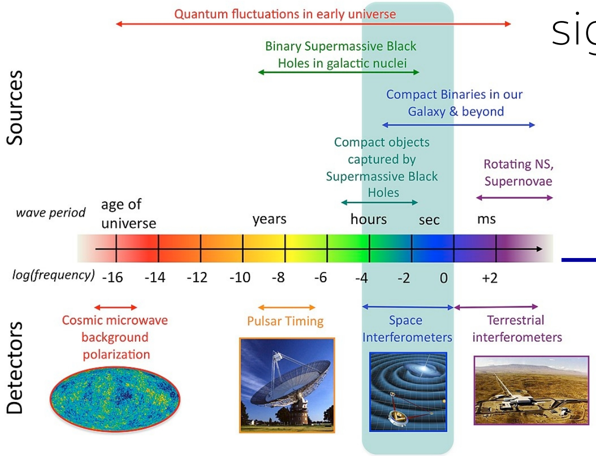


Image: NASA

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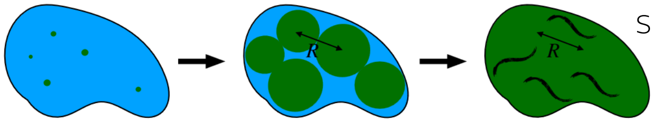
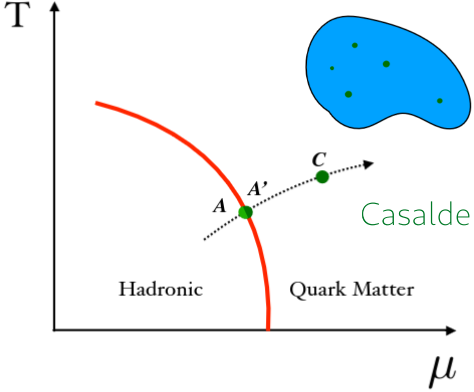
Potential sources:

- **1st order phase transition** in Early Universe at T>> 100 GeV
- **Primordial Black Hole mergers**
- **Phase transition in neutron star mergers** if QCD has 1st order PT, nuclear matter compressed during merger → MHz GW

Bubble nucleation collision longlived (1ms) soundwaves





Casalderrey-Solana, Mateos, Sanchez-Garitaonandia '22

GW sources: high frequency

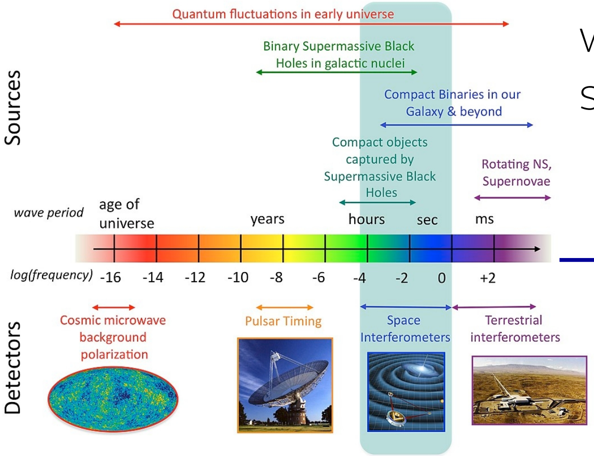


Image: NASA

Ultrahigh frequency >10 kHz:

no known astrophysical sources with large enough signal

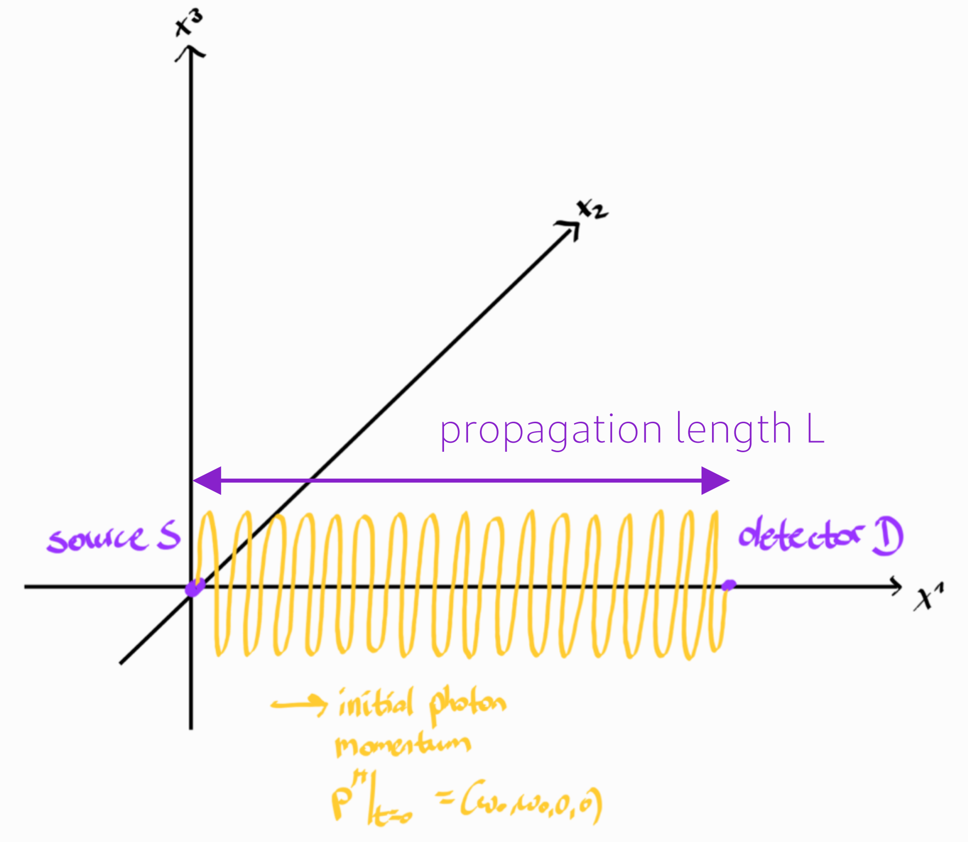
Potential sources:

- **1^{st} order phase transition** in Early Universe at T>> 100 GeV
- **Primordial Black Hole mergers**
- **Phase transition in neutron star mergers** if QCD has 1^{st} order PT, nuclear matter compressed during merger → MHz GW

Searches and proposals:

- Interferometers
- Levitated sensors
- Radio cavities

Photon in gravitational field

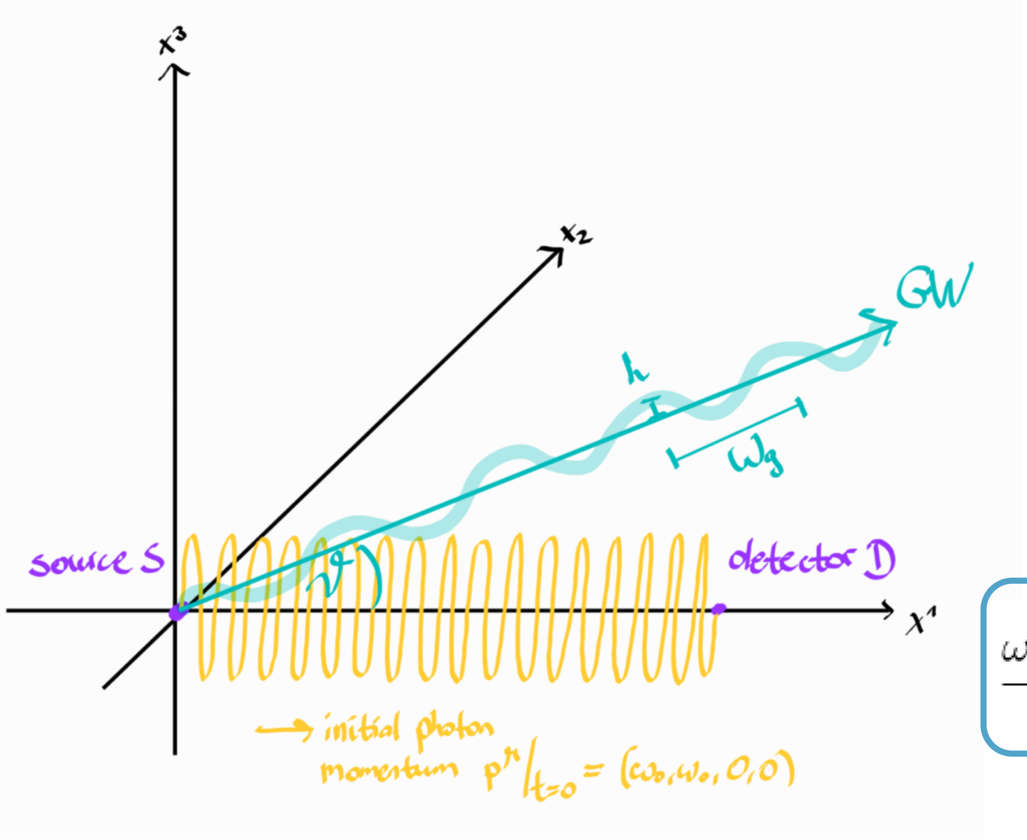


Goal: compare frequency of photon measured by S and D

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

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

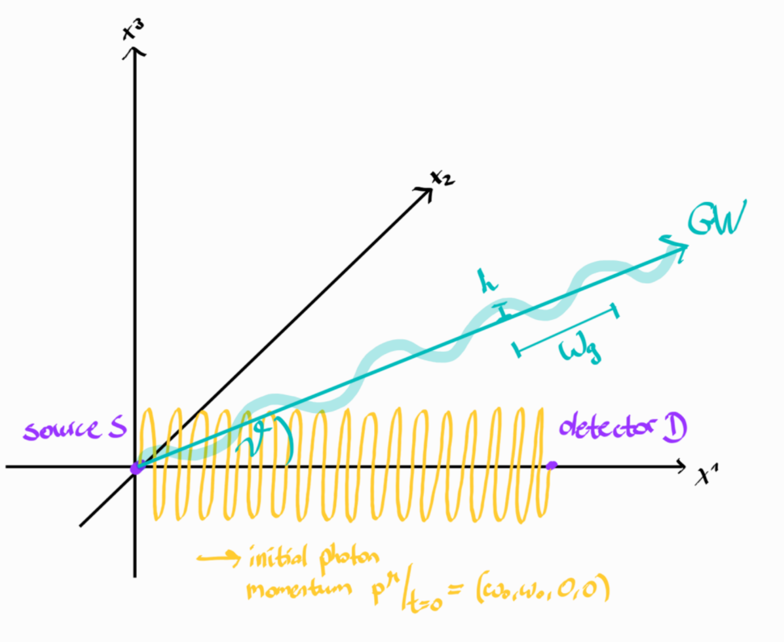
~h (GW strain)

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

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

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** $h^{TT}_{\mu 0} = 0\,, \qquad \partial^i h^{TT}_{ij} = 0\,, \qquad \eta^{ij} h^{TT}_{ij} = 0$
  where observers at rest remain at rest



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

Plane wave

Frequency shift by GW (in + polarization)

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

Rigid ruler – PD frame

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

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

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

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$$\left. + \left(\frac{1}{2}\boxed{\omega_g^2 L^2} - 1\right)\cos(\omega_g L + \varphi_0)\right\}$$

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

☒ no material is perfectly rigid at high frequencies!

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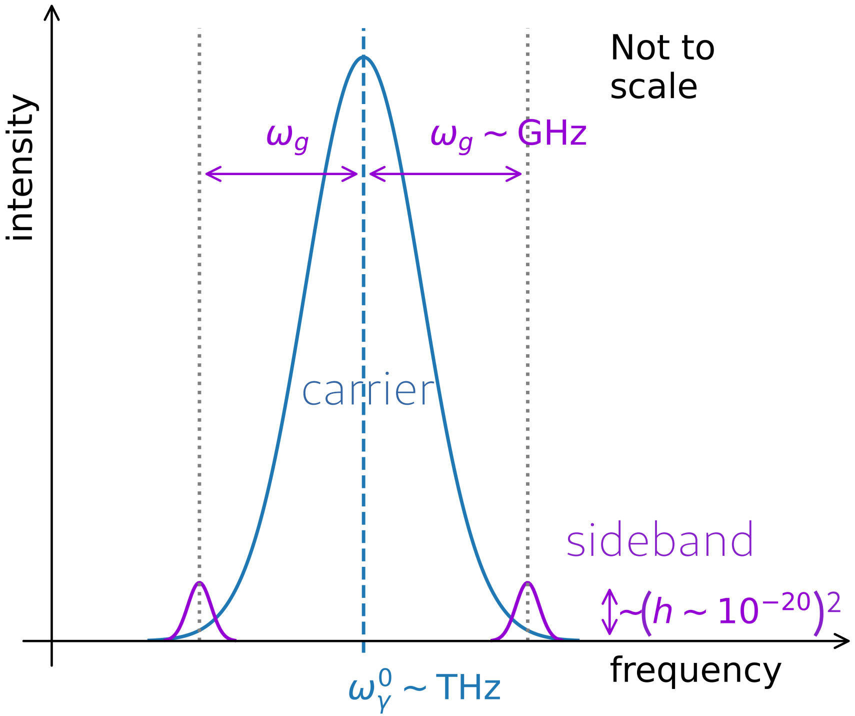
Enhanced sensitivity for large $\omega_g L \gg 1$?

❌ no material is perfectly rigid at high frequencies!

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

Detection: 1) Sidebands



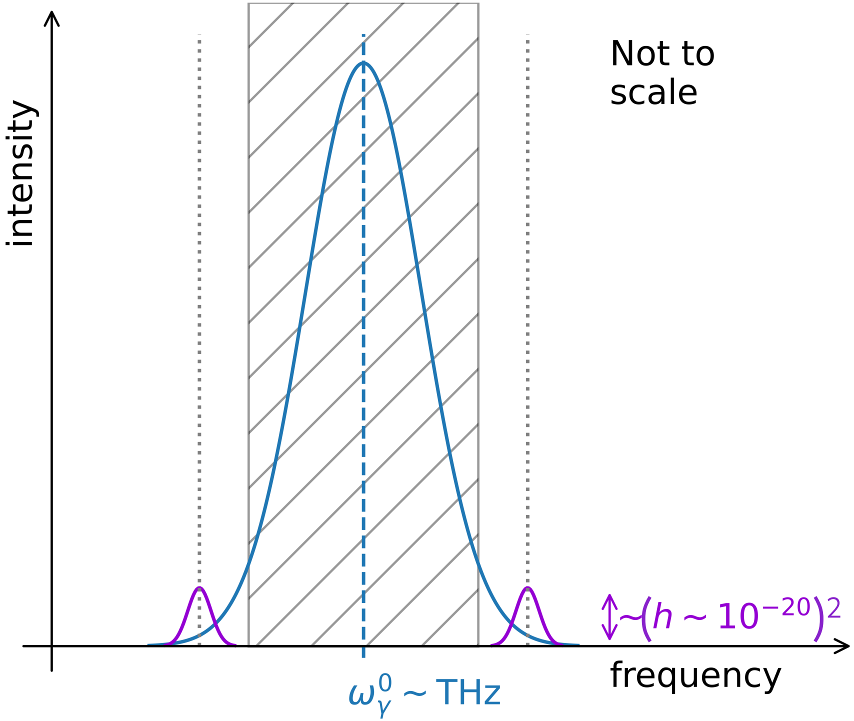
- Naive expectation was: GW changes photon frequency
- Instead: **tiny sidebands**
    - separated from carrier (original photon frequency) by **GW frequency** ω_g
    - suppressed by the **GW amplitude** $h^2 \sim 10^{-40}$

⇨ Advantage for high-frequency GWs

Still: tails from intense carrier line can hide the sidebands

⇨ How to make the sidebands detectable?

