The axion-photon coupling from lattice QCD

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Based on: 2603.29153

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- Axions
- Axion parameters
- Lattice observables
- Summary

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CRC-TR 211 Strong-interaction matter under extreme conditions
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Two problems

Strong CP:

QCD Lagrangian allows for terms, which would violate CP symmetry:

$$\mathcal{L}_\theta = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + i\bar{\psi}(\not{D} + m)\psi + \theta\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} = \mathcal{L}_{\mathrm{QCD}} + \theta q_{\mathrm{top}} \,.$$

QCD is **very** CP symmetric: (talks on Monday: by Fangcheng He and Rajan Gupta)

$$\text{neutron electric dipole moment} : d_{\mathrm{n}} \approx 2 \times 10^{-16}\theta \ e\mathrm{cm} = (0.0 \pm 1.1) \times 10^{-26} \ e\mathrm{cm} \,.$$

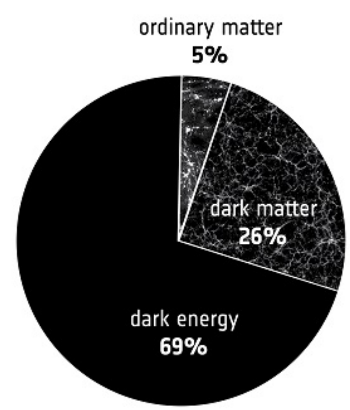
Liang et al. 2301.04331; Pospelov+Ritz hep-ph/9908508; Abel et al. 2001.11966

Mass in the Universe:

Ordinary matter is about 5% of all mass.
The rest is dark energy (69%)
and **dark matter** (26%).
We do not know what either of those are.

https://sci.esa.int/web/euclid/-/cosmic-energy-budget

plenary by Simon Catterall this morning



Axions

- Yield a **solution** to the **strong CP** problem:
  new dynamical field, A, with spontaneously broken $U(1)^{\mathrm{PQ}}$ symmetry ($\mathcal{L}_A$)

$$\mathcal{L}_{\mathrm{QCD}+A} = \mathcal{L}_{\mathrm{QCD}} + \mathcal{L}_A + \left(\frac{A}{f_A} + \theta\right) q_{\mathrm{top}} \,.$$

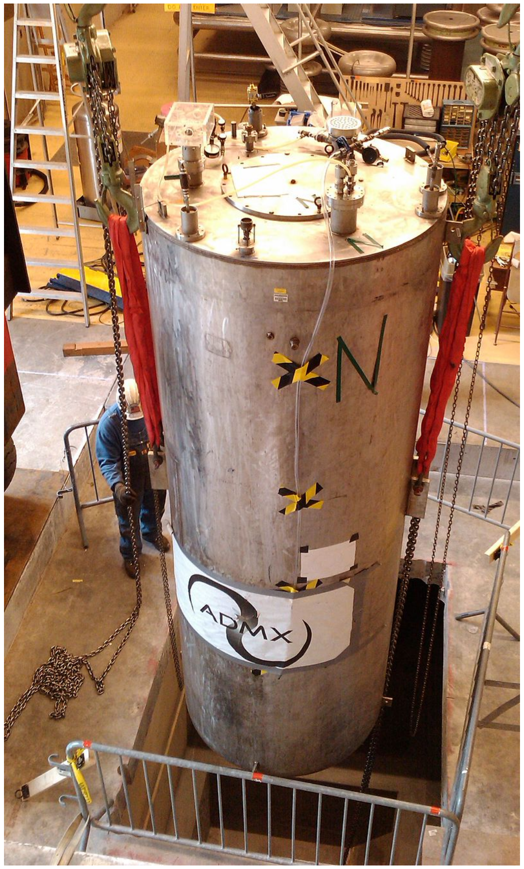
  Action is minimized at $A = -\theta f_A$, restoring CP symmetry.

Peccei+Quinn PRL 38 (1977); Weinberg PRL 40 (1978); Wilczek PRL 40 (1978)

- Prime **dark matter candidate**:
  - Not introduced solely to be a dark matter candidate.
  - 10^9 GeV $< f_A < 10^{12}$ GeV suppresses couplings, making it dark and stable.
  - Experimentally testable, in principle.

Dine+Fischler PLB 120 (1983); Preskill et al. PLB 120 (1983); Abbott+Sikivie PLB 120 (1983)

Some axions experiments



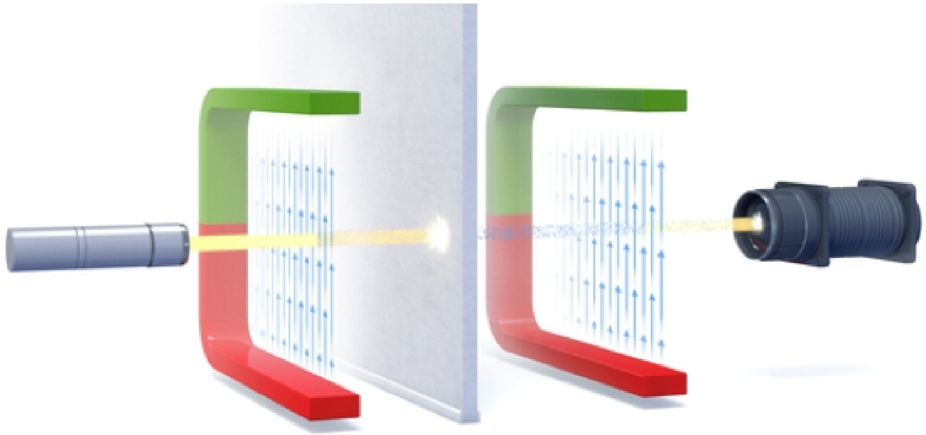
ADMX Asztalos et al. PRL 104 (2010)

Haloscope:
DM axions → photons, resonant cavity to enhance signal.

CAST

CAST coll. Nature Phys. (2017)

Helioscope:
Solar axions → coherent X-rays.



