Variation of masses and interaction constants due to dark matter: theory and observations

Y. Stadnik, V. Flambaum, et al.

Physical Review Letters 120, 0132024 (2018)

Physical Review Letters **119**, 223201 (2017)

Physical Review Letters **118**, 142501 (2017)

Physical Review Letters **116**, 023201 (2016)
Physical Review Letters **117**, 271601(2016)

Physical Review Letters **115**, 201301 (2015)
Physical Review Letters **114**, 161301 (2015)
Physical Review Letters **113**, 151301 (2014)
Physical Review Letters **113**, 081601 (2014)
Physical Review D **89**, 043522 (2014)
Physical Review D **90**, 096005 (2014)

Low-mass Spin-0 Dark Matter

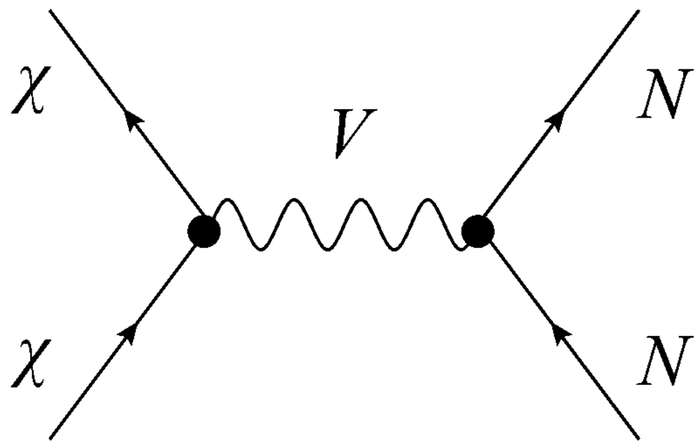
- *Low-mass spin-0 particles* form a *coherently oscillating classical* field $\varphi(t) = \varphi_0 \cos(m_\varphi c^2 t/\hbar)$, with energy density $\langle\rho_\varphi\rangle \approx m_\varphi^2 \varphi_0^2/2$ ($\rho_{DM,local} \approx 0.4$ GeV/cm^3)
- Coherently oscillating field, since *cold* ($E_\varphi \approx m_\varphi c^2$)
- Classical field for $m_\varphi \leq 0.1$ eV, since $n_\varphi(\lambda_{dB,\varphi}/2\pi)^3 \gg 1$
- Coherent + classical DM field = **"Cosmic maser"**
- 10^{-22} eV $\leq m_\varphi \leq 0.1$ eV <=> 10^{-8} Hz $\leq f \leq 10^{13}$ Hz

$\lambda_{dB,\varphi} \leq L_{\text{dwarf galaxy}} \sim 1$ kpc (↑ lower bound) — Classical field (↖ upper bound)

- $m_\varphi \sim 10^{-22}$ eV <=> $T \sim 1$ year

Motivation

Traditional "scattering-off-nuclei" searches for heavy WIMP dark matter particles (m_χ ~ GeV) have not yet produced a strong positive result.



$$\mathcal{M} \propto (e')^2$$

$$=> \frac{d\sigma}{d\Omega} \propto |\mathcal{M}|^2 \propto (e')^4$$

Problem: Observable is **quartic** in the interaction constant e', which is extremely small ($e' << 1$)! We consider **linear** effects. Enormous advantage!

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars (or axion φ^2):	**Pseudoscalars (Axions):**
$\varphi \xrightarrow{P} +\varphi$	$\varphi \xrightarrow{P} -\varphi$
$\rightarrow$ **Time-varying fundamental constants**	$\rightarrow$ **Time-varying spin-dependent effects**
10^{15} improvement	**10^{3} improvement**

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

Consider an oscillating classical *scalar* field, $\varphi(t) = \varphi_0 \cos(m_\varphi t)$, that interacts with SM fields (e.g. a fermion *f*) via *quadratic couplings* in φ.

$$\mathcal{L}_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \quad \text{c.f.} \quad \mathcal{L}_f^{\text{SM}} = -m_f \bar{f} f \quad => \quad m_f \to m_f \left[1 + \frac{\phi^2}{(\Lambda'_f)^2} \right]$$

$$=> \frac{\delta m_f}{m_f} = \frac{\phi_0^2}{(\Lambda'_f)^2} \cos^2(m_\phi t) = \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2}} + \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2} \cos(2 m_\phi t)}$$

'Slow' drifts [Astrophysics (high ρ_{DM}): BBN, CMB]

Oscillating variations [Laboratory (high precision)]

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

[Stadnik, and V.F. *PRL* **114**, 161301 (2015); *PRL* **115**, 201301 (2015)]

Fermions:

$$\mathcal{L}_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \quad => m_f \to m_f \left[1 + \frac{\phi^2}{(\Lambda'_f)^2}\right]$$

Photon:

$$\mathcal{L}_\gamma = \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{F_{\mu\nu}F^{\mu\nu}}{4} \quad => \alpha \to \frac{\alpha}{1 - \phi^2/(\Lambda'_\gamma)^2} \simeq \alpha \left[1 + \frac{\phi^2}{(\Lambda'_\gamma)^2}\right]$$

W and *Z* Bosons:

$$\mathcal{L}_V = \frac{\phi^2}{(\Lambda'_V)^2} \frac{M_V^2}{2} V_\nu V^\nu \quad => M_V^2 \to M_V^2 \left[1 + \frac{\phi^2}{(\Lambda'_V)^2}\right]$$

“ **Fine tuning”** of fundamental constants is needed for life to exist. If fundamental constants would be even slightly different, life could not appear!

Variation of coupling constants in space provide natural explanation of the “fine tuning”: we appeared in area of the Universe where values of fundamental constants are suitable for our existence.

Source of the variation: Dark matter/Dark energy?

Dzuba et al 1998-2022. We performed calculations to link change of atomic transition frequencies to change of α :

quasar and star spectra, atomic clocks ,
highly charged ions,

$$\omega = \omega_0 + q(\alpha^2/\alpha_0^2 - 1), \quad \Delta\omega/\omega_0 = K \; \Delta\alpha/\alpha$$

QCD and nuclear calculations: quark mass variation

Microwave transitions: hyperfine frequency is sensitive to α and nuclear magnetic moments.

Molecular transitions – sensitive to nucleon mass.

Nuclear clock ^{229}Th .

Mossbauer transitions.

Oklo natural nuclear reactor.

Big Bang Nucleosynthesis (BBN)

Dependence of hadronic properties, BBN, Oklo on quark masses.
V.V. Flambaum, E.V. Shuryak. PRD 65, 103503,2002; 67, 083507 (2003).

Dependence of nucleon magnetic moments on quark masses.
V.V. Flambaum, D.B. Leinweber, A.W. Thomas, R.D. Young, PRD69, 115006, 2004.
I.C. Cloet, G. Eichmann, V.V. Flambaum, C.D. Roberts, M.S. Bhagwat and A. Holl, Few Body Syst. 42, 91 (2008)

Dependence of nucleon mass on quark masses.
V.V. Flambaum, A. Hoell, P. Jaikumar, C.D. Roberts and S.V. Wright nucl-th/0510075, Few Body Systems 38, 31 (2006).

Dependence of nuclear magnetic moments on quark masses.
V.V. Flambaum and A.F. Tedesco, Phys.Rev. C 73, 05550 (2006).

Dependence of nuclear binding and radius on quark mass variation.
V.V. Flambaum, R.B. Wiringa. Phys. Rev. C 76, 054002 (2007).
Phys. Rev. C 79, 034302 (2009).

Varying the light quark mass: impact on the nuclear force and BBN.
J. C. Berengut, E. Epelbaum, V. V. Flambaum, C. Hanhart,
U.-G. Meissner, J. Nebreda, J. R. Pelaez, Phys. Rev. D87,085018, 2013.

Astrophysical Constraints on 'Slow' Drifts in Fundamental Constants Induced by Scalar Dark Matter (BBN)

[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]

- Largest effects of scalar dark matter are in the early Universe (highest ρ_{DM} => highest φ_0^2).
- Earliest cosmological epoch that we can probe is Big Bang nucleosynthesis (from $t_{weak} \approx$ 1s until $t_{BBN} \approx$ 3 min).
- Primordial ^{4}He abundance is sensitive to relative abundance of neutrons to protons (almost all neutrons are bound in ^{4}He by the end of BBN).

