Search for FIPs with LUXE

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KIT - Karlsruhe Institute of Technology

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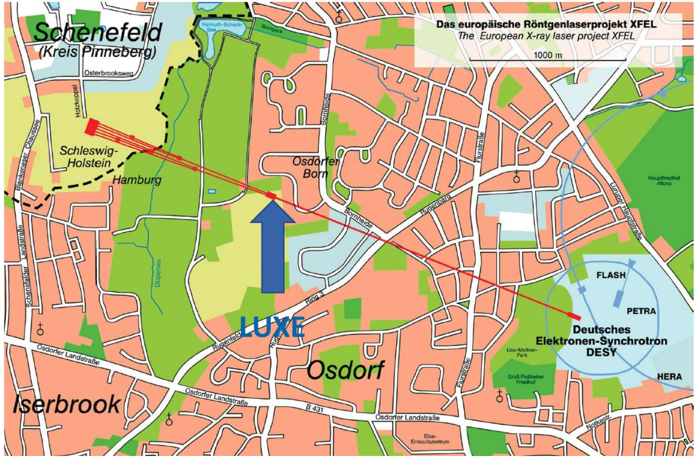
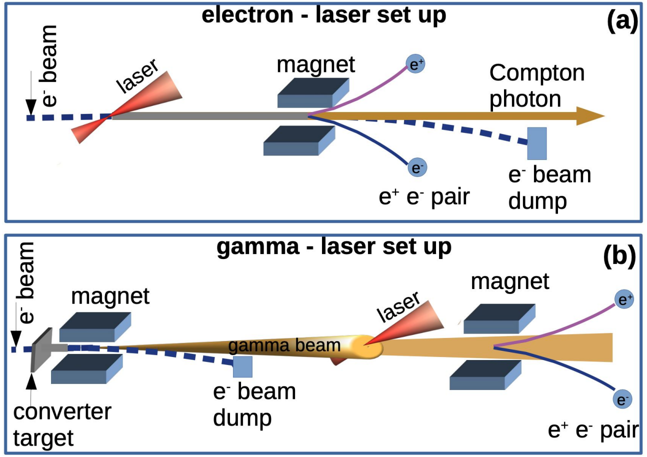
The LUXE Project at DESY

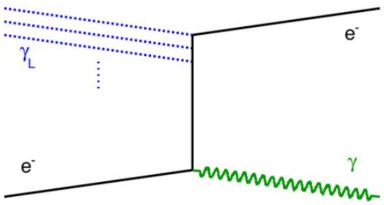
LUXE: Laser Und XFEL Experiment

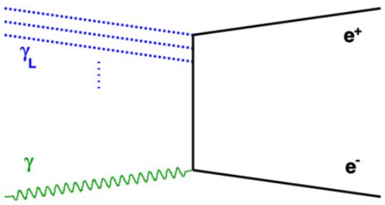
- XFEL provides a 16.5 GeV electron beam - and bremsstrahlung photons
- The electrons (or photons) and the laser photons “collide” producing high-intensity interactions
- Currently a project, first data foreseen in 2026





The Physics at LUXE





LUXE:

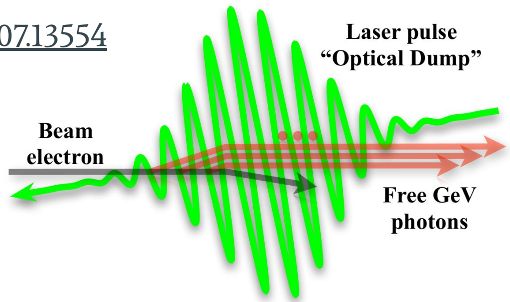
- Compare the predictions of full and perturbative QED in the Schwinger limit with the experimental results:

$$E_c = \frac{m_e^2 c^3}{q_e \hbar} \simeq 1.32 \times 10^{18}\ \mathrm{V/m}$$

- Measuring the e^+e^- flux produced by electron-laser or photon-laser interactions

arXiv:2102.02032

arXiv:2107.13554



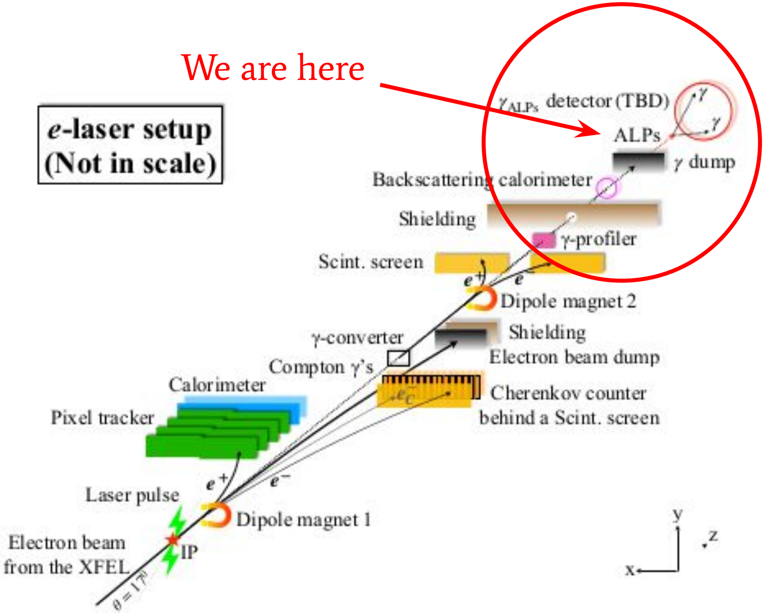
LUXE-NPOD:

- Collide a beam of 16.5 GeV electrons with the laser
- With the correct choice of the laser parameters:
  - The laser acts as a 'solid' dump for electrons, producing O(GeV) photons
  - Photons see the laser as a transparent medium and can reach the physical dump

Overview the LUXE-NPOD Project

arXiv:2107.13554

NPOD: New Physics searches with an Optical Dump



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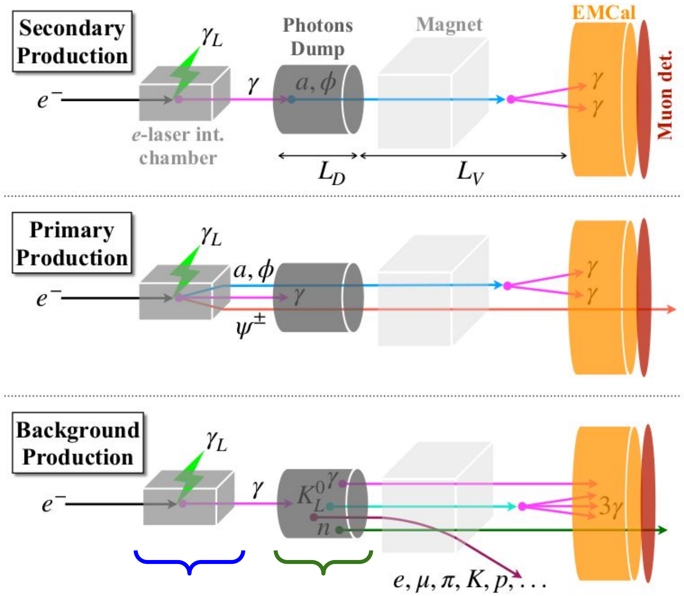
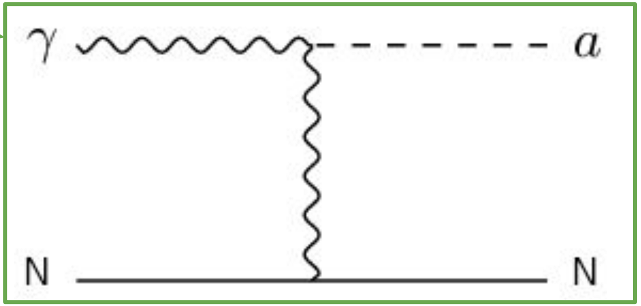


Photons from the optical dump can reach the physical dump and produce axion-like particles (ALPs). These, in turn, decay into pairs of photons.

Signal Definition and Production

ALP production can happen via the Primakoff mechanism:

$$\mathcal{L}_{a/\phi} = \frac{a}{4\Lambda_{a/\phi}} F_{\mu\nu}\tilde{F}^{\mu\nu} + \left(i g_{a/\phi\, e}\, a \bar{e}\gamma^5 e \right)$$

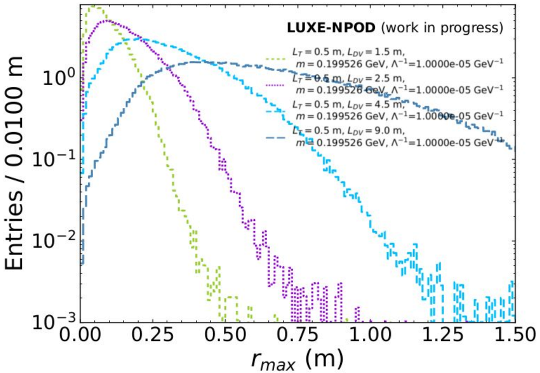


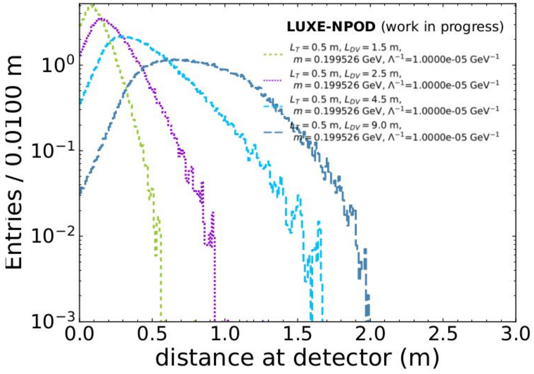
$$N_a \approx \mathcal{L}_{\text{eff}} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_a(E_\gamma) \left(e^{-\frac{L_D}{L_a}} - e^{-\frac{L_V + L_D}{L_a}} \right) \mathcal{A}$$