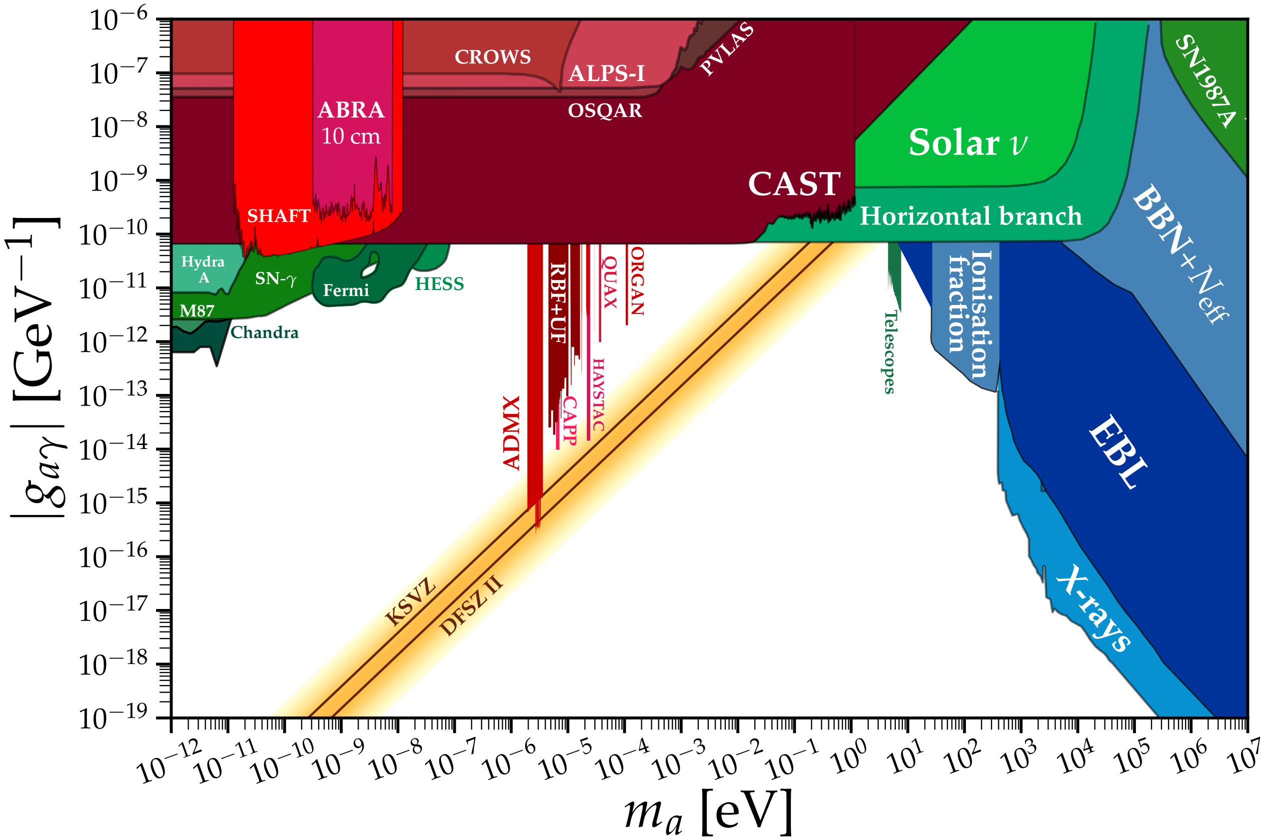
ALPS II Spector et al. 2601.18684

Light-Shining-through-Walls:
laser → axions → through wall → photons

Axions parameters

Most experiments rely on two main parameters:

the axion **mass** and the **coupling to photons**.



Theory predicts **slope**, experiments put **constraints** on **both**.

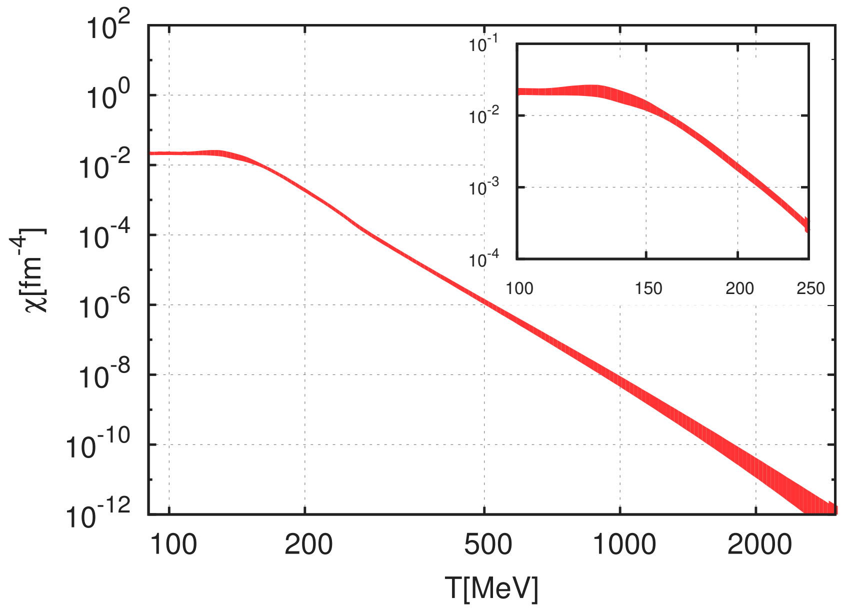
cajohare/AxionLimits https://doi.org/10.5281/zenodo.3932429

Axion mass

Mass from curvature of axion effective potential $\overset{A=-\theta f_A}{\Longleftrightarrow}$ QCD with a θ-term.

$$m_A^2 f_A^2 = -\frac{1}{V_4} \frac{\partial^2 \log Z_{\mathrm{QCD}}[\theta]}{\partial \theta^2}\bigg|_{\theta=0} = \chi_{\mathrm{top}} = \frac{1}{V_4}\left\langle Q_{\mathrm{top}}^2 \right\rangle \, .$$

- chiral perturbation theory, e.g. di Cortona et al. JHEP 01 (2016),
- but more importantly, precise results on the lattice as well:
  Borsányi et al. Nature (2016); Bonati et al. JHEP (2016); Petreczky et al. PLB (2016); Jahn et al. PRD (2018); Athenodorou et al. JHEP (2022); Kanamori et al. 2603.23022



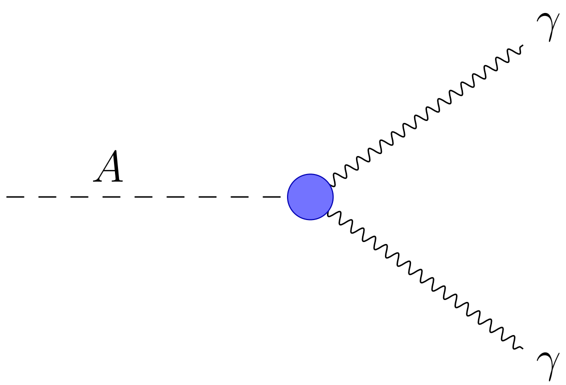
Borsányi et al. Nature (2016)

