

New physics – new light particles?

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Standard Model of particle physics: so far

SM - explains enormous amount of experimental results

Yet!

Observations:

- Neutrino oscillations
 $\nu_\alpha \rightarrow \nu_\beta, m_\nu \neq 0$
- Baryon asymmetry of the Universe
- Dark matter
- Accelerated expansion of the Universe
- Perturbations

New physics is required!

Questions from theory side:

- Gauge hierarchy
 $v \ll M_{Pl}$
- Strong CP problem
- Pattern of fermionic mass
 $m_e \ll m_\mu, m_u \ll m_t, ..$
- Gauge unification
- Quantum gravity

Possible guiding principles ?

New Physics: at TeV scale?

Naturalness? Unification of gauge interactions?

- Supersymmetry
- Compositeness
- Extra dimensions
- New particles at EW scale with large couplings
- WIMP-like dark matter candidates

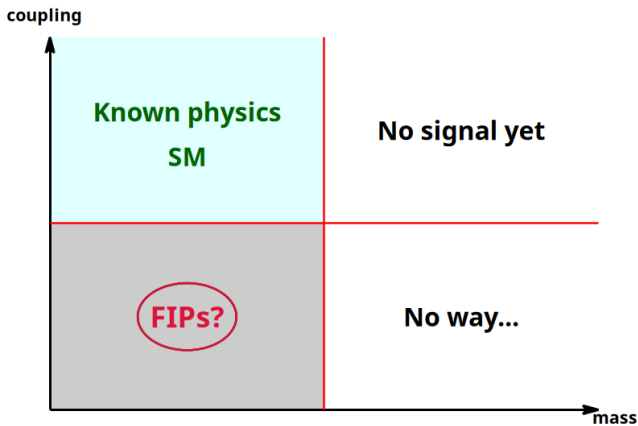
So far:

- No signal from TeV new physics
- No (direct or indirect) signal from WIMPs

Strong bounds from flavour physics:

Absence of charged lepton flavour violation and non-SM contributions to FCNC imply $\Lambda_{NP} > 10 - 10^5$ TeV (unless some symmetries are involved)

New Physics: where to look?



FIPs - Feebly Interacting Particles could still avoid detection!
(small masses – less than few GeV)

FIPs: portals to a hidden sector

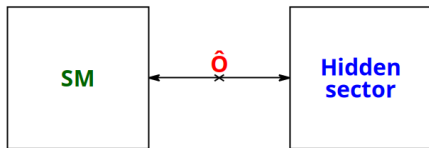
Simple guiding principles:

1. FIPs - **singlets** with respect to $SU(3)_c \times SU(2)_L \times U(1)_Y$
2. Interactions of FIPs - singlet **operators of the lowest dimension**

Simplest possibilities:

- Scalar portal, S – dark scalar, $(\mu S + \lambda S^2)H^\dagger H$
- Vector portal: X_μ – dark photon, $\frac{\epsilon}{2 \cos \theta_W} B_{\mu\nu} X^{\mu\nu}$
- Fermion portal: N – sterile neutrino, $y_N L \tilde{H} N$
- Axion portal, a – pseudoscalar (ALP)
 $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}, \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$ (non-renormalizable)
- More complicated scenarios

- By themselves, portals solve nothing.
- Should be considered as a part of ...



$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2}S^2 - \lambda S^2 H^\dagger H - \mu S H^\dagger H + V(S)$$

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + h) \end{pmatrix} \quad S = v_S + s$$

(h, s) mixing \rightarrow mass states (h_{125}, ϕ)

Parameters of the model: $m_\phi, \sin \theta$ – mixing with Higgs boson

Phenomenology:

- Scalar mediator to dark matter
freeze-out, $\mathcal{L} \sim g_\chi \phi \bar{\chi} \chi$
- Dark matter candidate (light or \mathbb{Z}_2 symmetry)
freeze-in, $\sin \theta \sim 10^{-12} - 10^{-10}$
- Inflaton at GeV scale, [0912.0390](#)

$$\mathcal{L}_V = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}X_\mu X^\mu$$

