New effects of dark matter in cavity resonators, capacitors, underground detectors and clocks.

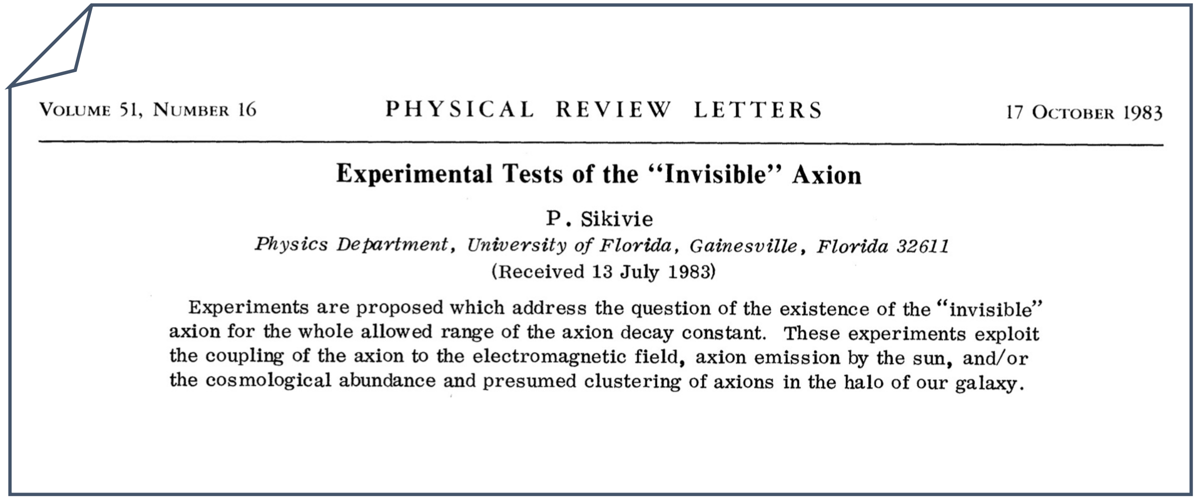
V.V. Flambaum

Proposals for searches of scalar field dark matter using cavity resonators and capacitors

V. V. Flambaum, Ben McAllister, I. B. Samsonov, and Michael E. Tobar

arXiv: 2207.14437

Introduction: The axion story



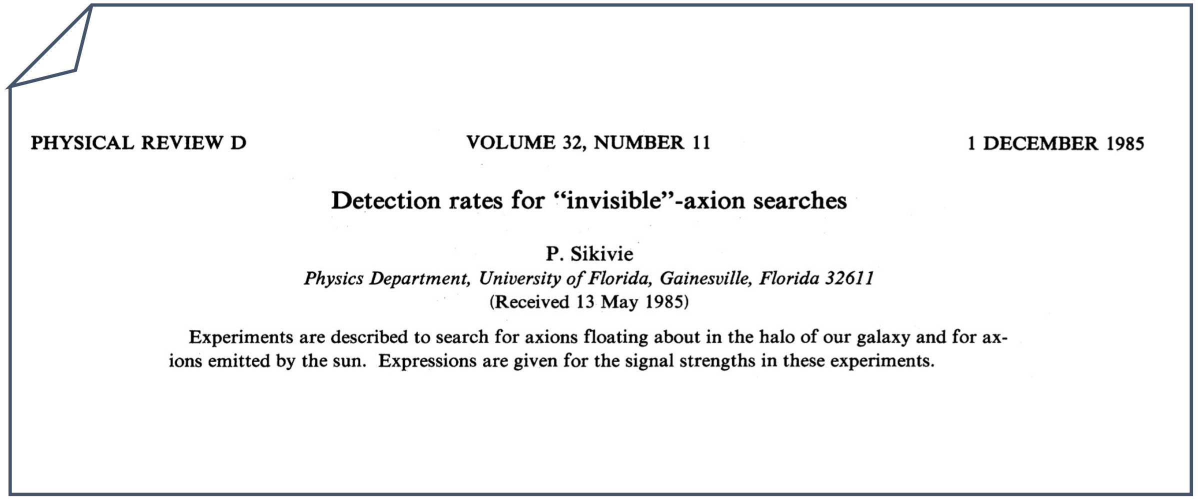
VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611

(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.



PHYSICAL REVIEW D VOLUME 32, NUMBER 11 1 DECEMBER 1985

Detection rates for "invisible"-axion searches

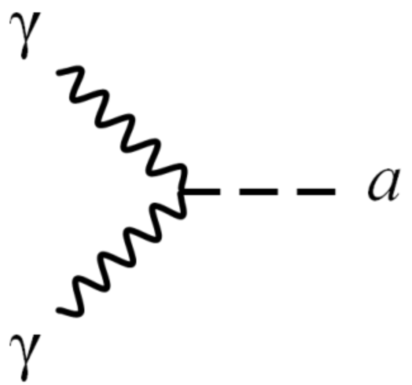
P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611

(Received 13 May 1985)

Experiments are described to search for axions floating about in the halo of our galaxy and for axions emitted by the sun. Expressions are given for the signal strengths in these experiments.

$$\mathcal{L}_{int} = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

axion-photon coupling constant



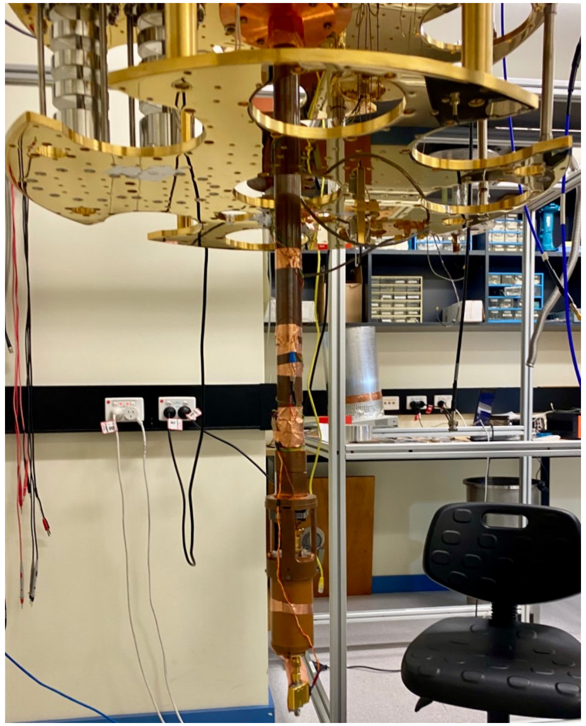
Introduction: Axion detection experiments

ADMX

CAST

Light shining through a wall

ORGAN



And others…

Introduction: scalar field dark matter

$$\mathcal{L}_{\rm int} = -\frac{1}{4} g_{\phi\gamma\gamma} \phi F_{\mu\nu} F^{\mu\nu} = \frac{1}{2} g_{\phi\gamma\gamma} \phi (\vec{E}^2 - \vec{B}^2)$$

scalar-photon coupling constant

- ϕ is a dilaton-like scalar field motivated by e.g. string theory
- Are axion-search experiments sensitive to the scalar-photon coupling $g_{\phi\gamma\gamma}$?
- How to maximize the sensitivity of these experiments to $g_{\phi\gamma\gamma}$?
- New experimental techniques for searching scalar dark matter with the dilaton-like interaction?

Theory: scalar-photon interaction

$$\mathcal{L} = \frac{1}{2}(\epsilon\vec{E}^2 - \frac{1}{\mu}\vec{B}^2) + \underbrace{\frac{1}{2}g_{\phi\gamma\gamma}\phi(\vec{E}^2 - \vec{B}^2)}_{\text{scalar photon interaction}}$$

dielectric constant

magnetic susceptibility

$$\phi = \mathrm{Re}[\phi_0 e^{i(\vec{p}\cdot\vec{x} - \omega t)}]$$

plane-wave solution

$$\phi_0 = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_\phi}$$

local DM density

scalar field mass

Modified Maxwell equations

$$\boxed{\begin{aligned} \nabla\cdot(\epsilon\vec{E} + g_{\phi\gamma\gamma}\phi\vec{E}) &= 0 \\ \nabla\times(\mu^{-1}\vec{B} + g_{\phi\gamma\gamma}\phi\vec{B}) - \partial_t(\epsilon\vec{E} + g_{\phi\gamma\gamma}\phi\vec{E}) &= 0 \\ \nabla\times\vec{E} + \partial_t\vec{B} &= 0 \\ \nabla\cdot\vec{B} &= 0 \end{aligned}}$$

$$\Rightarrow$$

E_0 and B_0 are static background electric and magnetic fields

$$\boxed{\begin{aligned} \nabla\cdot(\epsilon\vec{E}) &= \rho_\phi \\ \nabla\times(\mu^{-1}\vec{B}) - \partial_t(\epsilon\vec{E}) &= \vec{j}_\phi \end{aligned}}$$

effective charge and current densities

$$\boxed{\begin{aligned} \rho_\phi &= -g_{\phi\gamma\gamma}\nabla\cdot(\phi\vec{E}_0)\,, \\ \vec{j}_\phi &= g_{\phi\gamma\gamma}\vec{E}_0\partial_t\phi - g_{\phi\gamma\gamma}\nabla\times(\phi\vec{B}_0) \end{aligned}}$$

Theory: Scalar-photon transformation

Photon signal power

$$P = \frac{g^2_{\phi\gamma\gamma}\rho_{\rm DM}}{16\pi^2\epsilon}\int d^3k\,\delta(|\vec{k}|-\omega)\left|\int_V d^3x\,e^{i(\vec{p}-\vec{k})\cdot\vec{x}}\vec{n}\times[\vec{E}_0+\vec{\beta}\times\vec{B}_0]\right|^2$$

Compare with the power of axion-photon transformation

[P. Sikivie, Phys. Rev. D 32, 2988 (1985)]

$$P_{\rm axion} = \frac{g^2_{a\gamma\gamma}\rho_{\rm DM}}{16\pi^2\epsilon}\int d^3k\,\delta(|\vec{k}|-\omega)\left|\int_V d^3x\,e^{i(\vec{p}-\vec{k})\cdot\vec{x}}\vec{n}\times[\vec{B}_0-\vec{\beta}\times\vec{E}_0]\right|^2$$

Theory: Scalar-photon transformation (E_0=0)

$$P = \frac{g^2_{\phi\gamma\gamma}\rho_{\rm DM}}{16\pi^2\epsilon}\int d^3k\,\delta(|\vec{k}|-\omega)\left|\int_V d^3x\, e^{i(\vec{p}-\vec{k})\cdot\vec{x}}\vec{n}\times\vec{\beta}\times\vec{B}_0\right|^2$$

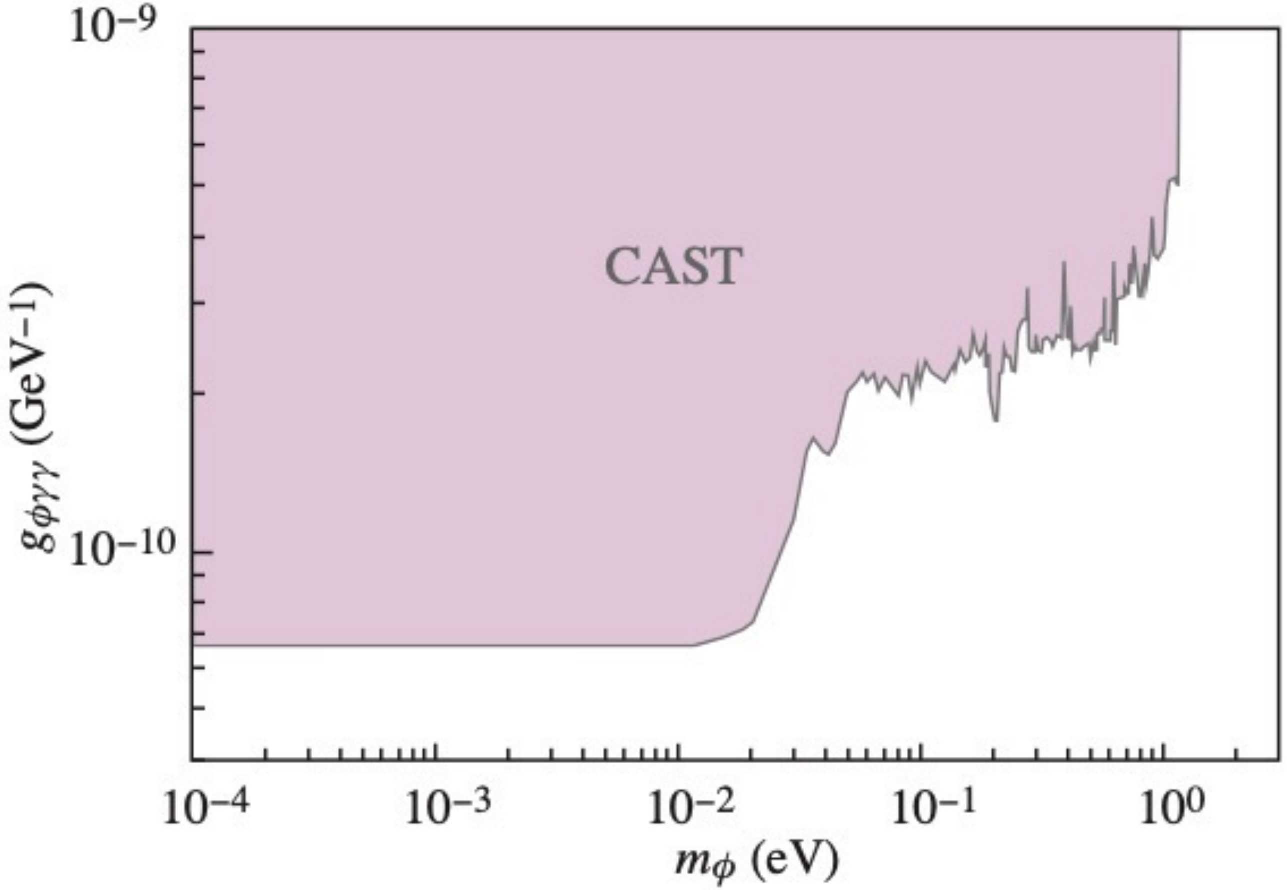
- β=10^{-3} is the velocity of DM particles

$$|\vec{\beta}\times\vec{B}_0|^2 = \beta^2 B_0^2\sin^2\theta$$

- β^2=10^{-6} is the suppression; $\sin^2\theta$ is responsible for signal modulation

- CAST experiment searches for axions produced in the Sun with β=1
- CAST experiment is equally sensitive to both axions and scalars thermally produced in the Sun!