Detection: 1) Sidebands



Idea: design **filter** to cut out the intense carrier line
→ **direct detection of sidebands**

→ need to detect photons above background

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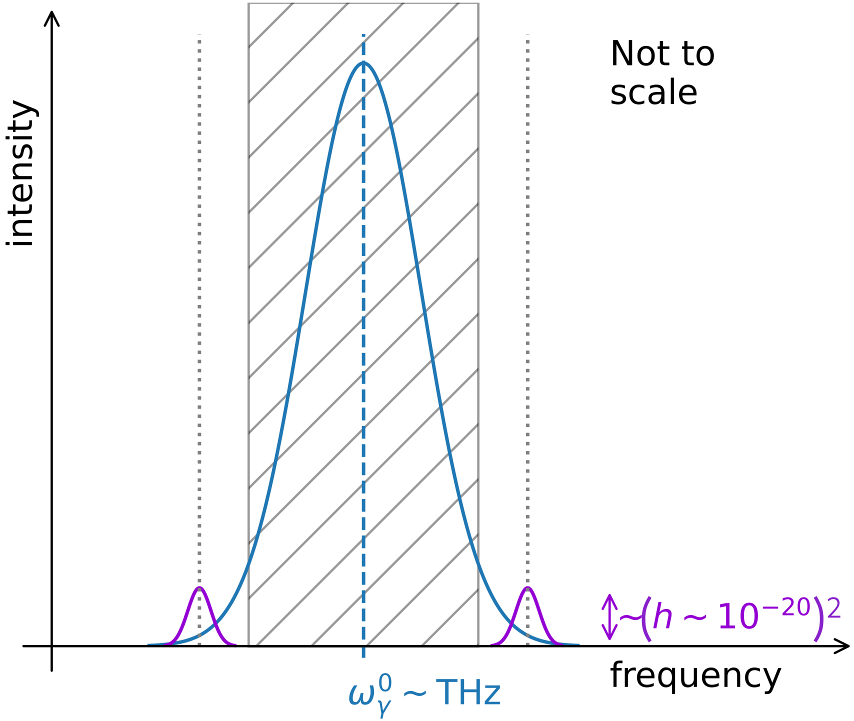

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  - → modulate carrier line? (further investigation)

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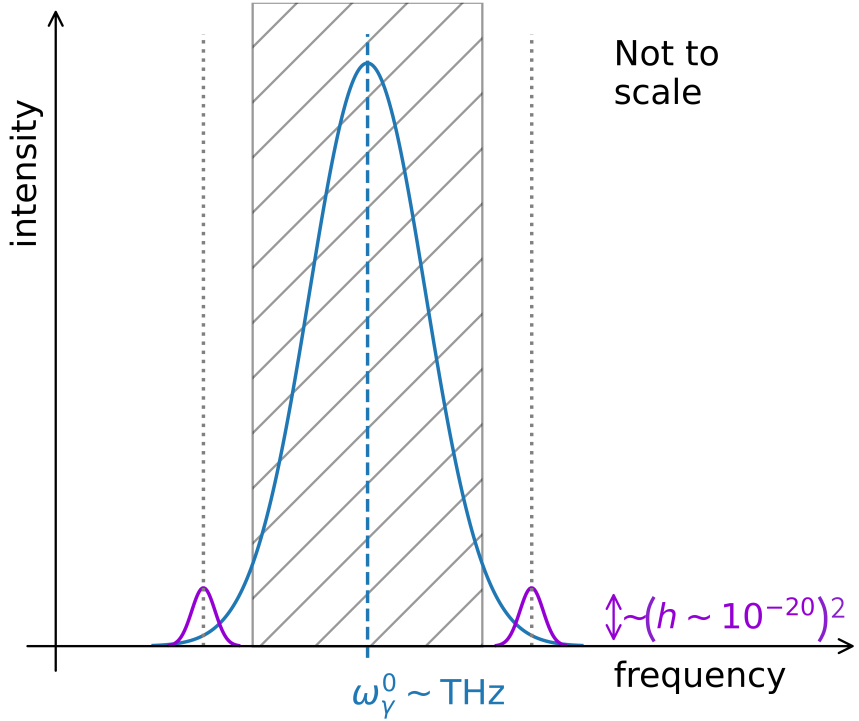

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- **Narrow filter** of bandwidth $\Delta\lambda$ and suppression of carrier $\alpha_T \ll 1$
  - Optical cavity tuned to sideband
    PTB: finesse 500,000, L=30cm, $\Delta\lambda = \mathrm{kHz}$

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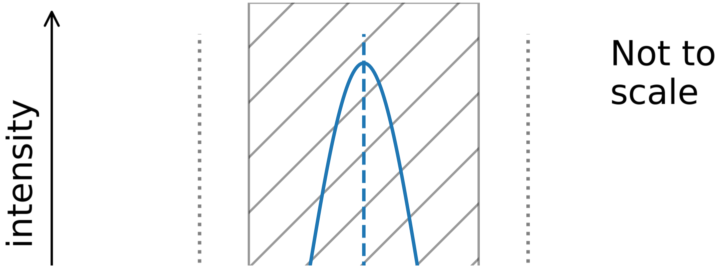

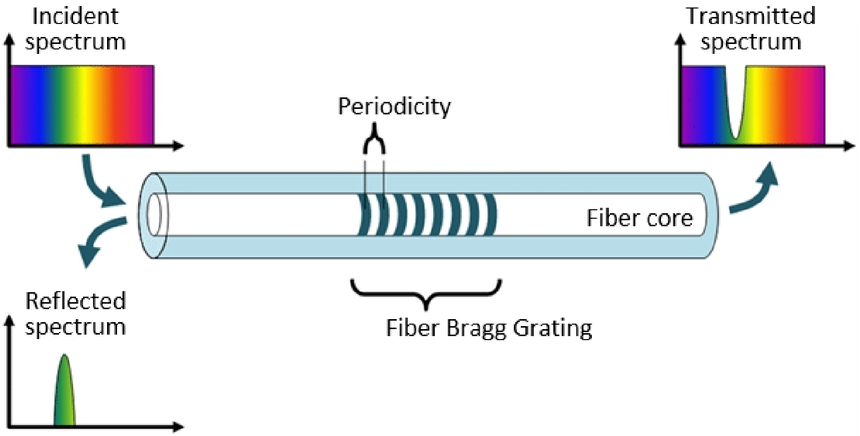

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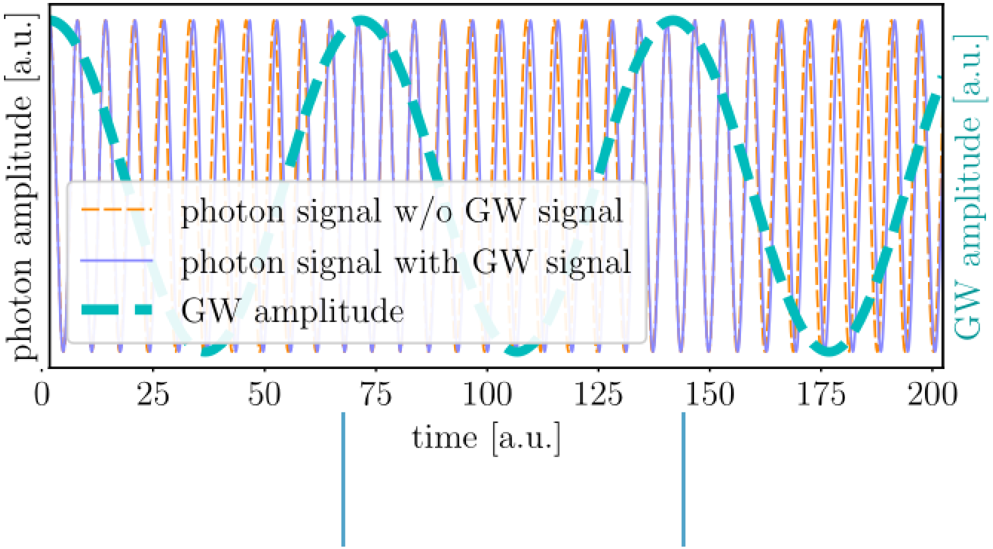
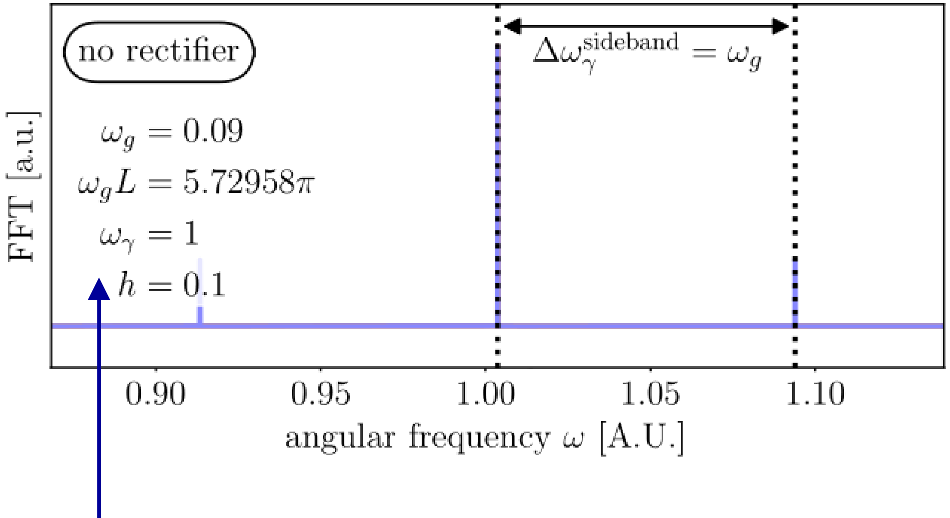
  - Fiber Bragg Grating

Detection: 2) Optical clocks

Original setup:





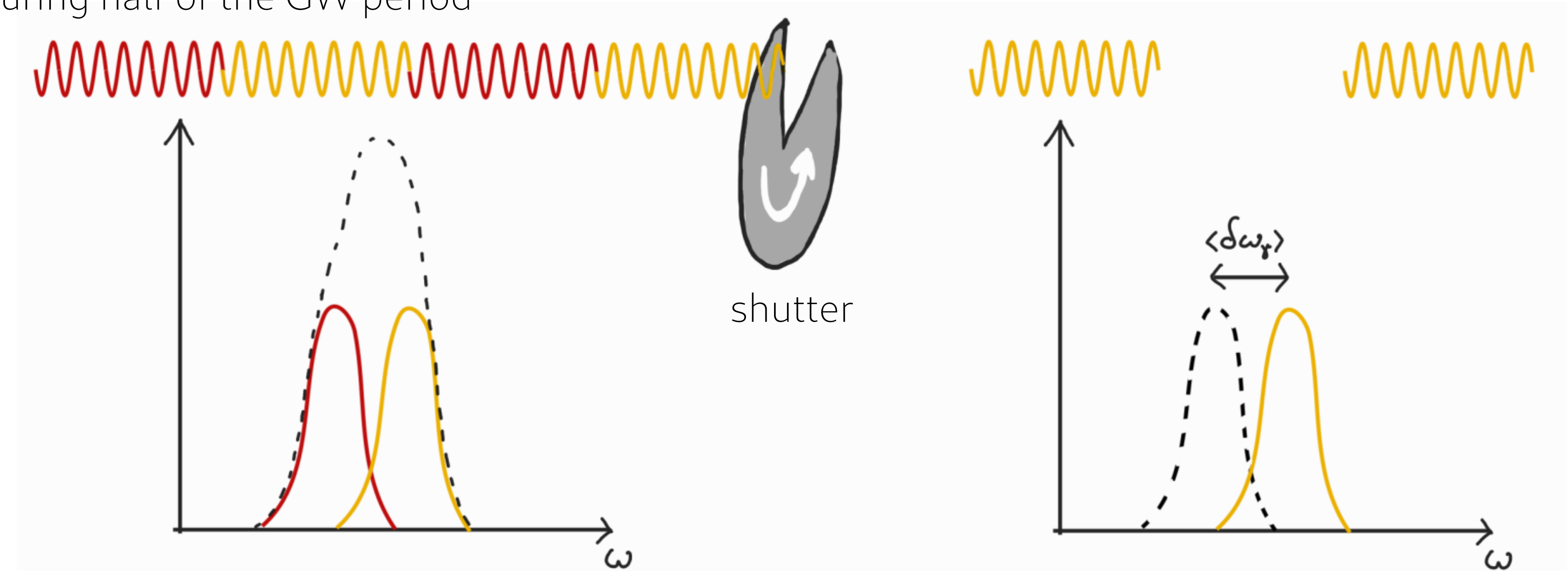
Parameters chosen for illustration purposes only

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

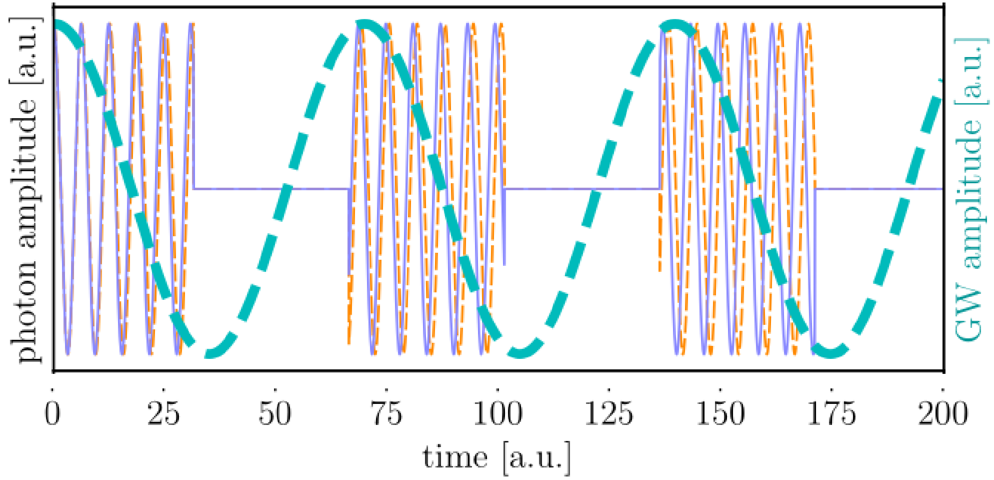


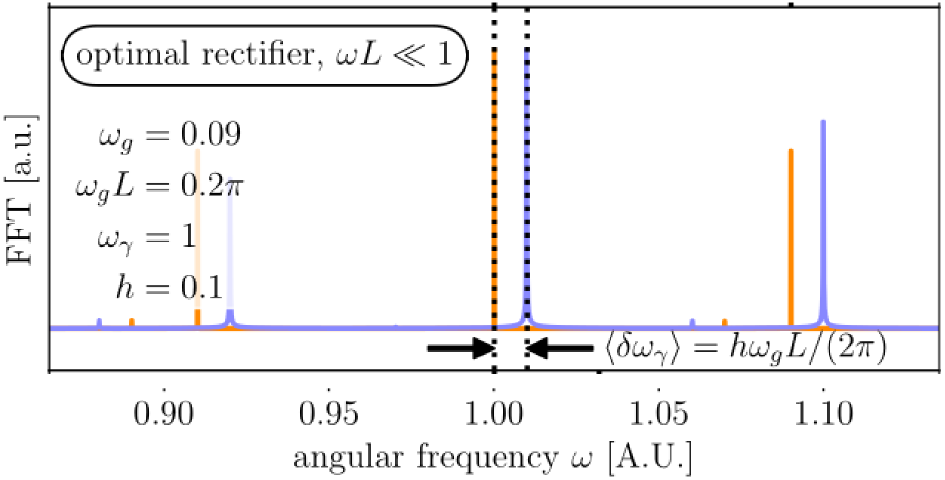
Photon net frequency shift detectable by Ramsey spectroscopy