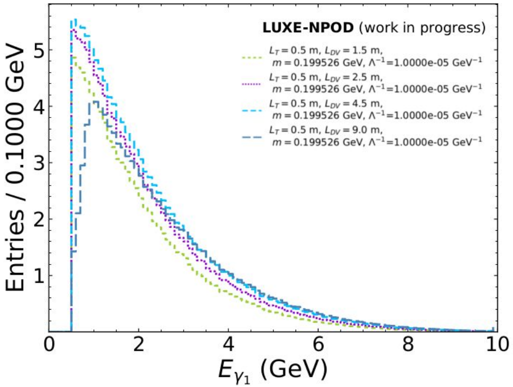
$$\mathscr{L}_{eff} = N_e N_p \frac{9 \rho_N X_0}{7 A_N m_0}$$

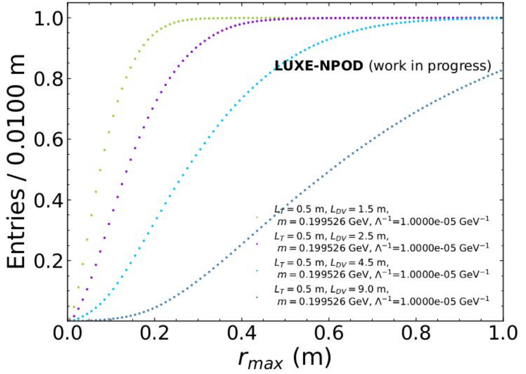
Acceptance Studies

- Photons produce ALPs in the first mm of the dump
- Boosted $c\tau_{a/\phi}$ randomly drawn from $\exp(-L/L_{a/\phi})$ distribution
- ALP decay after target and before detector
- $E_\gamma > 0.5$ GeV
- No photon separation requirement yet
- Longer decay volumes require larger detector surface