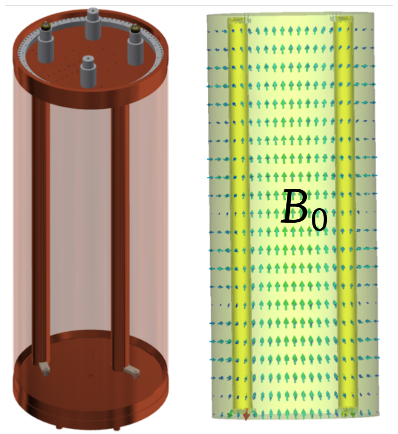
Results: Limits from CAST Experiment



Derived from Ref. [CAST Collaboration, Nature Physics 13, 584 (2017)] with a graphical accuracy

Theory: Transformation in a resonant cavity

Axion signal
[Sikivie 1985]



Signal power

volume

$$P_{\rm axion} = \frac{1}{m_a} g^2_{a\gamma\gamma} \rho_{\rm DM} B_0^2 V C_\alpha Q_\alpha$$

quality factor

Form factor

$$C_\alpha = \frac{\left| \int_V d^3x\, \vec{B}_0 \cdot \vec{E}_\alpha \right|^2}{B_0^2 V \int_V d^3x\, \epsilon \vec{E}_\alpha \cdot \vec{E}_\alpha}$$

Scalar field signal power in a cavity with electric E_0 and magnetic B_0 fields

$$P = \frac{1}{m_\phi} g^2_{\phi\gamma\gamma} \rho_{\rm DM} (B_0^2 + E_0^2) V C_\alpha Q_\alpha$$

Q_α is quality factor and C_α is the form factor

$$C_\alpha = \frac{1}{(B_0^2 + E_0^2) V} \frac{\left| \int_V d^3x\, e^{i\vec{p}\cdot\vec{x}} (\vec{B}_0 \cdot \vec{B}_\alpha + \vec{E}_0 \cdot \vec{E}_\alpha) \right|^2}{\frac{1}{2} \int_V d^3x (\mu^{-1} \vec{B}_\alpha \cdot \vec{B}_\alpha + \epsilon \vec{E}_\alpha \cdot \vec{E}_\alpha)}$$

E_α and B_α are eigenmodes of electric and magnetic fields in the cavity

Theory: Transformation in a resonant cavity

Cavity permeated by magnetic field B_0

$$P = \frac{1}{m_\phi} g^2_{\phi\gamma\gamma} \rho_{\rm DM} B_0^2 V C_\alpha Q_\alpha \,,$$

$$C_\alpha = \frac{1}{B_0^2 V} \frac{\left| \int_V d^3x \, e^{i\vec{p}\cdot\vec{x}} \vec{B}_0 \cdot \vec{B}_\alpha \right|^2}{\int_V d^3x \, \mu^{-1} \vec{B}_\alpha \cdot \vec{B}_\alpha}$$

$$P = 1.3 \times 10^8 {\rm W} \left(\frac{g_{\phi\gamma\gamma}}{\rm GeV^{-1}} \right)^2 \left(\frac{3\mu{\rm eV}}{m_\phi} \right) \left(\frac{\rho_{\rm DM}}{0.45 {\rm GeV/cm}^3} \right) \times \left(\frac{B_0}{7.6{\rm T}} \right)^2 \left(\frac{V}{136{\rm L}} \right) \left(\frac{C_\alpha}{0.4} \right) \left(\frac{Q_\alpha}{30000} \right) .$$

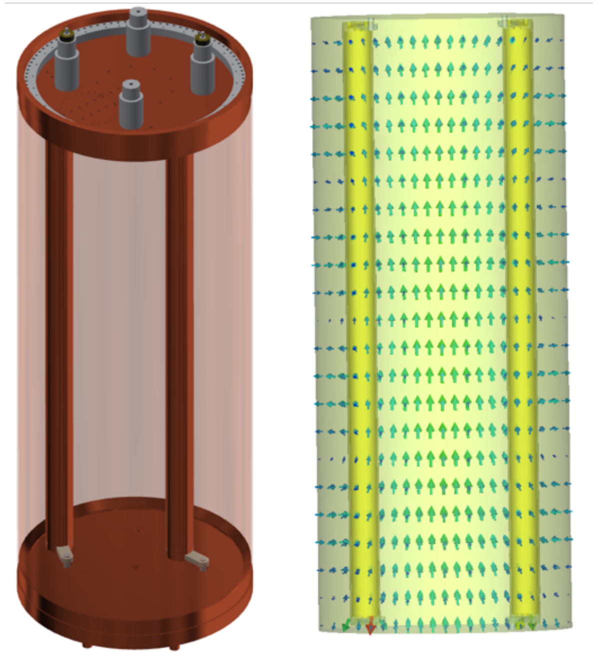
Cavity permeated by electric field E_0

$$P = \frac{1}{m_\phi} g^2_{\phi\gamma\gamma} \rho_{\rm DM} E_0^2 V C_\alpha Q_\alpha \,,$$

$$C_\alpha = \frac{1}{E_0^2 V} \frac{\left| \int_V d^3x \, e^{i\vec{p}\cdot\vec{x}} \vec{E}_0 \cdot \vec{E}_\alpha \right|^2}{\int_V d^3x \, \epsilon \vec{E}_\alpha \cdot \vec{E}_\alpha}$$

$$P = 38{\rm W} \left(\frac{g_{\phi\gamma\gamma}}{\rm GeV^{-1}} \right)^2 \left(\frac{3\mu{\rm eV}}{m_\phi} \right) \left(\frac{\rho_{\rm DM}}{0.45 {\rm GeV/cm}^3} \right) \times \left(\frac{E_0}{1\,{\rm MV/m}} \right)^2 \left(\frac{V}{136\,{\rm L}} \right) \left(\frac{C_\alpha}{0.4} \right) \left(\frac{Q_\alpha}{30000} \right) .$$

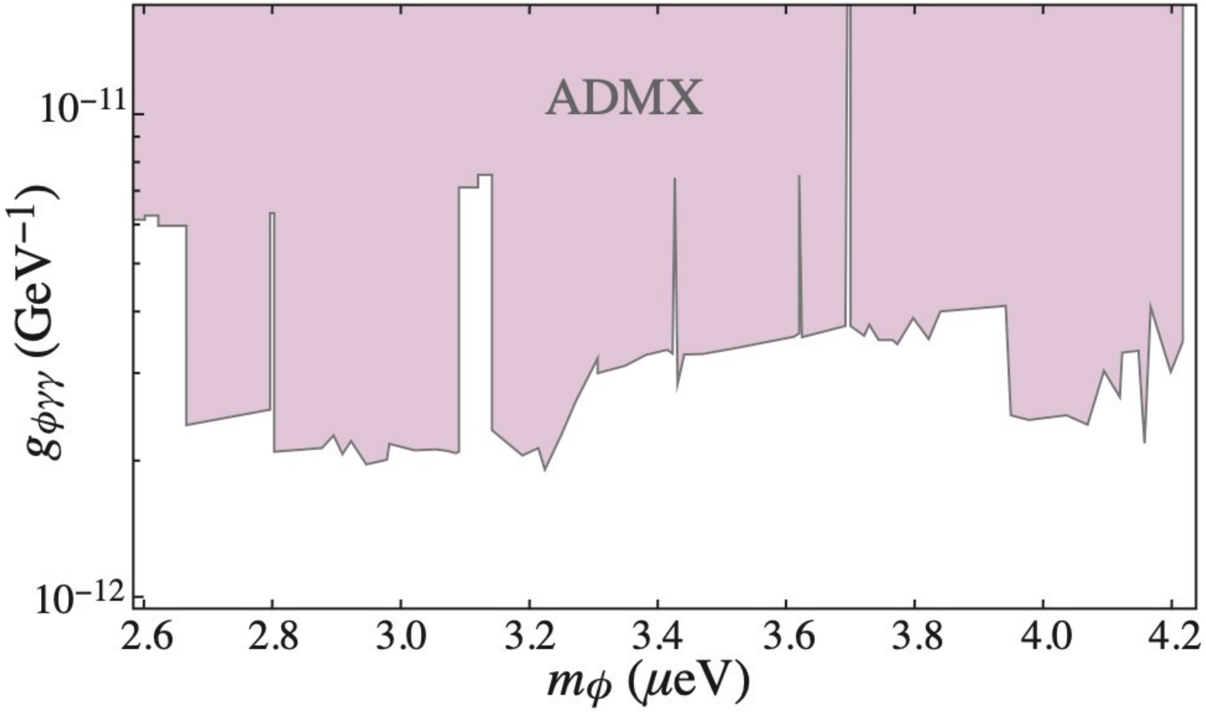
Results: Constraints from ADMX



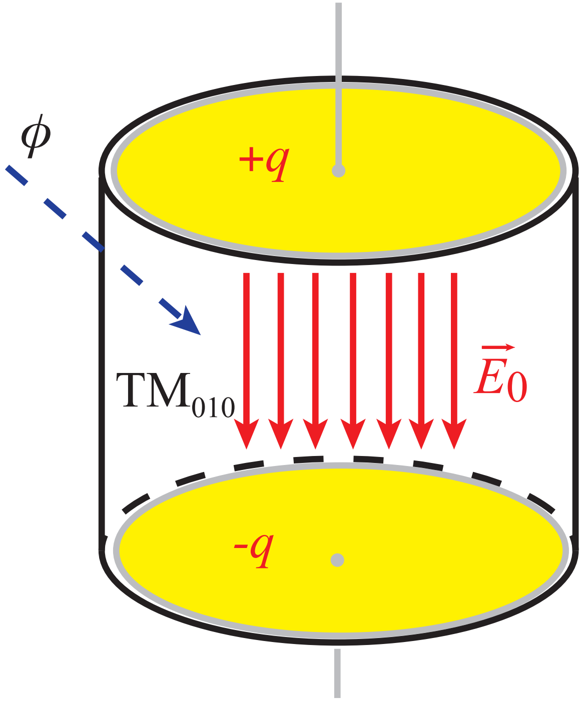
ADMX cavity scalar field form factor $C_\alpha \approx 10^{-12}$

ADMX sidecar scalar field form factor $C_\alpha \approx 10^{-8}$

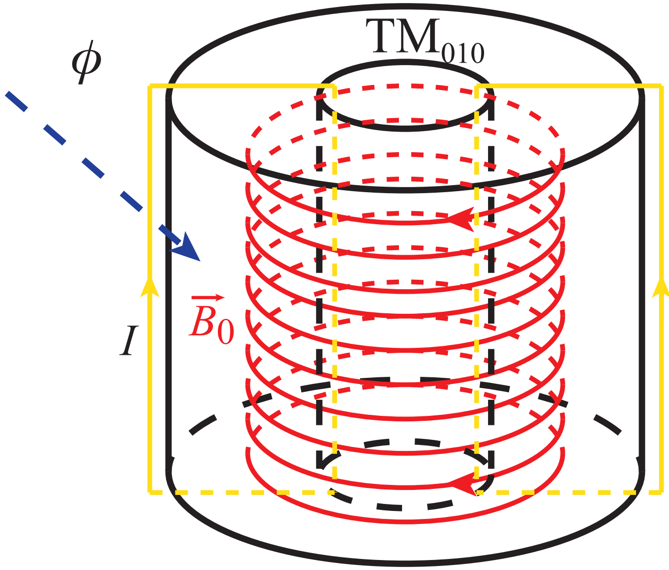
Upper limits on the scalar-photon coupling constant



Results: Cavity resonators proposals with maximized form factors to the scalar field DM

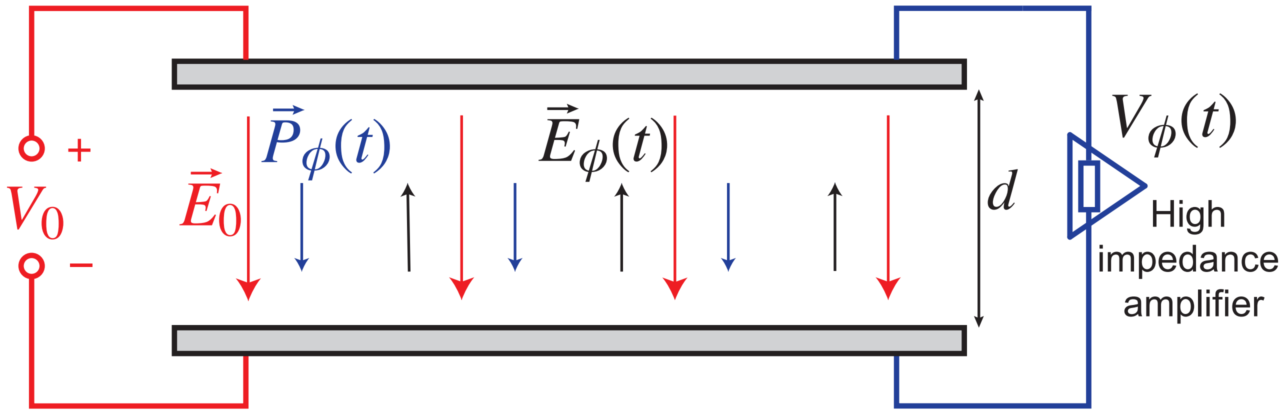


$$C_\alpha = 0.69$$



$$C_\alpha = O(1)$$

Results: Proposal for a broadband detection with a capacitor

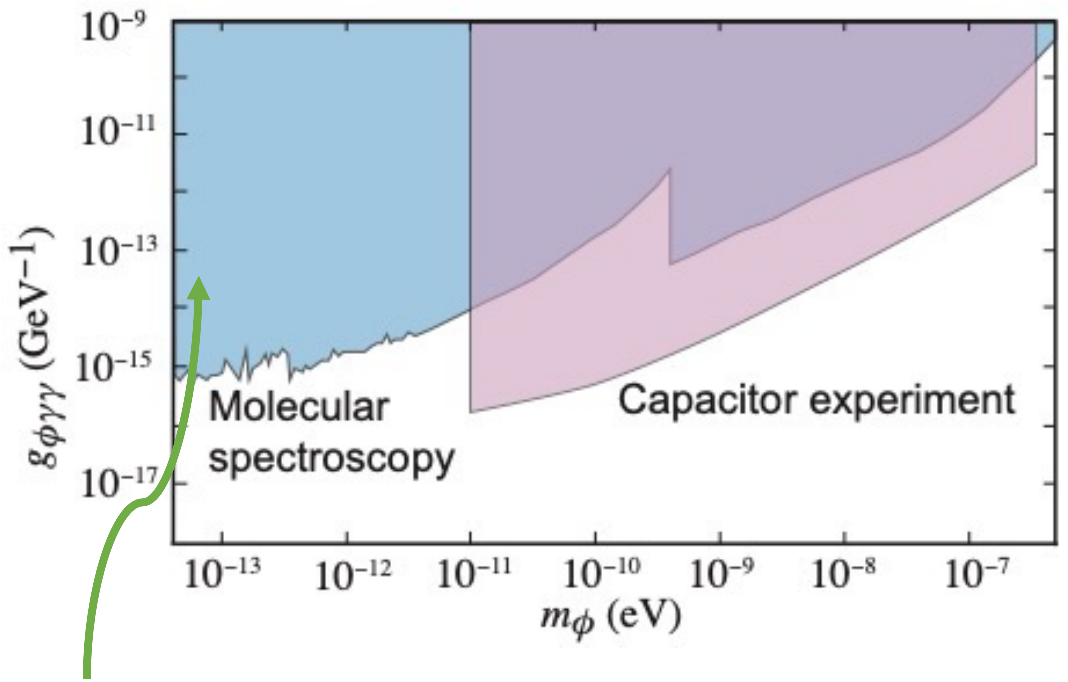


Effective polarization $\vec{P}_\phi = g_{\phi\gamma\gamma}\phi\vec{E}_0$

Signal is AC voltage $\langle V_\phi\rangle = g_{\phi\gamma\gamma}\epsilon^{-1}V_0\frac{\sqrt{\rho_{\rm DM}}}{m_\phi}$

Applied voltage $V_0 \sim 600\ \mathrm{kV}$

Estimated sensitivity of such experiment



R. Oswald et al. arXiv:2111.06883 [hep-ph].

Summary

- Calculated the power of photon signal from scalar photon transformation in a resonant cavity
- New limits on the scalar-photon coupling constant from re-purposing the results of CAST and ADMX experiments
- Proposals for cavity experiments with maximized sensitivity to the scalar field dark matter
- A capacitor-based broadband experiment is proposed

Atomic ionization by scalar dark matter and solar scalars

H. B. Tran Tan, A. Derevianko, V. Dzuba, V.V. Flambaum. PRL 127, 081301 (2021)

Relativistic Hartree-Fock calculations corrected several orders of magnitude error. Born approximation does not work due to violation of orthogonality condition between bound and continuum electron wave functions.

New limits on electron-scalar coupling from Xenon1T data.

Data files for scalars and axions: arXiv:2105.08296.