<u>**Weak interactions:**</u> freeze-out of weak interactions occurs at $t_{weak} \approx$ 1s ($T_{weak} \approx$ 0.75 MeV).

$$p + e^- \rightleftharpoons n + \nu$$
$$n + e^+ \rightleftharpoons p + \bar{\nu}$$

$$\left(\frac{n}{p}\right)_{\text{weak}} = e^{-(m_n - m_p)/T_{\text{weak}}}$$

Astrophysical Constraints on 'Slow' Drifts in Fundamental Constants Induced by Scalar Dark Matter (CMB)

[Stadnik, Flambaum, *PRL* **115**, 201301 (2015)]

- Weaker astrophysical constraints come from CMB measurements (lower ρ_{DM}).
- Variations in α and m_e at the time of electron-proton recombination affect the ionisation fraction and Thomson scattering cross section, $\sigma_{Thomson} = 8\pi\alpha^2/3m_e^2$, changing the mean-free-path length of photons at recombination and leaving distinct signatures in the CMB angular power spectrum.

$$\Lambda'_\gamma \gtrsim \frac{1\ \mathrm{eV}^2}{m_\phi}, \quad \Lambda'_e \gtrsim \frac{0.6\ \mathrm{eV}^2}{m_\phi}$$

Evidence for spatial variation of the fine structure constant

$$\alpha = e^2/2\varepsilon_0 hc = 1/137.036$$

We calculated sensitivity to α for all transitions observed in quasar absorption spectra.

Measurements: spatial variation of α

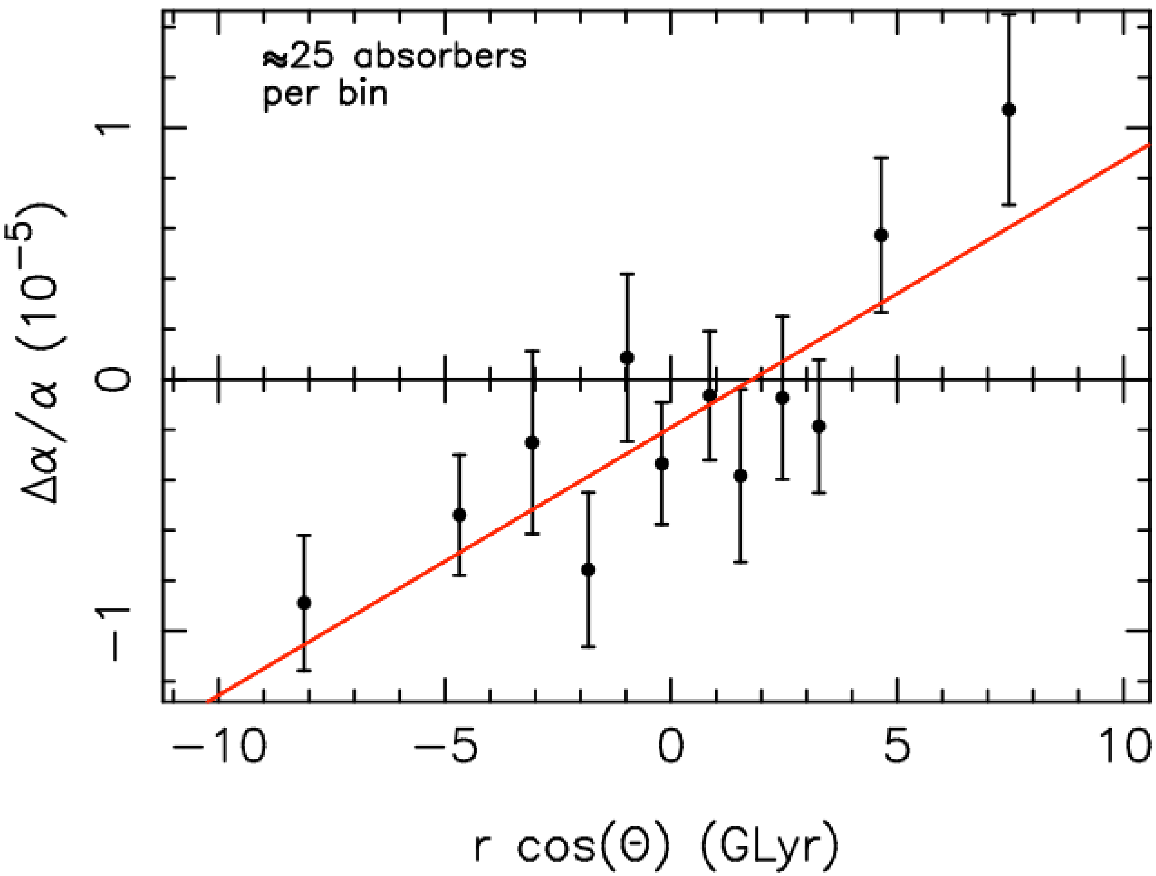
Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNRAS2012

$$\alpha(x) = \alpha(0) + \alpha'(0)\, x + \ldots$$

$x = r\cos(\phi)$, $r = ct$ – distance (t - light travel time, c - speed of light)

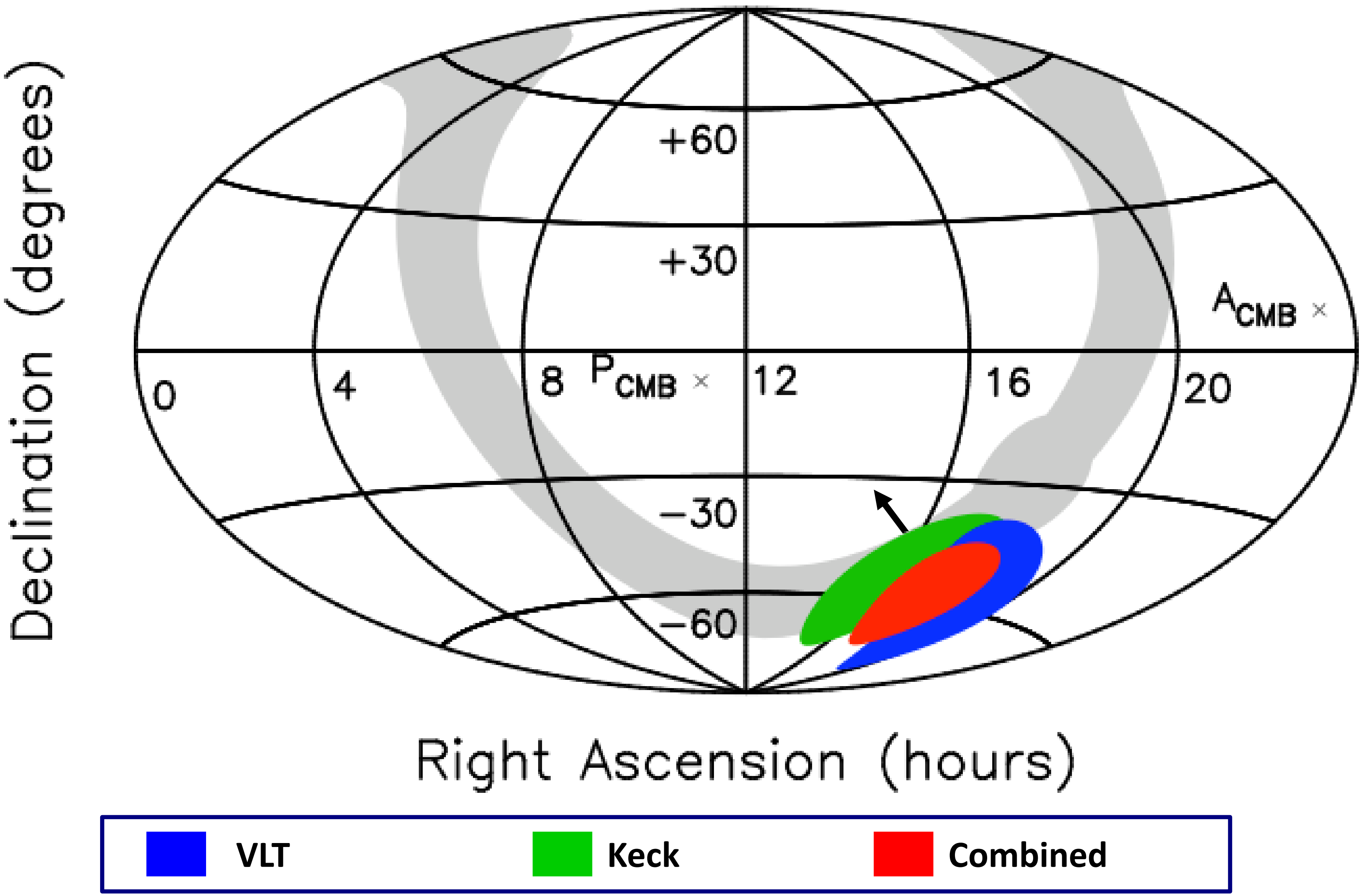
Reconciles all measurements of the variation

Distance dependence



Δα/α vs BrcosΘ for the model Δα/α=BrcosΘ+m showing the gradient in α along the best-fit dipole. The best- fit direction is at right ascension 17.4 ± 0.6 hours, declination −62 ± 6 degrees, for which B = (1.1 ± 0.2) × 10^{-6} $GLyr^{-1}$ and m = (−1.9 ± 0.8) × 10−6. This dipole+monopole model is statistically preferred over a monopole-only model also at the 4.1σ level. A cosmology with parameters (H_0 , Ω_M , Ω_Λ) = (70.5, 0.2736, 0.726).