Axion-photon coupling

Effective coupling between axions and photons, $g_{A\gamma\gamma}$, may have two origins:

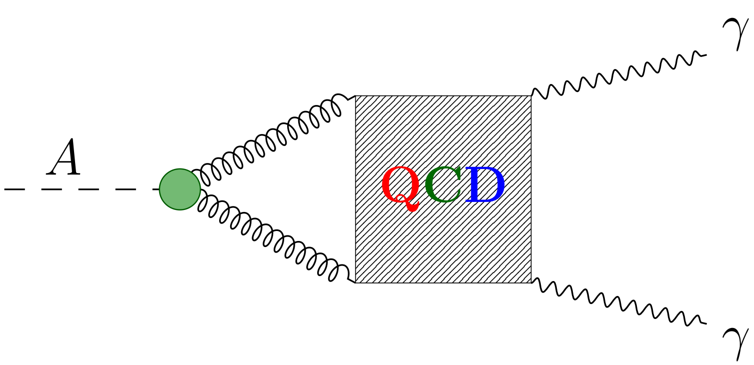
- Direct

$$g^0_{A\gamma\gamma} f_A = \frac{1}{8\pi^2}\frac{E}{N}$$



- Through QCD

$$g^{\mathrm{QCD}}_{A\gamma\gamma} f_A = ?$$



- The total coupling is

$$\boxed{g_{A\gamma\gamma} = g^0_{A\gamma\gamma} + g^{\mathrm{QCD}}_{A\gamma\gamma}\,.}$$

Axion-photon coupling

- Axion models admitting small axion-electron and axion-nucleon couplings

$$g^0_{A\gamma\gamma} f_A = \frac{1}{8\pi^2}\frac{E}{N}, \qquad 0 \leq \frac{E}{N} \leq \frac{44}{3}$$

Di Luzio et al. PRL 118 (2017)

- QCD contribution only known in chiral perturbation theory

$$-0.026 \leq g^{\mathrm{QCD}}_{A\gamma\gamma} f_A \leq -0.020$$

systematic uncertainty across effective theory descriptions.

di Cortona et al. JHEP 01 (2016); Lu et al. JHEP 05 (2020); Gao et al. JHEP 04 (2023); Meggiolaro+Tamburini, PRD 111 (2025)

- The PDG currently uses di Cortona et al. JHEP 01 (2016) $\rightarrow$ **first-principles lattice QCD calculation needed.**

F. Takahashi et al. (Particle Data Group), Int. J. Mod. Phys. A41, 2630011 (2026).

Axion-photon coupling

- Effective potential for constant axion fields $\equiv \theta$ *and* **constant background electromagnetic** fields A_μ

$$Z(\theta, A_\mu) = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}U_\mu \, e^{-S_{\mathrm{QCD}}[\bar{\psi},\psi,U_\mu,A_\mu]-i\theta Q_{\mathrm{top}}} \, .$$

- Axion couples to CP-odd combination

$$Q^\gamma = \int d^4x \, q^\gamma(x), \qquad q^\gamma = \frac{1}{4\pi^2} \, i\boldsymbol{E}\cdot\boldsymbol{B} \, .$$

- Axion-photon coupling

$$g_{A\gamma\gamma}^{\mathrm{QCD}} f_A = \frac{1}{V_4} \frac{\partial^2 \log \mathcal{Z}}{\partial\theta\partial(\boldsymbol{E}\cdot\boldsymbol{B})}\bigg|_{\substack{\theta=0\\ \boldsymbol{E}\cdot\boldsymbol{B}=0}} = -i\frac{1}{V_4} \frac{\partial\langle Q_{\mathrm{top}}\rangle}{\partial(\boldsymbol{E}\cdot\boldsymbol{B})}\bigg|_{\boldsymbol{E}\cdot\boldsymbol{B}=0} = \frac{1}{V_4} \frac{\partial\langle Q_{\mathrm{top}}\rangle}{\partial(i\boldsymbol{E}\cdot\boldsymbol{B})}\bigg|_{\boldsymbol{E}\cdot\boldsymbol{B}=0} \, .$$

Lattice observables

- Simulate using constant magnetic $\boldsymbol{B}$ and constant and imaginary $\boldsymbol{E}$ background fields since a real $\boldsymbol{E}$ causes a sign problem.

- Construct gluonic and fermionic observables to build the derivative

$$g_{A\gamma\gamma}^{\mathrm{QCD}} f_A = \frac{1}{V_4} \frac{\partial \langle Q_{\mathrm{top}} \rangle}{\partial (i\boldsymbol{E} \cdot \boldsymbol{B})} \bigg|_{\boldsymbol{E} \cdot \boldsymbol{B} = 0} .$$

- Both electromagnetic fields: quantized flux due to the finite volume (n_b, n_e).

- Numerical derivative $\rightarrow$ linear coefficient in $\boldsymbol{E} \cdot \boldsymbol{B}$ dependence.

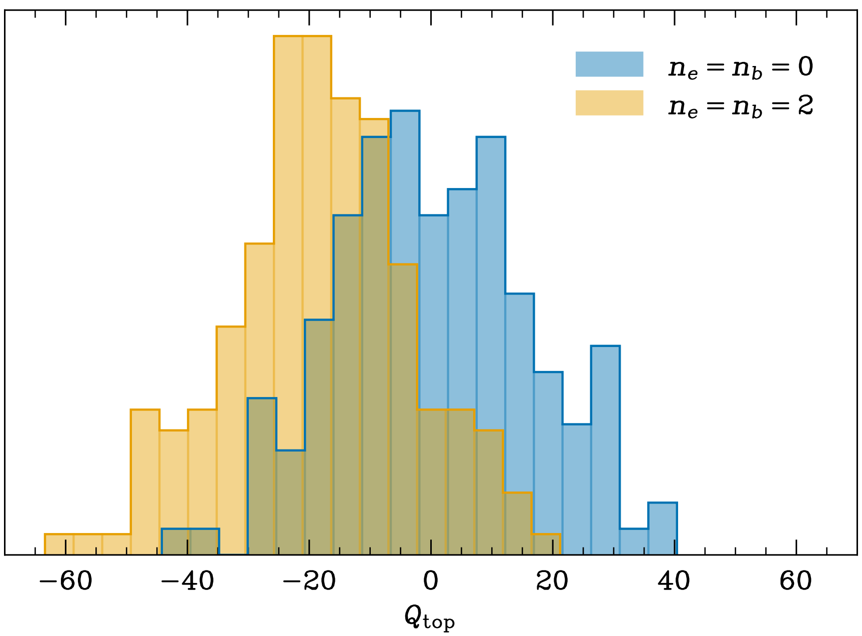
- **Gluonic** topological charge: [**naive** or $\mathcal{O}(a^2)$ **improved** w/ or wo/ rounding] + **gradient flow**.

