

Pseudoscalar portals into the dark sector

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New Physics at the Intensity Frontier

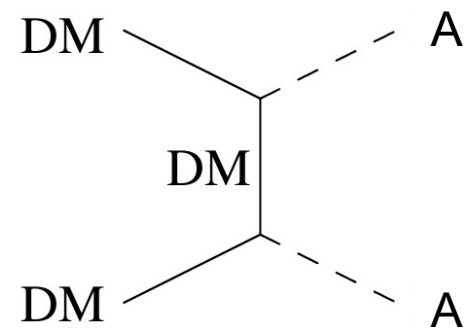
20 February – 3 March 2017

CERN

- Introduction: Pseudoscalars and portal interactions
- Bounds on pseudoscalar-fermion interactions
- Bounds on pseudoscalar-photon interactions
 - The relevance of proton beam dump experiments
 - Constraints on pseudoscalar portals from Primakoff production
 - Constraints from heavy-ion collision
- Conclusions and outlook

Why consider weakly-coupled light particles?

- Light particles may still remain to be discovered if they have very small interactions with SM particles – and thus with our experiments.
- Such new weakly-coupled light particles may have interesting implications for the phenomenology of Dark Matter (DM).
- Even if these particles themselves are unstable, they may act as the *mediator* for the interactions between the SM and the dark sector.
- Moreover, if the new state is lighter than DM ($m_A < m_\chi$) DM can directly annihilate into pairs of mediators, which subsequently decay into SM states.
- Requiring that the new state decays before BBN then places a lower bound on the coupling of the new state to SM particles.



The pseudoscalar portal

- An attractive and well-motivated example for such light and weakly-coupled new states are axions and axion-like particles (ALPs).
- ALPs naturally arise as pseudo-Goldstone bosons from spontaneously broken approximate global symmetries.
- The underlying symmetry protects their mass from receiving large corrections, while interactions with SM particles are typically suppressed by the large scale of spontaneous symmetry breaking.
- In particular, ALPs can couple to the SM via derivative interactions with fermions

$$\sum_{f=q,\ell} \frac{C_{Af}}{2f_A} \bar{f} \gamma^\mu \gamma^5 f \partial_\mu A$$

and dimension-5 couplings to gauge bosons

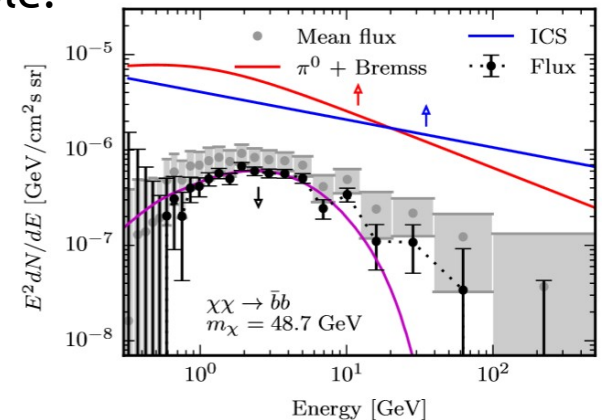
$$-\frac{1}{4} g_{\phi\gamma} \phi F^{\mu\nu} \tilde{F}_{\mu\nu} \quad g_{\phi\gamma} \sim \frac{\alpha}{2\pi f_A}$$

- We take the ALP mass as a free parameter, although in many models there is a common origin for the small mass and the weak couplings.



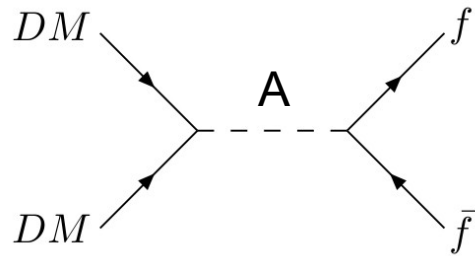
Pseudoscalars and dark matter

- Pseudoscalar mediators with $\mathcal{L}_{\text{DM}} = i g_\chi A \bar{\chi} \gamma^5 \chi$ (or analogous derivative interactions) are particularly attractive for dark matter phenomenology, because they predict a strong suppression of event rates in direct detection experiments.
- In the absence of strong constraints from direct detection experiments, a range of other interesting signals may be observable:
 - It is possible to obtain observable indirect detection signals and potentially explain the Fermi-LAT Galactic Centre gamma-ray excess.
 - Coy Dark Matter (Boehm et al., arXiv:1401.6458)
 - A light mediator offers the possibility to obtain large self-interactions in the dark sector and to explain the discrepancies between N -body simulations and the observations of small-scale structures.
 - Note: for pseudoscalar mediators self-scattering is suppressed in the same way as scattering off nucleons – very difficult to obtain sizeable self-interactions