$(B_\mu, W_\mu^3, X_\mu) \rightarrow$ mass states (Z_μ, A_μ, A'_μ)

A'_μ – massive dark photon

Parameters: $m_X, \epsilon, X - \gamma$ mixing

Phenomenology:

- Vector mediator to dark matter

$$\mathcal{L} \sim g_X \bar{\chi} \gamma^\mu \chi X_\mu$$

- Dark matter candidate (for small m_X and ϵ)
- Millicharged particles $\epsilon e \bar{\psi} \gamma^\mu \psi A_\mu$
- New $U(1)$ s appear in many BSM scenarios

Fermion (lepton) portal

e.g. type-I seesaw

$$\mathcal{L}_F = i\bar{N}_a\gamma^\mu\partial_\mu N_a - y_{\alpha a}\bar{L}^\alpha\tilde{H}N_a - \frac{1}{2}M_{N_a}\bar{N}_a^C N_a + \text{h.c.}$$

Mass matrix in neutrino sector

$$m = \begin{pmatrix} 0 & m_D \\ m_D^\top & M_{N_a} \end{pmatrix} \text{ with } m_{D,\alpha a} = \frac{1}{\sqrt{2}}y_{\alpha a}v$$

For $M_N \gg m_D$:

- 3 active neutrino states, $m_\nu \sim \frac{m_D^2}{M_N}$
- 3 (almost) sterile neutrino states

$$\nu_\alpha = U_{\alpha i}\nu_i + \tilde{U}_{\alpha a}N_a, \text{ active-sterile mixing } \tilde{U}_{\alpha a} \ll 1$$

Phenomenology:

- Address smallness of neutrino mass
- Lightest sterile state – dark matter candidate
- Baryon asymmetry – leptogenesis (additional CP-phases)

$$\mathcal{L}_{ALP} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a} \sum_{\text{fermions}} c_F \bar{\psi} \gamma^\mu \gamma^5 \psi$$

$$+ c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} + c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f_a} W_{\mu\nu}^a \tilde{W}^{a\mu\nu} + c_{BB} \frac{\alpha_Y}{4\pi} \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}.$$

Nonrenormalizable interactions

Phenomenology:

- $a(x)$ – pseudo-Nambu-Goldstone boson

Spontaneous ~~symmetry~~ $\rightarrow \varphi(x) = \langle \varphi \rangle e^{i \frac{a(x)}{f_a}}$, $\langle \varphi \rangle \sim f_a$

- strong CP problem $\mathcal{L}_{QCD} = \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \rightarrow \mathcal{CP}$

$$|d_n| < 1.8 \cdot 10^{-26} e \text{ cm} \rightarrow |\theta| \lesssim 10^{-10}$$

QCD axion $\theta \rightarrow a(x)$, so that $\langle a \rangle = 0$ Peccei, Quinn

$m_a \sim m_\pi \frac{f_\pi}{f_a}$ – for more general models m_a is a free parameter

- dark matter candidate
- mediator to dark matter sector

$$\mathcal{L} \sim \frac{\partial_\mu a}{f} c_\chi \bar{\chi} \gamma^\mu \gamma^5 \chi$$

Searches for new light particles. I

see talks at Section "Cosmology and Astroparticle Physics" on Friday

see talk by E.Dmitrieva

Astrophysical and Cosmological Probes

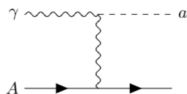
- FIPs can be produced and emitted in stars → an extra cooling channel → changes stellar evolution (population of red giants, white dwarfs, horizontal branch stars).
- FIP-induced energy loss influence duration of neutrino burst in Supernova 1987A
- Light dark matter searches (XENON, DarkSide, ...)
- Cosmological observables: from BBN, CMB → sensitive to FIP abundance and lifetime.