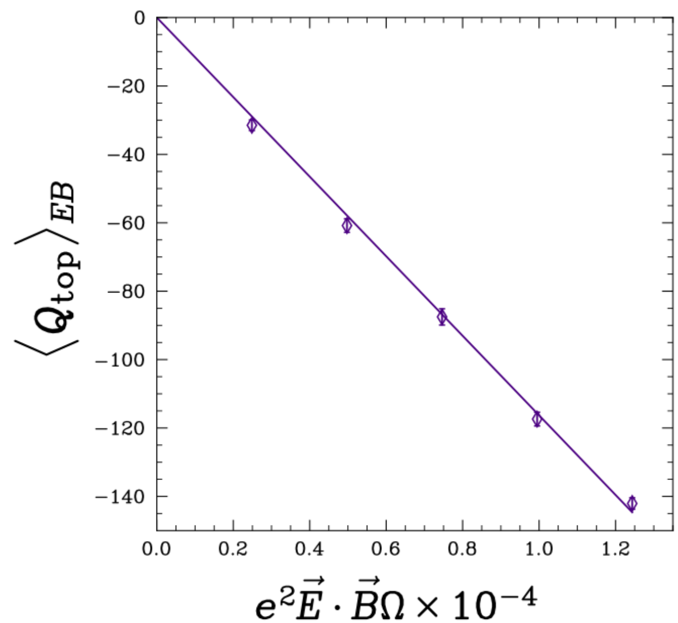
- **Fermionic** based on the anomalous Ward identity.

Gluonic method

- Shift of mean topology to $\langle Q_{\rm top}\rangle \neq 0$ for $i\boldsymbol{E}\cdot\boldsymbol{B}\neq 0$ due to CP symmetry being explicitly broken.
- Measure at quantized fluxes and fit.

D'Elia et al. PRL 110 (2013); Brandt, Endrődi, Hernández, Markó, Pannullo, 2603.29153





Fermionic method - 1

- Continuum AWI true flavor-by-flavor (overlaps with isosinglet)

$$\partial_\mu J_\mu^{5,f} = 2m_f \bar{\psi}_f \gamma_5 \psi_f + 2q_{\text{top}} + 2N_c \frac{q_f^2}{4\pi^2} \boldsymbol{E} \cdot \boldsymbol{B} \, .$$

- Integrate over V_4

$$0 = m_f \underbrace{\int d^4x \bar{\psi}_f \gamma_5 \psi_f}_{P_f^5} + Q_{\text{top}} + V_4 N_c \frac{q_f^2}{4\pi^2} \boldsymbol{E} \cdot \boldsymbol{B} \, .$$

- Measure $\left\langle P_f^5 \right\rangle$, but how to separate Q_{top} from $\boldsymbol{E} \cdot \boldsymbol{B}$?

Fermionic method - 2

- Separate contributions using sea-valence trick!

$$\left\langle P_f^5 \right\rangle_{\boldsymbol{EB}} = \int \mathcal{D}U \, \overbrace{Z_{\boldsymbol{EB}}^{-1} \det M(\boldsymbol{E}\cdot\boldsymbol{B})}^{\text{sea}} \, \mathrm{e}^{-S_g} \underbrace{\mathrm{Tr}\,[M^{-1}\Gamma_5](\boldsymbol{E}\cdot\boldsymbol{B})}_{\text{valence}},$$

$$\left\langle P_f^5 \right\rangle_0 = Z_0^{-1} \int \mathcal{D}U \det M(0) \, \mathrm{e}^{-S_g} \, \mathrm{Tr}\,[M^{-1}\Gamma_5](\boldsymbol{E}\cdot\boldsymbol{B}) \,.$$

$$0 = m_f \left\langle P_f^5 \right\rangle_{\boldsymbol{EB}} + \left\langle Q_{\mathrm{top}} \right\rangle_{\boldsymbol{EB}} + V_4 N_c \frac{q_f^2}{4\pi^2} \boldsymbol{E}\cdot\boldsymbol{B} \,,$$

$$0 = m_f \left\langle P_f^5 \right\rangle_0 + \overbrace{\left\langle Q_{\mathrm{top}} \right\rangle_0}^{0} + V_4 N_c \frac{q_f^2}{4\pi^2} \boldsymbol{E}\cdot\boldsymbol{B} \,.$$