Calculations for Na, I, Tl, Xe, Ar, Ge atoms

University of Nevada, Reno

UNSW SYDNEY

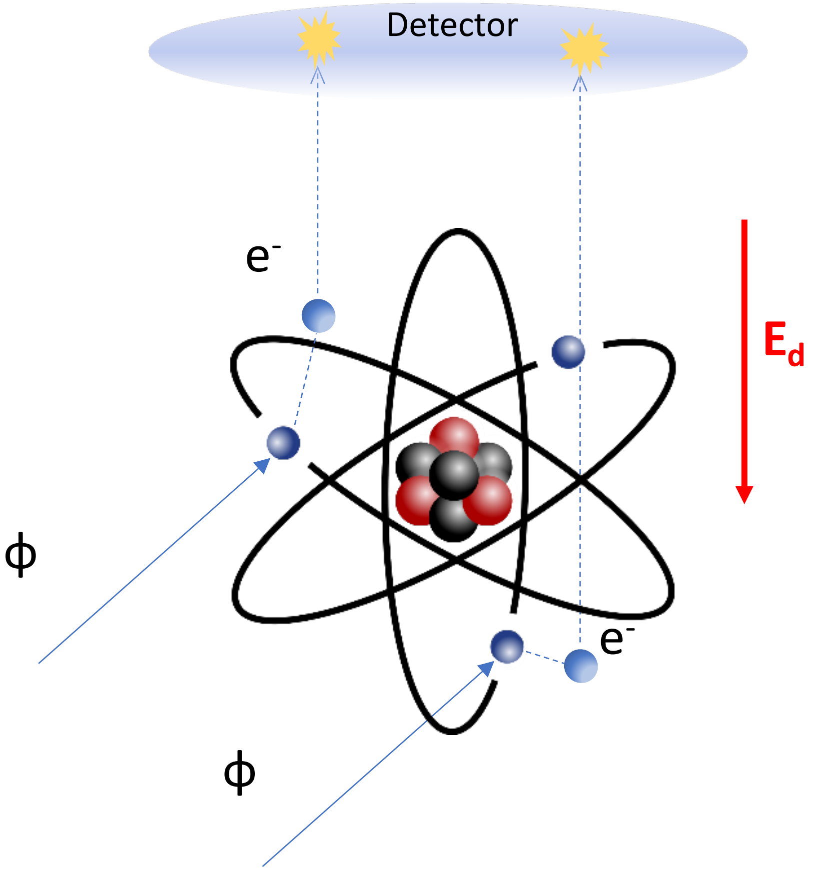
HIM Helmholtz-Institut Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Atomic ionization by scalars

$$\mathcal{L}_{\phi\bar{e}e} = \sqrt{\hbar c}\, g_{\phi\bar{e}e}\,\phi\bar{\psi}\psi$$

- ϕ : scalar familon, sgoldstino, dilaton, relaxon, moduli, Higgs-portal DM, etc.
- Absorption of scalar causes atomic ionization (similar to photoelectric effect)→ detectable by current DM and solar axion searches.
- Xenon1T, PandaX-II, EDELWEISS-III, DAMA/LIBRA, SABRE, SuperCDMS, ArDM, DarkSide-20k, DEAP-3600.



Pitfall: wrong wave functions → wrong results

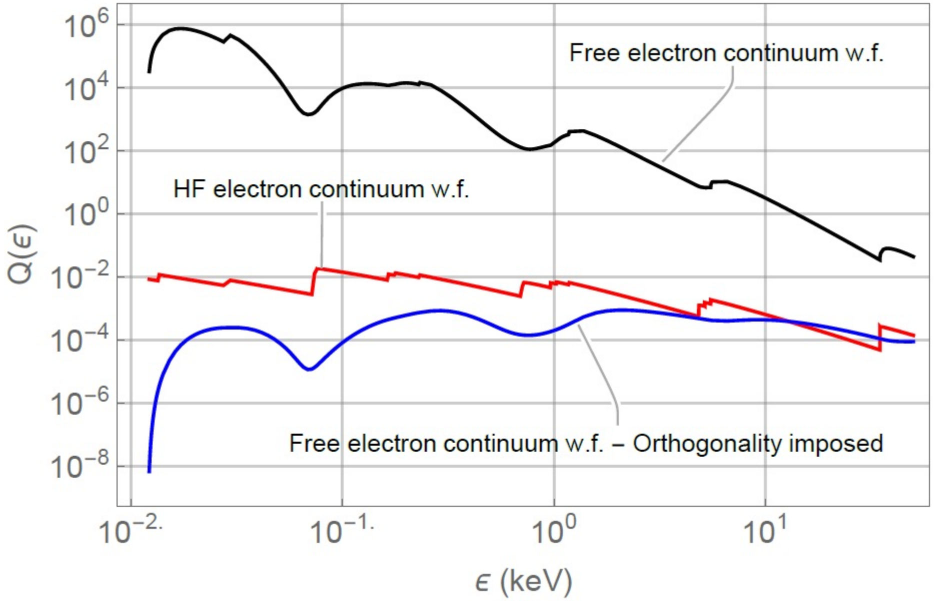
- Orthogonality condition → Born approximation does not work!
- Previous work Int. J. Mod. Phys. A 21:1445-1470, 2006: plane wave continuum function → errors by many orders of magnitude.
- Pitfall also exists for axioelectric effect and Migdal effect→ affects low-energy cross section only.
- Relativistic Hartree-Fock calculations for scalars and axions.
- Migdal and boosted DM effects: V.F., L. Su, L. Wu, B. Zhu, arXiv:2012.09751

$$M_{b\to c} \sim \int \left(f_b f_c - \alpha^2 g_b g_c\right) j_0\left(k_\phi r\right) dr$$

$$= \int \left(f_b f_c - \alpha^2 g_b g_c\right) dr + \int \left(f_b f_c - \alpha^2 g_b g_c\right)\left(j_0\left(k_\phi r\right) - 1\right) dr$$

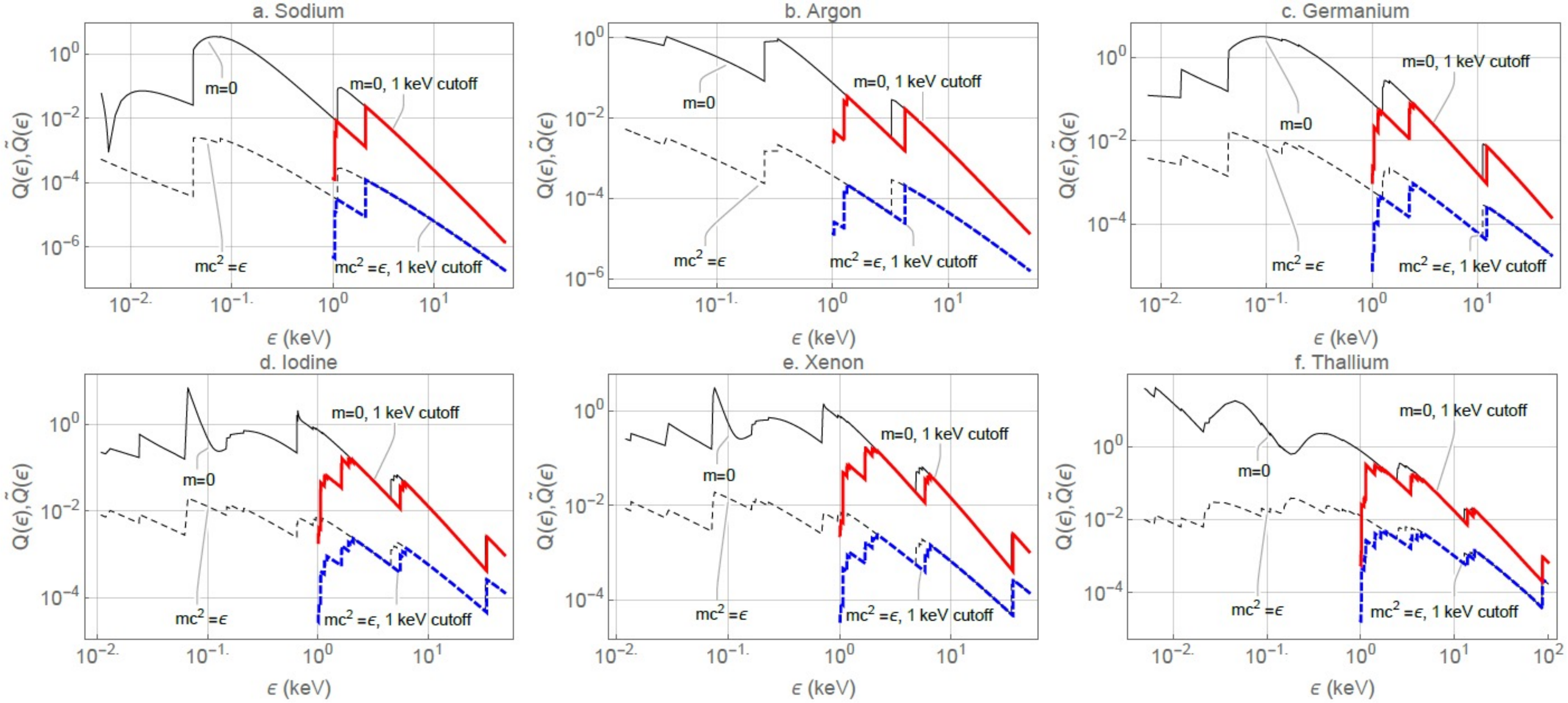
$$= \underbrace{\int \left(f_b f_c + \alpha^2 g_b g_c\right) dr}_{0} - \underbrace{2\alpha^2 \int g_b g_c \, dr}_{\text{relativistic}}$$

$$+ \int \left(f_b f_c - \alpha^2 g_b g_c\right) \underbrace{\left(j_0\left(k_\phi r\right) - 1\right)}_{\approx \frac{k_\phi^2 r^2}{6} \ll 1} dr$$



Results: cross sections for Na, Ar, Ge, I, Xe, Tl

- With and without 1 keV cutoff.
- Accuracy a few %, up to 10% near threshold.
- Accurate scalar and axion data, relativistic Hartree-Fock calculations: PRL 127, 081301 (2021) arXiv:2105.08296.



$$\sigma_\phi = g^2_{\phi\bar{e}e}(c/v)Q(\epsilon)a_0^2$$

$$\frac{\sigma_\phi\left(m_\phi=0\right)}{\sigma_\gamma\left(\varepsilon_\gamma=\varepsilon_\phi\right)} \approx \frac{g^2_{\phi\bar{e}e}}{4\pi\alpha}$$

Check against photoelectric experimental data

Scalar DM and solar scalar limits from Xenon1T data

- Detection rate for scalar DM:

$$R \approx \frac{4.8}{A} \frac{\tilde{Q}(m = \frac{\epsilon}{c^2})}{\text{year}} \left(\frac{g_{\phi\bar{e}e}}{10^{-17}}\right)^2 \left(\frac{\text{keV}}{mc^2}\right) \left(\frac{M}{\text{ton}}\right)$$

- Detection rate for solar scalar:

$$R \approx \frac{8.3}{A} \frac{\tilde{Q}(m = 0)}{\text{year}} \left(\frac{g_{\phi\bar{e}e}}{10^{-15}}\right)^4 \left(\frac{\text{keV}}{\epsilon}\right)^2 \left(\frac{M}{\text{ton}}\right)$$

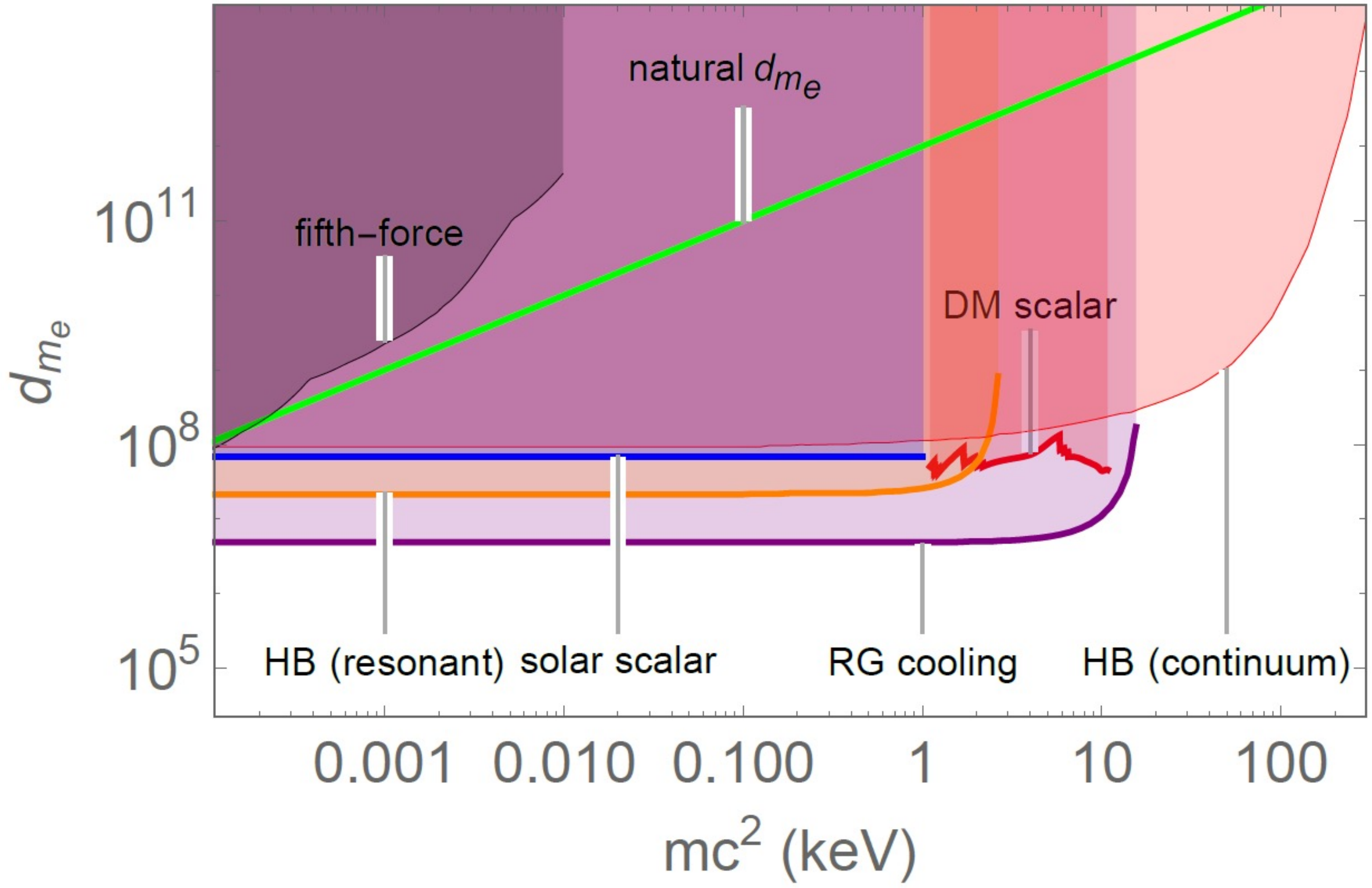
- <u>New limits from Xenon1T data:</u>

$$|g_{\phi\bar{e}e}|_{\text{DM}} \approx 8.2 \times 10^{-15} \qquad |g_{\phi\bar{e}e}|_{\text{solar}} \approx 1.0 \times 10^{-14}$$

$$g_{\phi\bar{e}e} = \sqrt{4\pi} d_{m_e} m_e / m_P \quad \longrightarrow \quad |d_{m_e}|_{\text{solar}} \leq 6.8 \times 10^7$$

Comparison with astrophysical bounds

- Direct limits well inside naturalness region.
- Always better than fifth-force & comparable to HB star cooling.
- An order of magnitude less stringent than RG star cooling → similar to Xenon1T axion limit.



Relativistic effects increase ionisation by WIMP scattering on electrons by up to 3 orders of magnitude!