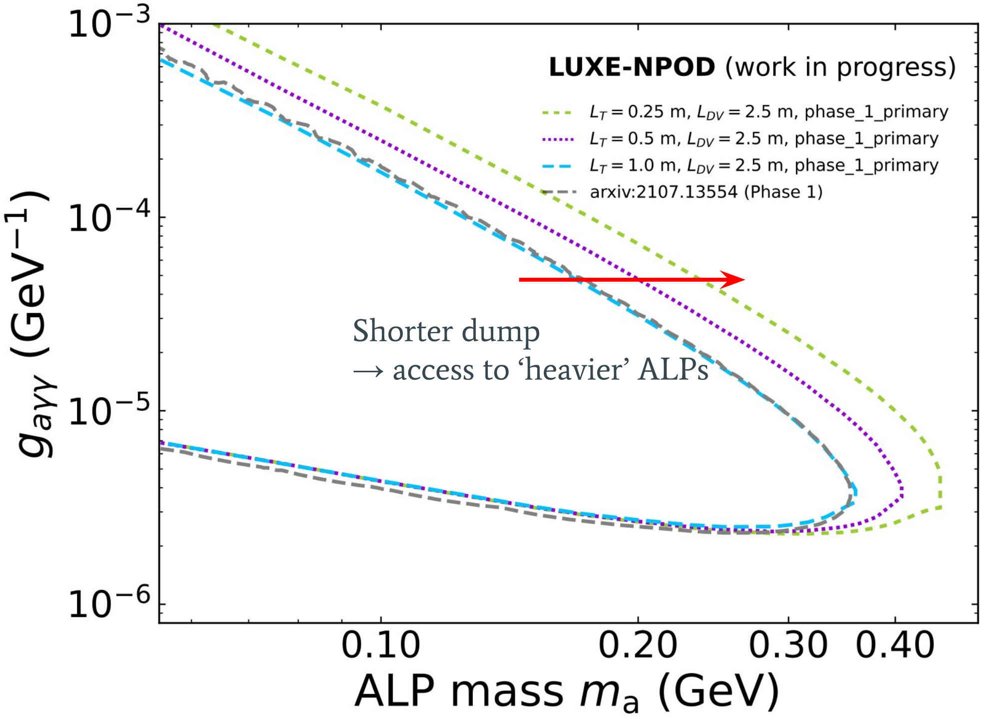




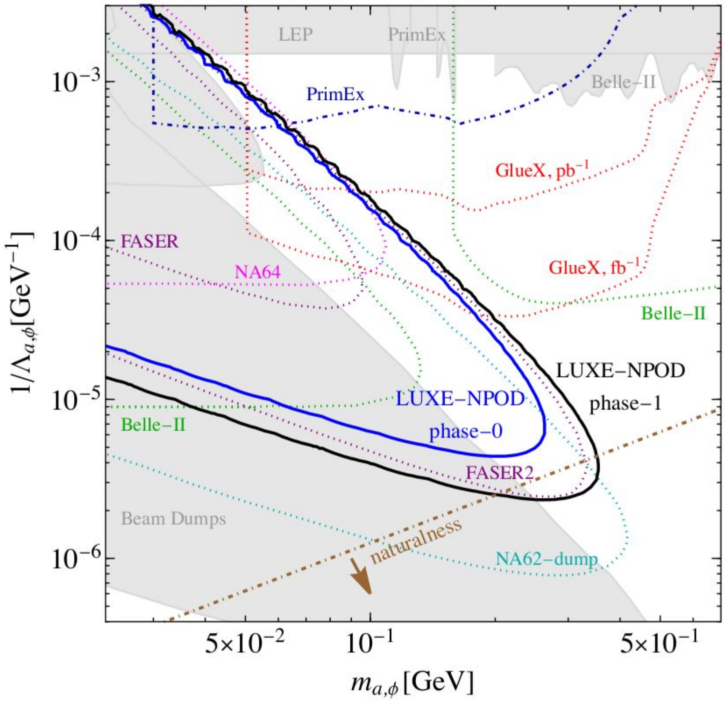


Expected Results in Phase 1: Dump Length

arXiv:2107.13554

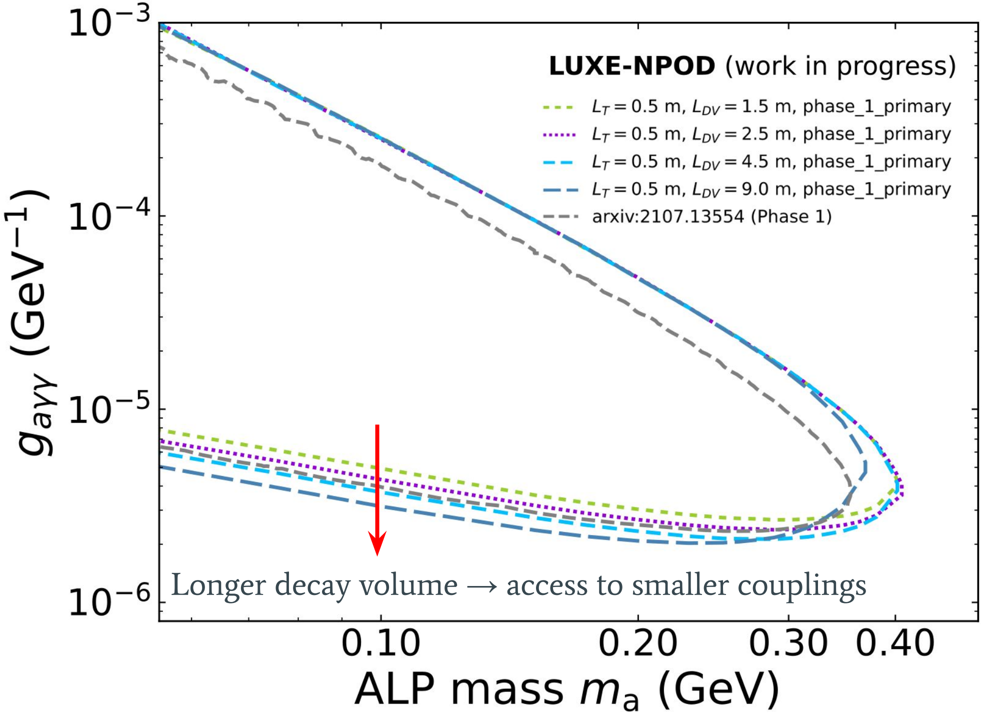


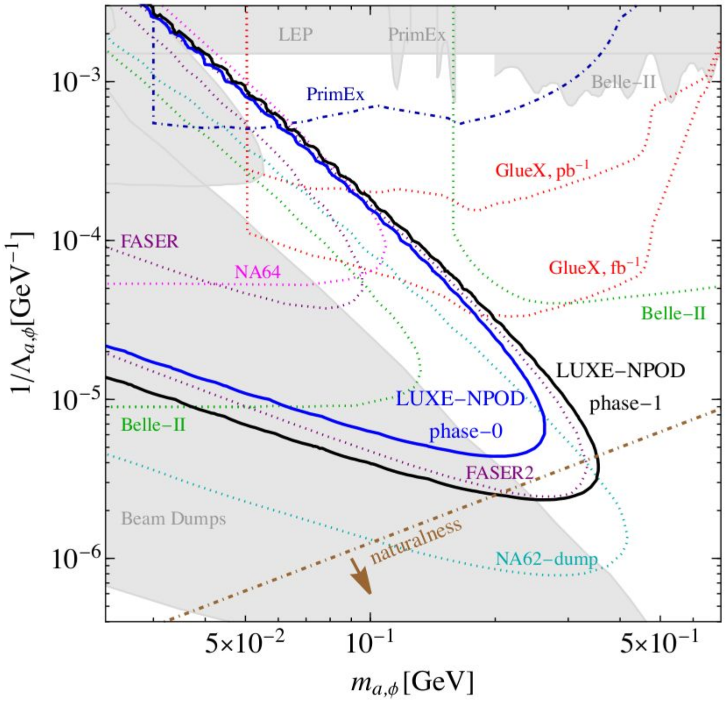
Shorter dump
→ access to 'heavier' ALPs



Expected Results in Phase 1: Decay-Volume Length

arXiv:2107.13554

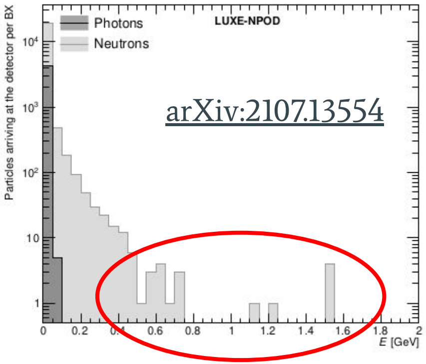


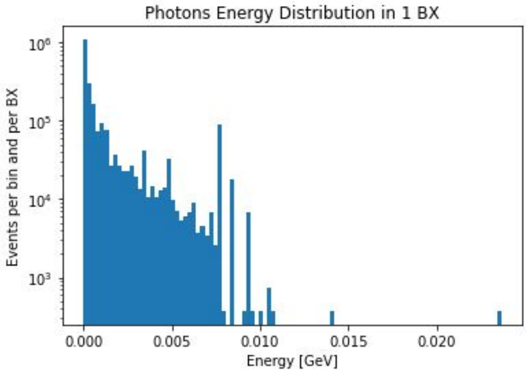


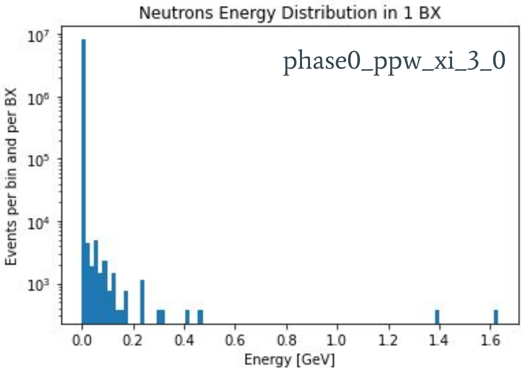
Background Studies

The expected results are obtained assuming zero background:

- Studies in the LUXE-NPOD paper and more recent ones confirm it