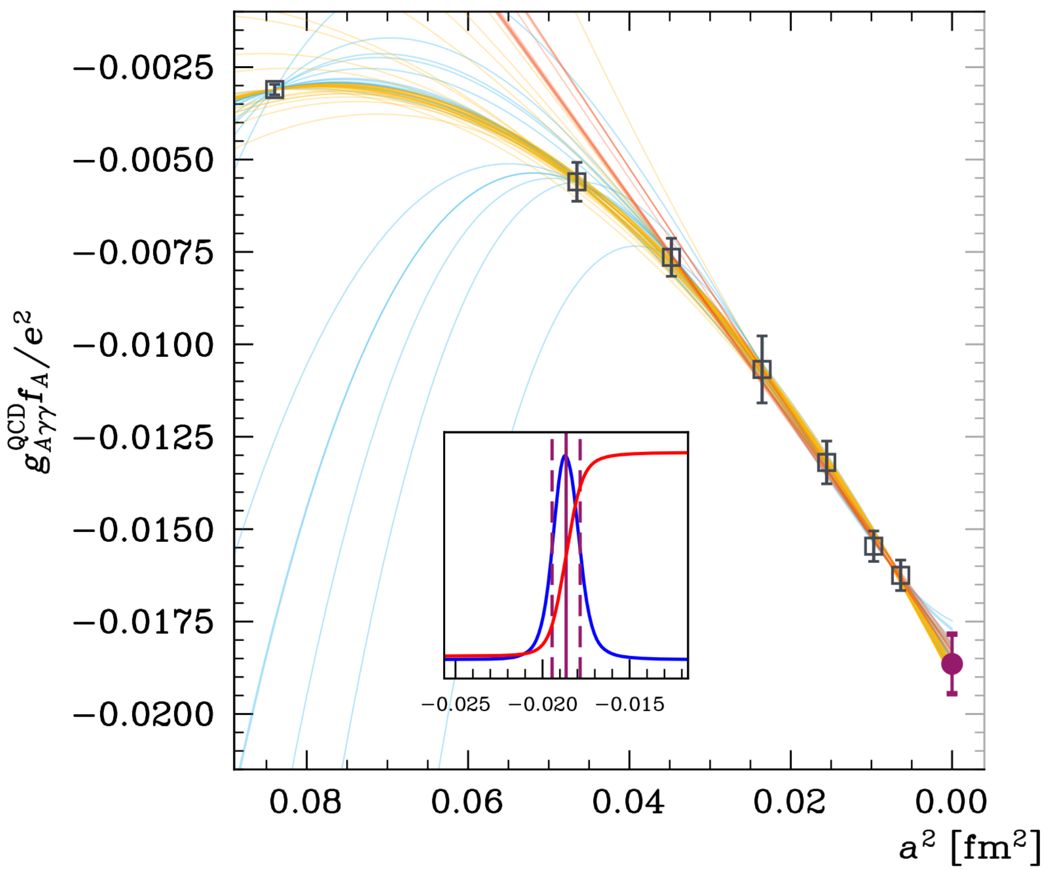
- $g_{A\gamma\gamma}^{\mathrm{QCD}}$ with purely fermionic observables

$$\boxed{g_{A\gamma\gamma}^{\mathrm{QCD}} = \lim_{\boldsymbol{E}\cdot\boldsymbol{B}\to 0} \frac{N_c q_f^2}{4\pi^2} \left(\frac{\left\langle P_f^5 \right\rangle_{\boldsymbol{EB}}}{\left\langle P_f^5 \right\rangle_0} - 1 \right) \,.}$$

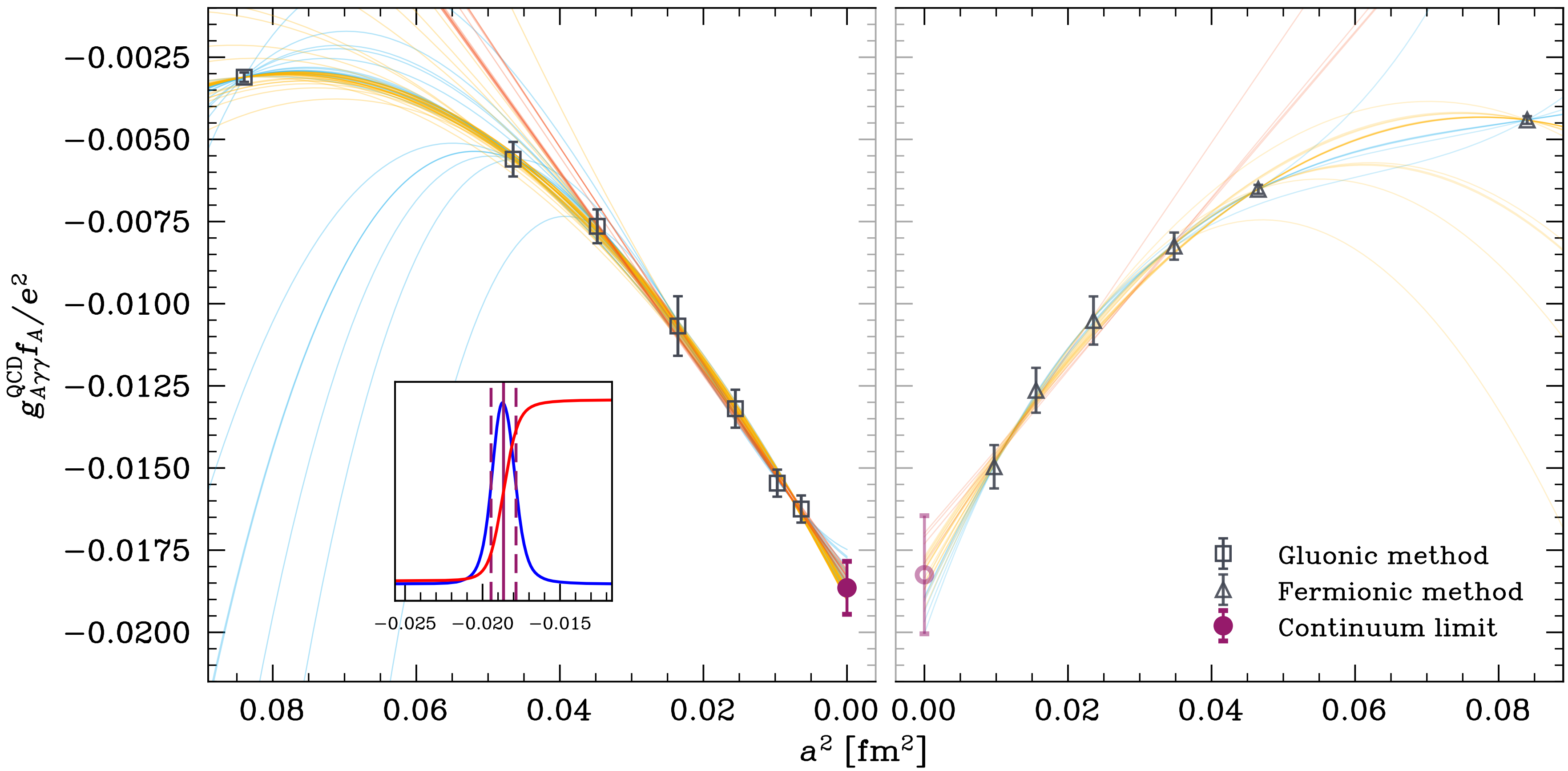
Technical details

- tree level improved Symanzik gluon action + 2+1 flavors of twice stout-smeared rooted staggered fermions,
- degenerate light-quark masses and physical light-to-strange ratio,
- 6 or 7 lattice spacings depending on the observable,
- 6 continuum equivalent gluonic definitions,
- 4 continuum equivalent fermionic definitions,
- at least 5 pairs of n_e, n_b at each lattice spacing (except the finest),
- gradient flow up to $\tau_f = 1\,\mathrm{fm}^2$,
- $\boldsymbol{E} \cdot \boldsymbol{B} \to 0$ and $a \to 0$ limits taken sequentially,
- end result built from AIC weighted histogram of $\mathcal{O}(200)$ methods.