Ionization of atoms by slow heavy particles, including dark matter
B.M. Roberts, V.V. Flambaum, G.F. Gribakin, Phys. Rev. Lett. 116, 023201 (2016)]

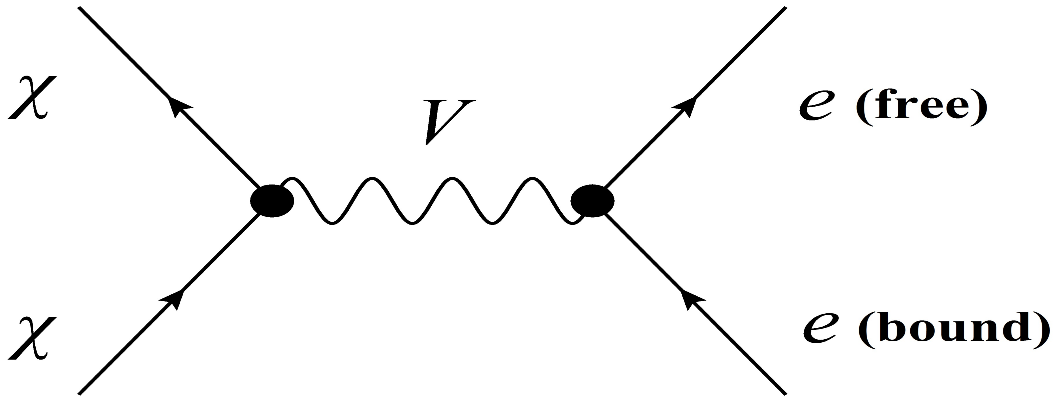
Dark matter scattering on electrons: Accurate calculations of atomic excitations and implications for the DAMA signal. B. M. Roberts, V. A. Dzuba, V. V. Flambaum, M. Pospelov, and Y. V. Stadnik, Phys. Rev. D 93, 115037 (2016)

Electron-interacting dark matter: implications from DAMA/LIBRA-phase2 and prospects for liquid xenon and NaI detectors, B. M. Roberts, V. V. Flambaum, Phys. Rev. D 100, 063017 (2019).

Relativistic Hartree-Fock calculations for Na, I, Xe, Tl, Ge atoms, scalar and vector portals. Annual modulation due to variation of velocity of WIMPs 20 - 50%

WIMP-Electron Ionising Scattering

- Search for annual modulation in $\sigma_{\chi e}$ (velocity dependent)



- Previous analyses treated atomic electrons *non-relativistically. Plane wave for outgoing electron,* $Z_{effective}$ *for bound electrons.*
- Non-relativistic treatment of atomic electrons inadequate for m_χ > 1 GeV. Coulomb interaction is important for outgoing electron.

Why are electron relativistic effects so important?

[Roberts, Flambaum, Gribakin, *PRL* 116, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* 93, 115037 (2016)]

- Non-relativistic and relativistic contributions to $\sigma_{\chi e}$ are very different for large q

(for scalar, pseudoscalar, vector and pseudovector interaction portals):

Non-relativistic [s-wave, $\psi \propto r^{0}(1 - Zr/a_B)$ as $r \rightarrow 0$)], tends to constant as $r \rightarrow 0$:

$$d\sigma_{\chi e} \propto 1/q^{8}$$

Relativistic [$s_{1/2}$, $p_{1/2}$-wave, $\psi \propto r^{\gamma-1}$ as $r \rightarrow 0$, $\gamma^2 = 1 - (Z\alpha)^2$], increases as $r \rightarrow 0$:

$$d\sigma_{\chi e} \propto {}^{(Z\alpha)^2}/q^{6-2(Z\alpha)^2} \qquad (d\sigma_{\chi e} \propto 1/q^{5.7} \text{ for Xe and I})$$

- Relativistic contribution to $\sigma_{\chi e}$ dominates by several orders of magnitude for large q!

Accurate relativistic atomic calculations

[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* **93**, 115037 (2016)]

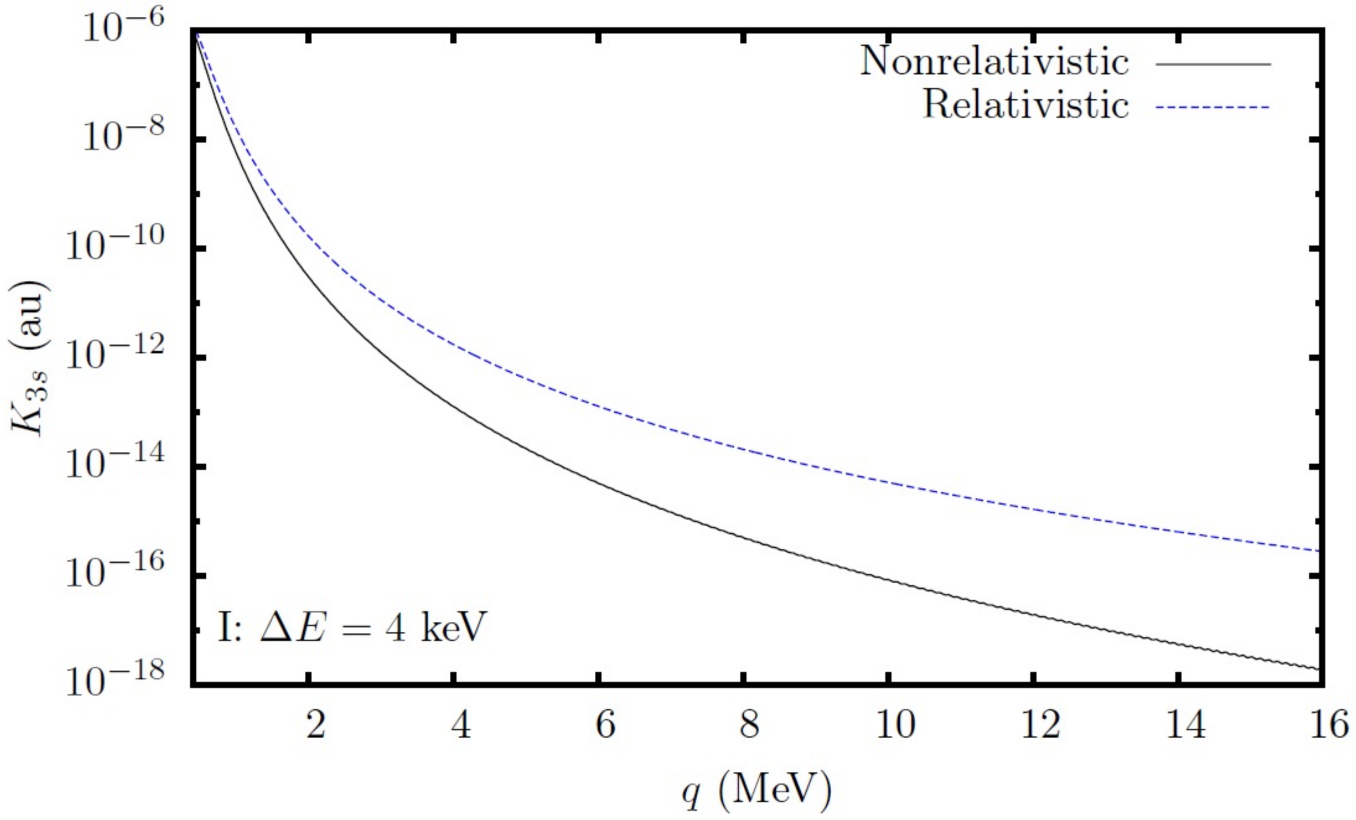
- Performed accurate (*ab initio* Hartree-Fock-Dirac) relativistic atomic calculations of $\sigma_{\chi e}$ for Na, Ge, I, Xe and Tl, and event rates of various experiments: DAMA, XENON10, XENON100
- Outgoing electron in the Hartree-Fock field (not plane wave, the problem is not reduced to momentum distribution of atomic electrons!)
- 3 parameter problem: m_χ, m_V, α_χ; *vector or scalar interaction vertex*

$$\langle \mathrm{d}\sigma v_\chi \rangle = \frac{4\alpha_\chi^2}{\pi} \int_0^\infty \mathrm{d}v \, \frac{f_\chi(v)}{v} \int_{q_-}^{q_+} \mathrm{d}q \, \frac{q}{(q^2 + m_v^2 c^2)^2} \times \sum_{n,\kappa} m_e \sqrt{2m_e(\Delta E - I_{n\kappa})} K_{n\kappa} \mathrm{d}(\Delta E)$$

$$K_{n\kappa}(\Delta E, q) = \sum_{\kappa'} \sum_{m,m'} |\langle \varepsilon\kappa' m' | e^{i\boldsymbol{q}\cdot\boldsymbol{r}} | n\kappa m \rangle|^2 \qquad q_\pm = k \pm \sqrt{k^2 - 2m_\chi \Delta E}$$

Why are electron relativistic effects so important?

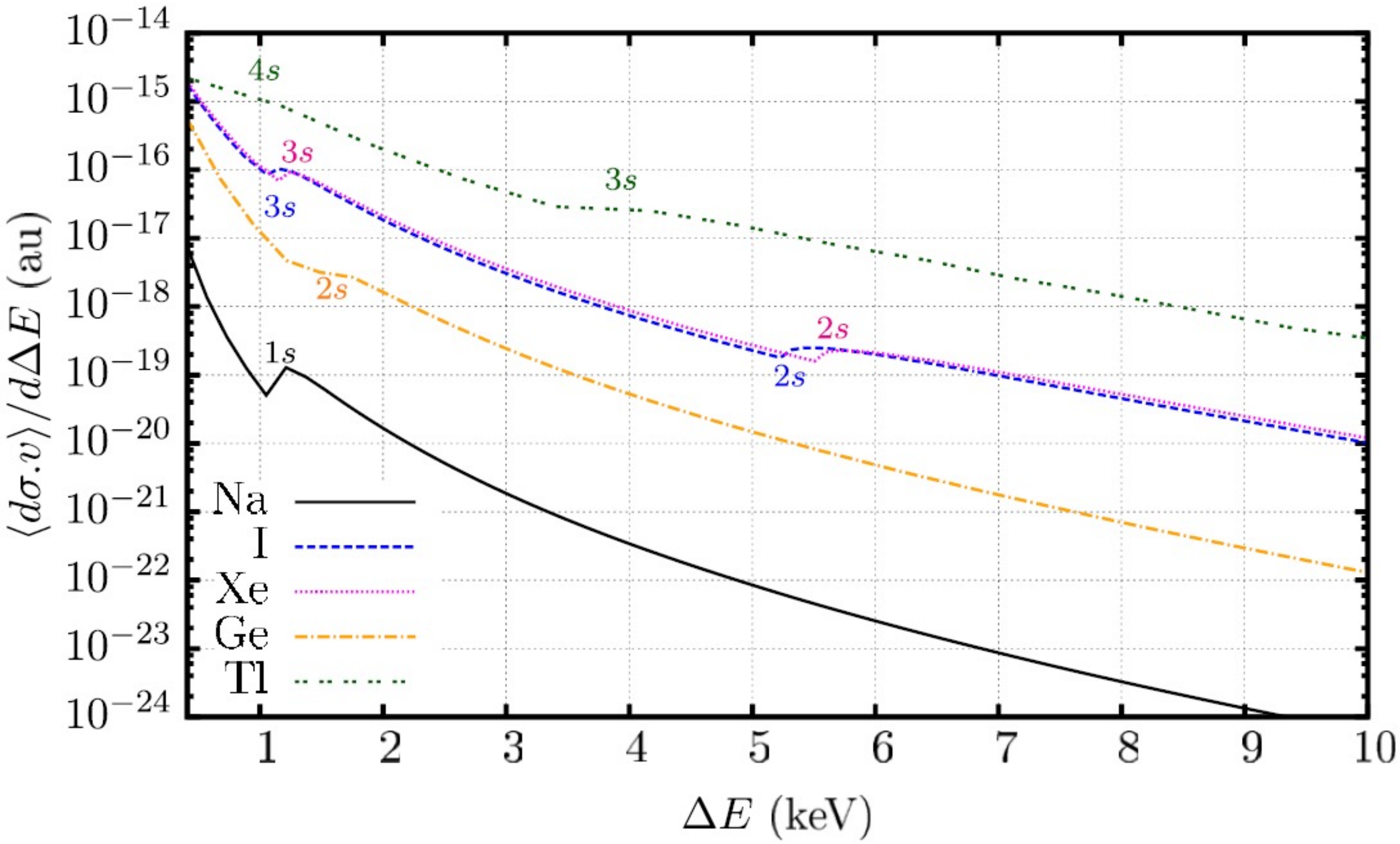
[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* **93**, 115037 (2016)]



Calculated atomic-structure functions for ionisation of I from 3*s* atomic orbital as a function of *q*; Δ*E* = 4 keV, vector interaction portal

Accurate relativistic atomic calculations

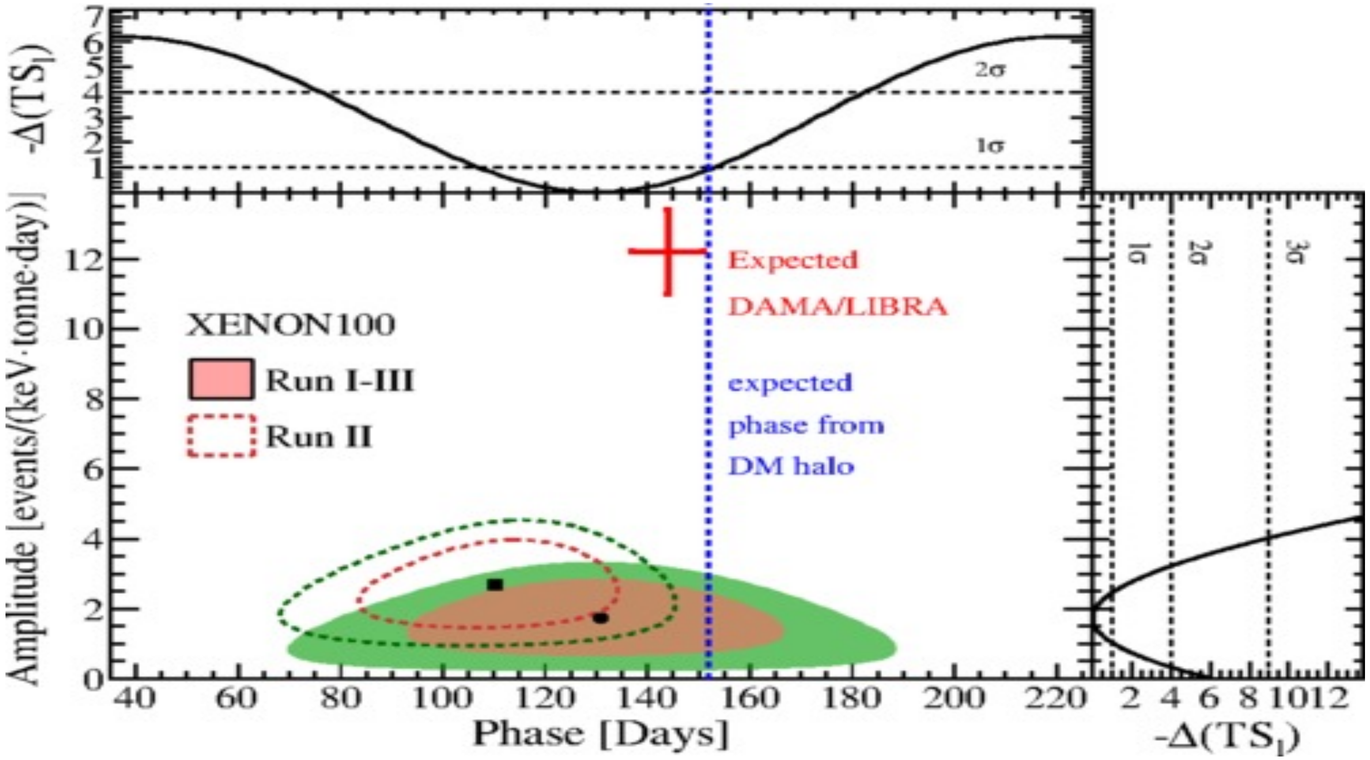
[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* **93**, 115037 (2016)]



Calculated differential $\sigma_{\chi e}$ as a function of total energy deposition (ΔE); m_χ = 10 GeV, m_V = 10 MeV, α_χ = 1, vector interaction portal. Annual modulation due to variation of velocity of WIMPs 20 - 50%

Constraints from XENON Collaboration using our atomic calculations

[XENON Collaboration, *PRL* 118, 101101 (2017)]



Conclusion for underground detectors

- Relativistic Hartree-Fock calculations correct several orders of magnitude error for the dark matter scalars and solar scalars.
- Plane wave approximation does not work due to violation of orthogonality condition between bound and continuum electron wave functions → Error up to 8 orders of magnitude!
- Such effect also exists for axions and Migdal effect but the error is significant for small energies only.
- New limits on electron-scalar coupling from Xenon1T data.
- Data files for scalars and axions: arXiv:2105.08296.
- Relativistic effects increase ionisation by WIMP scattering on electrons by up to 3 orders of magnitude. Plane wave approximation does not work. Annual modulation due to variation of velocity of WIMPs is 20 - 50%. Results for DAMA/LIBRA and XENON collaborations.