Rectifier: small ωL

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

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





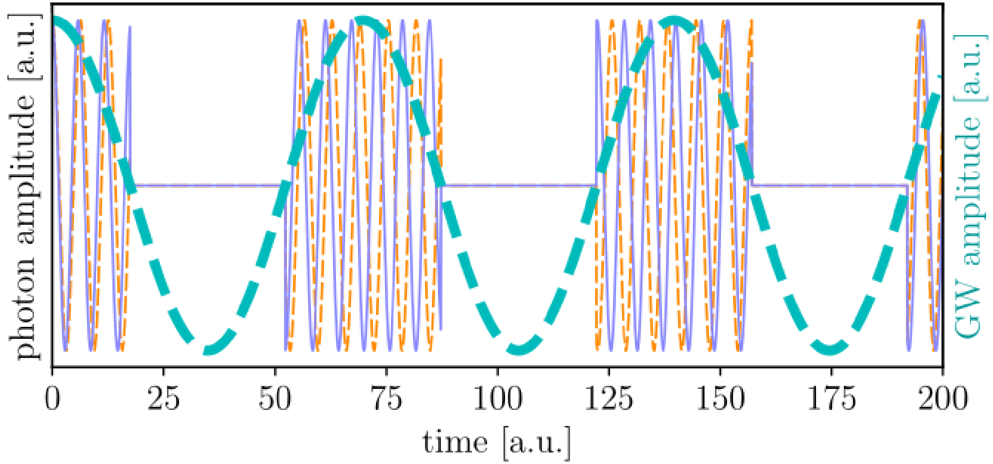
Orange sideband: effect of shutter

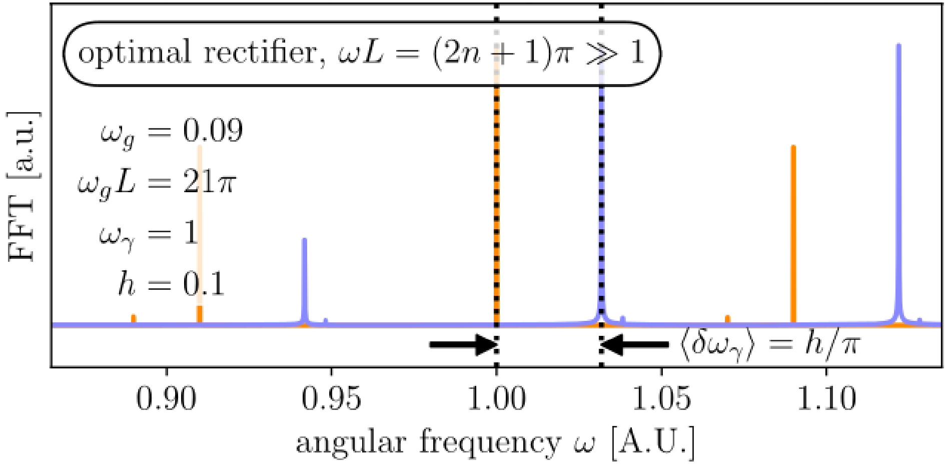
Not only sideband, but also frequency shift of photon carrier line

Rectifier: large ωL

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

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





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

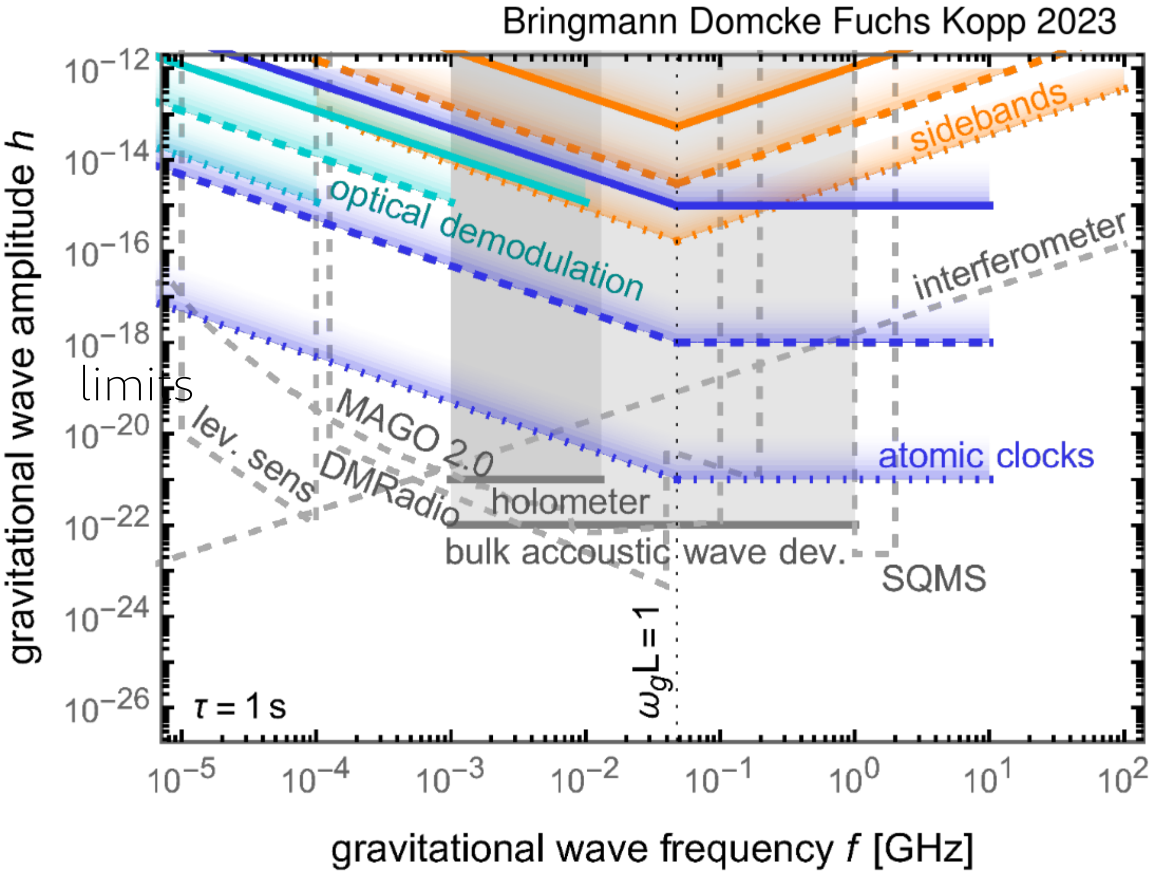
$$(\alpha_\mathrm{T}, \alpha_\mathrm{th})$$

$= \{(10^{-10}, 10^{-15}),$ conservative

$(10^{-15}, 10^{-17}),$ realistic

$(10^{-20}, 10^{-19})\}$ optimistic

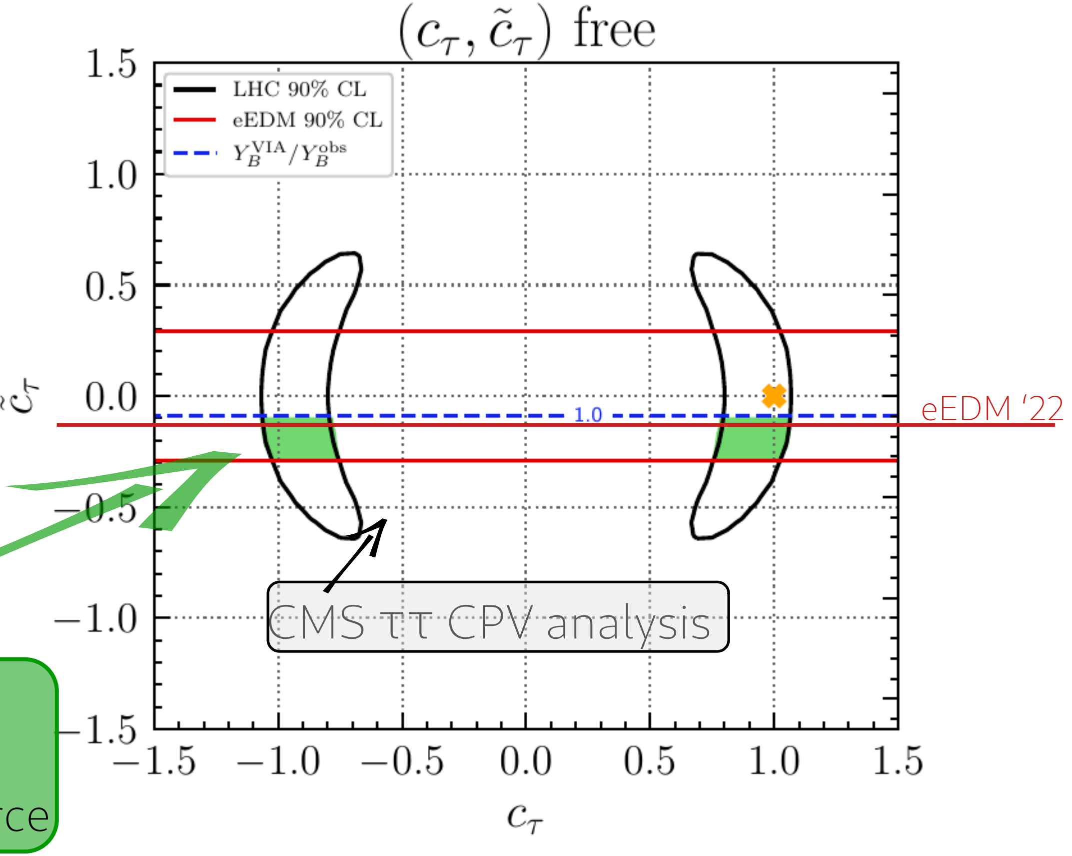
Promising approach over broad frequency range


Bringmann Domcke Fuchs Kopp 2023

Complementary: LHC, EDM, cosmo

Bahl, EF, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein '22

See also
Brod, Haisch, Zupan '13
De Vries, Postma, van de Vis '18
EF, Losada, Nir, Viernik '19, '20, '20
Aharony-Shapira '21
Brod, Cornell, Skodras, Stamou '22



Electron electric dipole moment
$d_e \propto \tilde{c}_f$

Allowed by LHC, EDM, EWBG (if VIA correct)
⟶ τ may be single source

Electroweak baryogenesis
$Y_B \propto \tilde{c}_f$

Caveat: "optimistic" scenario, large uncertainty (vev-insertion approximation)
⟶ approx. upper bound

Basler, Mühlleitner, Müller '20
Cline, Kainulainen '20
Cline, Laurent '21, Postma '21
Kainulainen '21
Postma, van de Vis, White '22

CERN Quantum Technology Initiative

CERN Quantum Technology Initiative

Accelerating Quantum Technology Research and Applications

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 → visitors!
Also collaboration with industry (e.g. IBM-Q)

Nov 2022: Quantum Technologies for High Energy Physics (QT4HEP)
Next week: **QTI Phase 2** proposal in Council
01/2024 – 12/2028: planned QTI Phase 2 with e.g. cavities→ axions, exotic atoms, quantum computing

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Stay tuned, get involved!

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QUANTUM TECHNOLOGY INITIATIVE

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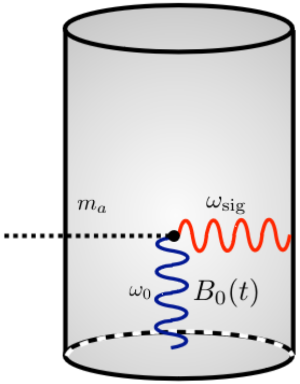
Quantum sensing in Phase 2

Searches for **axions and GWs** with tuneable RF cavities Heterodyne Resonator:

$$\omega_{\rm sig} \sim \omega_0 \pm m_a \sim V^{-1/3}$$



JHEP 07 (2020) 088, hep-ph/1912.11048
A. Berlin, R. T. D'Agnolo, SARE, P. Schuster, N. Toro, C. Nantista, J. Neilson, S. Tantawi, K. Zhou