Continuum limit



Continuum limit



- Counter-checking with a completely independent approach.
- Controlled continuum extrapolation is possible.

$$g^{\mathrm{QCD}}_{A\gamma\gamma}\frac{f_A}{e^2} = -0.0224(2)_{\mathrm{stat}}(2)_{\mathrm{def}}(5)_{\mathrm{a}}(8)_{\mathrm{EB}}(1)_{\mathrm{vol}}(2)_{\mathrm{m}}$$

Combining $g_{A\gamma\gamma}^{\mathrm{QCD}}$ with $g_{A\gamma\gamma}^{0}$

- Use the selection of models mentioned earlier

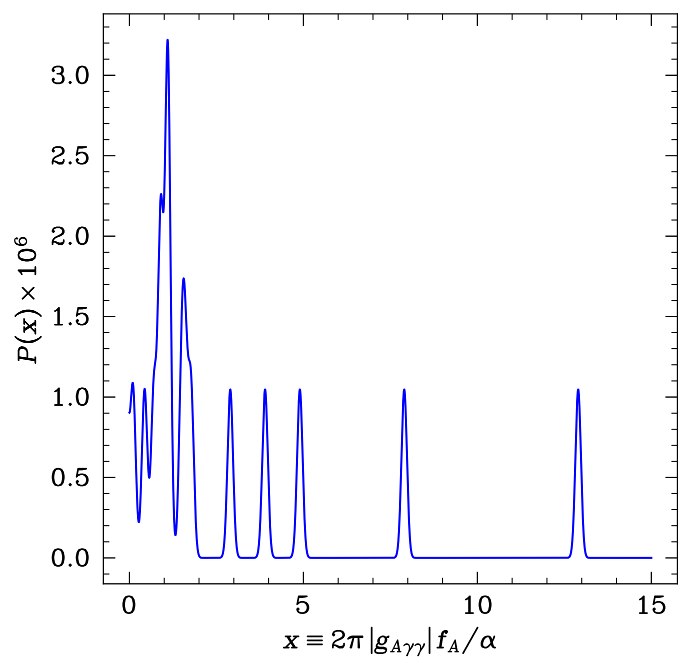
Di Luzio et al. PRL 118 (2017)

$$g_{A\gamma\gamma}^{0} f_A = \frac{1}{8\pi^2}\frac{E}{N}, \qquad 0 \le \frac{E}{N} \le \frac{44}{3}\,.$$

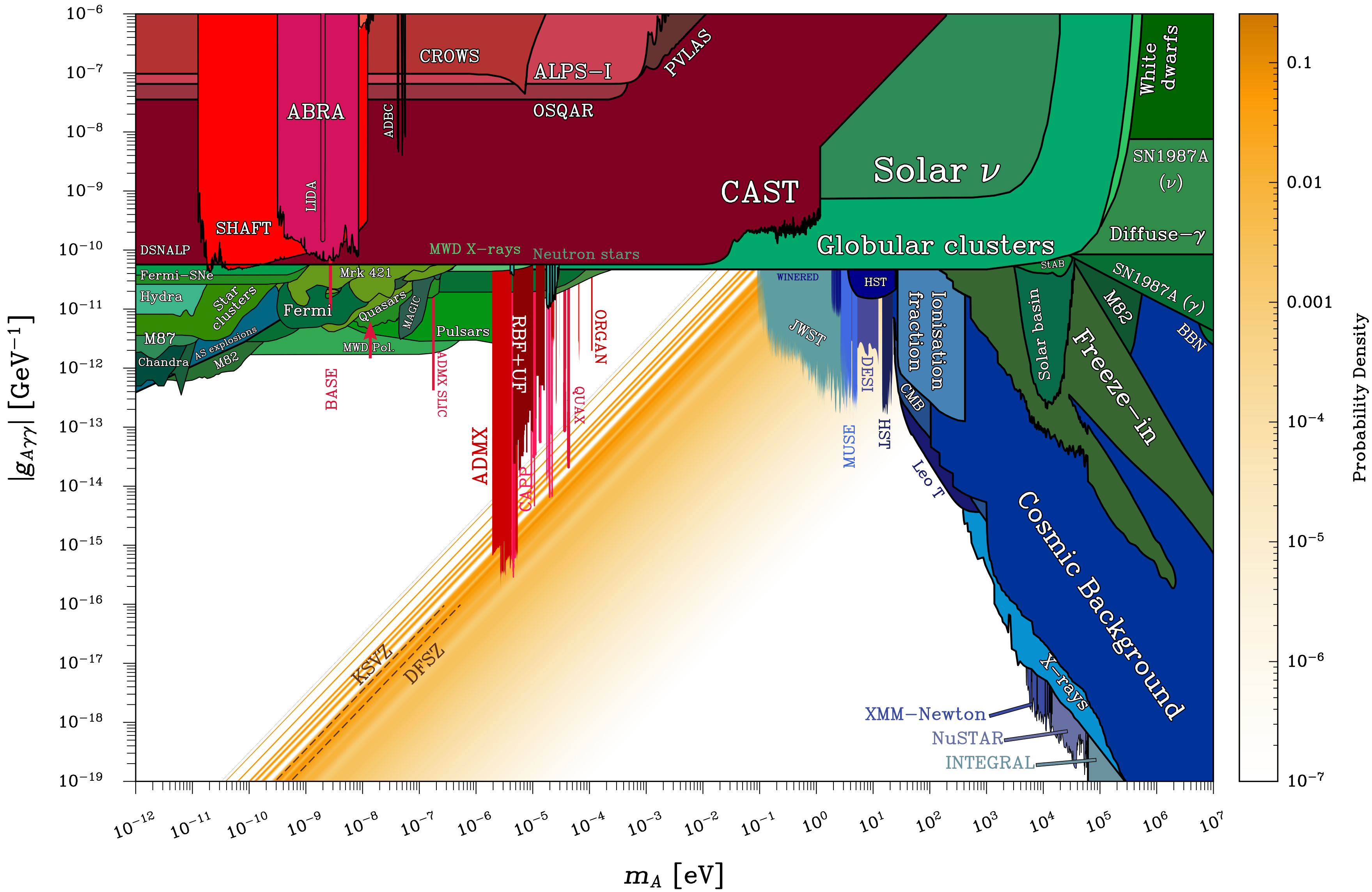
- Build total coupling probability density with distribution of

$$g_{A\gamma\gamma}^{\mathrm{QCD}} f_A = -0.0224(10),$$

- and uniform distribution for the possible axion models.