Low-mass Spin-0 Dark Matter

Dark Matter

Scalars

(or axion φ^2):

$\varphi \xrightarrow{P} +\varphi$

Pseudoscalars

(Axions):

$\varphi \xrightarrow{P} -\varphi$

→ Time-varying fundamental constants

10^{15} improvement

→ Time-varying spin-dependent effects, 10^3 improvement

nEDM collaboration, CASPEr electric, JILA eEDM

(E.Cornell and Jun Ye group)

Dark Matter-Induced Cosmological Evolution of the Fundamental Constants

Consider an oscillating classical *scalar* field, ϕ(*t*) = $\phi_0 \cos(m_\phi t)$, that interacts with SM fields (e.g. a fermion *f*) via *quadratic couplings* in ϕ (which may be scalar or axion field).

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

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

'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,

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

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)

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

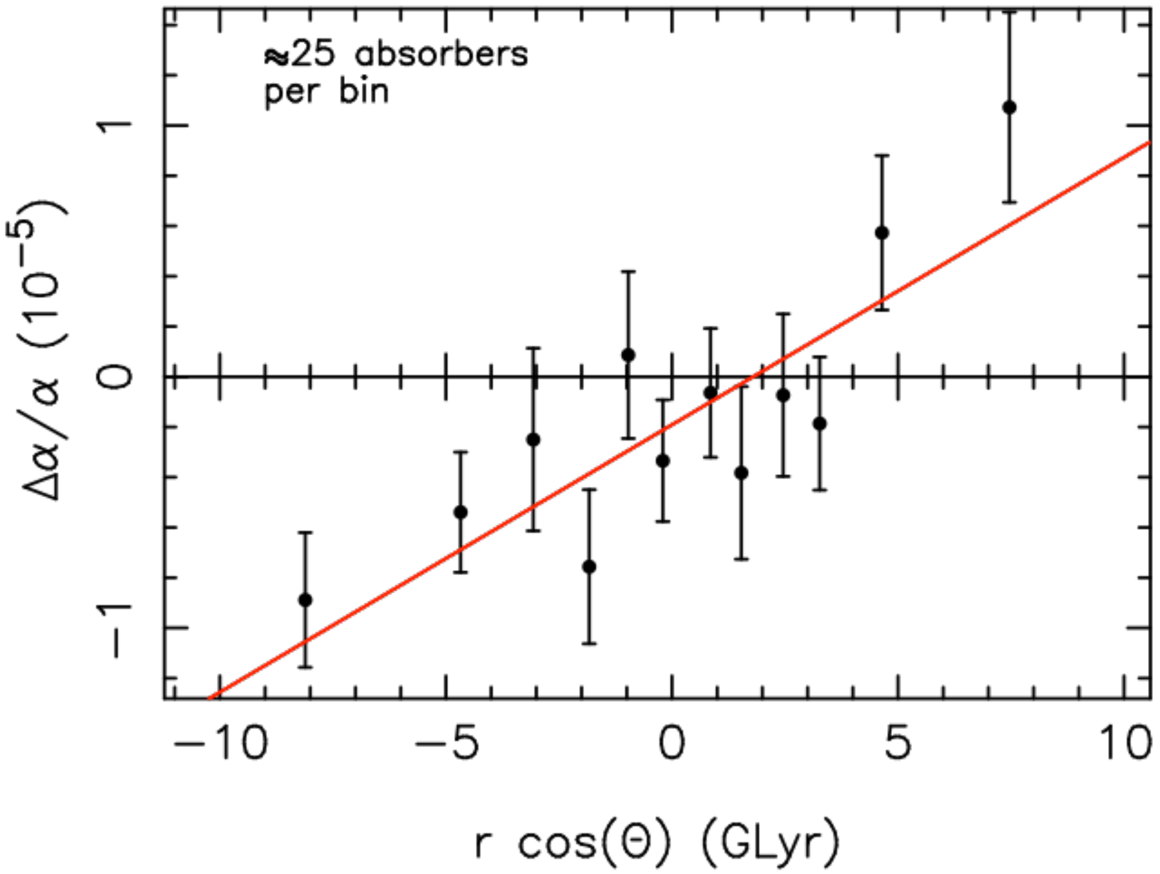
Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNRAS2012

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

$x=r\cos(\phi)$, $r=ct$ – 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).

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

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

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

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}=(-5.8\pm6.9)\times10^{-17}\,\text{yr}^{-1}$$

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

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}=(-1.6\pm2.3)\times10^{-17}\,\text{yr}^{-1}$$

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

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}=(-0.7\pm2.1)\times10^{-17}\,\text{yr}^{-1}$$

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

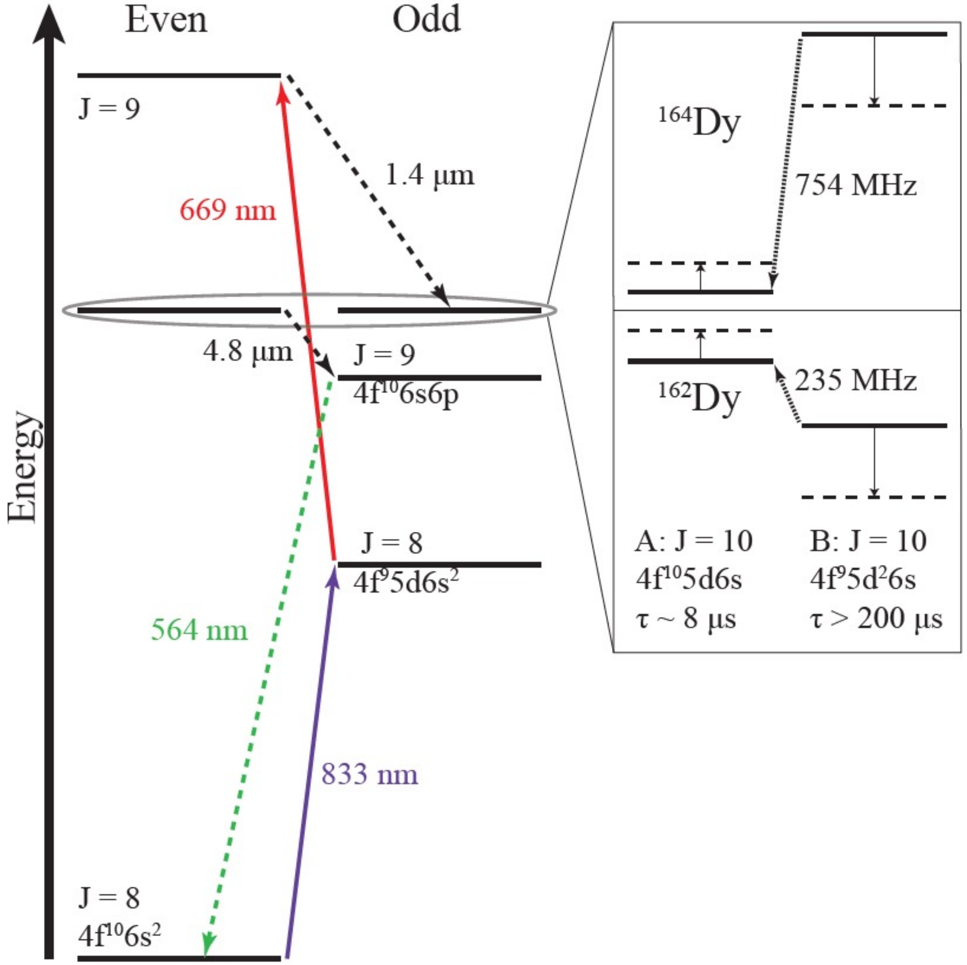
$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}=1.0(1.1)\times10^{-18}\ \text{yr}^{-1}$$

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_α(Dy) ~ $10^6 – 10^8$
  - Molecules
  - Highly-charged ions
  - Nuclei ^{229}Th K=10^4 Mossbauer transitions



Nuclear clock: 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

$\Delta E_C=67(19)$ keV ($= 10^{-4} E_C$)

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

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

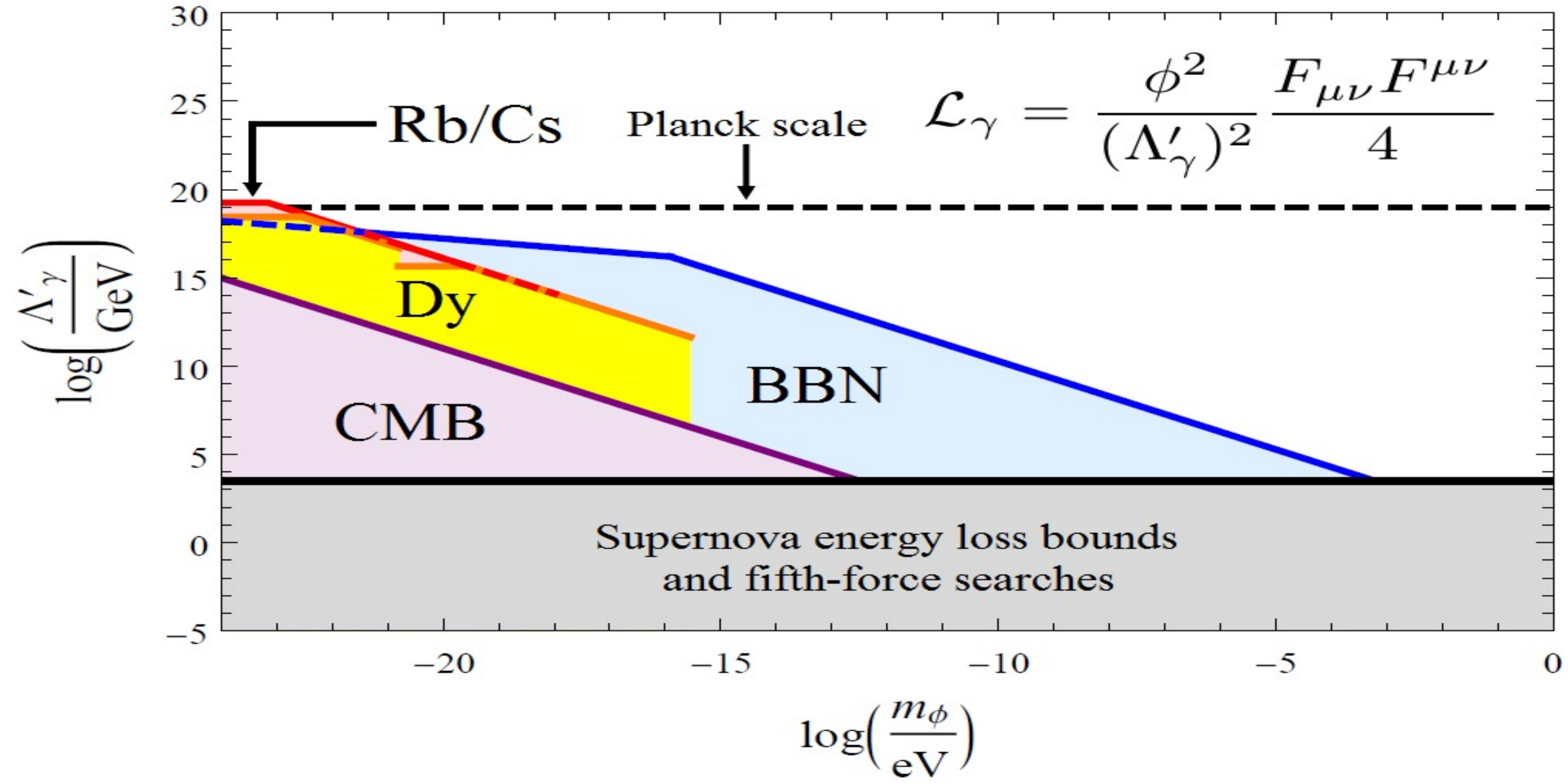
Strong interaction $\Delta\omega/\omega_0 = 1.2\ 10^4\ \Delta m_q/m_q$

Fadeev, Berengut, V.F. 2021

Constraints on Quadratic Interaction of Scalar Dark Matter with the Photon

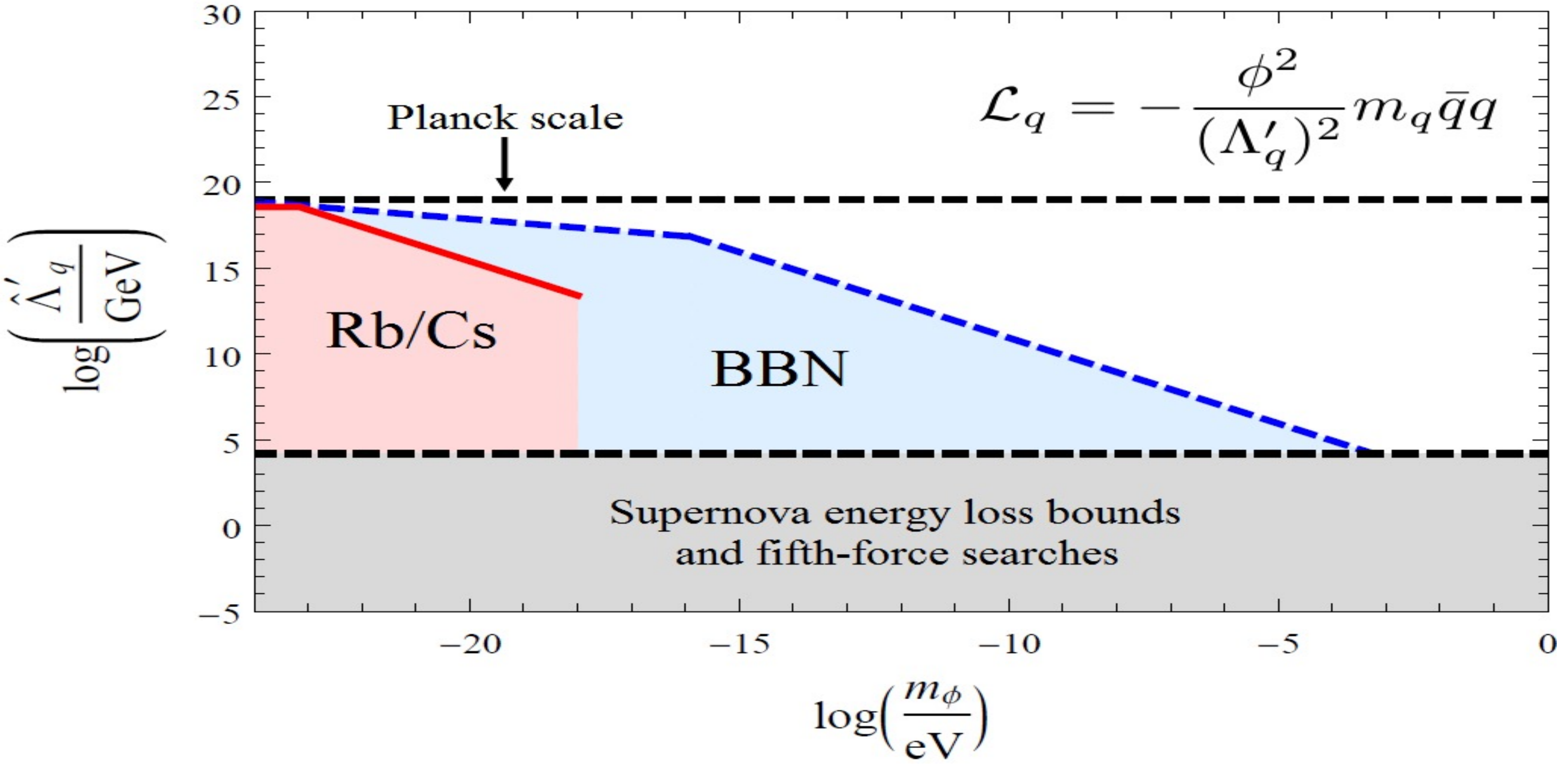
BBN, CMB, Dy and Rb/Cs constraints: [Stadnik and V.F., *PRL* 115, 201301 (2015) + Phys. Rev. D 2016]

15 orders of magnitude improvement!