Keck & VLT dipoles independently agree, p=4%

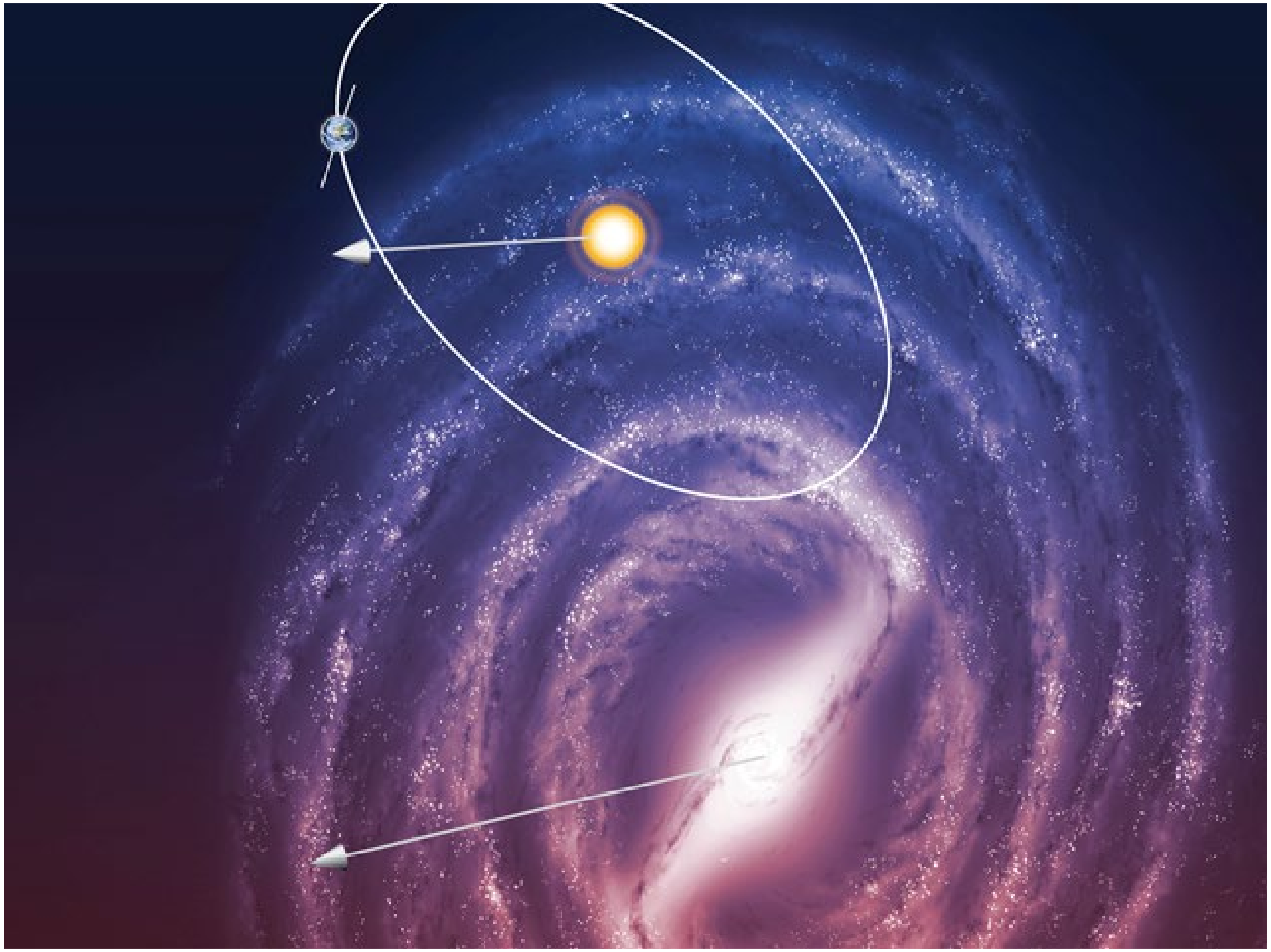


Consequences of quasar result, variation of α in space, for atomic clocks

- Sun moves 369 km/s relative to CMB
  $\cos(\phi)=0.1$
  This gives average laboratory variation
  $\Delta\alpha/\alpha = 1.5 \; 10^{-18} \; \cos(\phi) = 10^{-19}$ per year

- Earth moves 30 km/s relative to Sun-
  $1.6 \; 10^{-20} \cos(\omega t)$ annual modulation
  [Berengut and V.F. (2012)]

Gradient α points down



Limits on slow drift of α, m_q/Λ_{QCD}, m_e/M_p or m_e/Λ_{QCD} from atomic clocks

$$d/dt \ln(m_q/\Lambda_{QCD}) = 7(4) \times 10^{-15}\ \text{yr}^{-1}$$

$$m_e/M_p \text{ or } m_e/\Lambda_{QCD} \quad -0.1(1.0)\times 10^{-16}\ \text{yr}^{-1}$$

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t} = (-5.8 \pm 6.9)\times 10^{-17}\,\text{yr}^{-1}$$

Leefer *et al*, PRL 111, 060801 (2013) (Dy/Cs)

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t} = (-1.6 \pm 2.3)\times 10^{-17}\,\text{yr}^{-1}$$

Rosenband *et al*, Science 319,1808 (2008) (Al^+/Hg^+)

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t} = (-0.7 \pm 2.1)\times 10^{-17}\,\text{yr}^{-1}$$

Godun *et al*, PRL 113, 210801 (2014) (Yb^+/Yb^+)

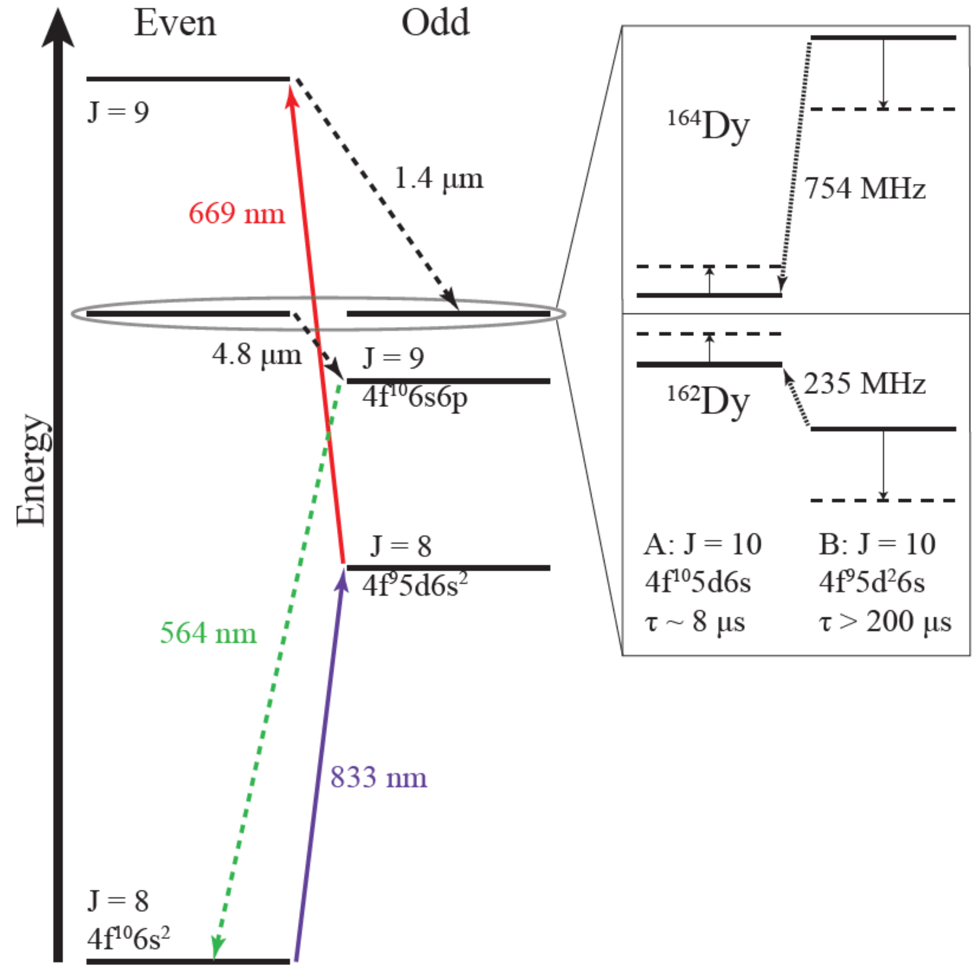
$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t} = 1.0(1.1)\times 10^{-18}\ \text{yr}^{-1}$$