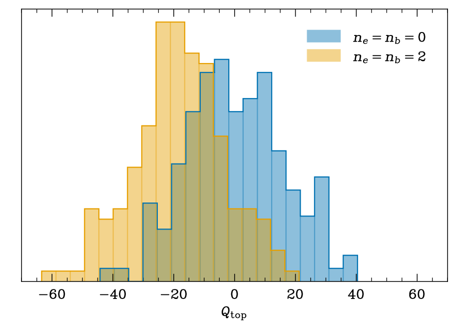
Updated experimental landscape



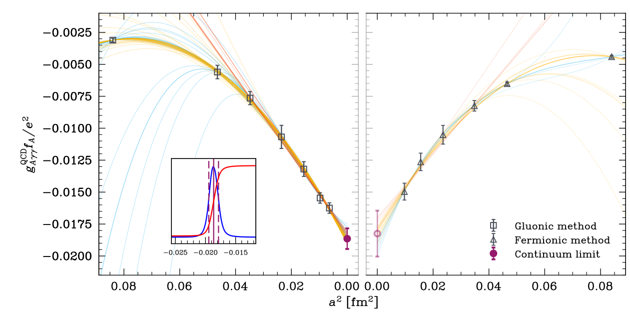
Summary

- Axions: strong CP problem, dark matter candidate, m_A, $g_{A\gamma\gamma}$.

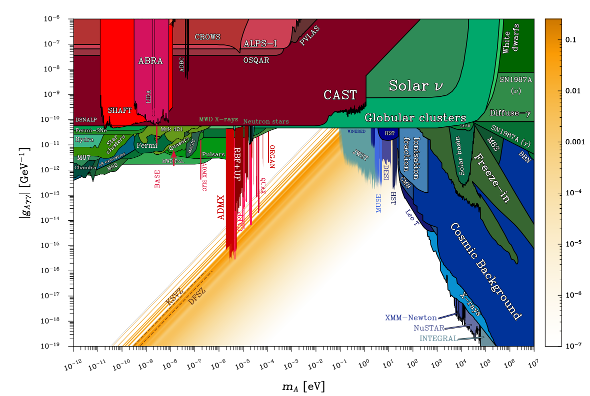
- Axion-photon coupling $\leftrightarrow$ topology shift due to $i\boldsymbol{E}\cdot\boldsymbol{B}$.



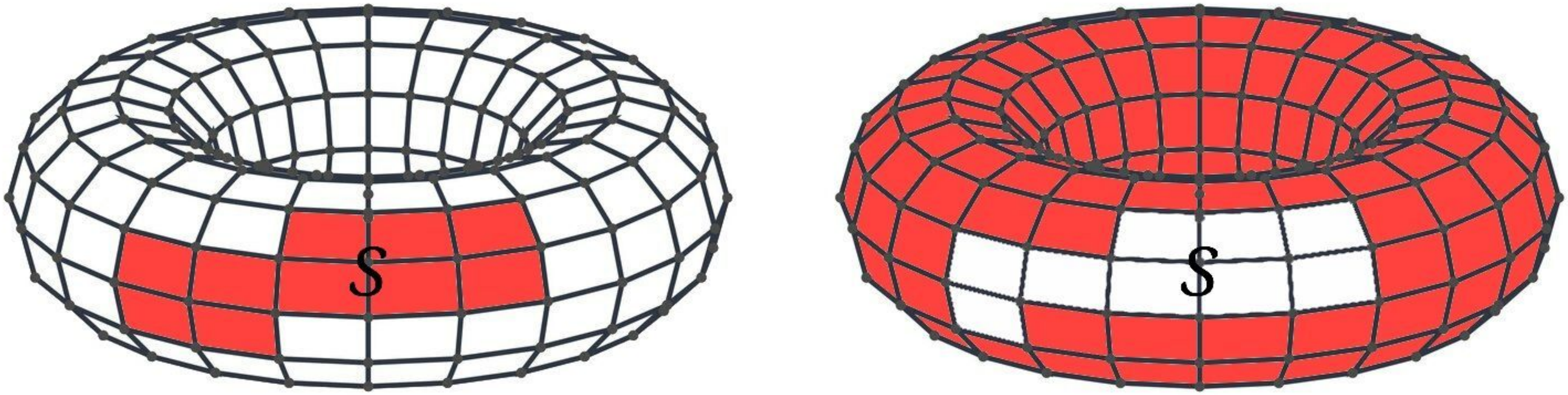
- First fully non-perturbative determination.



- Narrows down axion model landscape.