- Photons really seem too soft to be a source of background. For neutrons in particular, statistics in $E_n > 0.5$ GeV is extremely low
- We use now **4 BX** but we may want to use more to populate the tail of the distributions

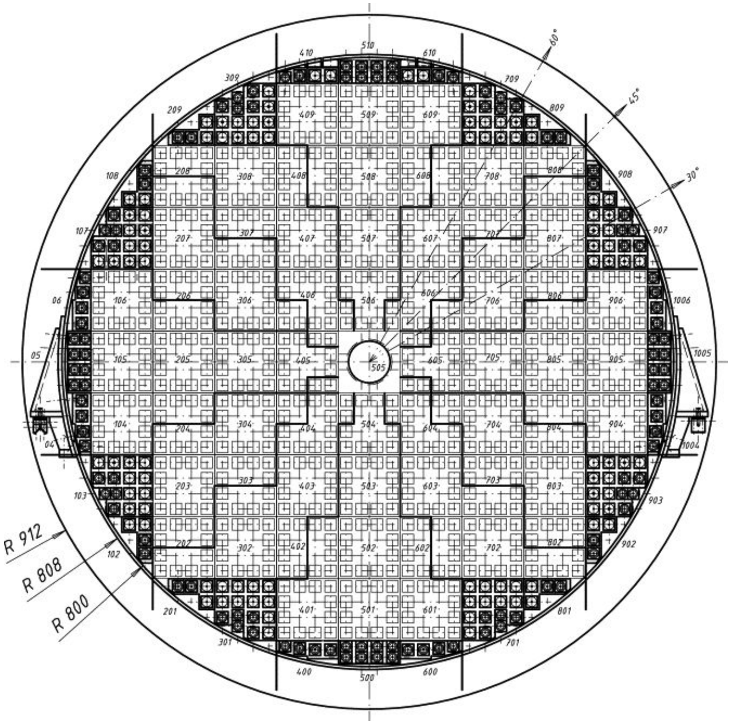






Detector Proposal

10.1016/j.cpc.2010.02.004



Detector physics goals:

- Signal efficiency
  → Photons shower separation (~ 2cm)
- Precise reconstruction of ALP invariant mass
  → Good resolution of photons direction and energy
- Background suppression
  → Vertex resolution (non-resonant photons)
  → Shower shape determination (neutrons)
  → Good time resolution (< 1ns) (neutrons)

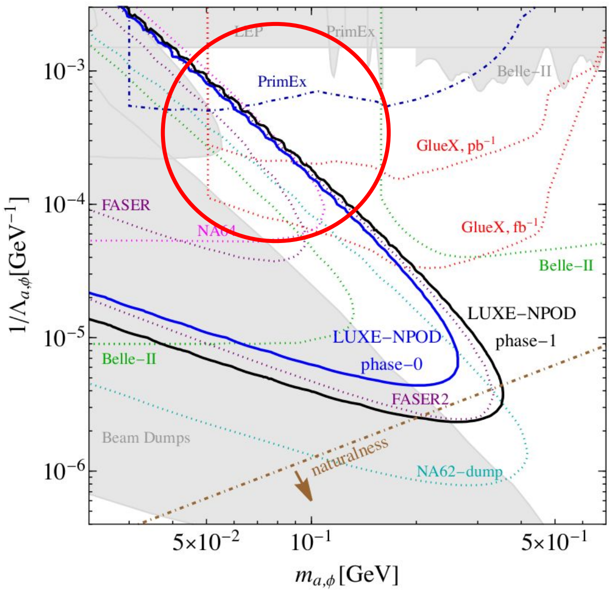
Current proposals:

- H1 lead/scintillating-fiber calorimeter
- “Tracking calorimeter” (e.g., HGCal) followed by an existing crystal or SpaCal ECAL to get the full energy
- Cheap: new scintillator/absorber detector

Conclusions

The LUXE-NPOD project has the potential to inspect an unexplored ALPs phase space

- Sweet spot is light ALPs with large couplings
- Preliminary studies already presented in arXiv:2107.13554 and arXiv:2102.02032 need to be reviewed and expanded with more accurate simulations
    - Working on extended simulation to overcome lack of statistics in the relevant regions
- An experimental setup to achieve high signal efficiency and zero background is required
    - Optimization of experimental setup to maximize signal production and acceptance
    - Detector technology and analysis techniques to reject background



Plenty of work but also exciting challenges ahead!

BACK-UP

Expected Number of ALPs

$$N_a \approx \mathcal{L}_{\text{eff}} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_a(E_\gamma) \left(e^{-\frac{L_D}{L_a}} - e^{-\frac{L_V+L_D}{L_a}} \right) \mathcal{A}$$

$$\mathscr{L}_{eff} = N_e N_p \frac{9\rho_N X_0}{7A_N m_0}$$

- $N_e = 1.5 \times 10^9$ electrons/bunch
- $N_p = 10^7$ laser pulses a year
- ρ_N density of dump, for tungsten 19.3 g/cm^3
- X_0 is the radiation length of tungsten (0.35 cm)
- A_N is the mass number of tungsten (184)
- m_0 is the atomic mass unit in gram: 1.661×10^{-24} g.

- L_D = dump length (also L_T = target length)
- L_V (also L_{DV}) = decay volume length
- $L_a = c\tau_{a/\phi}\, p_{a/\phi} / m_{a/\phi}$ = ALP decay length
- $\sigma_a(E_\gamma)$ = production cross-section as a function of E_γ
  - In our study, E_γ in bins of 0.1 GeV
- A = geometric acceptance of the detector

Laser Properties

Process	Timescale
Compton scattering: $e^-_V \rightarrow e^-_V + \gamma$	$\tau_\gamma = 1/\Gamma_\gamma \sim \mathcal{O}(10)$ fs
Breit-Wheeler pair production: $\gamma \rightarrow e^+_V + e^-_V$	$\tau_{ee} = 1/\Gamma_{ee} \sim \mathcal{O}(10^4 - 10^6)$ fs
Laser pulse duration at LUXE	$t_L \sim \mathcal{O}(10 - 200)$ fs
Time scale of LUXE's 800 nm	$\sim 1/\omega_L \sim 0.4$ fs

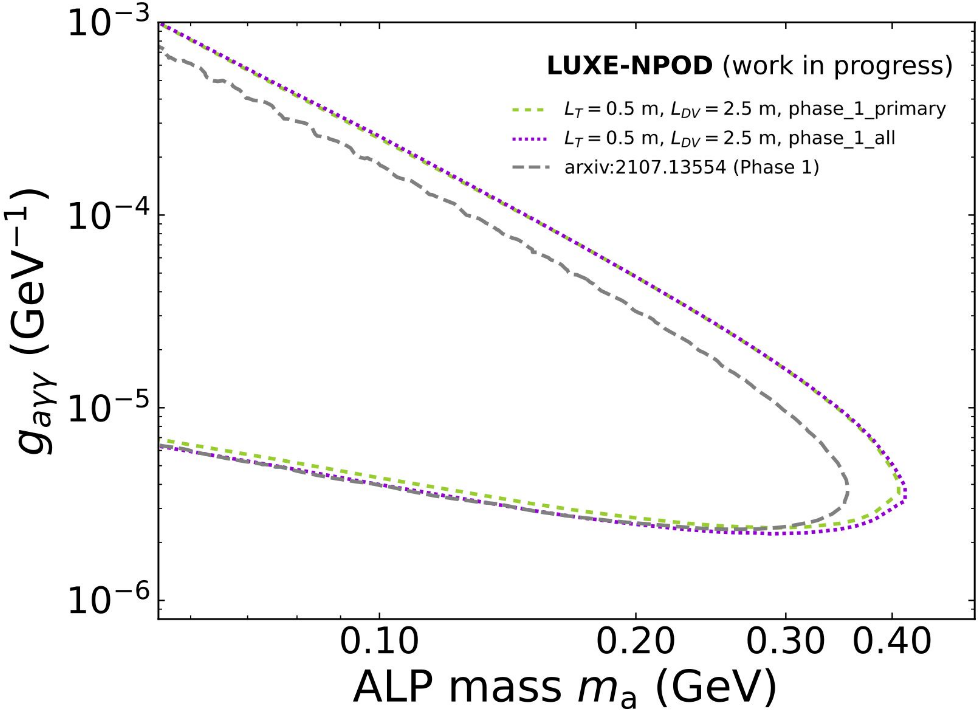
$$1/\omega_L << \tau_\gamma \lesssim t_L << \tau_{ee}$$