Laboratory non-accelerator experiments

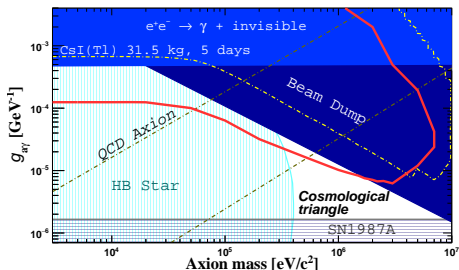
- Haloscopes: search for dark-matter (ALP, dark photons) via resonant conversion to photons *see talks by P.Satunin and D.Salnikov*
- Helioscopes: capture FIPs emitted by the Sun and convert them to X-rays in a magnetic field (CAST, future IAXO).
- Light-Shining-Through-Walls (LSW): laser \rightarrow FIP in a magnetic field, reconversion to light behind a barrier (ALPS II, OSQAR).
- Atomic and molecular spectroscopy: tiny shifts in energy levels induced by new forces.
- Fifth-force searches
- Reactor experiments

Searches at reactors

- Huge flux of MeV photons ($T \sim GW$)
$$\frac{dN_\gamma}{dE} = 0.58 \times 10^{21} \times \frac{T}{GW} \times \epsilon^{-\frac{E}{0.91 \text{ MeV}}} \text{ photons}/(\text{s} \times \text{MeV})$$
- Dark photon production: through mixing $\gamma \rightarrow A'$
- ALP production: Primakoff effect
- Experiments: TEXONO, NEOS, DANSS

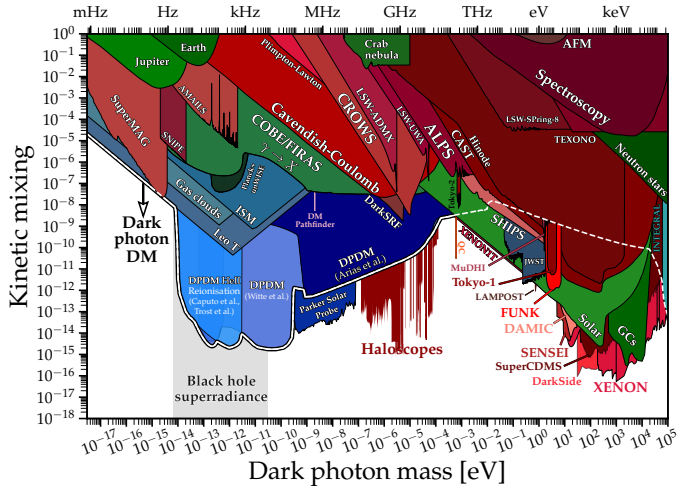


NEON, 2406.06117



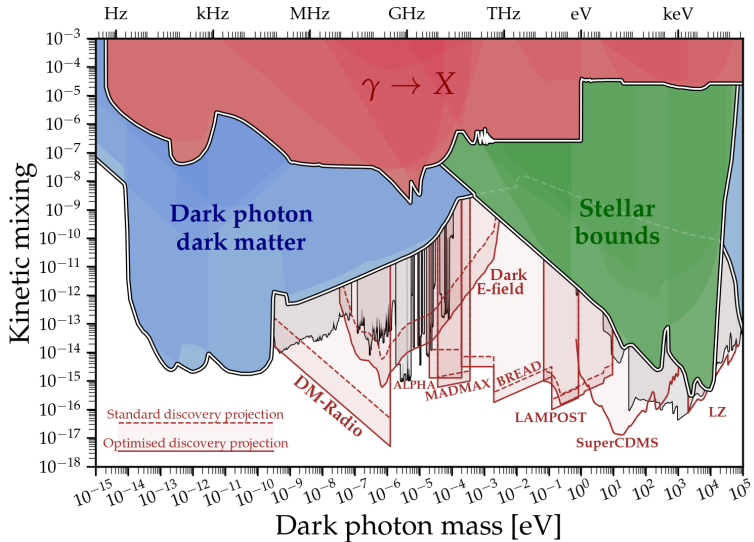
Existing limits: example of dark photon

2105.04565, <https://cajohare.github.io/AxionLimits>



Discovery limits: example of dark photon

2105.04565, <https://cajohare.github.io/AxionLimits>



Searches for new light particles. III

$m \gtrsim 1 \text{ MeV}$ small couplings – large statistics is required!