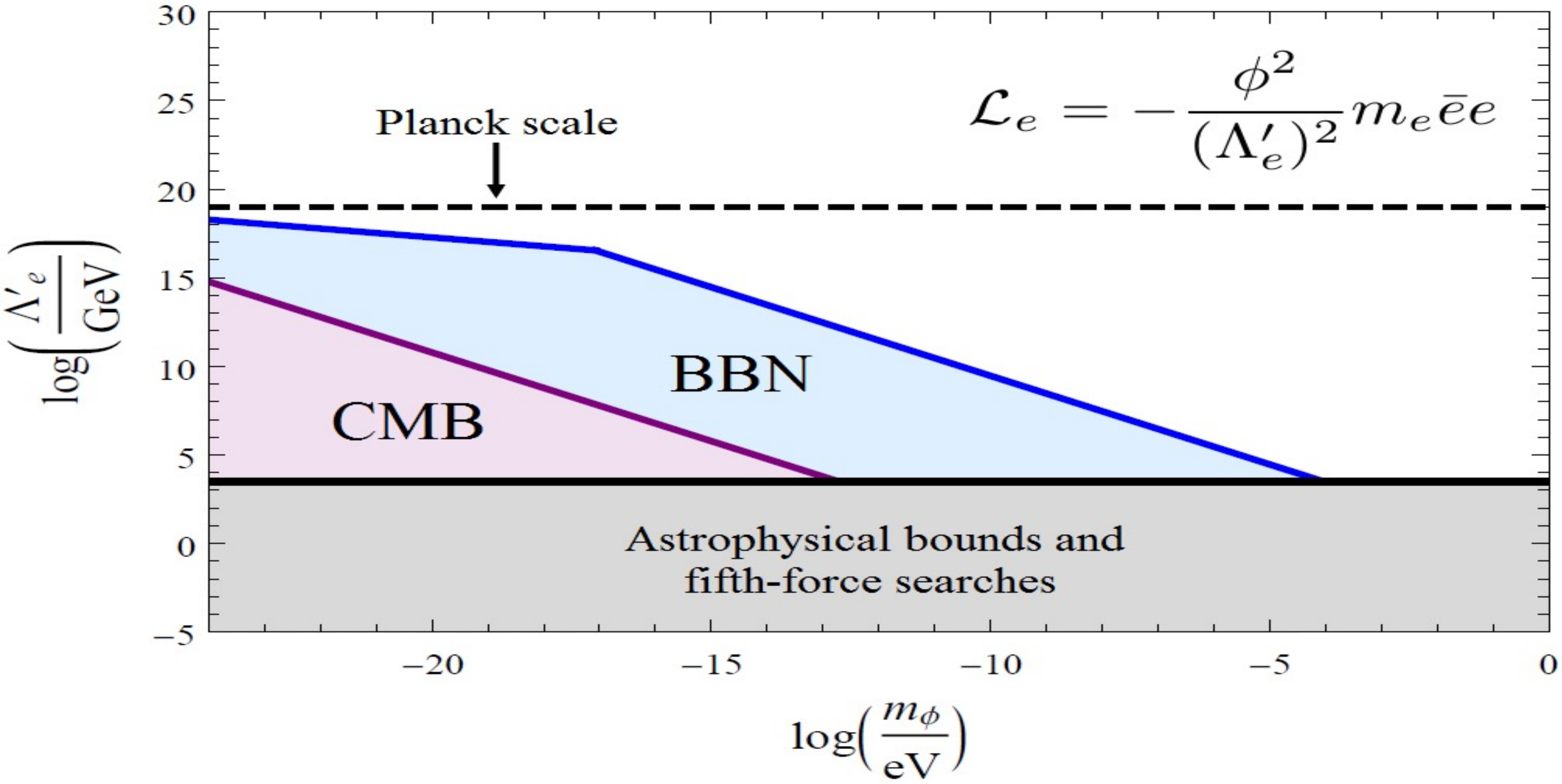
Constraints on Quadratic Interactions of Scalar Dark Matter with Light Quarks

BBN and Rb/Cs constraints: [Stadnik and V.F., *PRL* 115, 201301 (2015) + Phys. Rev. D 2016]



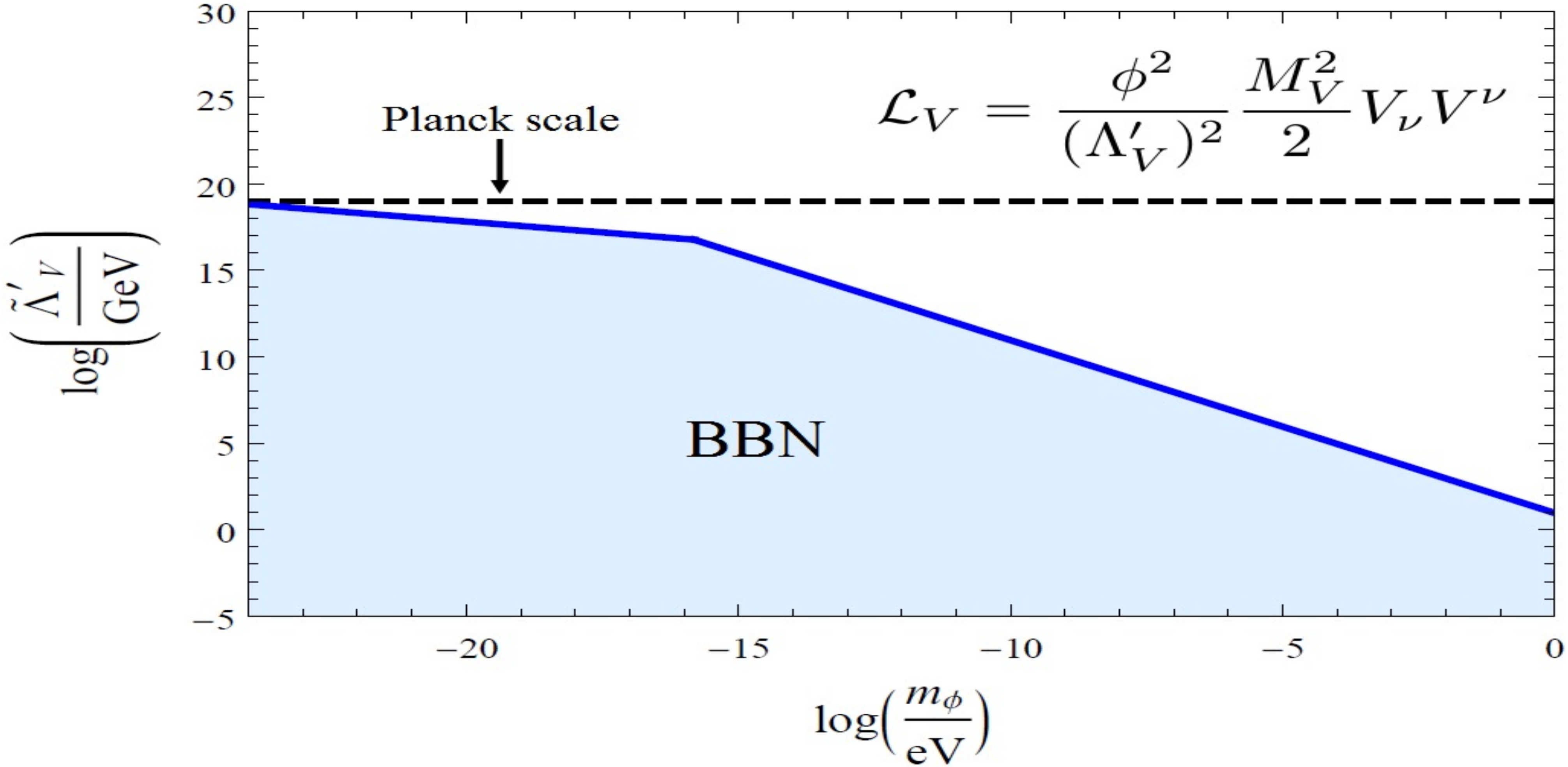
Constraints on Quadratic Interaction of Scalar Dark Matter with the Electron

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

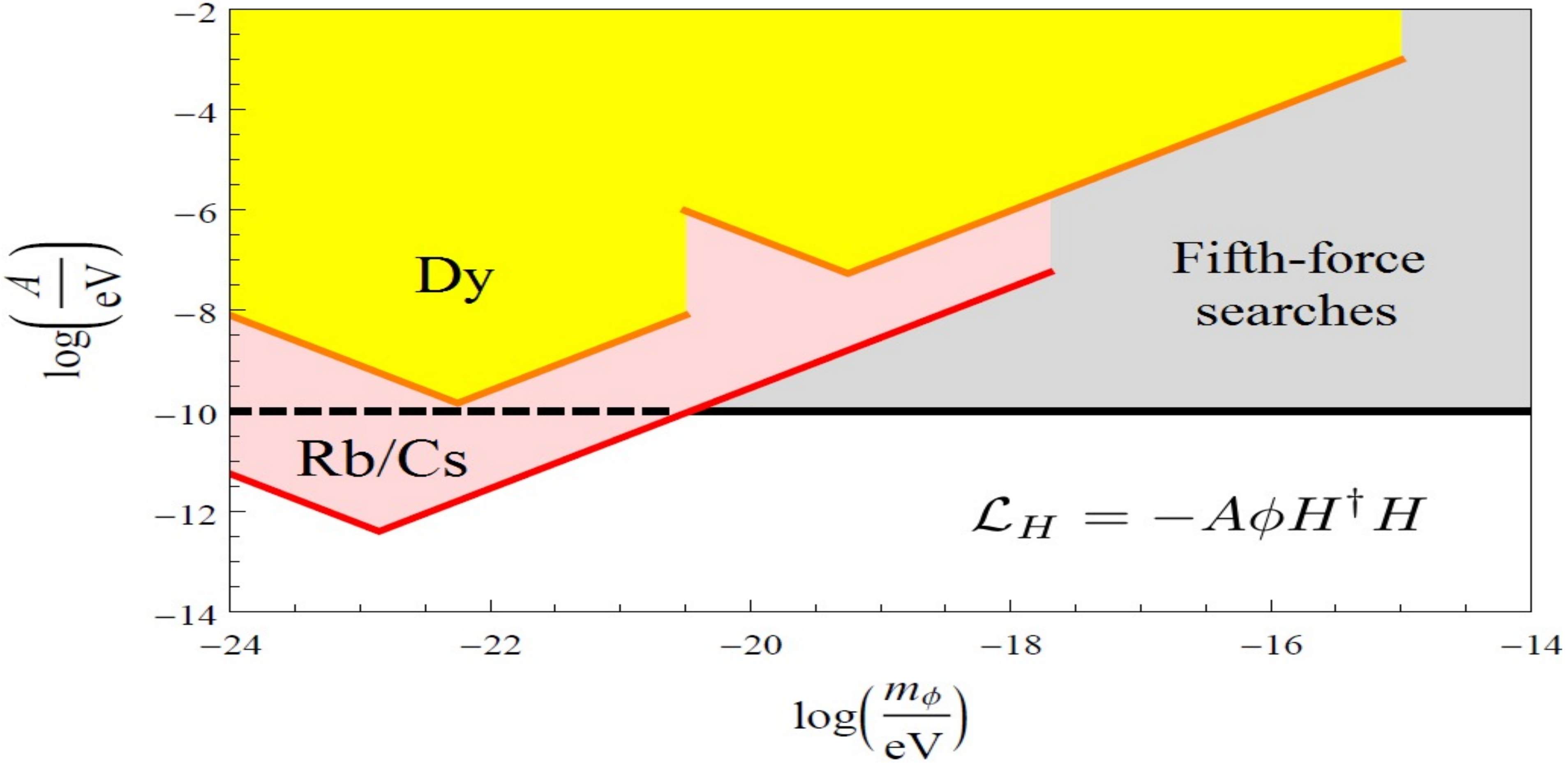
BBN constraints: [Stadnik and V.F., *PRL* 115, 201301 (2015)]



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!



Low-mass Spin-0 Dark Matter

Dark Matter

Scalars

(or axion φ^2):

$\varphi \xrightarrow{P} +\varphi$

Pseudoscalars

(Axions):

$\varphi \xrightarrow{P} -\varphi$

→ Time-varying fundamental constants

10^{15} improvement

→ Time-varying spin-dependent effects, 10^3 improvement

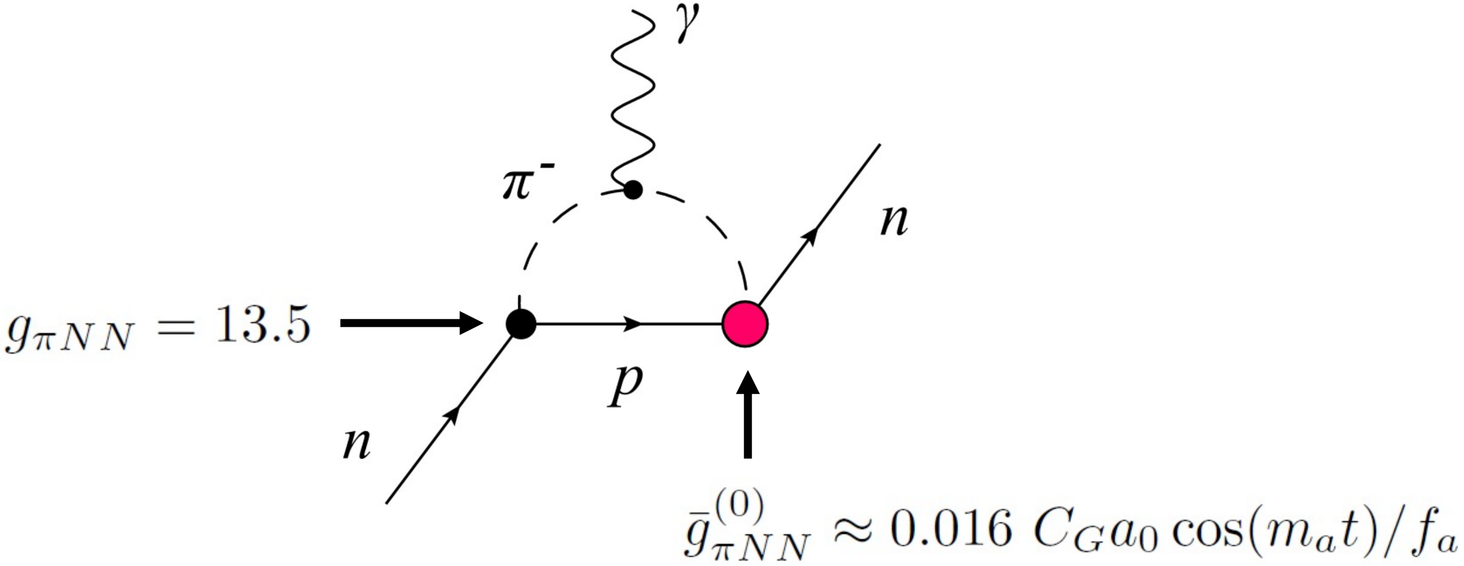
nEDM collaboration, CASPEr electric, JILA eEDM

(E.Cornell and Jun Ye group)

Axion-Induced Oscillating Neutron EDM

[Crewther, Di Vecchia, Veneziano, Witten, *PLB* 88, 123 (1979)],
[Pospelov, Ritz, *PRL* 83, 2526 (1999)], [Graham, Rajendran, *PRD* 84, 055013 (2011)]

$$\mathcal{L}_{aGG} = \frac{C_G a_0 \cos(m_a t)}{f_a} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \quad => \quad d_n(t) \propto \cos(m_a t)$$