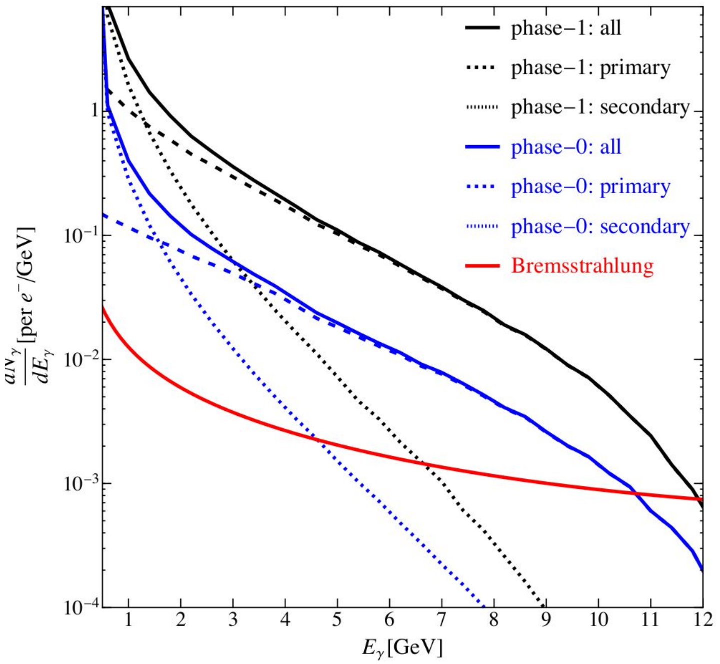
- Short τ_γ = plenty of time for electrons to produce photons → electrons see the laser as a thick target
- Long τ_{ee} = long timescale for a photon to produce electron pairs → photons see the laser as transparent

Expected Results in Phase 1: Primary vs All Photons

Torben Ferber

arXiv:2107.13554

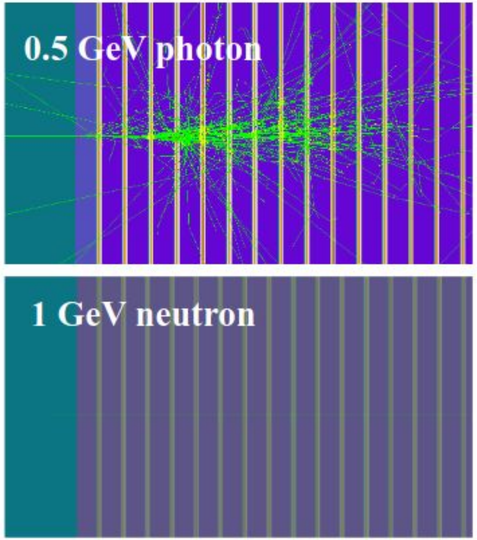




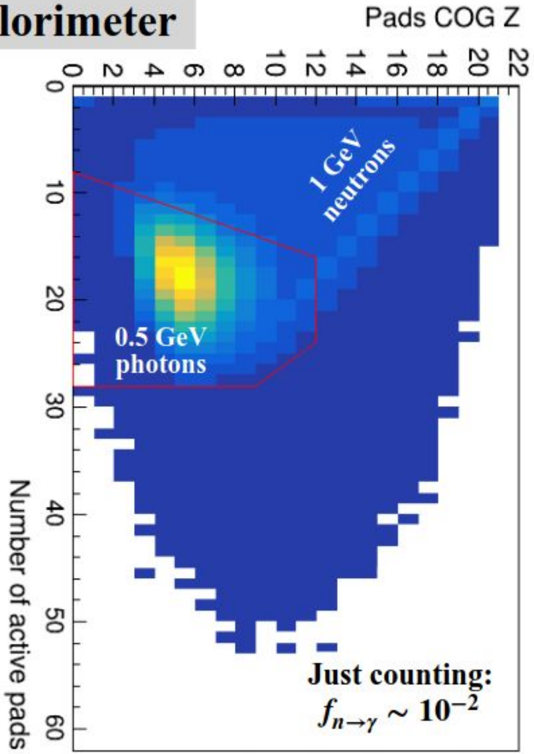
Fake photons from neutrons

- Most neutrons are very soft: one needs a few ~GeV neutron to fake a 0.5 GeV photon

sampling calorimeter



~20 layers of silicon sensors with $\sim 5\times 5$ mm^2 pads, between tungsten plates



- Very different shower shapes (γ vs n)
  - hard neutrons become more similar

- Study done by **Sasha Borysov**

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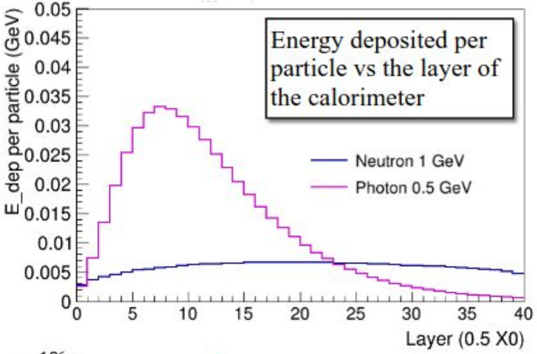
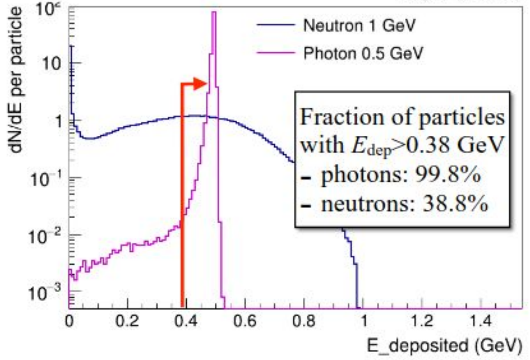
Lead Tungstate (PbWO4) calorimeter