Lange *et al*, PRL 126, 011102 (2021) (Yb^+/Yb^+)

Enhanced Effects of Varying Fundamental Constants on Atomic Transitions

[Dzuba,Flambaum,Webb,*PRL* **82**,888(1999); Flambaum PRL 97,092502(2006); PRA73,034101(2006); Berengut,Dzuba,Flambaum PRL105,120801 (2010)]

- Sensitivity coefficients may be greatly enhanced for transitions between nearly degenerate levels:
  - Atoms (e.g., $|K_\alpha(\text{Dy}) \sim 10^6 - 10^8$
  - Molecules
  - Highly-charged ions
  - Nuclei ^{229}Th K=10^4 Mossbauer transitions



Enhanced sensitivity to variation of fundamental constants in nuclear clocks

Peik, Tamm 2003: UV transition between first excited and ground state in ^{229}Th nucleus. Energy 8 eV, width 10^{-3} Hz, small systematics. Perfect clock!

V.F. PRL 2006: Nuclear/QCD estimate- Enhancement of variation **10^4**

He,Re; V.F. and Wiringa; V.F., Auerbach,Dmitriev; Hayes,Friar,Moller; Litvinova,Felmeier,Dobaczewski and V.F.;

$\Delta\omega/\omega_0 = \mathbf{10^4} \, (\Delta\alpha/\alpha + \Delta X_q/X_q)$, $X_q = m_q/\Lambda_{QCD}$ -strong interaction

Shift 200 Hz for $\Delta\alpha/\alpha = 10^{-17}$

Compare with atomic clock shift 0.01 Hz

Enhanced sensitivity to variation of fundamental constants in nuclear clocks

Berengut, Dzuba, V.F., Porsev PRL 2009: Fadeev, Berengut, V.F. 2020, 2022

Sensitivity to $\Delta\alpha/\alpha$ is expressed via difference of $<r^2>$ and difference of electric quadrupole moments Q_2 between ground excited nuclear states.

Measure isomeric shifts of ^{229}Th atomic lines
(atomic frequency in ^{229} Th) - (atomic frequency in ^{229}Th *).
Measured J. Thielking et al, Nature 556, 321, 2017.
$\Delta Q_2 = f(\Delta<r^2>)$

$E_{strong} + E_{Coulomb} = \omega_0 \sim 0 \qquad \Delta E_{Coulomb}/E_{Coulomb} = \Delta\alpha/\alpha.$

V.F. and Wiringa 2009 $\qquad \Delta E_{strong}/E_{strong} = -1.45\ \Delta m_q/m_q$

$$\Delta\omega/\omega_0 = -\,0.8\ 10^4\ \Delta\alpha/\alpha\ -\ 1.2\ 10^4\ \Delta m_q/m_q$$

We calculated sensitivity of Mossbauer transitions to $\Delta\alpha/\alpha$ **,** $\Delta m_q/m_q$,
$X_q = m_q/\Lambda_{QCD}$ -strong interaction

Why enhancement is so large?

Total Coulomb energy $E_C=10^9$ eV in ^{229}Th

Using the measured $\Delta\langle r^2\rangle$ we found difference of the Coulomb energies between the excited and ground state

ΔE_C=67(19) keV (= 10^{-4} E_C)

$\Delta\omega/\omega_0 = (\Delta E_C/\omega_0)\Delta\alpha/\alpha$ =

(7. 10^4 eV / 8 eV) $\Delta\alpha/\alpha$ = 0.8 10^4 $\Delta\alpha/\alpha$

Strong interaction $\Delta\omega/\omega_0$ = 1.2 10^4 $\Delta m_q/m_q$

Variation of Fundamental Constants Induced by a Massive Body

[Leefer, Gerhardus, Budker, V.F. and Stadnik, *PRL* **117**, 271601 (2016)]

Varying the distance away from a massive body hence alters the fundamental constants, in the presence of Yukawa-type interactions:

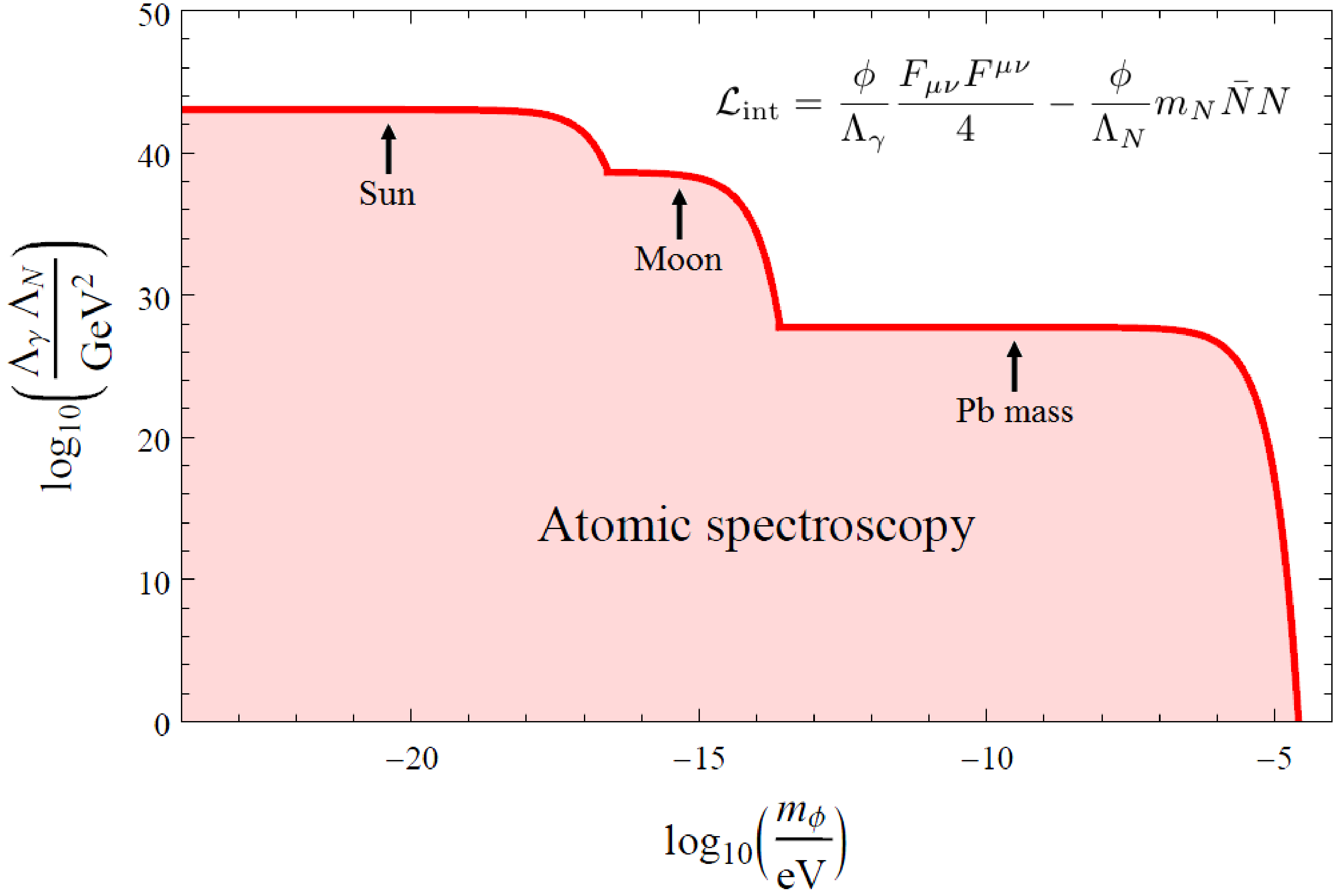
$$\frac{\delta m_f}{m_f} \propto \frac{e^{-m_\phi r}}{r}, \quad \frac{\delta \alpha}{\alpha} \propto \frac{e^{-m_\phi r}}{r}$$