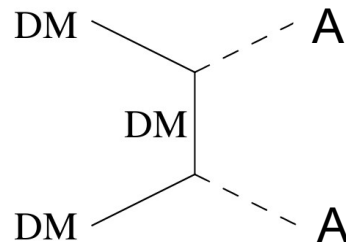


Dark matter annihilations

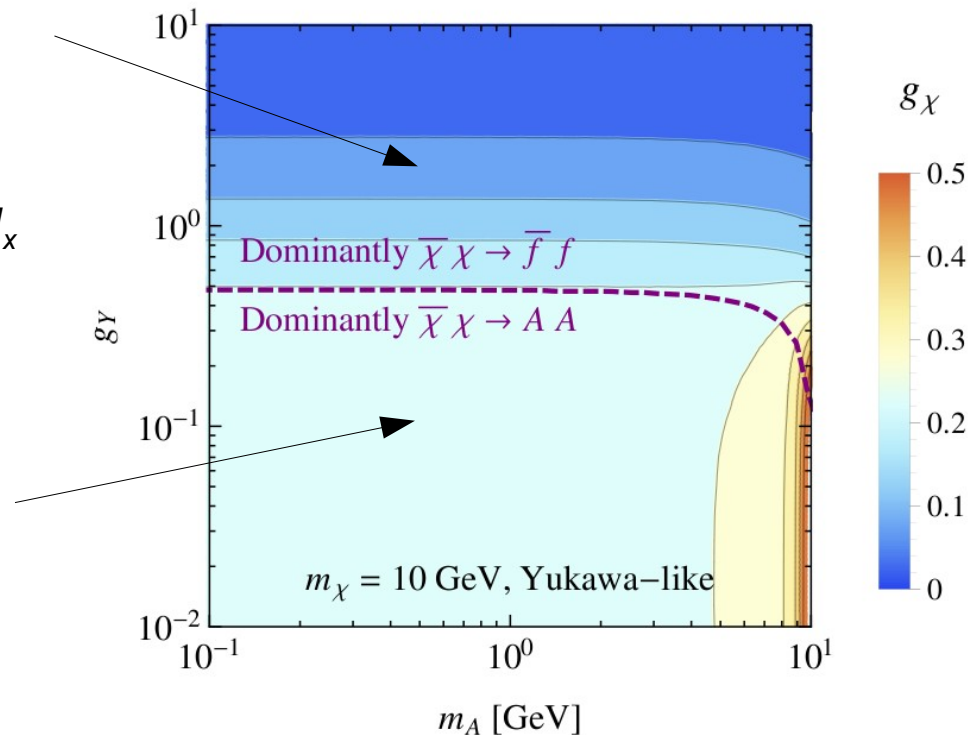
- Two processes can be relevant for the freeze-out of DM in the early Universe:



- depends on g_Y and g_X
- s-wave annihilation

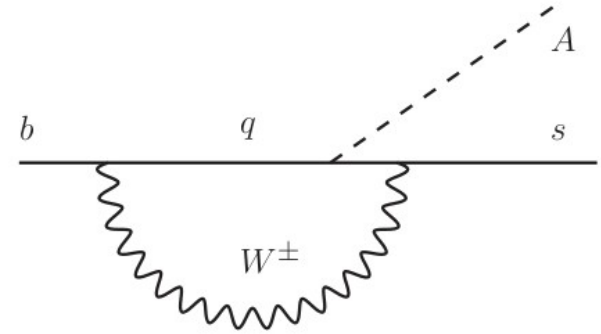
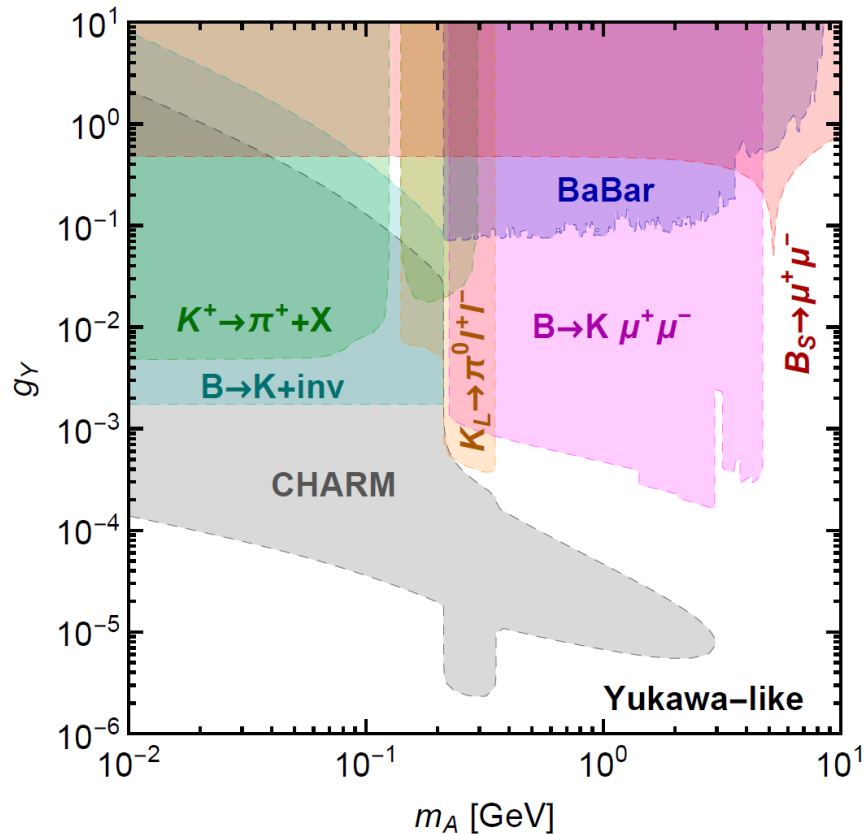


- depends only on g_X
- p-wave annihilation
- unobservable in indirect detection



Dark matter constraints

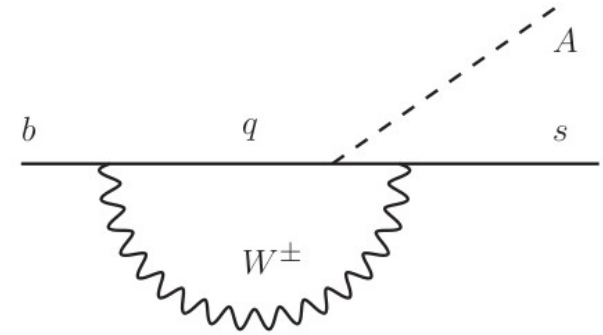
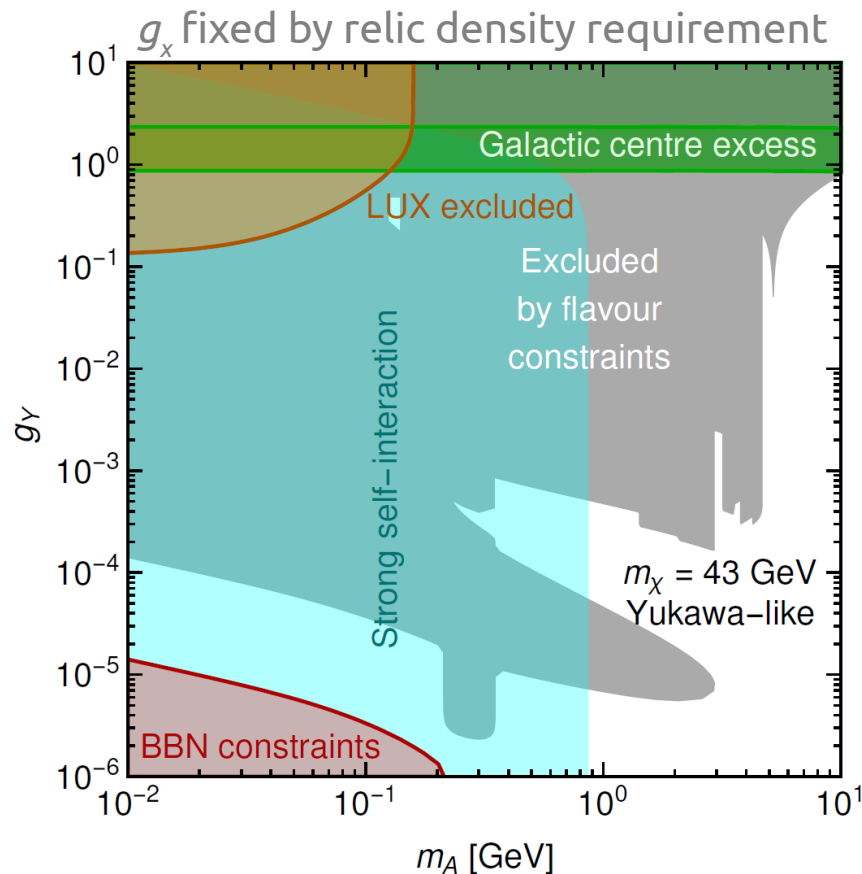
- The pseudoscalar-quark coupling g_Y is however tightly constrained by precision measurements of rare decays.