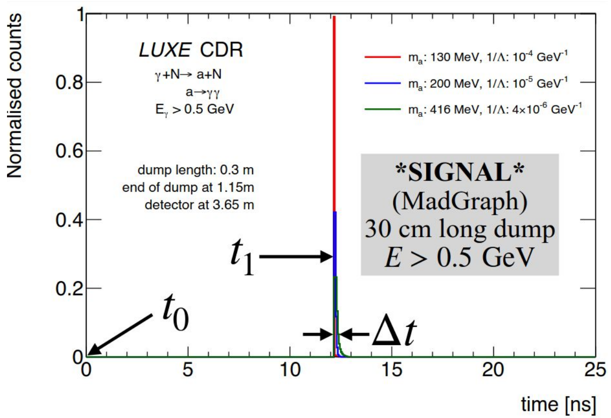
Background Rejection: Time of Arrival at the Detector

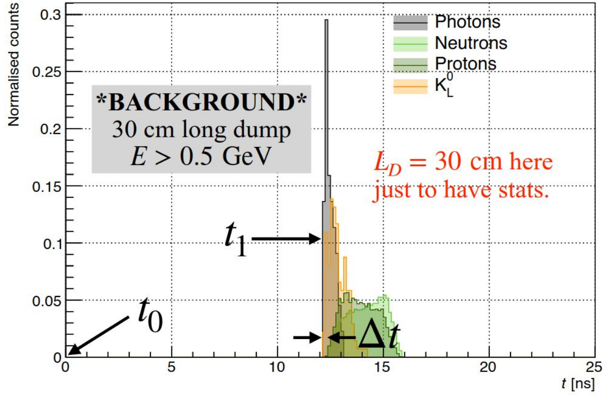
Noam Tal Hod

Particles have different velocities:

- Most signal (and bkg) photons arrive within Δt ~ 0.5 ns
- Almost all background hadrons arrive later
    - We need a time resolution of the order of $\sigma_t \sim 0.1$ ns

	Background rejection [%]				Signal efficiency [%] for m_a:$1/\Lambda_a$		
Δt [ns]	**γ**	**n**	**p**	**K_L**	**130:1e-4**	**200:e-5**	**416:e-5**
0.5	~16	~96	~94	~52	~99.9	~99.8	~95
1.0	~0	~80	~70	~13	100	~99.9	100



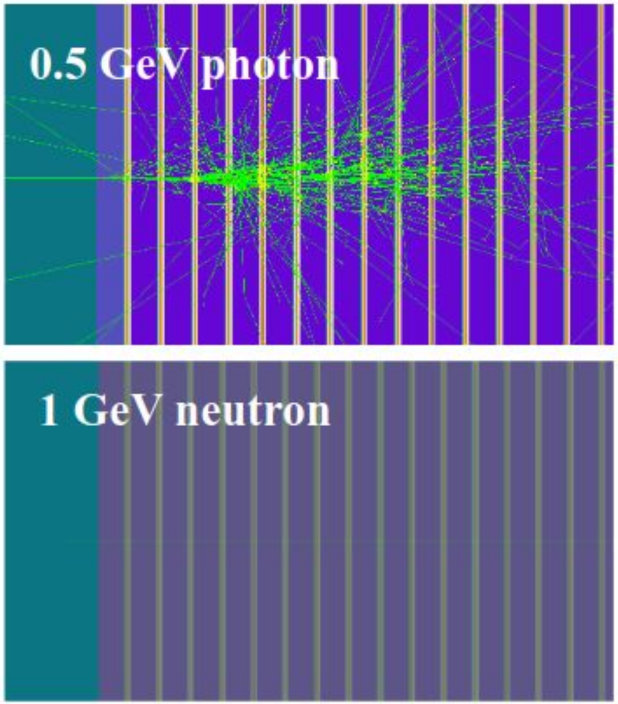


Background Rejection: Shower Shape

Noam Tal Hod

Neutrons can deposit energy in the calorimeter material, mimicking the signature of a photon

- In a sampling calorimeter, though, we expect different shower development
- This property can be used to discriminate neutrons from photons
  - Possible to create a neutron veto



Photons Separations at Detector Surface

m_X [MeV]	Λ_X [GeV^{-1}]	< 20 mm [%]	< 40 mm [%]	< 50 mm [%]
50	10^{-4}	13	30	38
100	10^{-5}	8.4	17	22
150	6×10^{-6}	5.2	11	13
200	4×10^{-6}	3.8	7.6	9.7