High intensity frontier: reach experimental program and plans

Experiments:

- Main LHC experiments (ATLAS, CMS, LHCb)
- e^+e^- colliders, BESIII, Belle II
- FASER(-2), NA64 *see talk by M.Kirsanov*
- SHiP (first data are expected in 2032-2033)
- T2HK, DUNE, SND, T2K, NA62, NA62-dump
- NICA *see talk by D.Gorbunov*

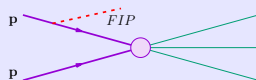
Proposals:

- FORMOSA, FLaRE, MilliQan, MATHUSLA, ANUBIS, SHADOWS, HIKE-K+, LDMX, M^3 etc.

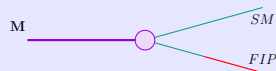
Production and decays of FIPs

Production

- Bremsstrahlung processes



- Decays of mesons



- Different beams are under study (π , μ)

see talks by E.Kriukova, L.Dudko

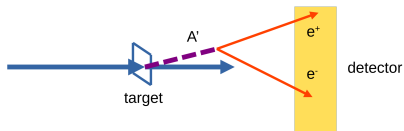
Decays

- Visible mode - reconstruction SM final states
Small coupling constants - long-lived particles!
- Invisible mode - decays into DM particles
- No decays, but hits (millicharged particles)

Sensitivity to couplings: example of dark photon

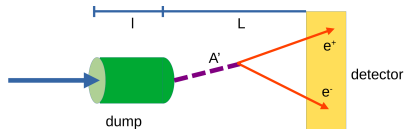
1. Thin-target experiments and colliders

- Production $\sigma \sim \epsilon^2$
- Decay $\Gamma \sim \epsilon^2$
- LLP - displaced vertices



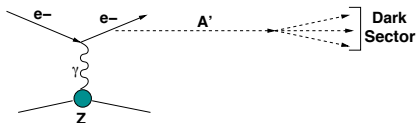
2. Beam-dump mode (thick shield)

- Production $\sigma \sim \epsilon^2$
 - Decay in detector
- $$\mathcal{P}_{\text{det}} = e^{-\frac{l}{\lambda}} \left(1 - e^{-\frac{L}{\lambda}}\right)$$
- A' decay length $\lambda = \gamma\beta\tau$



3. Missing energy/momentum

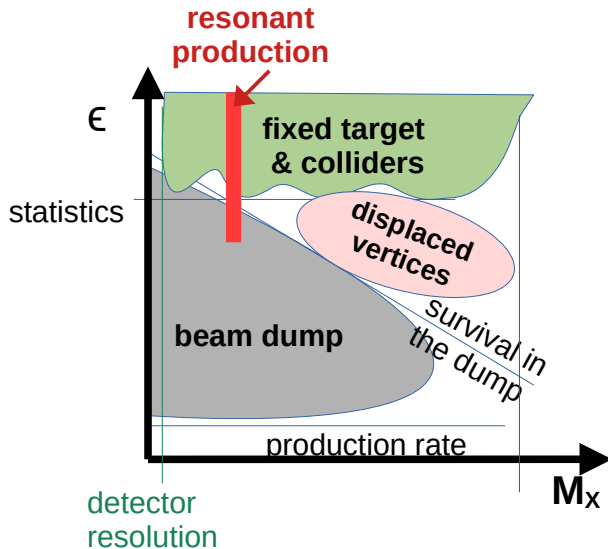
- Production $\sigma \sim \epsilon^2$
- see talk by D.Kirpichnikov*