Dolan, FK et al., arXiv:1412.5174

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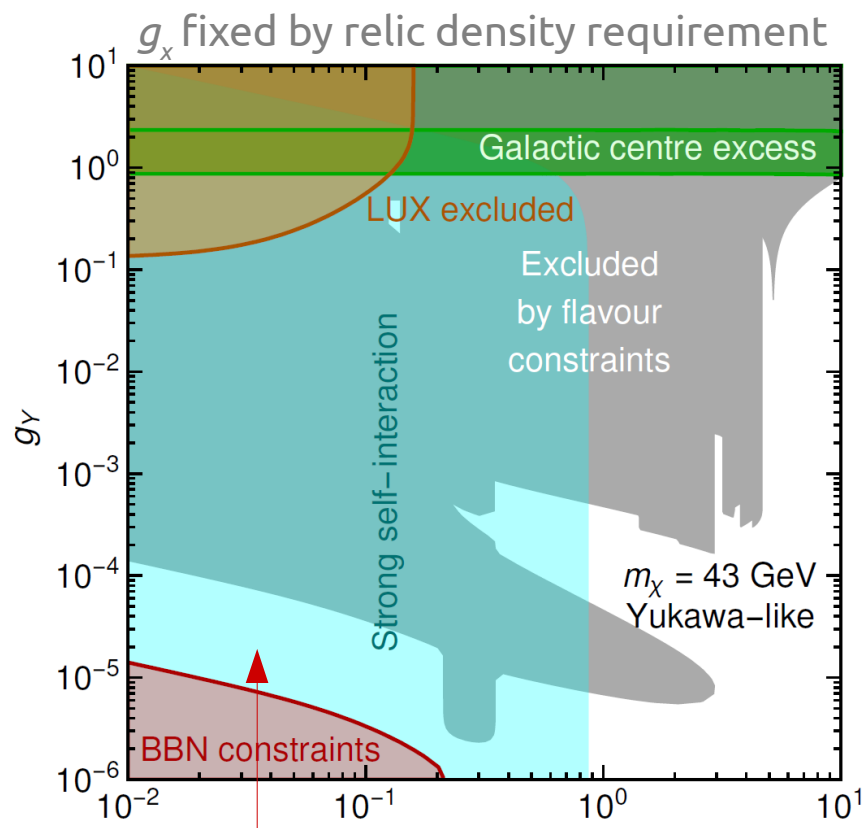


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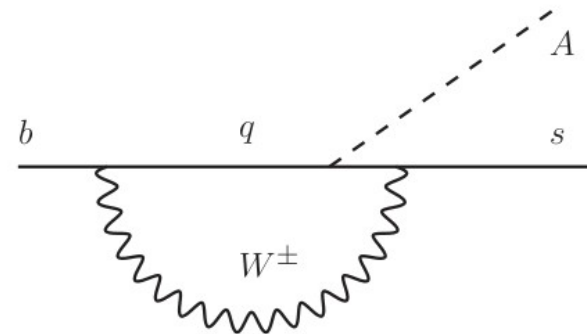
- For $m_A < 10 \text{ GeV}$, it is impossible to reproduce the relic abundance via the process $\text{DM DM} \rightarrow f\bar{f}$
- Annihilation into pseudoscalars must be dominant in the Early Universe.
- This raises the question which process causes the ALPs to decay before BBN.

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One possibility: m_A [GeV]
ALP-lepton coupling