We can search for such alterations in the fundamental constants, using **clock frequency comparison measurements** (ω_1/ω_2 => *scalar* quantities), **in the presence of a massive body at two different distances** away from the clock pair:

- Sun (elliptical orbit, e = 0.0167)
- Moon ($e \approx 0.05$, with seasonal variation and effect of finite Earth size)
- Massive objects in the laboratory (e.g., moveable 300kg Pb mass)

Constraints on a Combination of Linear Yukawa Interactions of a Scalar Boson

[Leefer, Gerhardus, Budker, V.F. and Stadnik, *PRL* **117**, 271601 (2016)]



Atomic Spectroscopy Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Arvanitaki, Huang, Van Tilburg, *PRD* **91**, 015015 (2015)], [Stadnik and V.F., *PRL* **114**, 161301 (2015)]

$$\frac{\delta\left(\omega_1/\omega_2\right)}{\omega_1/\omega_2} \propto \sum_X \left(K_{X,1} - K_{X,2}\right)\cos\left(\omega t\right)$$

$\omega = m_\varphi$ (linear portal) or $\omega = 2m_\varphi$ (quadratic portal)

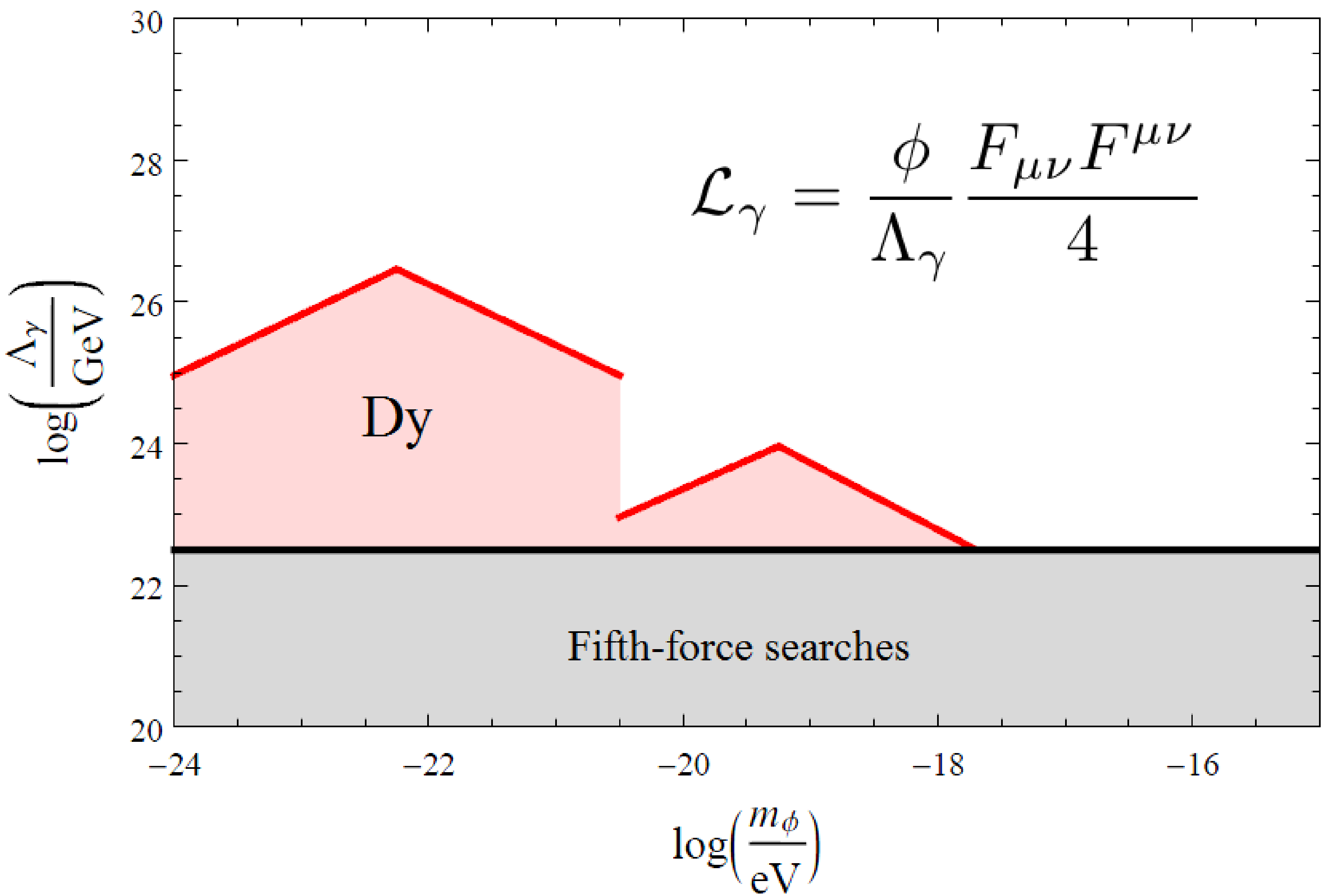
- Precision of optical clocks approaching $\sim 10^{-18}$ fractional level
- Sensitivity coefficients K_X calculated extensively by our group
- Mossbauer transitions in nuclei, $\sim 10^{-18}$ fractional level

Dy/Cs: [Van Tilburg *et al.*, *PRL* **115**, 011802 (2015)], [Stadnik and V.F., *PRL* **115**, 201301 (2015)]

Rb/Cs: [Hees *et al.*, *PRL* **117**, 061301 (2016)], [Stadnik and V.F., *PRA* **94**, 022111 (2016)]

Laboratory Search for Oscillating Variations in Fundamental Constants using Atomic Dysprosium

[Van Tilburg, Leefer, Bougas, Budker, *PRL* **115**, 011802 (2015)]