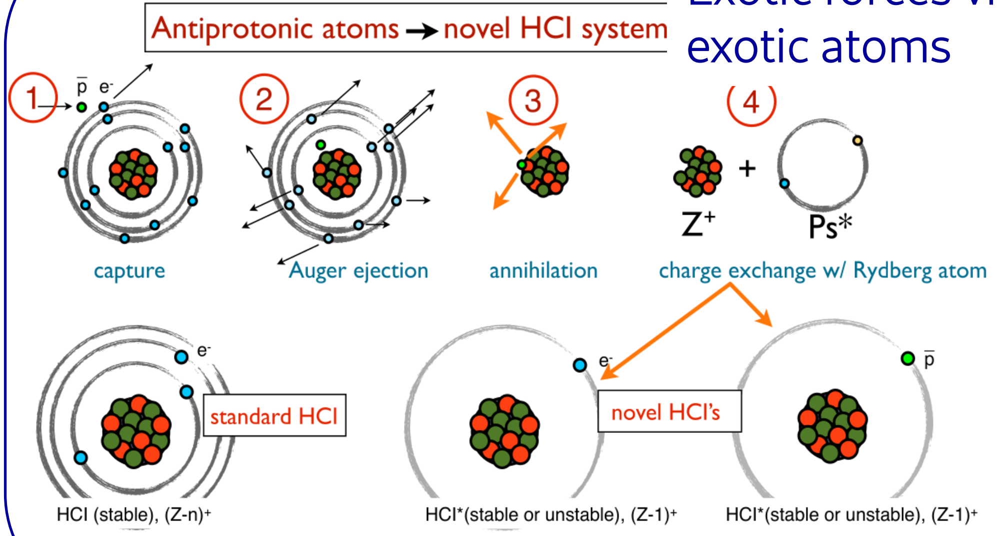
Also: R. Lasenby hep-ph/1912.11467

Dark Matter via Atom interferometer

Dark Matter via nuclear clock

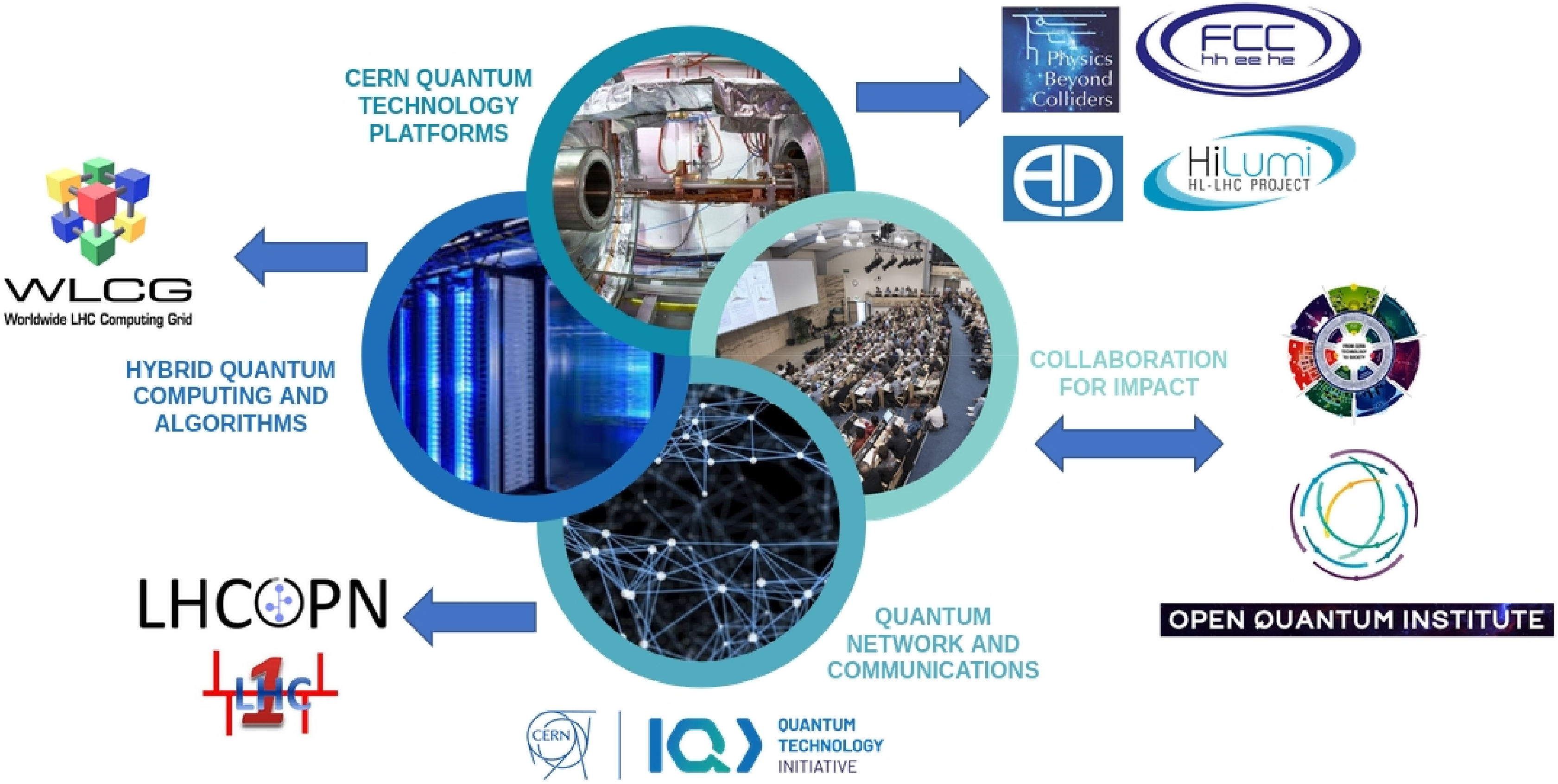
Millicharged particles via Transition Edge Sensor (low threshold)

Exotic forces via exotic atoms



M. Doser, Prog. Part. Nucl. Phys., (2022), https://doi.org/10.1016/j.ppnp.2022.103964

QTI Phase 2 Vision



CERN QUANTUM TECHNOLOGY PLATFORMS

HYBRID QUANTUM COMPUTING AND ALGORITHMS

COLLABORATION FOR IMPACT

QUANTUM NETWORK AND COMMUNICATIONS

Particle questions Quantum sensing

Baryon Asymmetry

Dark Matter

Strong CP problem

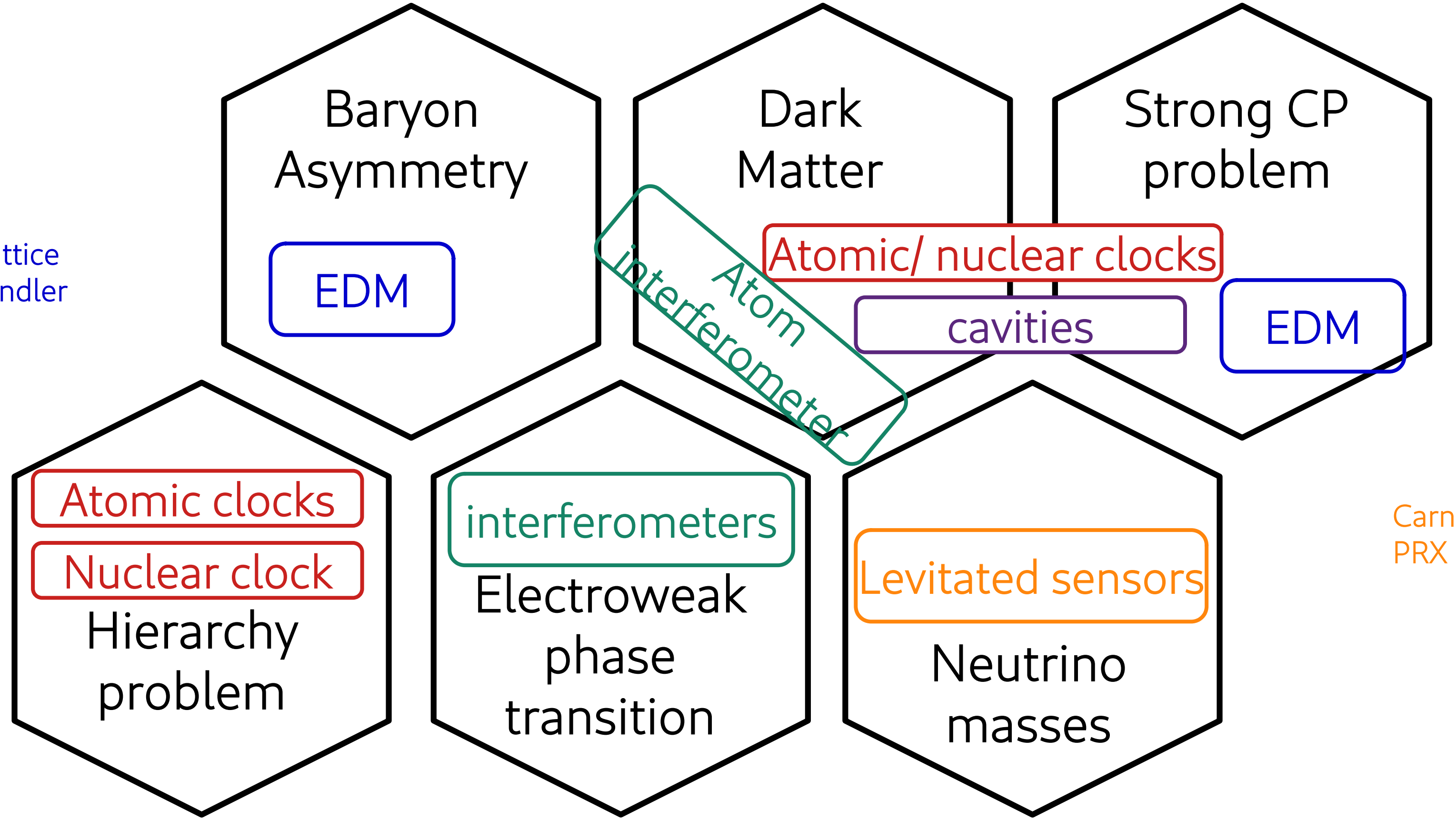
Hierarchy problem

Electroweak phase transition

Neutrino masses

Particle questions   Quantum sensing

→ yesterday's lattice coffee by A. Shindler



Baryon Asymmetry

EDM

Dark Matter

Strong CP problem

Atomic/ nuclear clocks

Atom interferometer

cavities

EDM

Atomic clocks

Nuclear clock

Hierarchy problem

interferometers

Electroweak phase transition

Levitated sensors

Neutrino masses

Engelhardt, Boonah, Liu 2304.05863

Carney, Leach, Moore PRX Quantum '23

Summary: Light NP vibrant

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

→ Quantum sensors can enable measurement & enhance the sensitivity

→ Isotope shifts of atomic clocks probe light new bosons

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

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CERN is an exciting place for QT4HEP with unique opportunities for breakthroughs

QUANTUM
TECHNOLOGY
INITIATIVE

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

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Thank you!

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QUANTUM TECHNOLOGY INITIATIVE

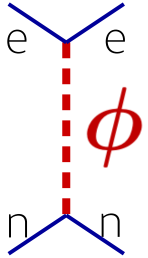
Exciting developments across frontiers over past few years and expected in the very near future

APPENDIX

NP shifts of atomic spectra

Energy shift due to new long-range interaction

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



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

NP ϕ coupling to electrons and neutrons

theory input: NP electronic coefficients

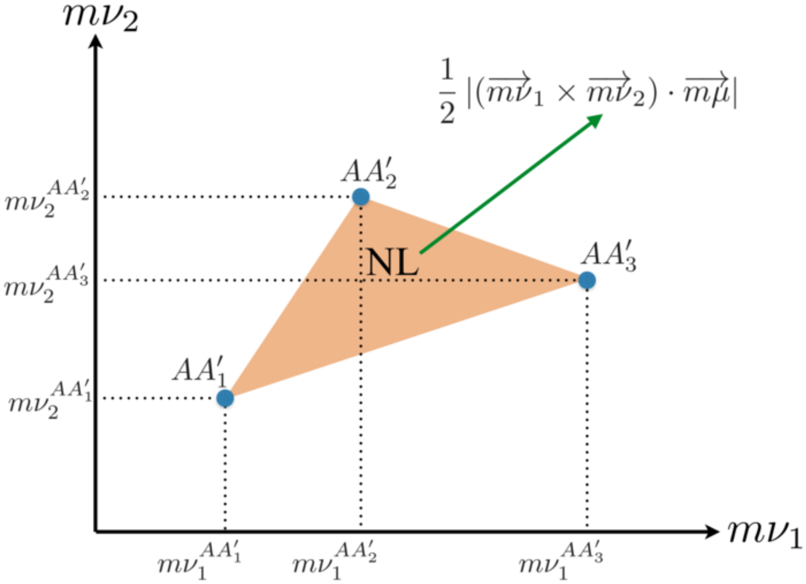
overlap of wavefunctions with NP potential

$X_i = X_i(m_\phi)$

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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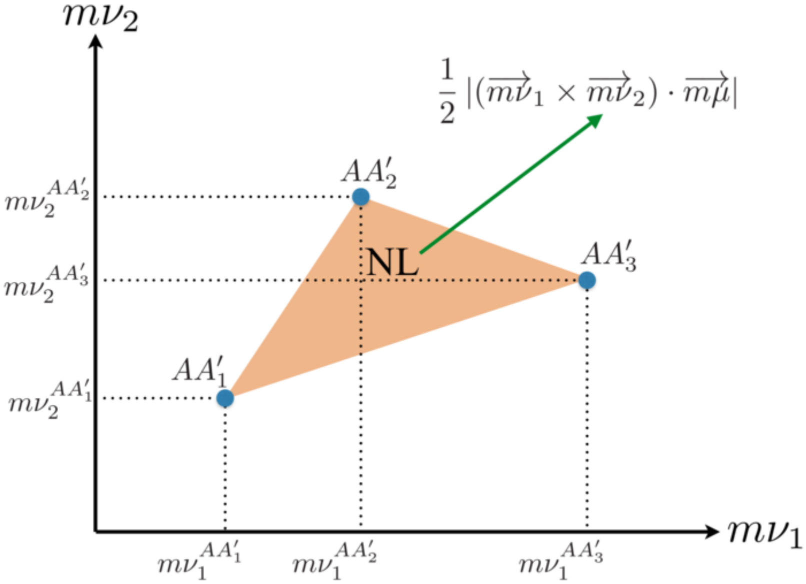
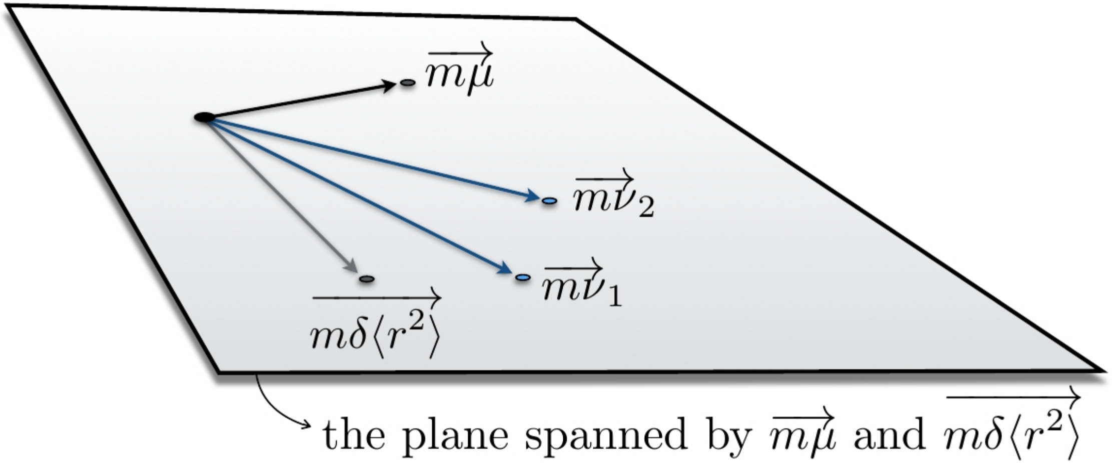


- Linearity plane: linear combinations of FS+MS
- Volume of parallelepiped = measure of NL



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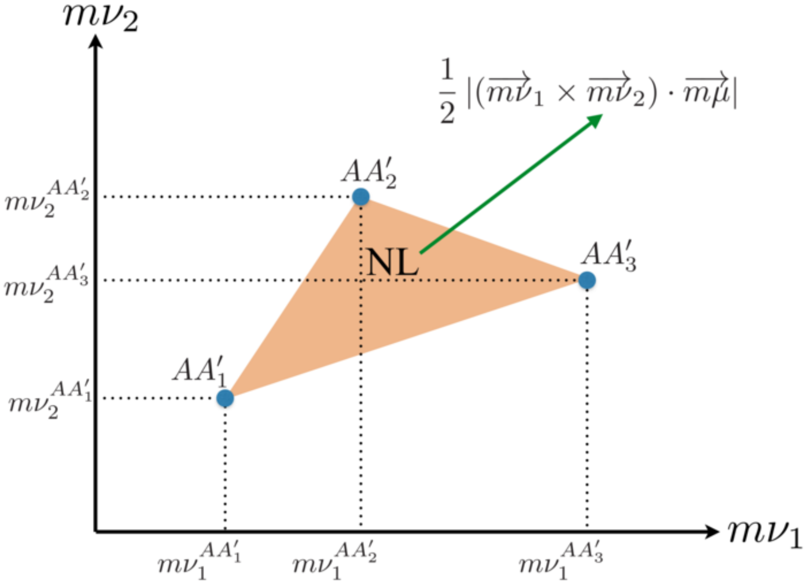