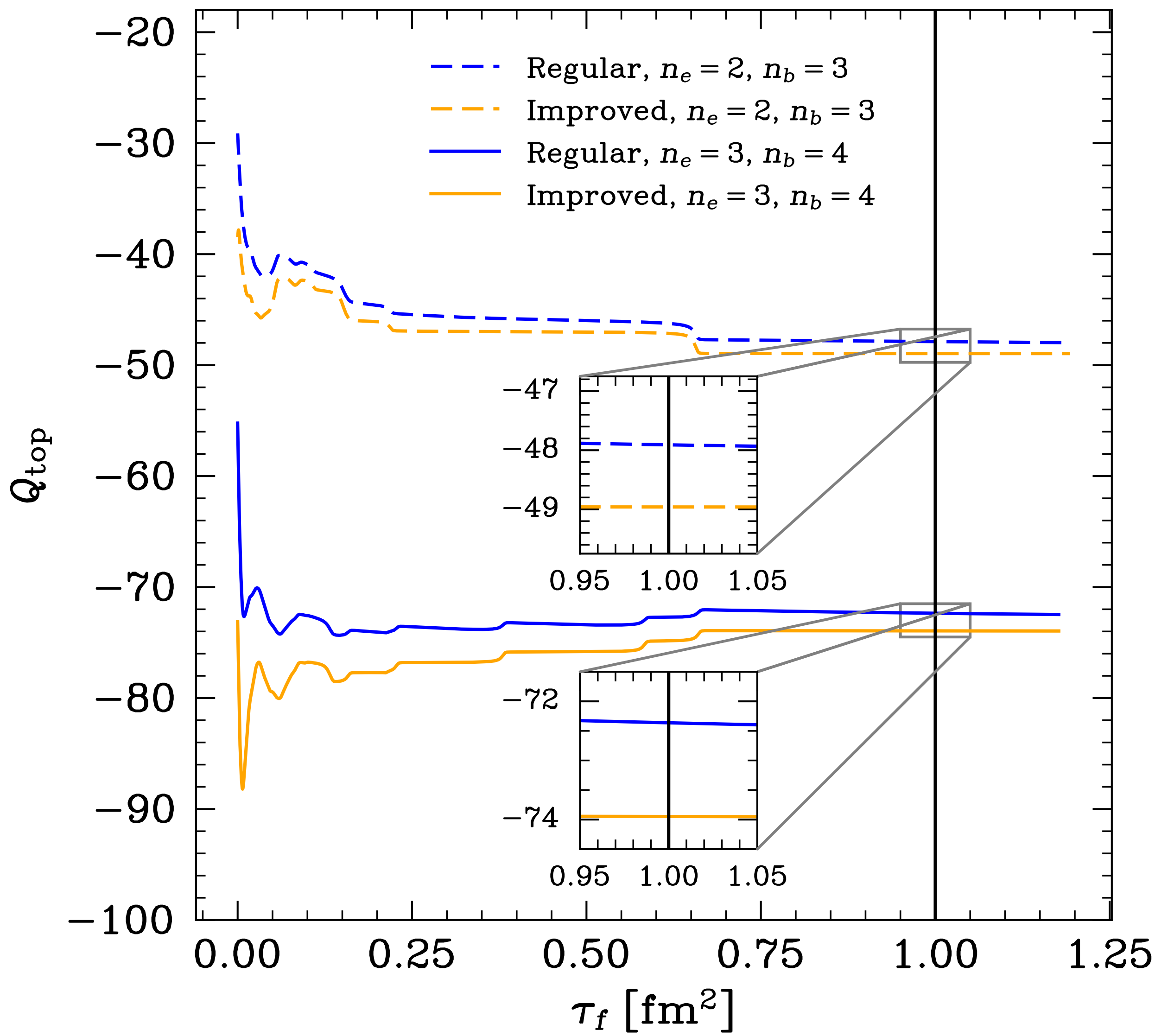
Backup 1 - EM field quantization



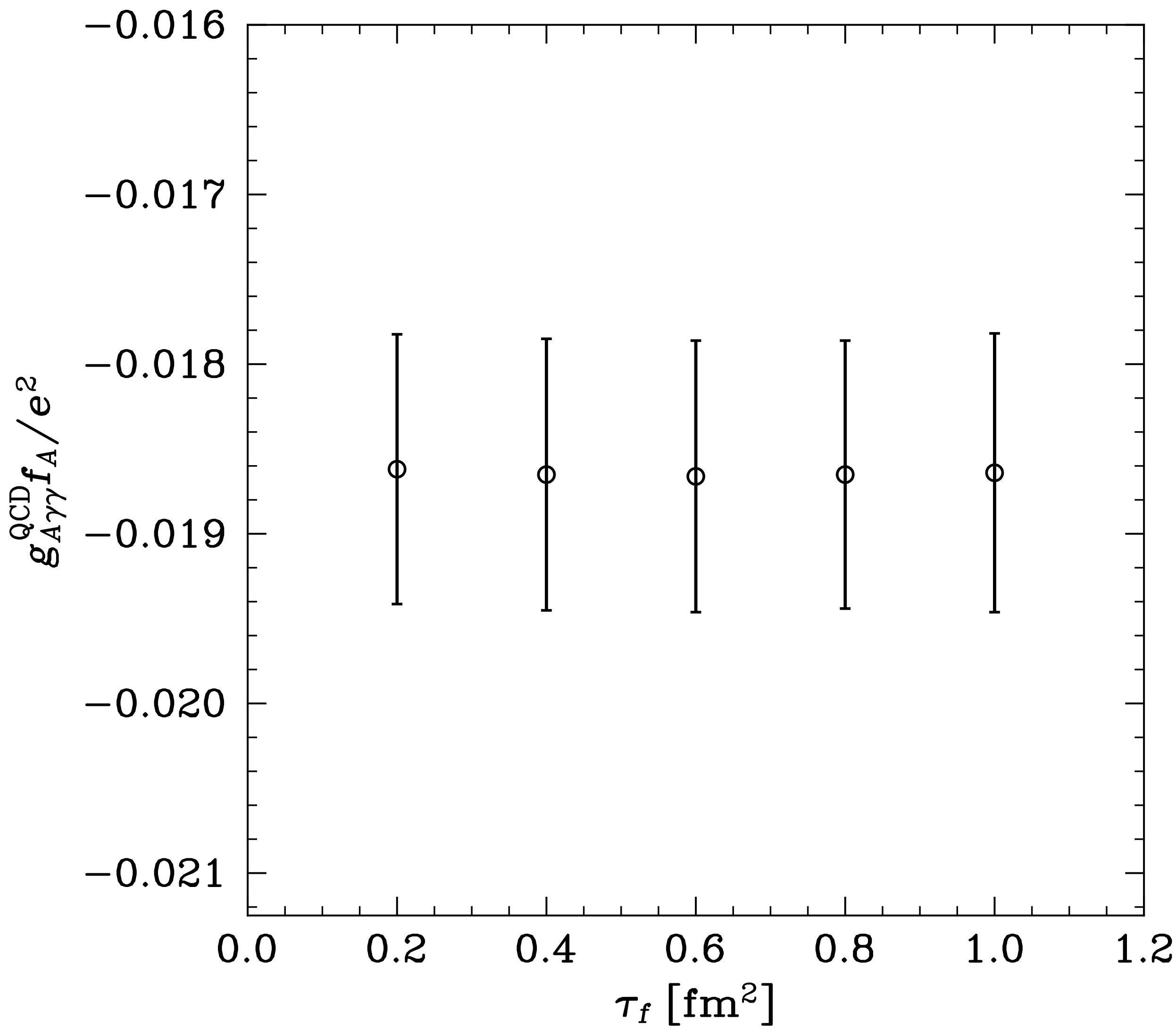
$$eB = \frac{6\pi n_b}{L_x L_y},$$

$$eE = \frac{6\pi n_e}{L_z L_t}.$$

Backup 2 - $Q_{\rm top}$



Backup 3 - flowtime dependence



(At degenerate light-quark masses.)