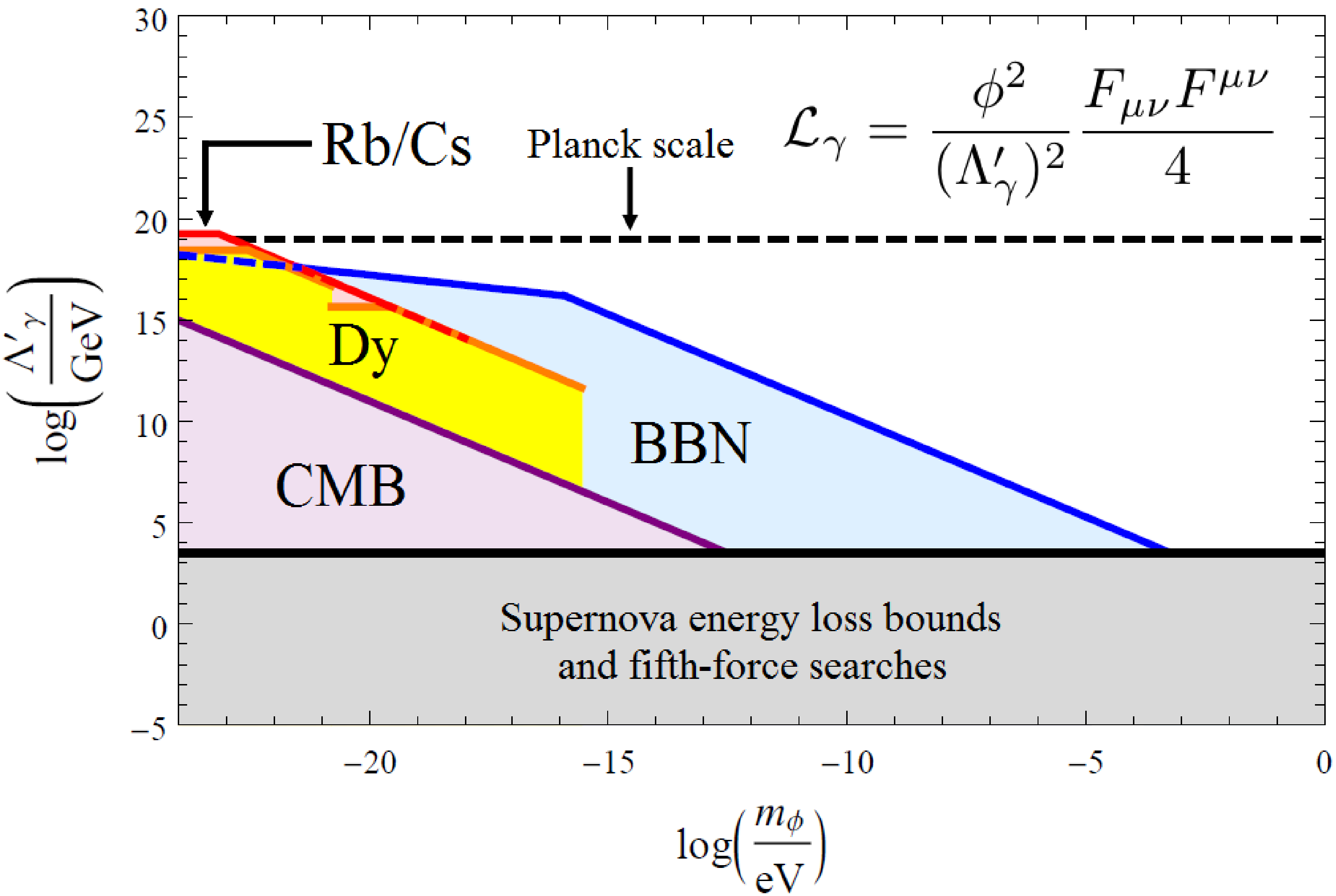


Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

BBN, CMB, Dy and Rb/Cs constraints:

[Stadnik and V.F., *PRL* **115**, 201301 (2015) + Phys. Rev. D 2016]

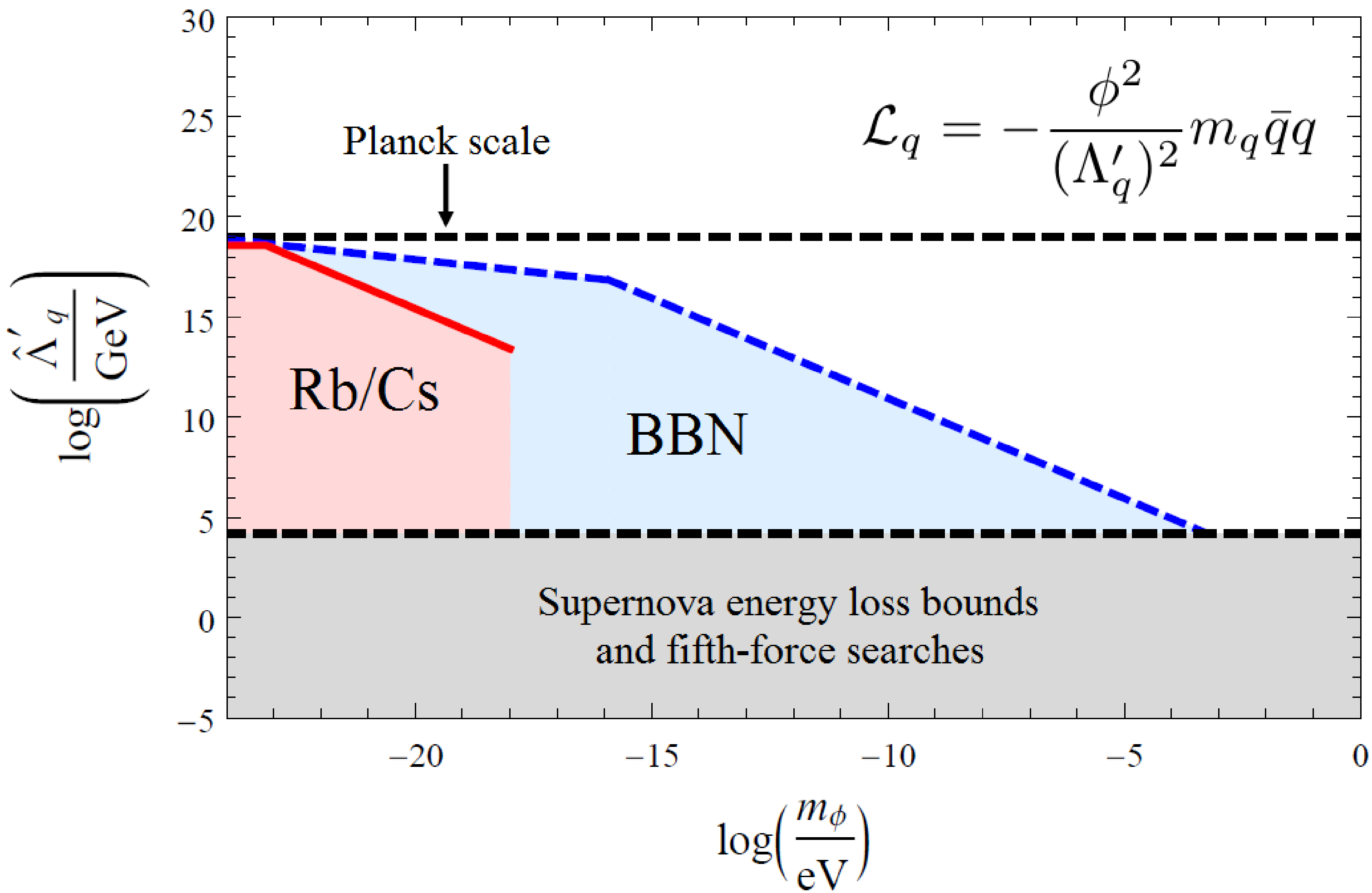
15 orders of magnitude improvement!



Constraints on Quadratic Interactions of Scalar Dark Matter with Light Quarks

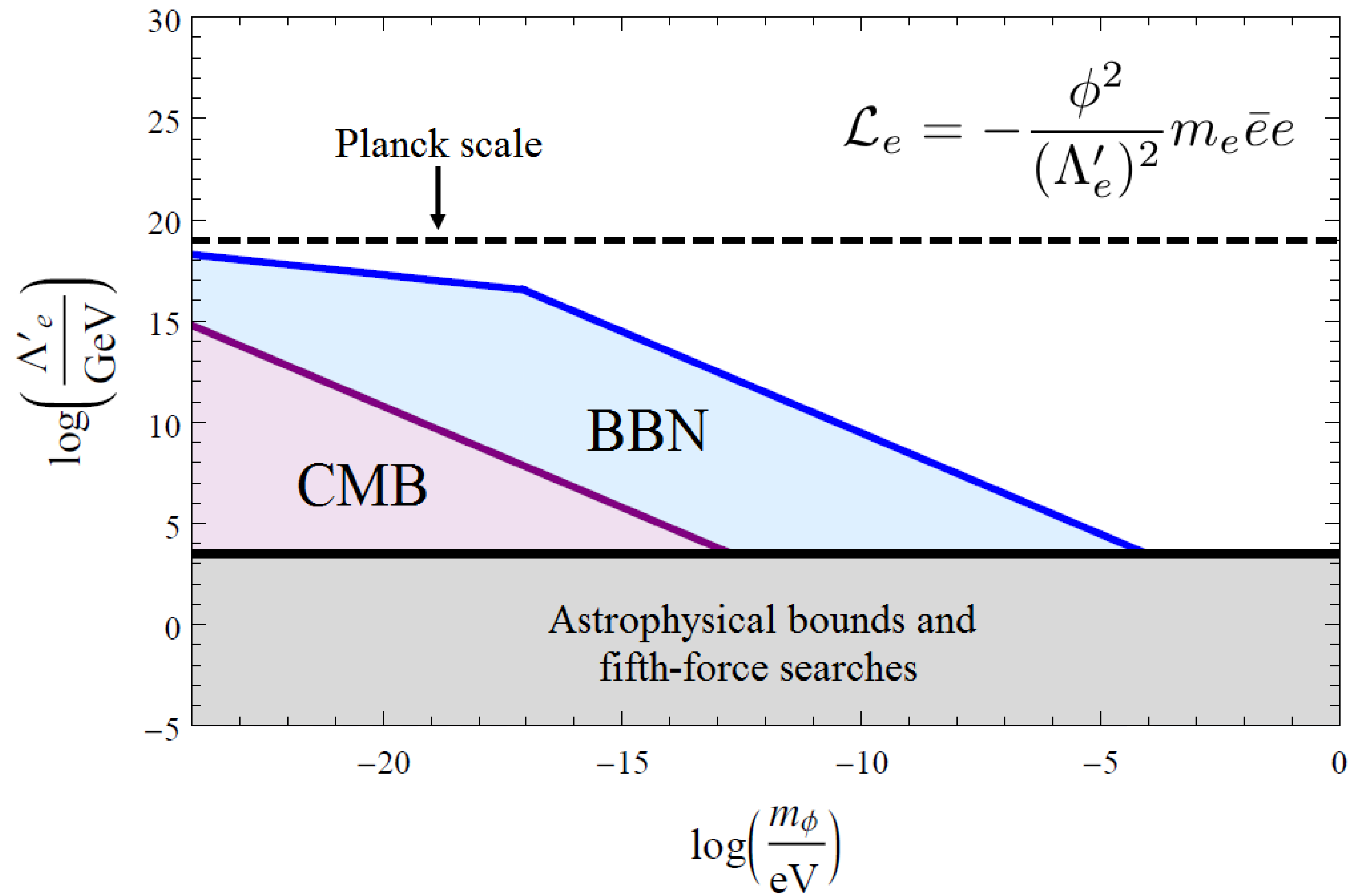
BBN and Rb/Cs constraints:

[Stadnik and V.F., *PRL* **115**, 201301 (2015) + Phys. Rev. D 2016]



Constraints on Quadratic Interaction of Scalar Dark Matter with the Electron

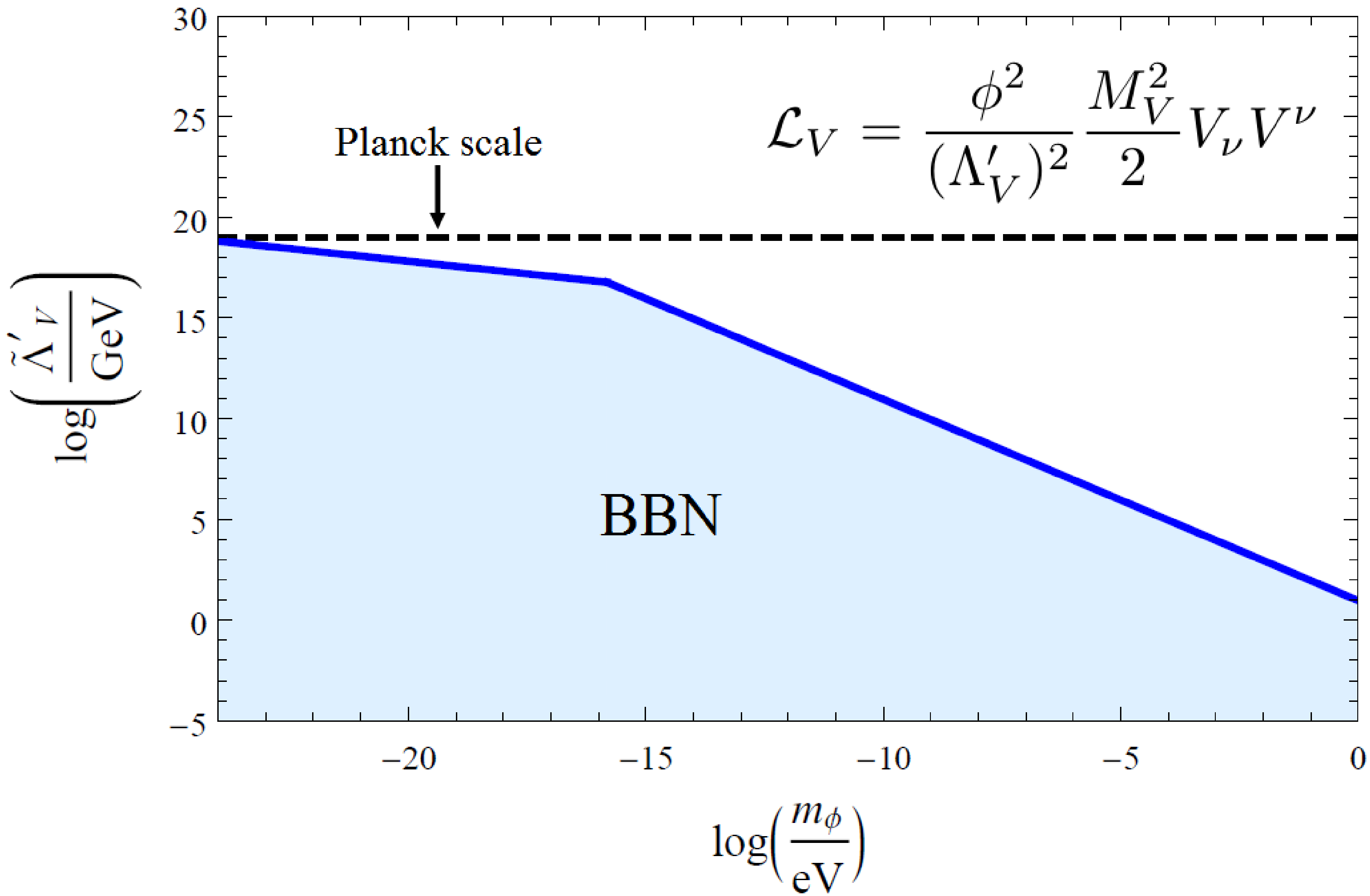
BBN and CMB constraints:
[Stadnik and V.F., *PRL* **115**, 201301 (2015)]



Constraints on Quadratic Interactions of Scalar Dark Matter with W and Z Bosons

BBN constraints:

[Stadnik and V.F., *PRL* **115**, 201301 (2015)]