Axion-Induced Oscillating Atomic and Molecular EDMs

[O. Sushkov, Flambaum, Khriplovich, *JETP* 60, 873 (1984)], [Stadnik , Flambaum, *PRD* 89, 043522 (2014)]

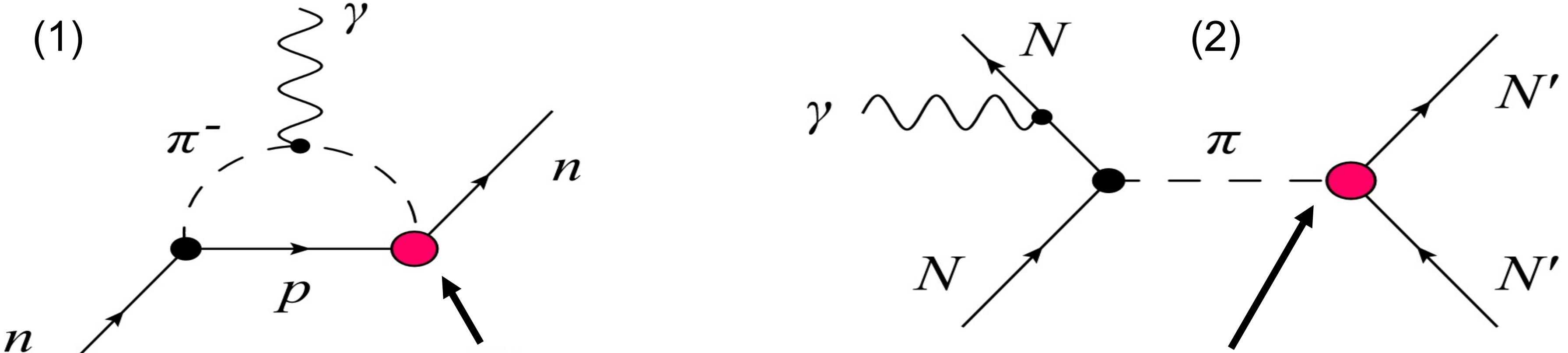
Induced through *hadronic mechanisms*:

- Oscillating nuclear Schiff moments (*I* ≥ 1/2 => *J* ≥ 0)
- Oscillating nuclear magnetic quadrupole moments (*I* ≥ 1 => *J* ≥ 1/2; *magnetic* => no Schiff screening)

Underlying mechanisms:

(1) Intrinsic oscillating nucleon EDMs (1-loop level)

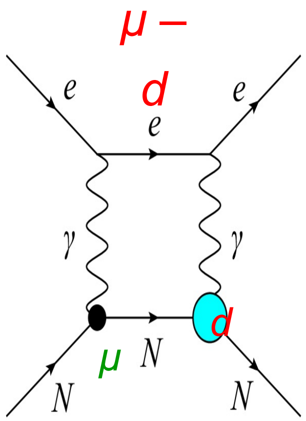
(2) Oscillating *P*,*T*-violating intranuclear forces (*tree level* => **larger by ~4π^2 ≈ 40**; up to **extra 1000-fold enhancement** in deformed nuclei, V.F. 1994; Auerbach, V.F., Spevak 1996))



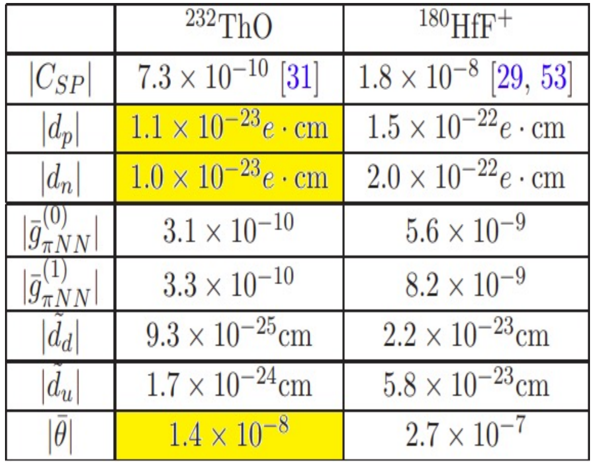
$$\bar{g}^{(0)}_{\pi NN} \approx 0.016\ C_G a_0 \cos(m_a t)/f_a$$

P,T-odd nuclear polarization

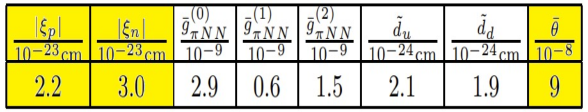
- atomic EDM due to nuclear T,P-odd polarizability.
- electric + magnetic vertices instead of 2 electric vertices for usual polarisabilty
- We studied this → electron EDM experiments are sensitive to hadron CP-violation, theta-term, axion dark matter, etc.



Internal nuclear excitations



	^{232}ThO	^{180}HfF$^+$
$\lvert C_{SP}\rvert$	7.3×10^{-10} [31]	1.8×10^{-8} [29, 53]
$\lvert d_p\rvert$	$1.1\times10^{-23}e\cdot\mathrm{cm}$	$1.5\times10^{-22}e\cdot\mathrm{cm}$
$\lvert d_n\rvert$	$1.0\times10^{-23}e\cdot\mathrm{cm}$	$2.0\times10^{-22}e\cdot\mathrm{cm}$
$\lvert\bar{g}^{(0)}_{\pi NN}\rvert$	3.1×10^{-10}	5.6×10^{-9}
$\lvert\bar{g}^{(1)}_{\pi NN}\rvert$	3.3×10^{-10}	8.2×10^{-9}
$\lvert\tilde{d}_d\rvert$	$9.3\times10^{-25}\mathrm{cm}$	$2.2\times10^{-23}\mathrm{cm}$
$\lvert\tilde{d}_u\rvert$	$1.7\times10^{-24}\mathrm{cm}$	$5.8\times10^{-23}\mathrm{cm}$
$\lvert\bar{\theta}\rvert$	1.4×10^{-8}	2.7×10^{-7}



$\frac{\lvert\xi_p\rvert}{10^{-23}\mathrm{cm}}$	$\frac{\lvert\xi_n\rvert}{10^{-23}\mathrm{cm}}$	$\frac{\bar{g}^{(0)}_{\pi NN}}{10^{-9}}$	$\frac{\bar{g}^{(1)}_{\pi NN}}{10^{-9}}$	$\frac{\bar{g}^{(2)}_{\pi NN}}{10^{-9}}$	$\frac{\tilde{d}_u}{10^{-24}\mathrm{cm}}$	$\frac{\tilde{d}_d}{10^{-24}\mathrm{cm}}$	$\frac{\bar{\theta}}{10^{-8}}$
2.2	3.0	2.9	0.6	1.5	2.1	1.9	9

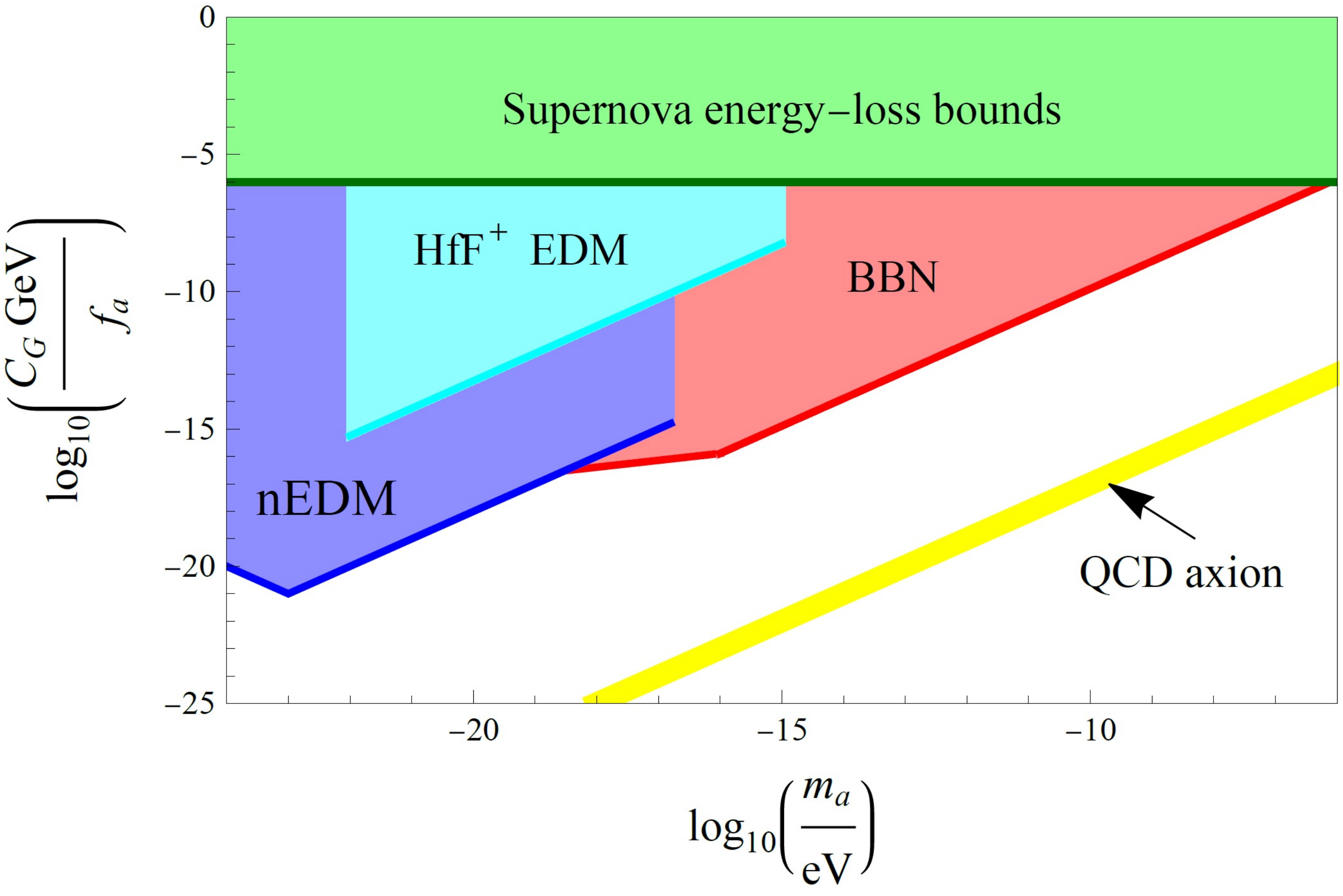
Limits on $\xi_{p,n}$, $\bar{g}^{(0,1,2)}_{\pi NN}$, $\tilde{d}_{u,d}$ and $\bar{\theta}$ obtained from the ThO limit on $|C_{SP}| < 7.3\times10^{-10}$.

V.V. Flambaum, J.S.M. Ginges, G. Mititelu, arXiv:nucl-th/0010100 (2000)
V.V. Flambaum, M. Pospelov, A. Ritz, and Y.V. Stadnik, PRD 102, 035001 (2020)
V.V. Flambaum, I.B. Samsonov, H.B. Tran Tan, JHEP 2020, 77 (2020)
V.V. Flambaum, I.B. Samsonov, H.B. Tran Tan, PRD 102, 115036 (2020)

Constraints on Interaction of Axion Dark Matter with Gluons

nEDM constraints: [nEDM collaboration, *PRX* **7**, 041034 (2017)]

HfF⁺ EDM constraints: [Roussy *et al*., *PRL* **126**, 171301 (2021)]



Conclusions – low mass dark matter

- 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

Quark Nugget Dark Matter
hunter's guide

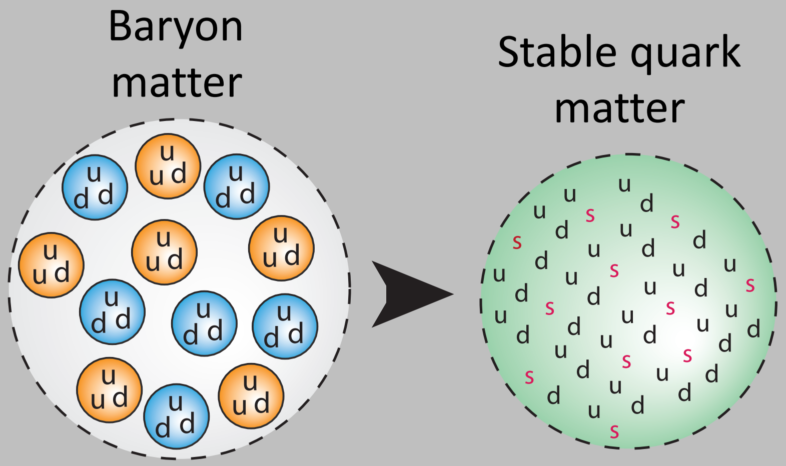
Victor Flambaum and Igor Samsonov

V. V. Flambaum, I. Samsonov,
Phys. Rev. D 106 (2022) 023006
Phys. Rev. D 105 (2022) 123011
Phys. Rev. D 104 (2021), 063042

UNSW
SYDNEY

Strangelet Model

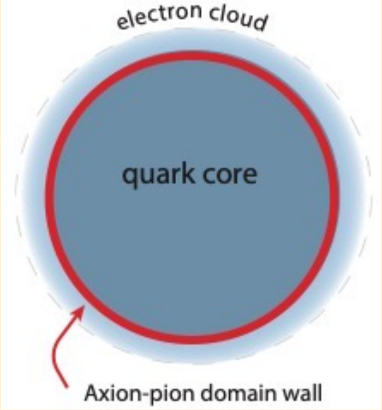
E. Witten, Phys. Rev. D 30, 272 (1984)
E. Farhi and R. L. Jaffe, Phys. Rev. D 30, 2379 (1984)



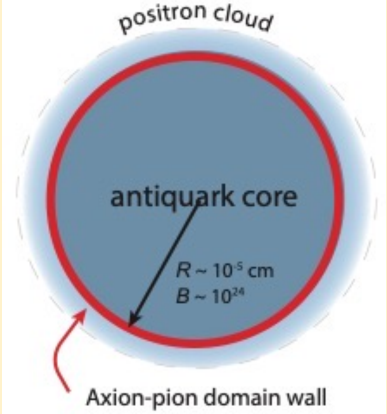
Axion-Quark nugget model

A. R. Zhitnitsky,
JCAP 2003 (10), 010.
Phys. Rev. D 74, 043515 (2006)
….

Quark Nugget



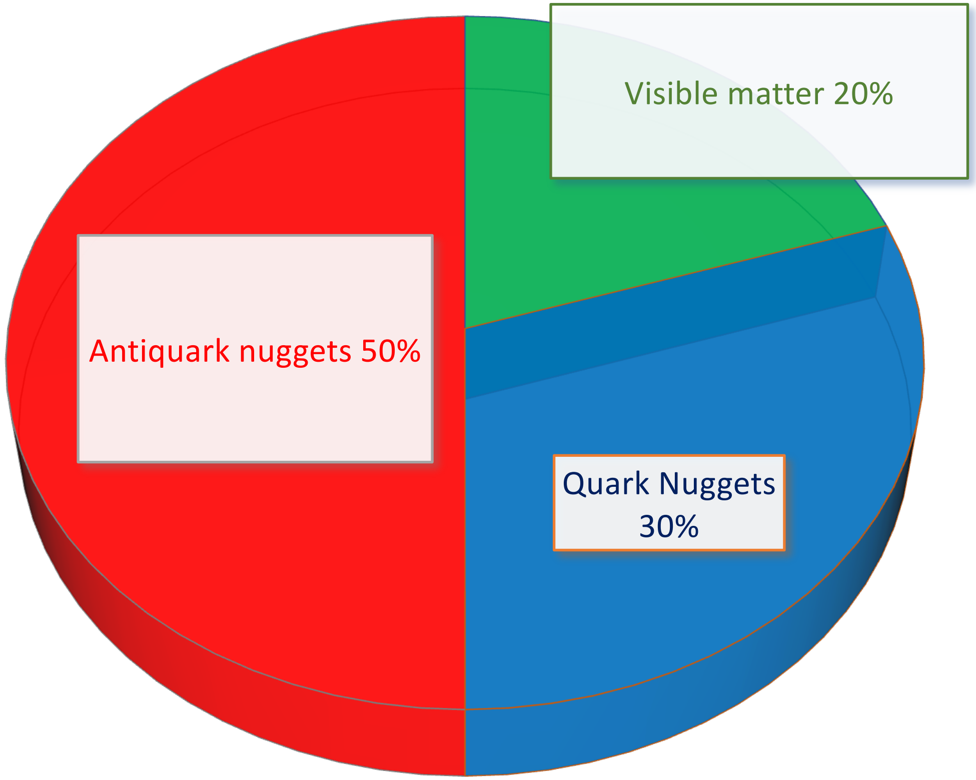
Anti-Quark Nugget



Why two phases?