1710.00971

Typical sensitivity regions

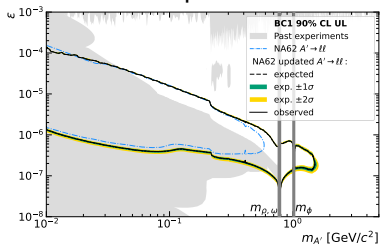
2603.03433



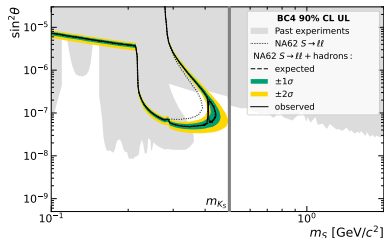
Latest results: NA62-dump

2502.04241

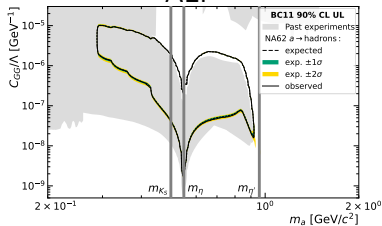
Dark photon



Dark scalar

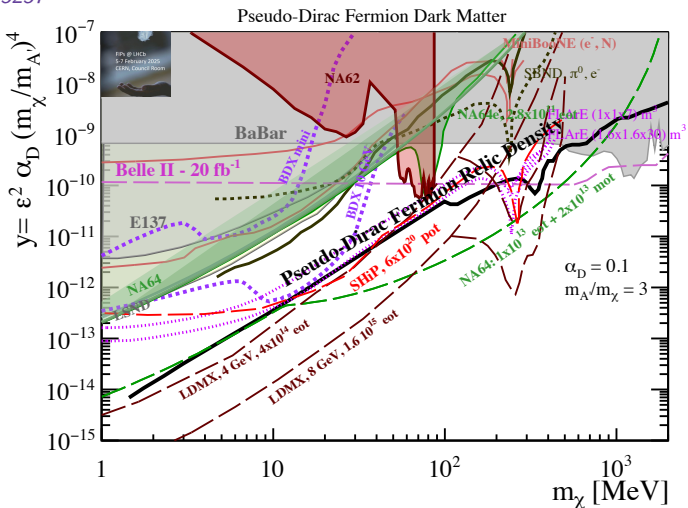


ALP



Dark photon: invisible mode

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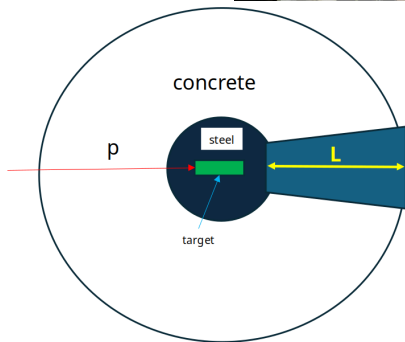


TiMoFey – the project of a fixed-target accelerator experiment based on the Complex of a high-current linear accelerator of protons and negative hydrogen ions of the INR RAS in the framework of Programs “Fundamental properties of matter”

- Two stages, 5 years each

Stage	I	II
T_p , MeV	423	1300
I_p , μA	300	100
N_{POT}	$1.8 \cdot 10^{22}$	$0.6 \cdot 10^{22}$

- Target – graphite ($L_m = 1.2$ m)
- Dump – concrete ($R = 7$ m), steel around ($R_0 = 2$ m) and behind the target ($L = 5$ m)