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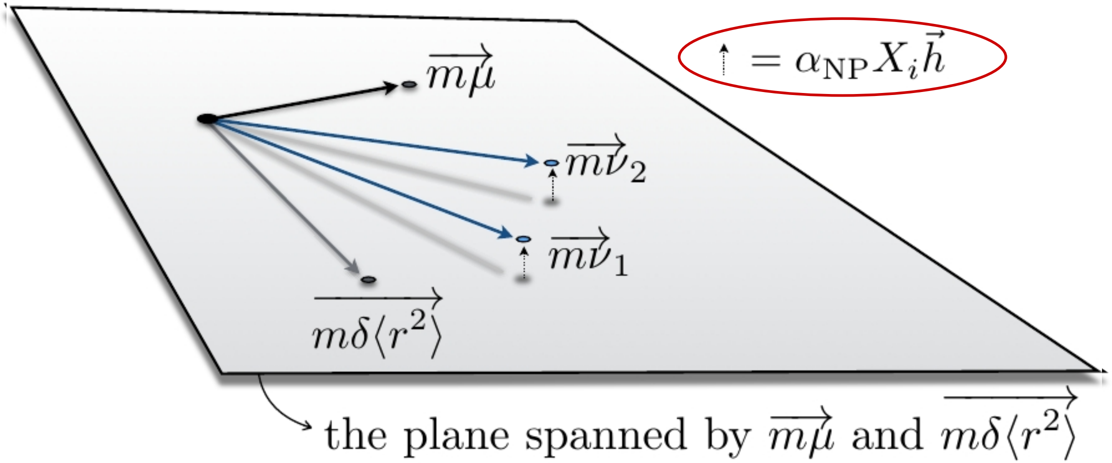

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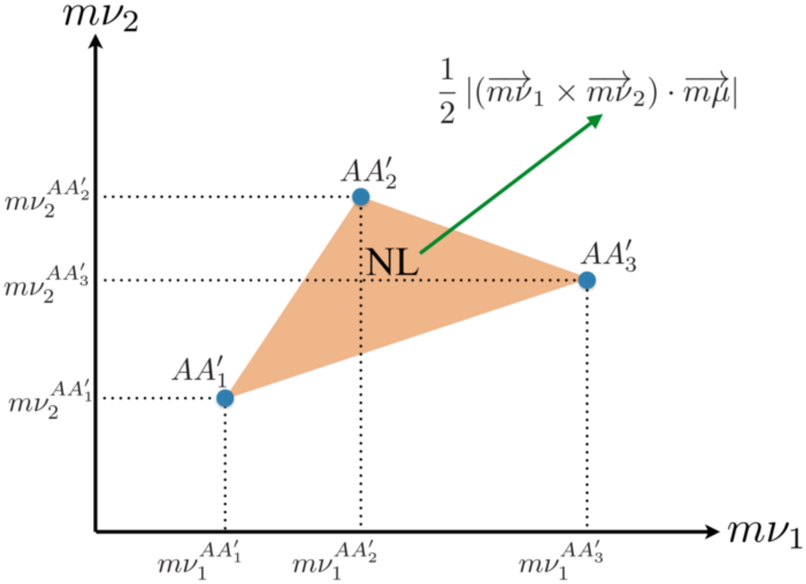

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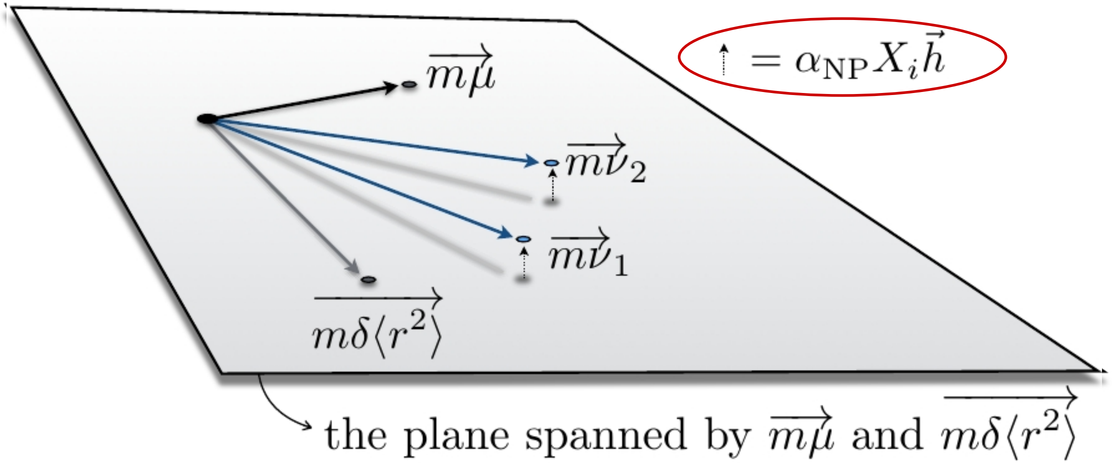

quantify NL

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 $\mathrm{NL}_{\mathrm{NP}}$

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

$\mathrm{NL}_{\mathrm{NP}} = 0$ 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

Data-driven bound:

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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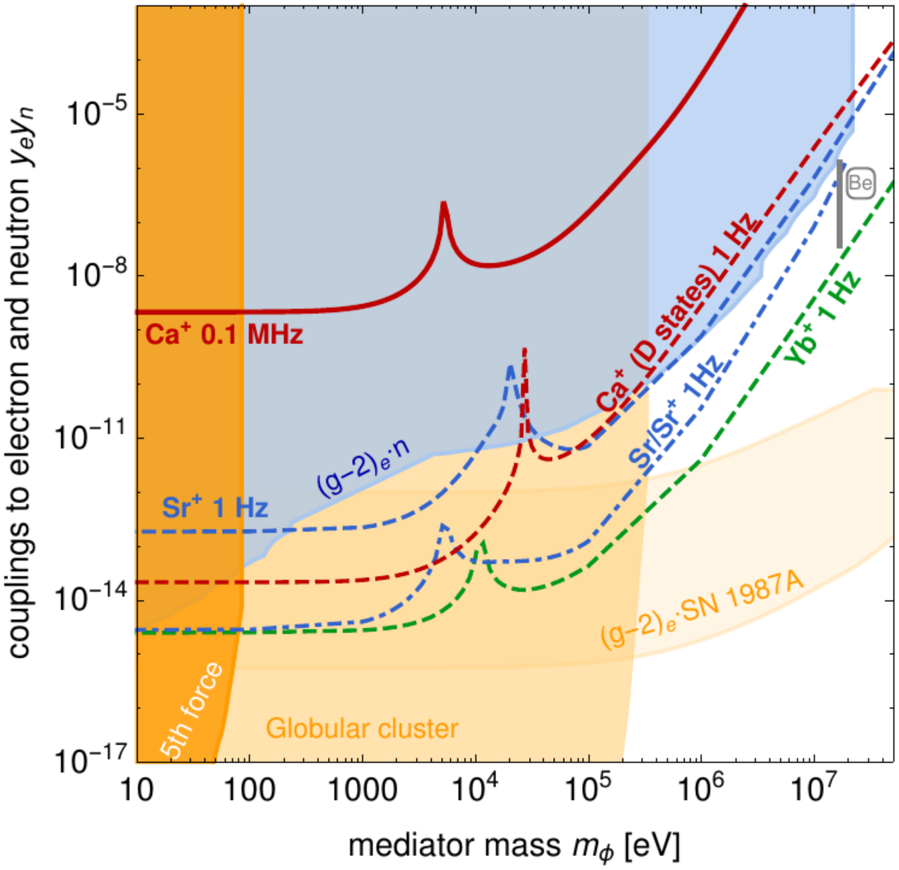

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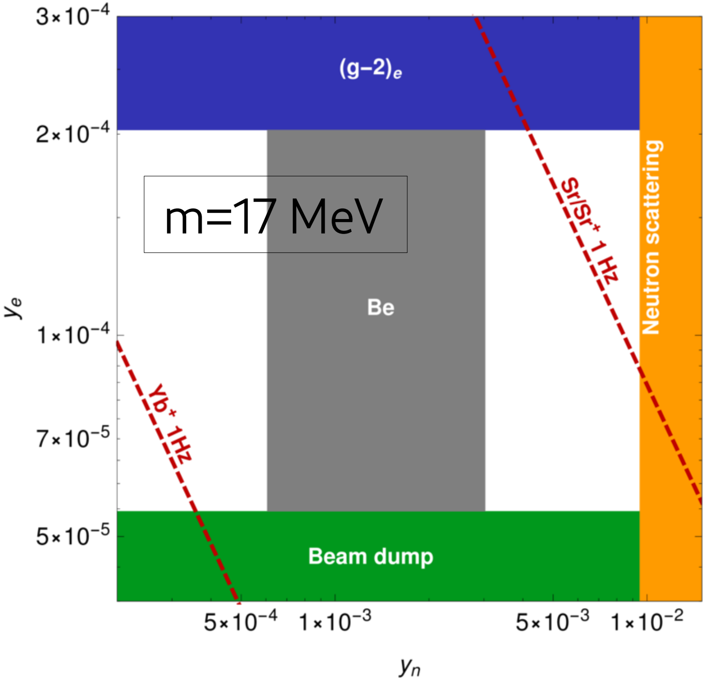
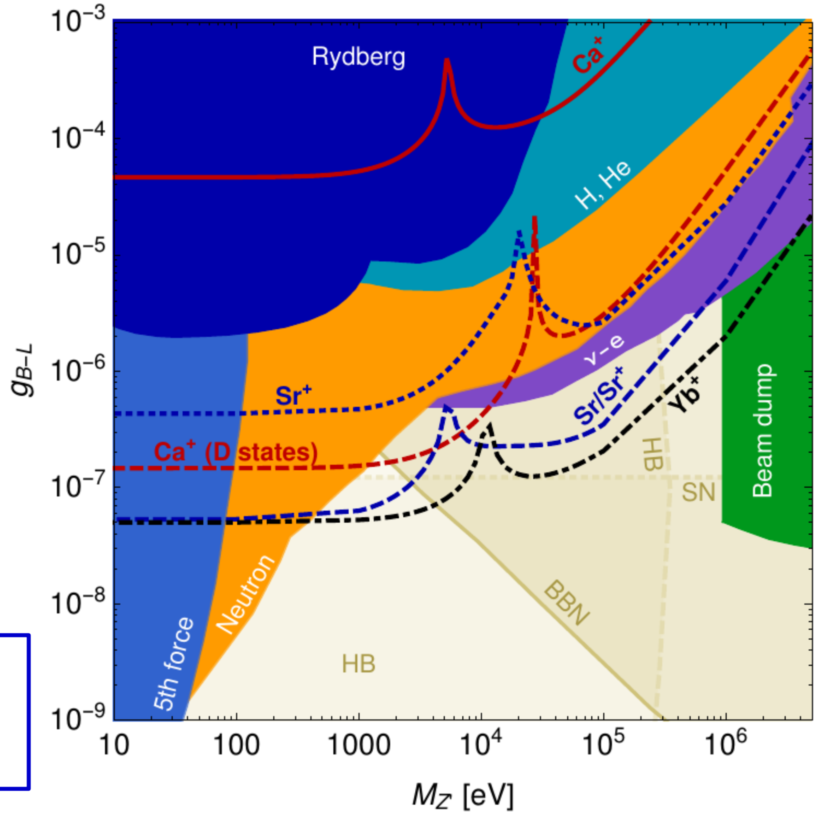
Implications for NP models



[Frugiuele, EF, Perez, Schlaffer '17]

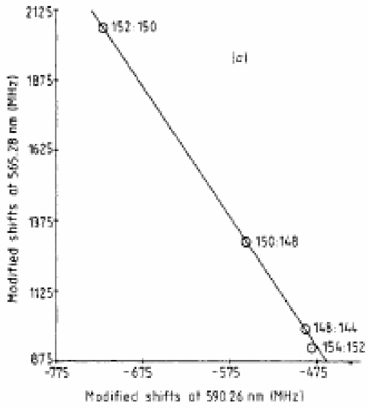


Yb+ 1Hz potential to rule out protophobic explanation of Atomki ^{8}Be anomaly

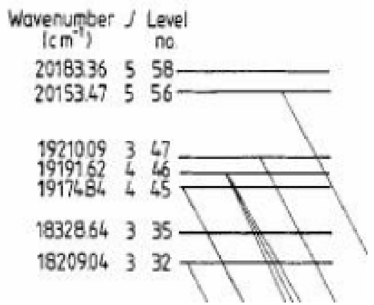
$U(1)_{B-L}$
New Z' boson

Caveat: Linearity breaking in SM

- SM nonlinearity
  - Mixing of degenerate energy levels [Griffith, Isaak, New, Rall '81]
  - **NLO field shift** [Palmer, Stacey '81] [Seltzer '69]
  - Nuclear **polarization** [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 [Flambaum, Geddes, Viatkina '18] in Ca$^+$, Sr$^+$, Ba$^+$, Yb$^+$, Hg$^+$
- SM nonlinearities: dependence on nuclear radii [Müller, Yerokhin, Artemyev, Surzhykov '21]
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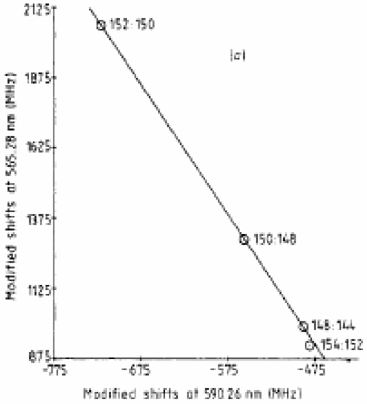
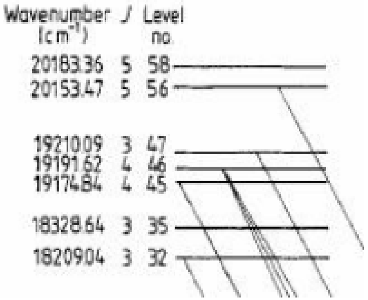


Samarium (Sm)