- Baryon symmetry of the universe is preserved!
- All antimatter is hidden in anti-quark nuggets
- No particles beyond SM are required

MATTER COMPOSITION OF THE UNIVERSE



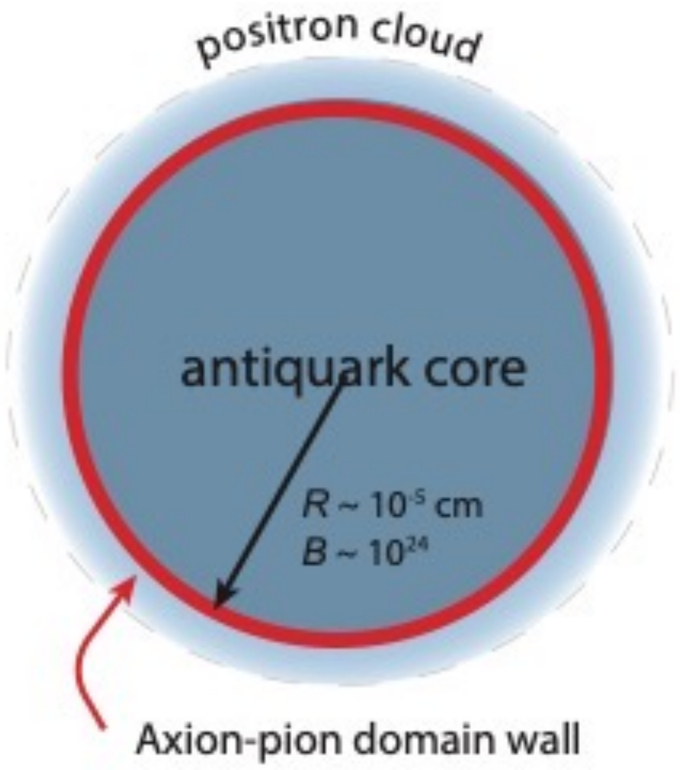
I. Samsonov

Why are they ``dark?''

- Because of an extremely small cross section-to-mass ratio!

$$\boxed{\frac{\sigma}{M} \ll 1\,\frac{\mathrm{cm}^2}{\mathrm{g}}}$$

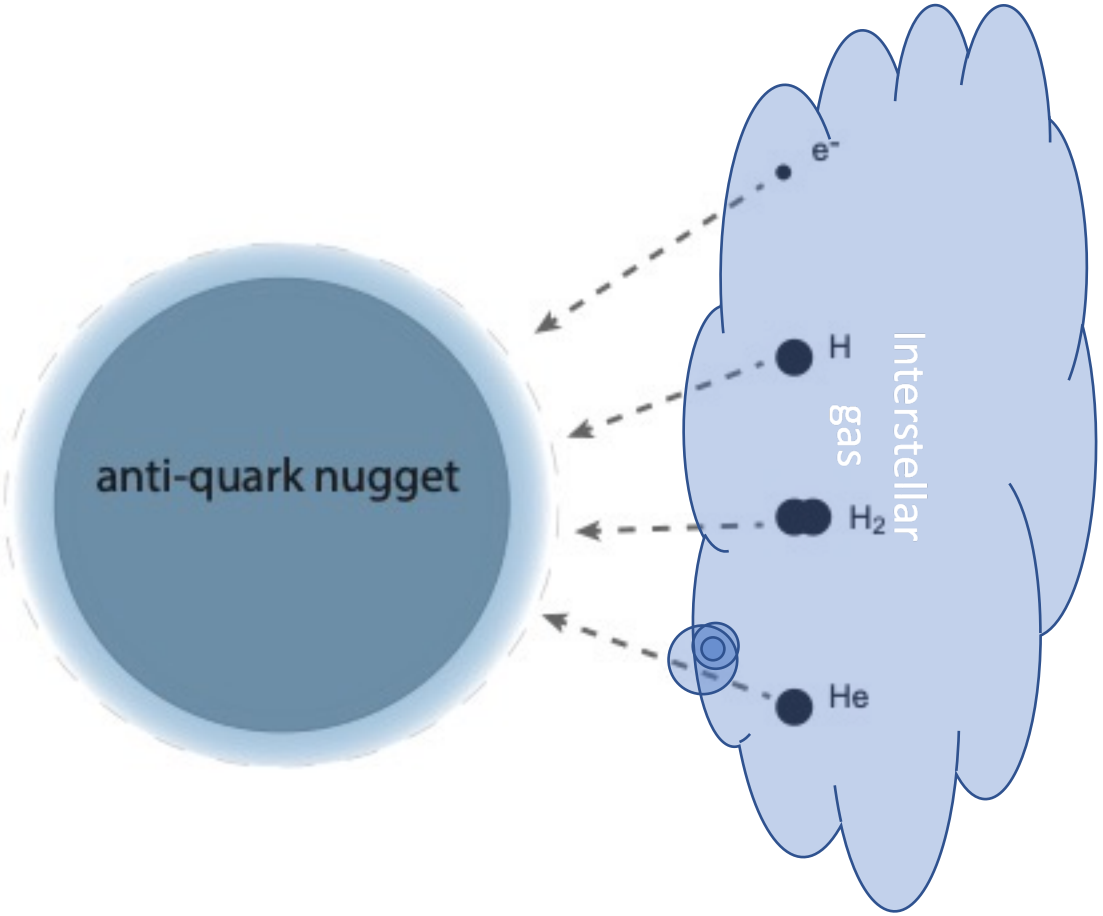
- Typical (anti)baryon number: B>10^{24}
- Typical size: $R = B^{1/3} * 1$ fm=10^{-5} cm
- Typical mass: $M = B * m_p = 10$ g



How to detect (anti)quark nuggets?

1. Antiquark nuggets annihilate visible matter => have better chances to be detected in contrast with QNs.
2. Anti-QNs hit the Earth and may cause rare axion waves, seismic and atmospheric (sound waves) events [Budker, Flambaum, Liang, Zhitnitsky, Phys. Rev. D 101, 043012 (2020); Symmetry 14 (2022) 459].
3. Anti-QNs annihilate with gas and dust in Galaxy and Sun=> look for specific radiation in our Galaxy and from Sun

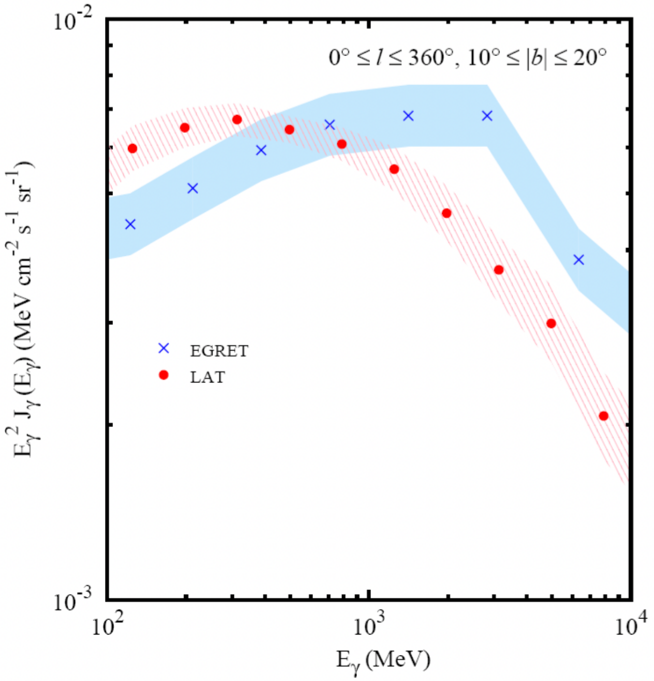
Interstellar gas particles scattering off the anti-quark nuggets



- Particles of the interstellar gas scatter off the antiquark nuggets, annihilate, and create excitations in the antiQN positron cloud.
- The excited antiquark nuggets radiate!
- Thermal radiation from positron cloud
- Non-thermal radiation from matter-antimatter decay products

Gamma-rays from neutral π mesons

Observed Fermi-LAT gamma-ray flux



P F Michelson, W B Atwood, S Ritz, Rep. Prog. Phys. 73 (2010) 074901

- Anti-QN annihilation rate with interstellar gas:

$$W = \sigma\, v\, n_{\mathrm{DM}} n_{\mathrm{gas}}$$

$$\sigma = \pi R^2 = \pi B^{2/3} \mathrm{fm}^2$$ Annihilation cross section

$$v = 10^{-3} c$$ Velocity of dark matter particles

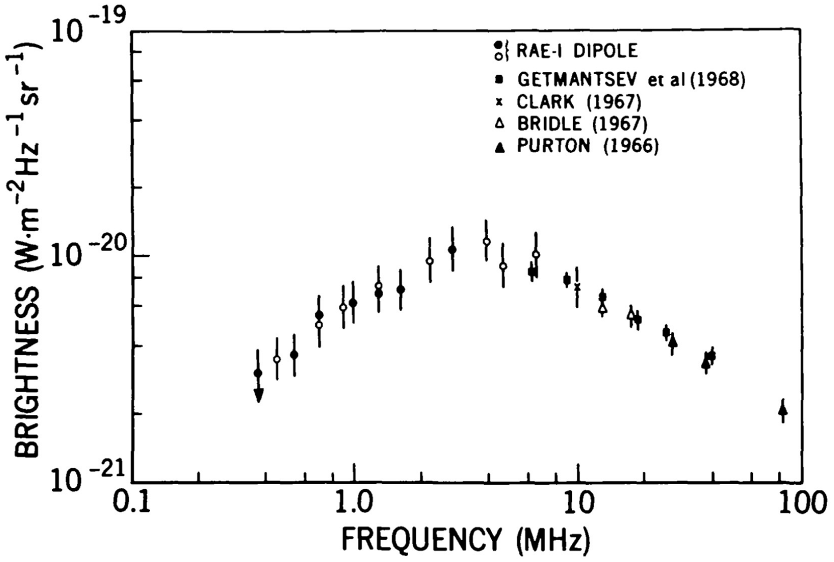
$$n_{\mathrm{DM}} = \rho_{\mathrm{DM}} / (B\ \mathrm{GeV})$$

- Photon flux at observation point is given by line-of-sight integral

$$F = \frac{1}{4\pi} \int_l W\, dl = \frac{2\times 10^4}{B^{1/3}} \frac{\mathrm{photons}}{\mathrm{s\ cm^2\ sr}}$$

- Comparing with the Fermi-LAT observation we find that the flux of Gamma-photons with E>100 MeV may be fully explained within the Quark Nugget model if $B < 2\times 10^{27}$

Synchrotron radiation from emitted electrons/positrons



J. K. Alexander et al, Astrophys. J., Vol. 157, 1969

- Charged Pi-mesons decay into electrons with energy up to 400 MeV
- These electrons produce synchrotron radiation in galaxy when they move in random magnetic fields with $H \sim 10\ \mu\text{G}$
- Maximum of synchrotron radiation at ω=44 MHz
- Intensity of radiation from one such electron

$$I \approx \frac{\sqrt{3} e^3 H}{2\pi\, mc^2} = 3.4 \times 10^{-28} \text{erg s}^{-1} \text{Hz}^{-1}$$

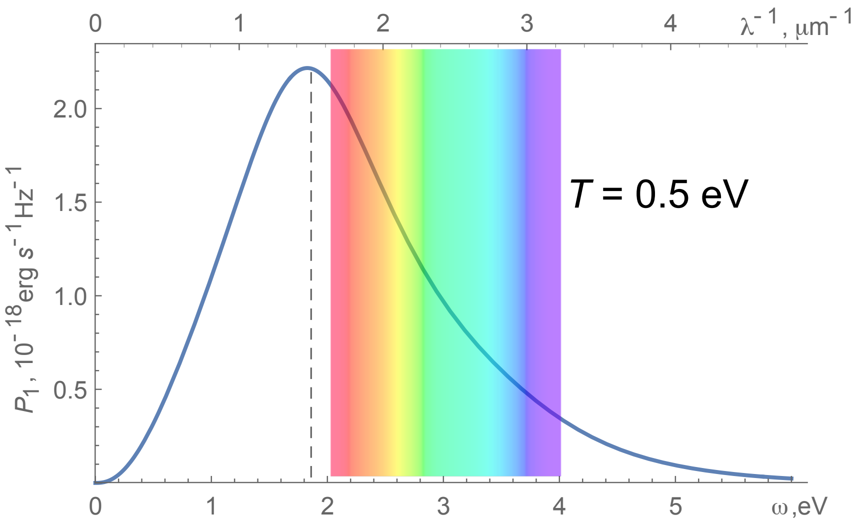
- Radiation power from all such electrons in the galaxy bulge at the observation point on Earth

$$P = \frac{2.7 \times 10^{-10}}{B^{1/3}} \frac{\text{erg}}{\text{s cm}^2 \text{Hz}}$$

- Comparing this with the RAE1 satellite observation, we find that

It is plausible that the observed rf radiation from the galactic bulge is partly produced by charged particles emitted from anti Quark Nuggets with $B < 8 \times 10^{23}$

Light from Taurus molecular cloud



- Distance to the cloud is *L*=140 pc
- Gas density *n*=300 to 1000 cm^{-3}
- Effective QN temperature in the cloud *T*=0.5eV
- Maximum of the thermal radiation from antiquark nuggets is in near infrared to visible light
- Estimated energy flux at λ=555 nm

$$\Phi = 1.2 \times 10^{-29} \frac{\text{erg}}{\text{s Hz cm}^2}$$

- This corresponds to visible and absolute magnitudes

$$m_{\text{AB}} = -2.5 \log_{10}(\Phi) - 48.6 = 23.2$$
$$M_{\text{AB}} = m_{\text{AB}} - 5 \log_{10} L + 5 = 17.5 .$$

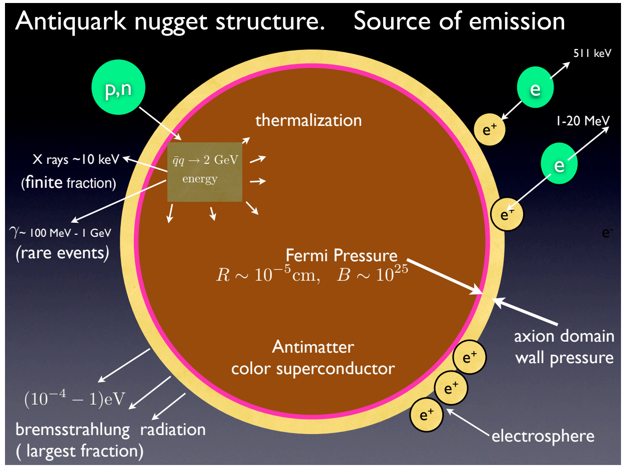
- Hubble Space Telescope can, potentially resolve faint objects with *m*=31.5. Thus, light from anti-QNs in molecular clouds may be observed if resolved from background.

Summary

- Anti-quark nuggets strongly interact with visible matter and radiate
- Annihilation of gas particles in the interstellar medium on anti-QNs can create an observable flux of ω>100MeV-range photons (Fermi-LAT telescope)
- Charged π mesons decay into ultrarelativistic electrons and positrons, which emit synchrotron radiation when move in the magnetic field in the galaxy. This radiation may represent a significant contribution to the galaxy RF background.
- Positrons from the positron cloud annihilate with atoms in the interstellar gas and produce a flux of 511 keV photons. This flux may be observed by the SPI-INTEGRAL satellite.
- It is predicted that anti-QNs can radiate in cold molecular clouds in visible light which can be detected.

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