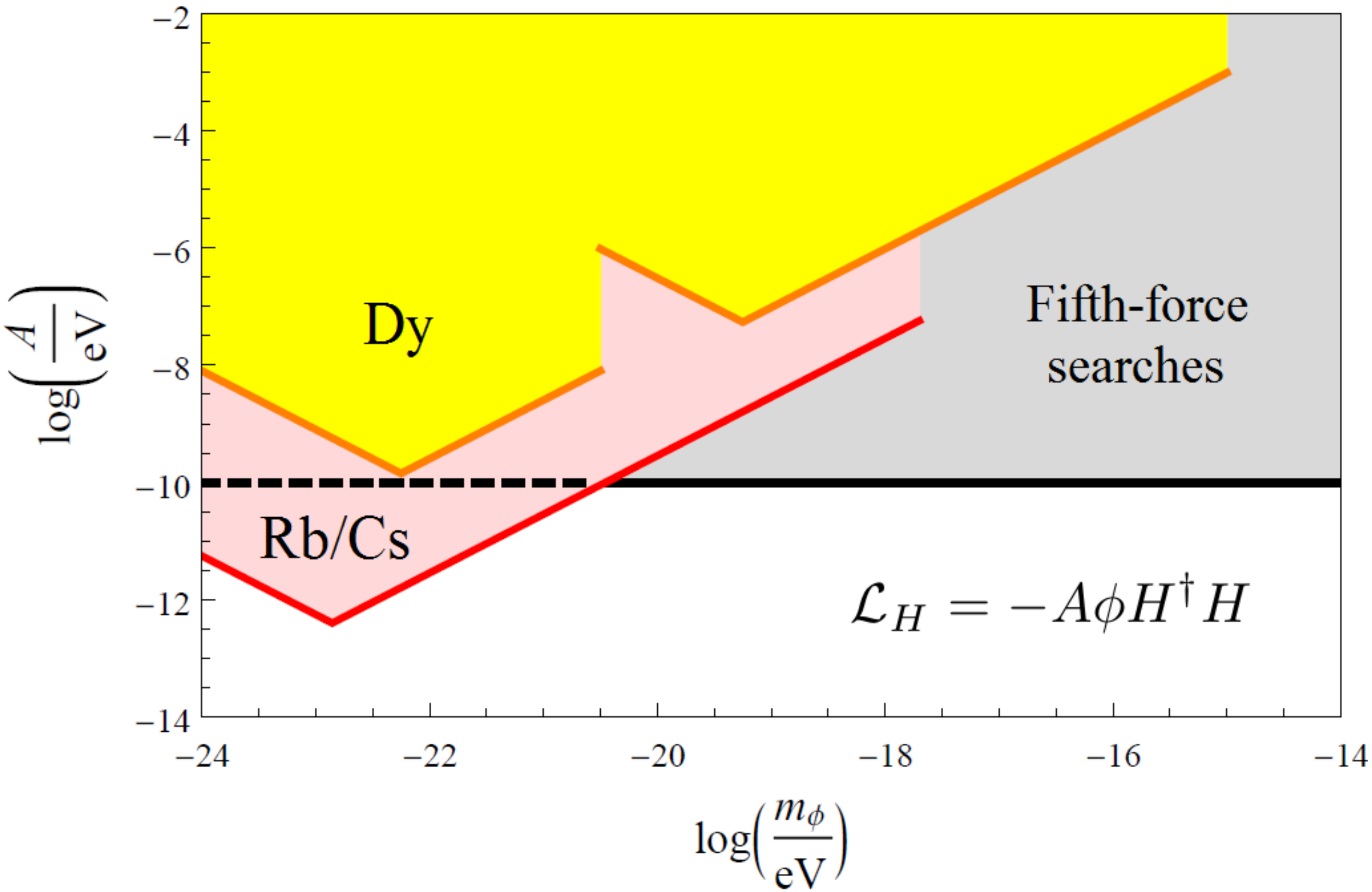


Constraints on Linear Interaction of Scalar Dark Matter with the Higgs Boson

Rb/Cs constraints:

[Stadnik and V.F., *PRA* **94**, 022111 (2016)]

2 – 3 orders of magnitude improvement!



Topological Defects, Bose stars

Detection of topological defects via transient-in-time effects requires searching for **correlated signals** using a terrestrial or space-based **network of detectors**.

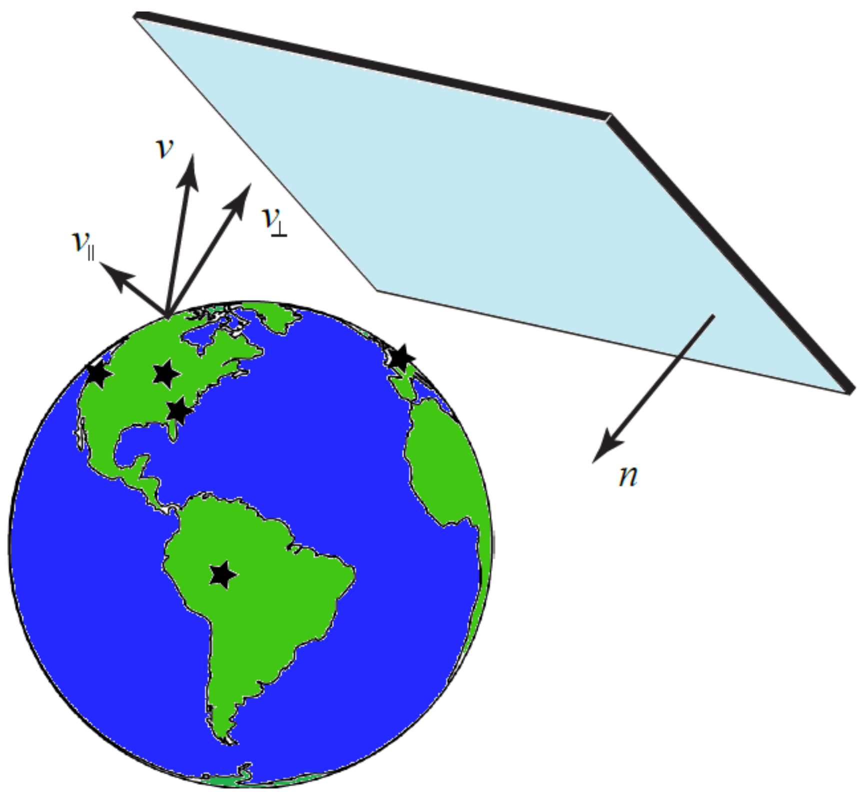
Recent proposals include:

Magnetometers [Pospelov *et al.*, *PRL* **110**, 021803 (2013)]
GNOMe

Pulsar Timing [Stadnik and V.F, *PRL* **113**, 151301 (2014)]

Atomic Clocks [Derevianko, Pospelov, *Nature Physics* **10**, 933 (2014)]

Laser Interferometers [Stadnik and V.F., *PRL* **114**, 161301 (2015); arXiv:1511.00447]



Laser Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Stadnik, Flambaum, *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

Gravitational-wave detector (LIGO/Virgo/GEO600), *L* ~ 4 km

Small-scale cavity, *L* ~ 0.2 m

Laser Interferometry Searches for Oscillating Variations in Fundamental Constants due to Dark Matter

[Stadnik and V.F., *PRL* **114**, 161301 (2015); *PRA* **93**, 063630 (2016)]

- Compare $L \sim Na_B$ with λ

$$\Phi = \frac{\omega L}{c} \propto \left(\frac{e^2}{a_B \hbar}\right)\left(\frac{N a_B}{c}\right) = N\alpha \quad => \quad \frac{\delta\Phi}{\Phi} \approx \frac{\delta\alpha}{\alpha}$$

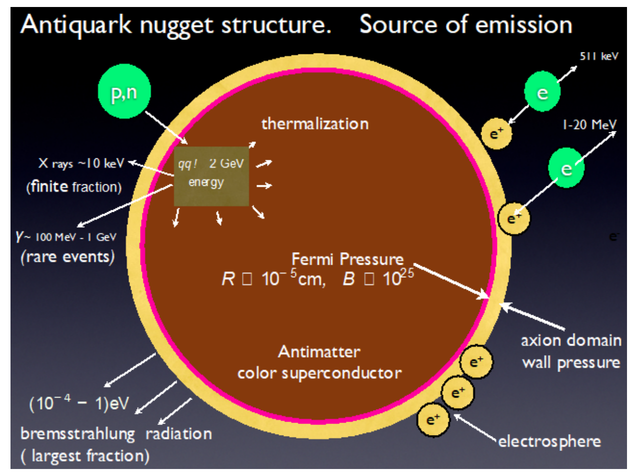
Multiple reflections of light beam enhance effect ($N_{eff} \sim 10^5$ in small-scale interferometers with highly reflective mirrors).

$\Phi = 2\pi L/\lambda$, $\delta\Phi = \Phi\, \delta\alpha/\alpha = 10^7\, \delta\alpha/\alpha$ single passage, $10^{12}\, \delta\alpha/\alpha$ for maximal number of reflections

Sr/Cavity (Domain wall DM): [Wcislo *et al.*, *Nature Astronomy* **1**, 0009 (2016)]

Axion-quark nuggets, QCD balls, Compact composite objects, etc.

- Quark matter nuggets are composed of large number of quarks surrounded by electron cloud
- Anti-quark nuggets consist of large number of anti-quarks, surrounded by the positron cloud
- Both quark and anti-quark nuggets amount to Dark Matter
- Explains matter-antimatter asymmetry in nature: anti-matter is hidden in anti-quark nuggets
- Has radiation which may (potentially) be detected. Annihilation of matter on antiQN: →microwave, infrared, visible, UV, X-ray, 511 keV, 100-500 MeV photons from center of Galaxy, molecular clouds and Sun;
  Axion, Infrasonic, acoustic and seismic waves from Earth
  Flambaum, Zhitnitsky, PRD 99, 023517 (2019),
  Budker, Flambaum, Liang, Zhitnitsky, PRD101,043012, 2020.
  Budker, Flambaum, Zhitnitsky, Symmetry 14, 459 (2022).
  Flambaum, Samsonov, PRD104, 063042 (2021); PRD 2022, arxiv: 2112.07201, 2203.14459



Adopted from the talk by A. Zhitnitsky

A. Zhitnitsky, JCAP10, 010 (2001)
And many subsequent papers

Conclusions

- There is a hint for spatial variation of the fine structure constant in quasar absorption spectra. May explain fine tuning of fundamental constants needed for life.
- New classes of dark matter effects that are **linear** in the underlying interaction constant (traditionally-sought effects of dark matter scale as second or fourth power), drift and oscillating variation of fundamental constants and violation of fundamental symmetries
- **Up to 15 orders of magnitude improvement** on interactions of scalar dark matter with the photon, electron, quarks, Higgs, W^+,W^-,Z^0
- New clocks: nuclear ^{229}Th,^{235}U, highly-charged ions, Mossbauer transitions. Enormous potential for atomic experiments to search for for variation of α, m_q ,new particles and dark matter with unprecedented sensitivity