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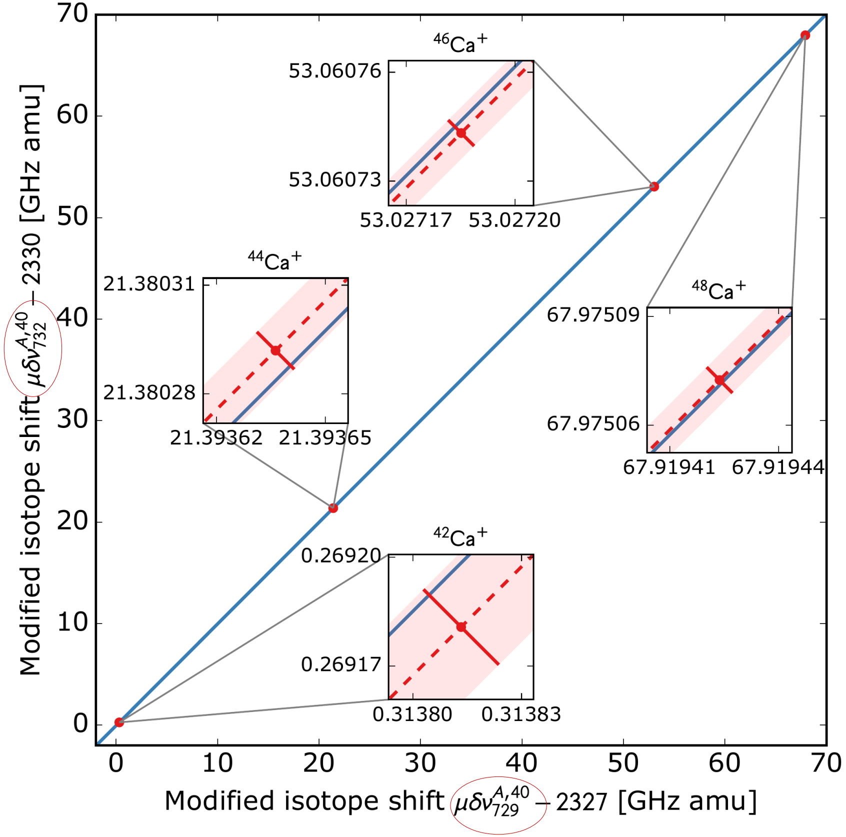
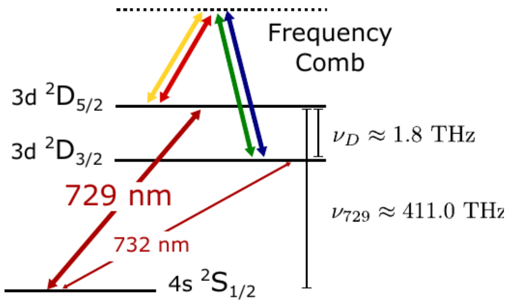
Strategy: consider predicted SM NL and constrain residual NL

Very precise Ca$^+$ King Plot

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





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

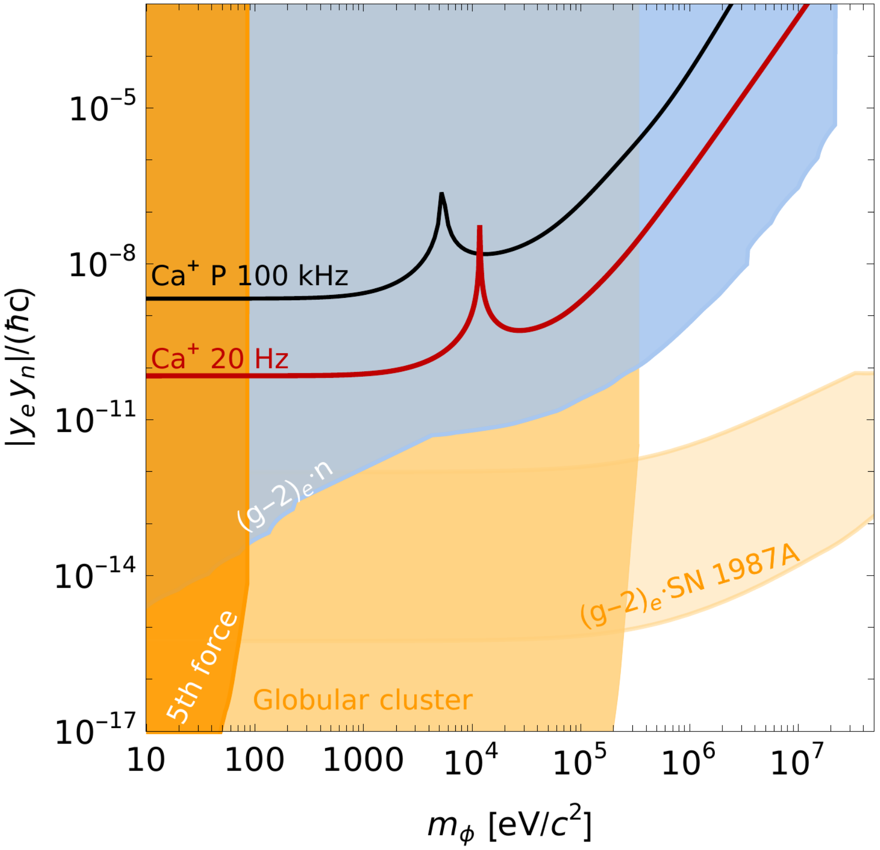
Aarhus: $D_{3/2}$-$D_{5/2}$ at **20 Hz**

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

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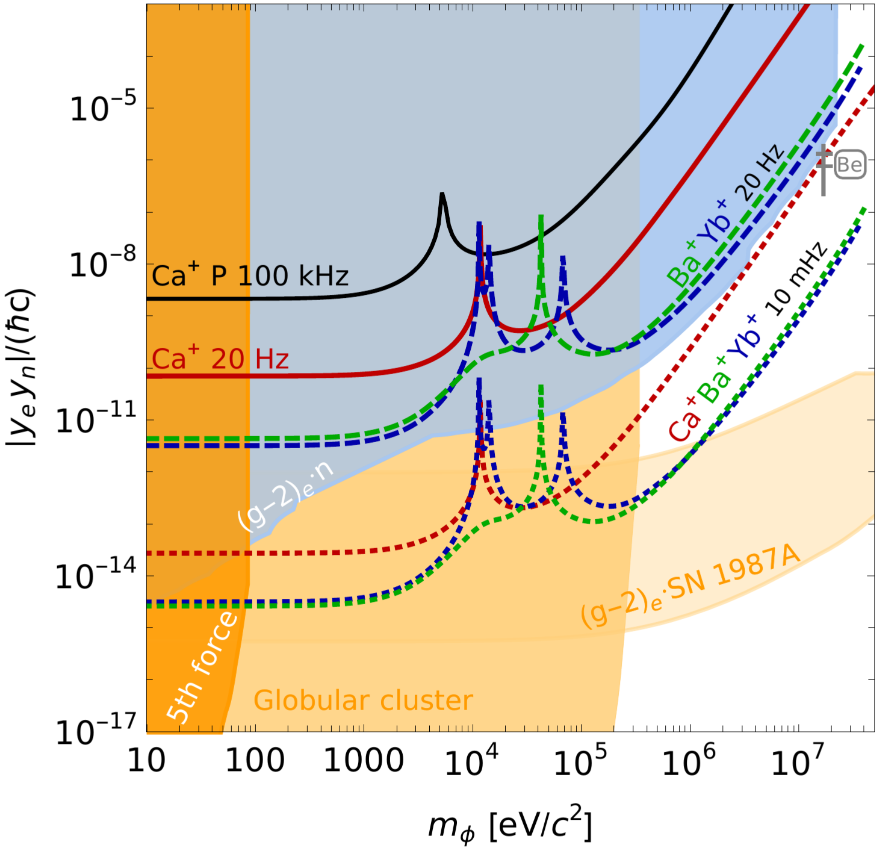

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Scrutinizing the Yb anomaly

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

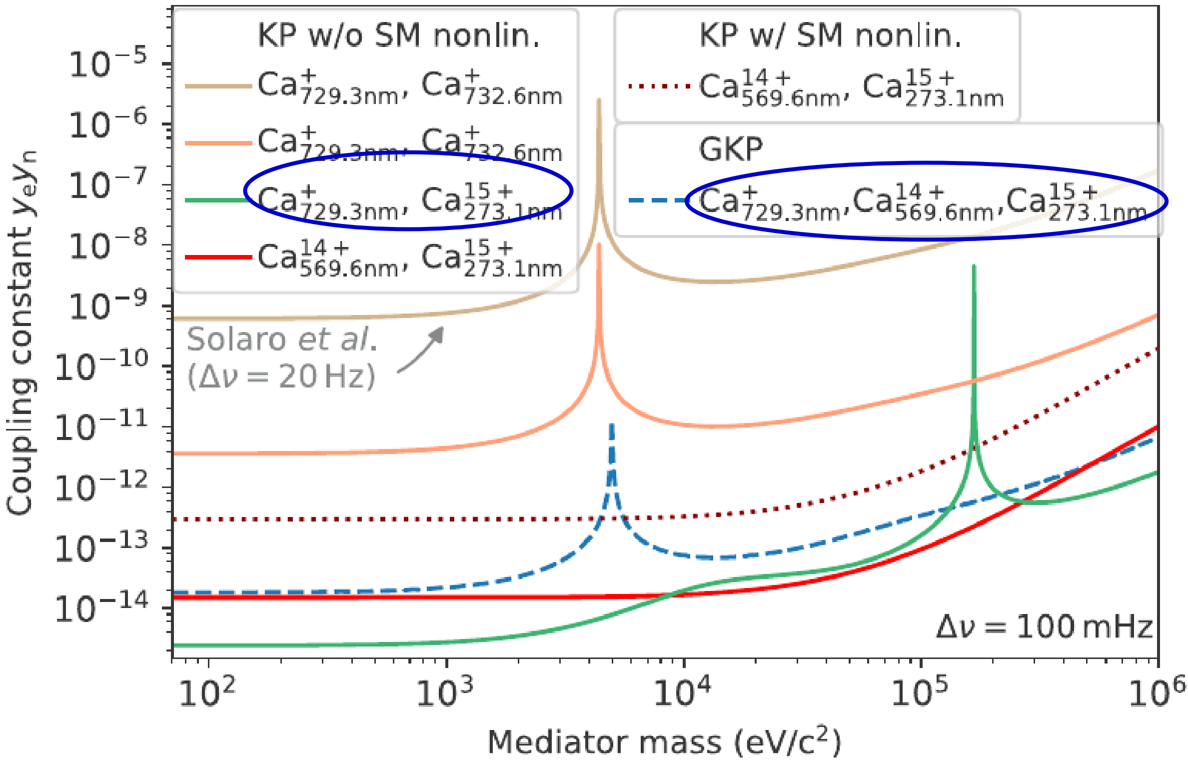
Highly charged ion (HCI) King plot

[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]
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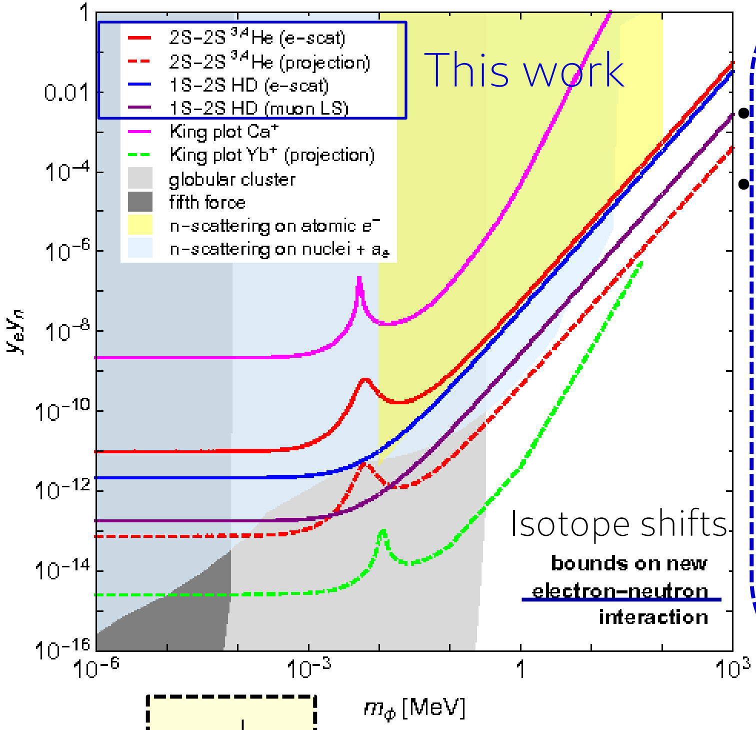
Direct comparison of theory and data

[Delaunay, Frugiuele, EF, Soreq ‘17]



scalar

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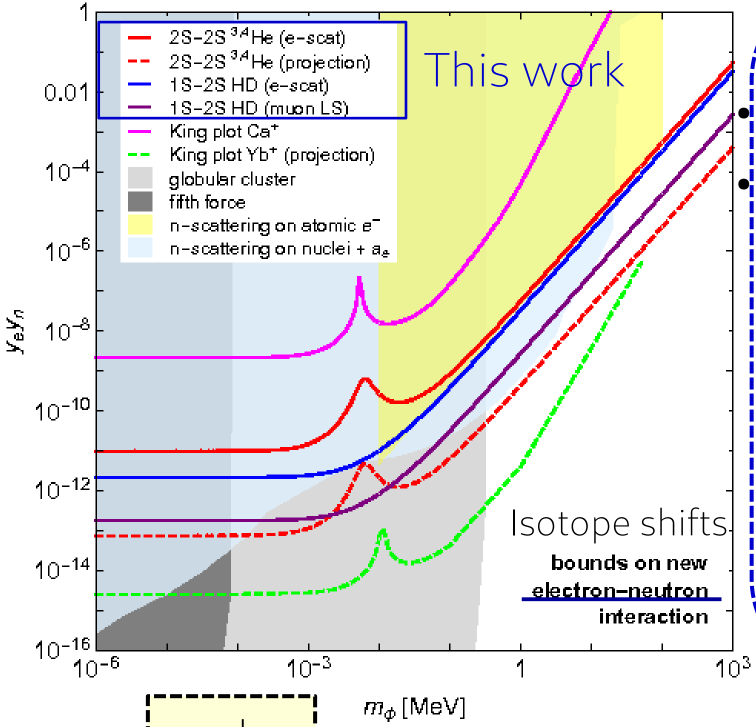

This work

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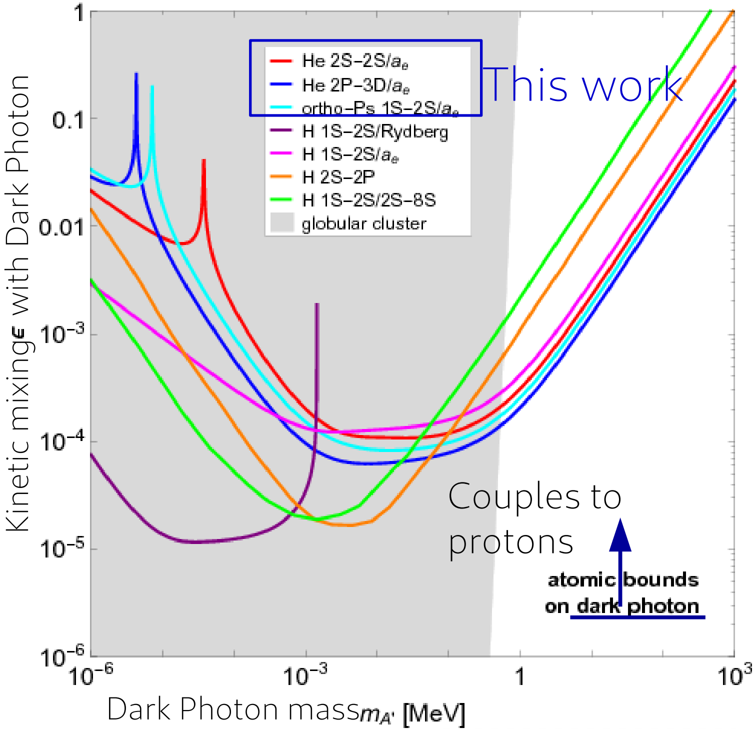