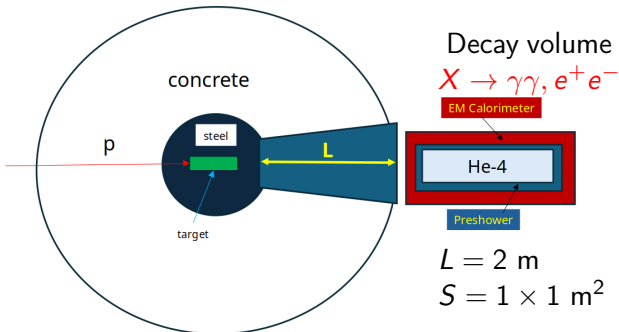


Physics at TiMoFey (moderate energies, high statistics)

- Production of X : in primary collisions or in meson decays

Signatures X : decays or hits

- Decays: $X \rightarrow \gamma\gamma$, $X \rightarrow e^+e^-$
- Interaction in detector $X + SM \rightarrow \dots$



- EW Cal $15X_0$
- Preshower $2 - 3X_0$
- Energy resolution
8–9% (at 100 MeV)
- Angular resolution
 $3 - 5^\circ$
- Time resolution 1-2 ns

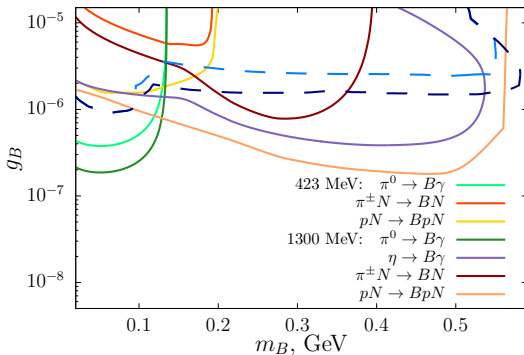
GEANT4 simulations: very good chance for background-free experiment

Leptophobic B-boson at TiMoFey (95 % CL)

B-boson – vector boson, interacting with baryon current $U(1)_B$

$$\mathcal{L}_{\text{int}} = \left(\frac{g_B}{3} + \epsilon Q_q e\right) \bar{q} \gamma^\mu q B_\mu - \epsilon e \bar{l} \gamma^\mu l B_\mu$$

Interactions with leptons – at loop level from из-за $B \leftrightarrow \gamma$ mixing, with mixing parameter $\epsilon = e g_B / (4\pi)^2$



$B \rightarrow e^+ e^-, \pi^0 \gamma$, 5 years

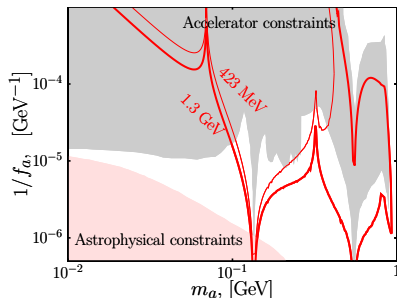
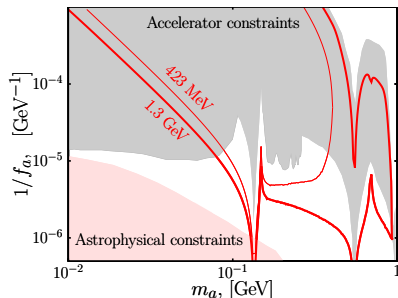
ALP at TiMoFey (95 % CL)

a – ALP: production in mixing with π^0, η

$$\mathcal{L}_{ALP} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu} \tilde{G}^{\mu\nu} \\ + c_{WW} \frac{\alpha_2}{4\pi} \frac{a}{f} W_{\mu\nu}^a \tilde{W}^{a\mu\nu} + c_{BB} \frac{\alpha_Y}{4\pi} \frac{a}{f} B_{\mu\nu} \tilde{B}^{\mu\nu}.$$

$$c_{WW} = c_{BB} = 0$$

$$c_{GG} = c_{WW} = c_{BB}$$



$a \rightarrow \gamma\gamma$, 5 years

- Models with FIPs are attractive from theoretical and from experimental sides
- Large experimental program in underway
- Waiting for discovery

Thank you!

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