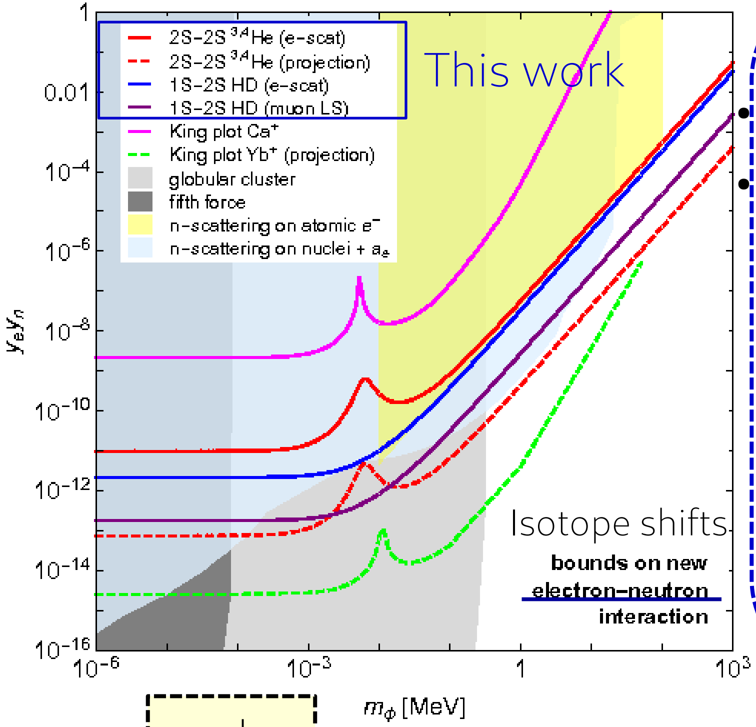
This work

Couples to protons

Dark photon

Direct comparison of theory and data

[Delaunay, Frugiuele, EF, Soreq ‘17]



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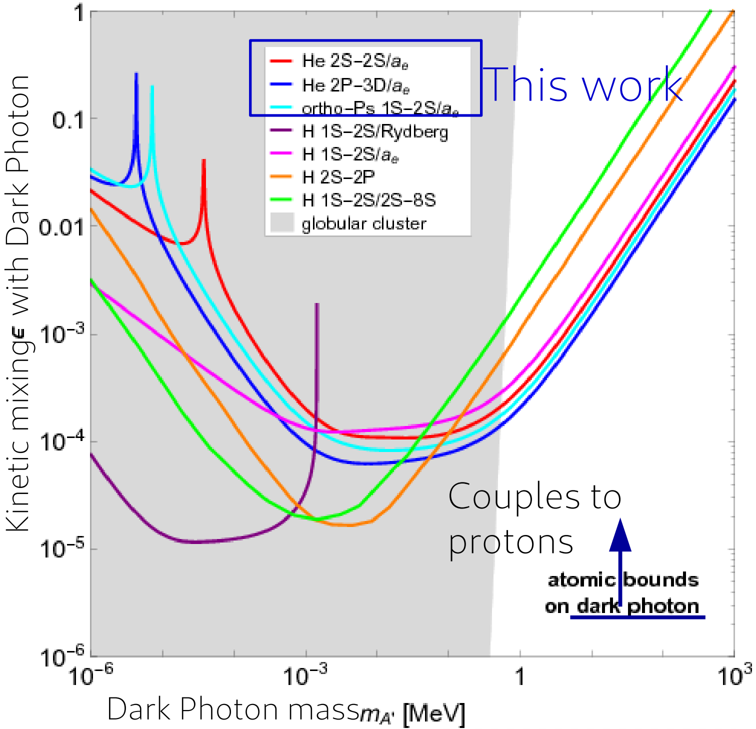

This work

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scalar

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Precise frequencies and isotope shifts
→ complementary to King plot

Direct comparison of theory and data

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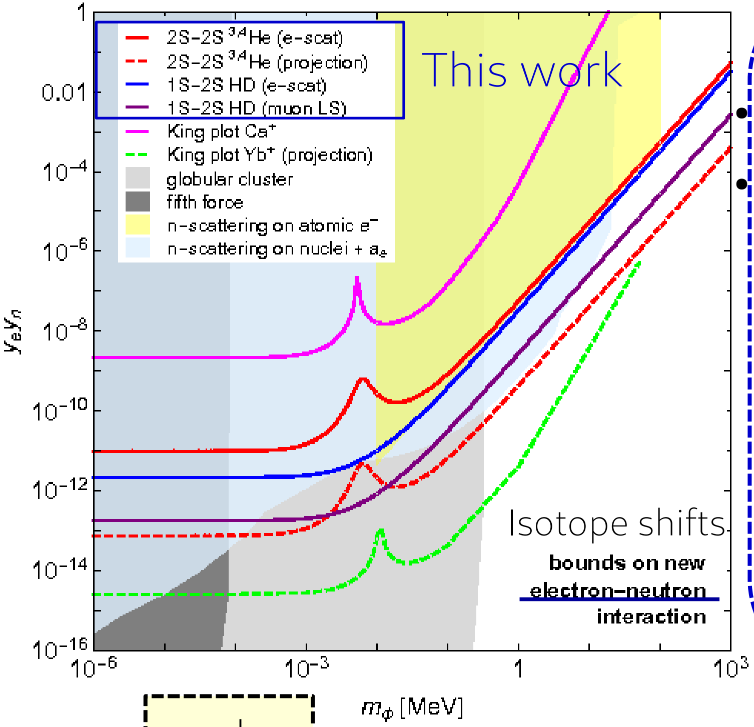

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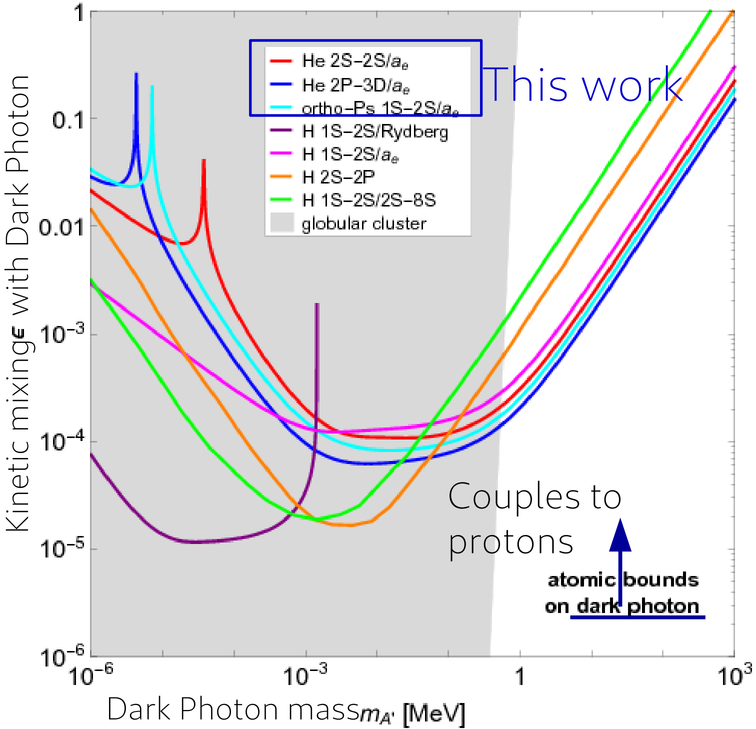

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→ complementary to King plot

New Ca$^+$ Isotope Shift Measurements

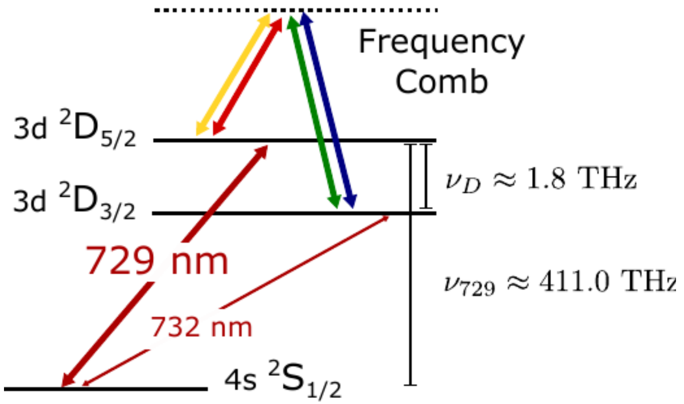
[Solaro, Meyer, Fisher, Berengut, EF, Drewsen, PRL 125, 123003 (2020)]

- 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}



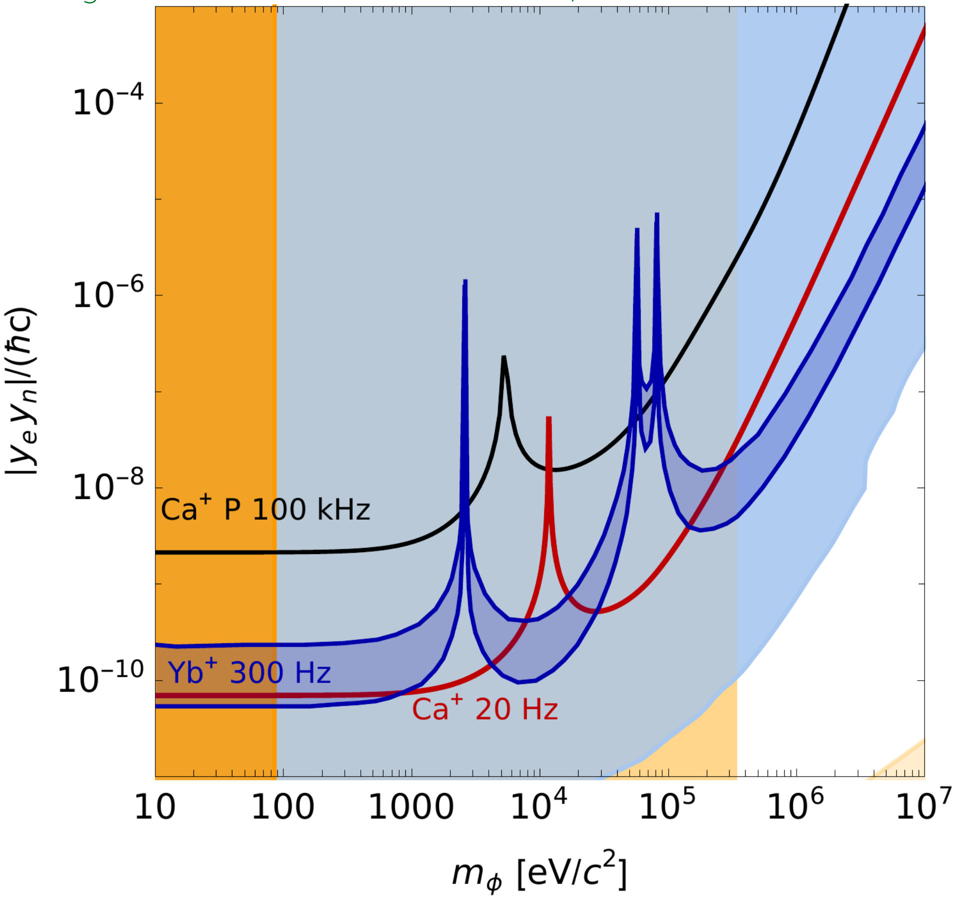
[Solaro, Meyer, Fisher, DePalatis, Drewsen (Aarhus University), PhysRevLett.120.253601]

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]



Ca vs Yb King plots – compatibility

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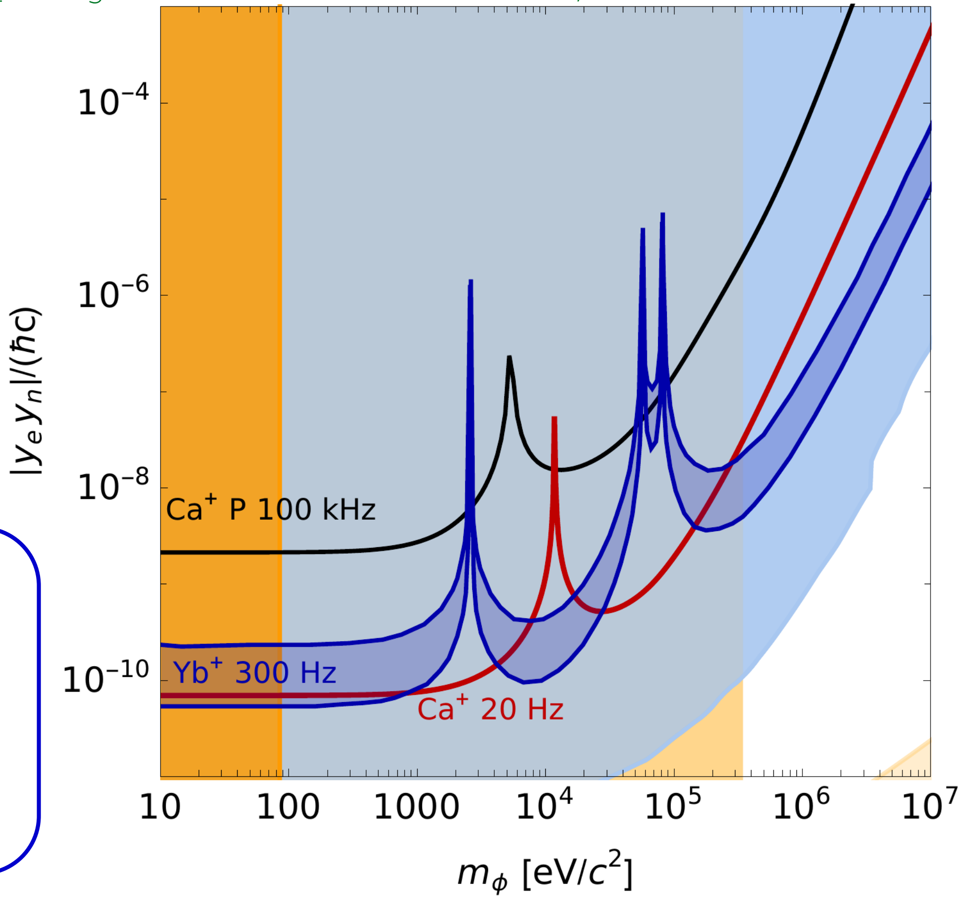
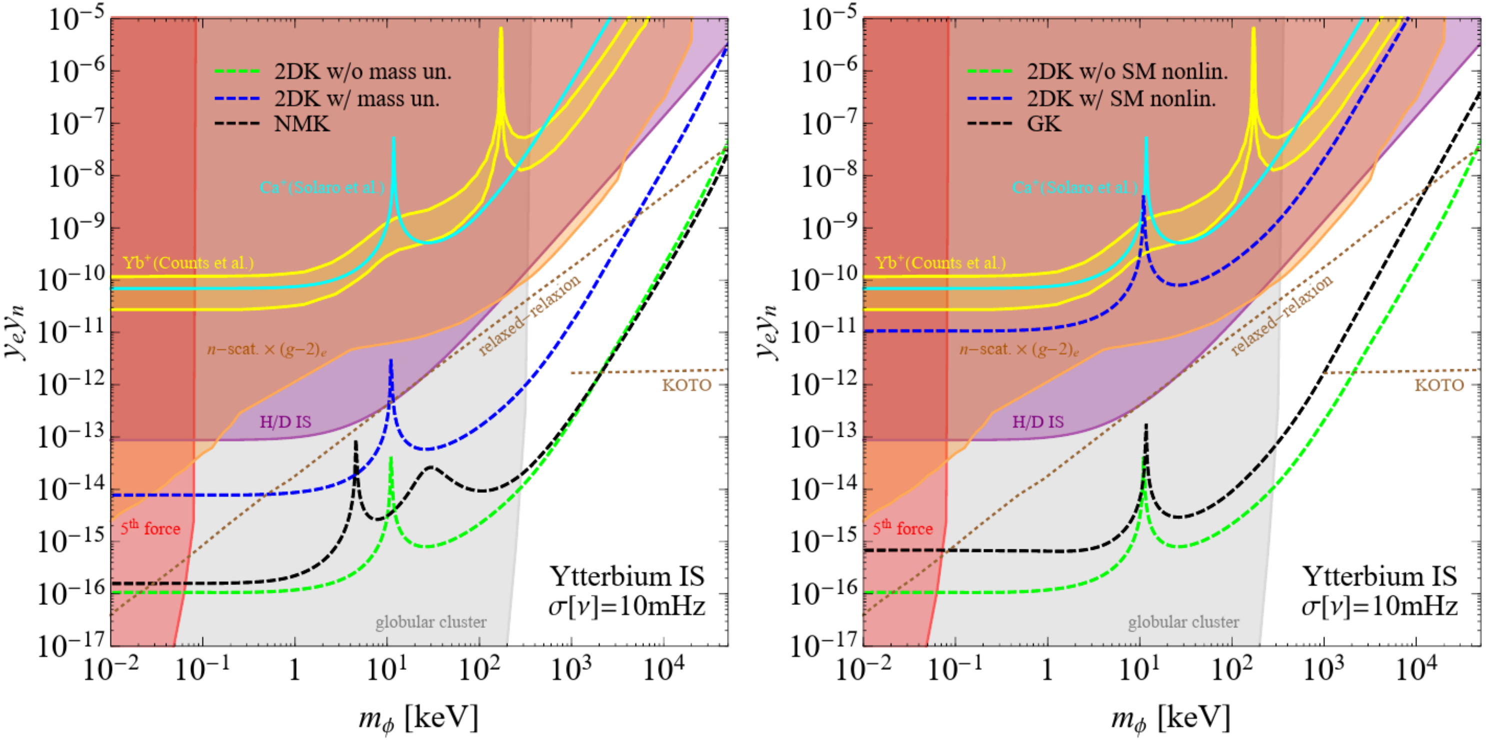
if Yb-NL assumed as *purely* New Physics:
→ necessary coupling range is
- partly excluded by Ca
- excluded by $(g-2)_e$*n-scattering

[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)

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

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

Chameleon search with King plot

Dark Energy

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

Matter density

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

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

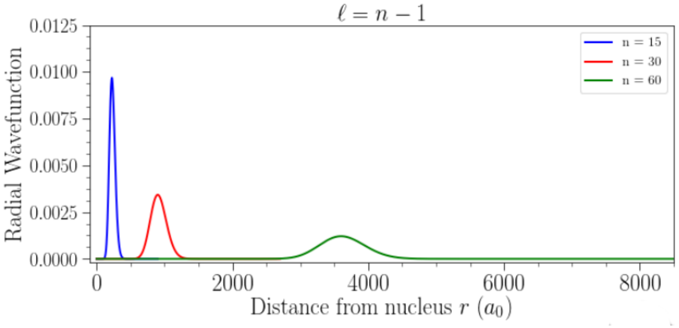
Rydberg states: reduce nucl. uncertainty

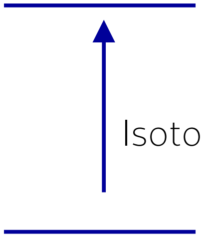
[Duque-Mesa, Firstenberg, EF, Geller, Ozeri, Perez, Shpilman; work in progress]

Highly excited states

→ less overlap with nucleus

→ but also with NP





high n

Isotope shift with 10mHz precision

Circular state, l=n-1

Rydberg states: reduce nucl. uncertainty

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

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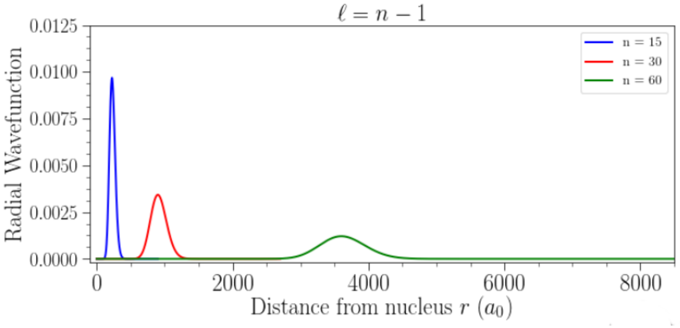
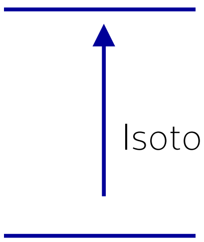


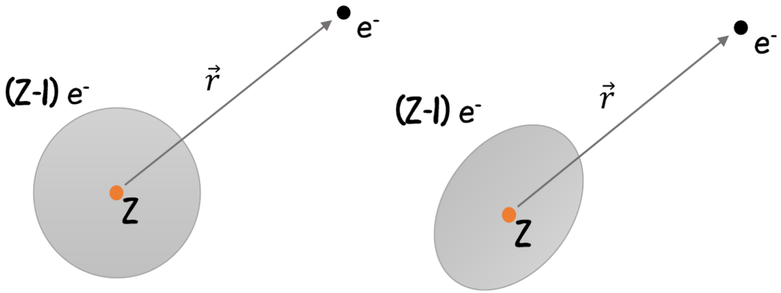


high n

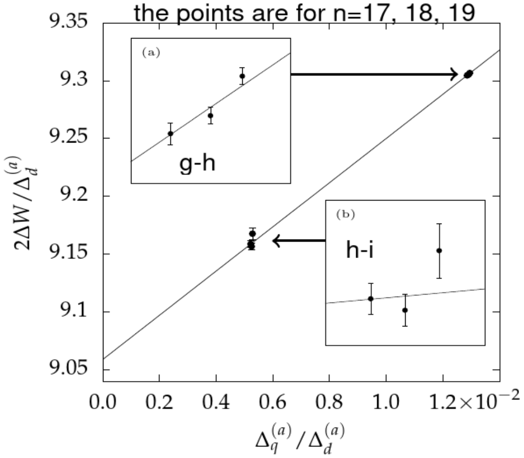
Isotope shift with 10mHz precision

Circular state, l=n-1

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

Expect points in plane

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

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

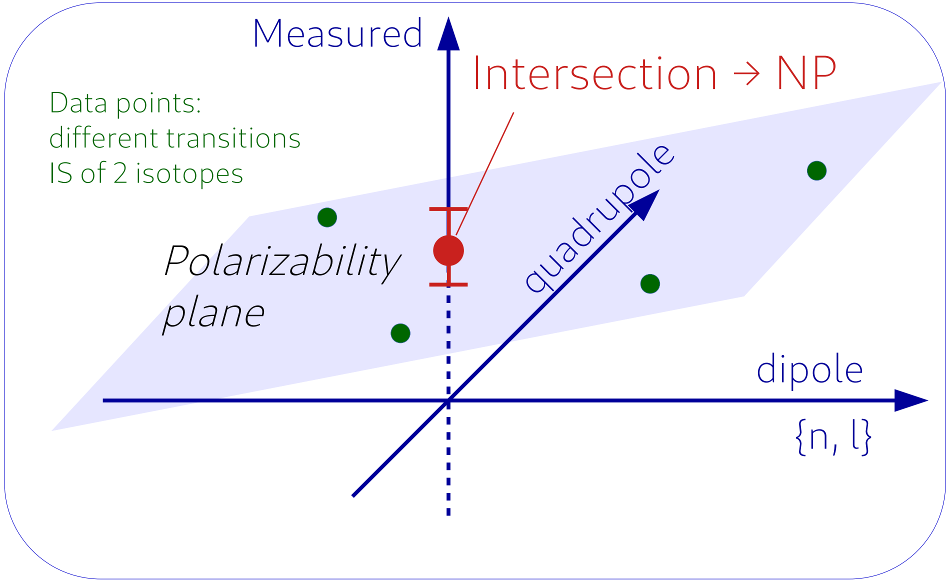
$$\delta_{r^q} = \langle r^q\rangle_{n_2 l_2} - \langle r^q\rangle_{n_1 l_1}$$

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

Vector:
Many n, l

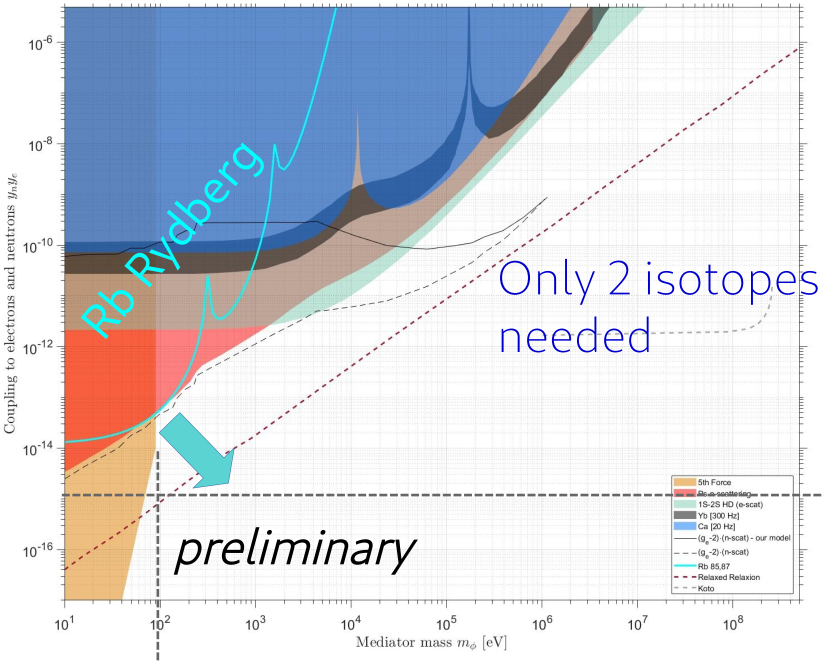
$$\vec{z} = C + A\vec{x} + B\vec{y}$$

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



Rydberg states: reduce nucl. uncertainty

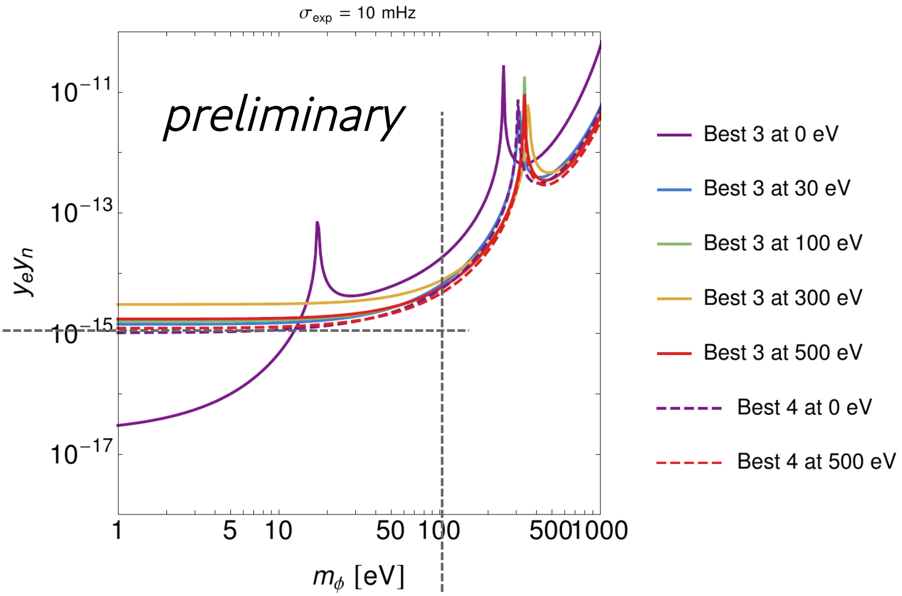
[Duque-Mesa, Firstenberg, EF, Geller, Ozeri, Perez, Shpilman; work in progress]



Only 2 isotopes needed

preliminary

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



preliminary

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

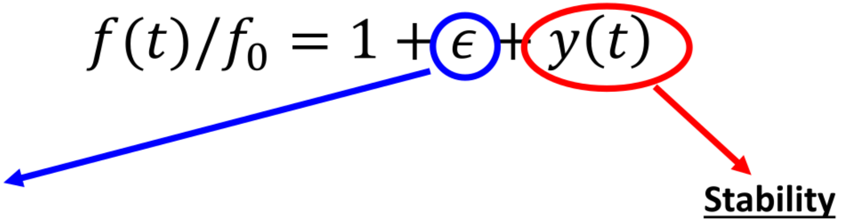
Possibly test new parameter space

Further NP atomic precision probes

- Rydberg states
- Few-electron systems (H, He, D, Li,…)
- Tests of Local Lorentz invariance violation

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

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

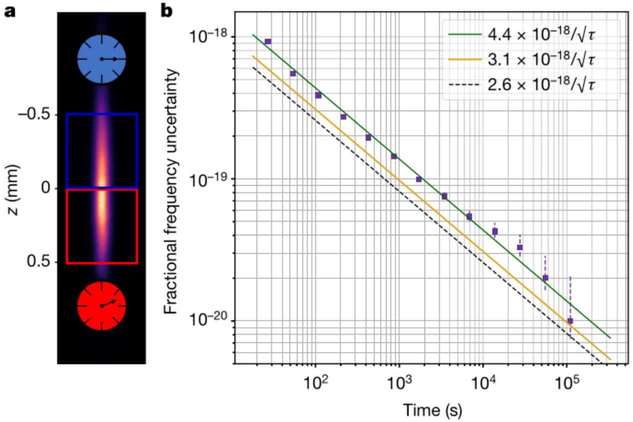
Stability

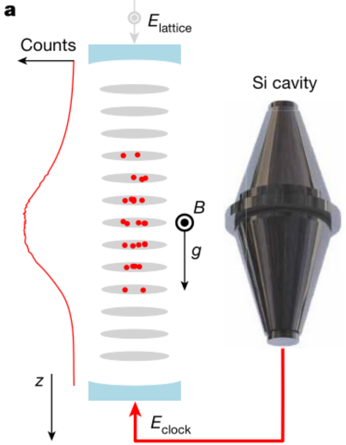
- Average fractional frequency variations
- Typically characterized by the *Allan deviation:*

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

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 x 10^{-21}
- 100,000 ultracold Sr atoms in an optical lattice
- narrow $S_0 \to P_0$ 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.

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nature

SEEING RED

Submillimetre-scale gravitational redshift within an atomic clock

Explosive power
The shocking science behind the Tongan volcanic eruption

Coronavirus
Why has disability been left out of COVID discussions?

Sound connections
Inner-ear anatomy affirms evolutionary tree of bats

Noise

- Quantum projection noise:
  - Discrete measurement outcomes 0,1 with probabilities p, (1-p)
  - Experiment repeated N times →
  - Variance of binomial distribution

$$p = \frac{N_1}{N}$$

$$\sigma^2_{p,\text{quantum}} = \frac{1}{N} p(1-p).$$

- 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