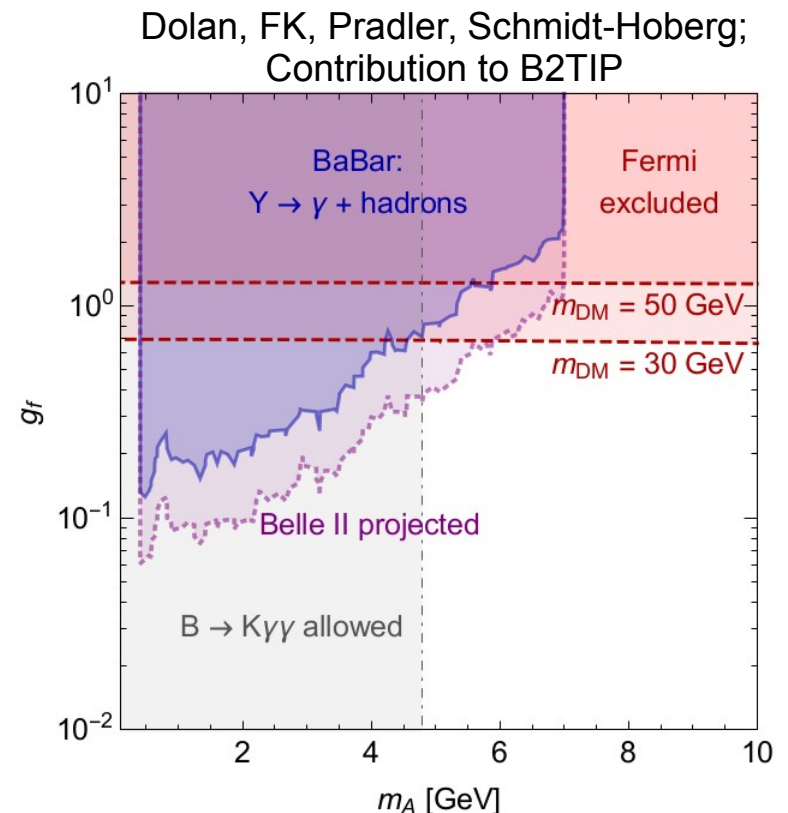


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Another possibility: leptophobic pseudoscalars

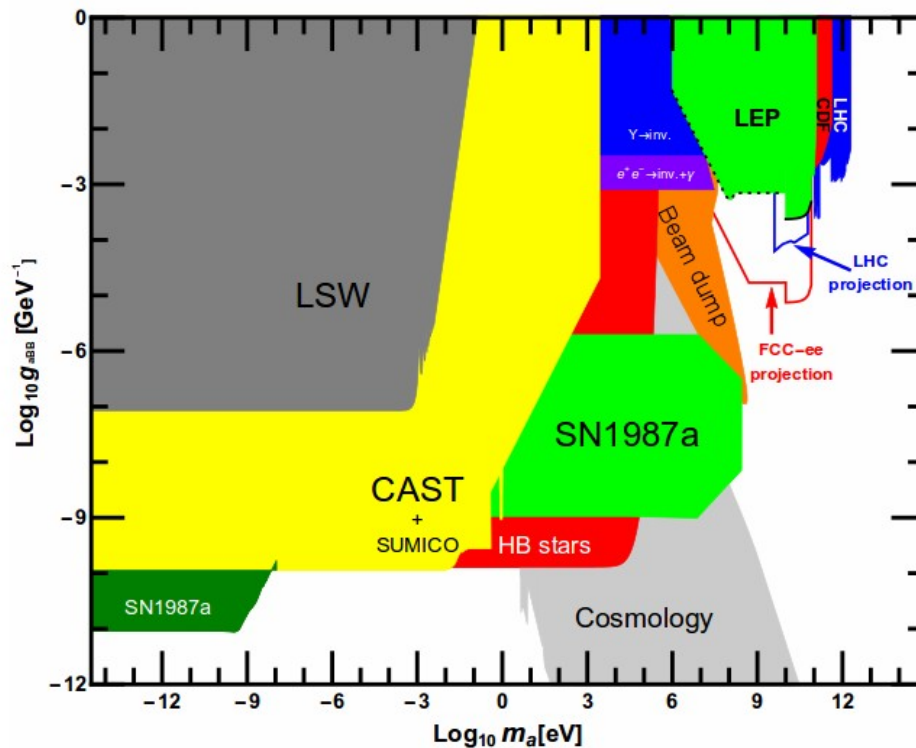
- Constraint from $B_s \rightarrow \mu\mu$ disappears
- Possible to have direct annihilation into SM fermions provided the pseudoscalar mass is sufficiently large that $B \rightarrow K\gamma\gamma$ is forbidden
- A possible way to test such a scenario: radiative Y decays
- Specifically, consider the decay $Y(2S) \rightarrow \gamma + A (\rightarrow \text{hadrons})$ and look for features in the distribution of the photon momentum.
- Strong constraints from BaBar, further improvements possible with Belle II



ALP-photon coupling

- The focus of this talk will be on the case where the interactions between ALPs and the Standard Model (and hence ALP decays) are dominated by the effective ALP-photon coupling

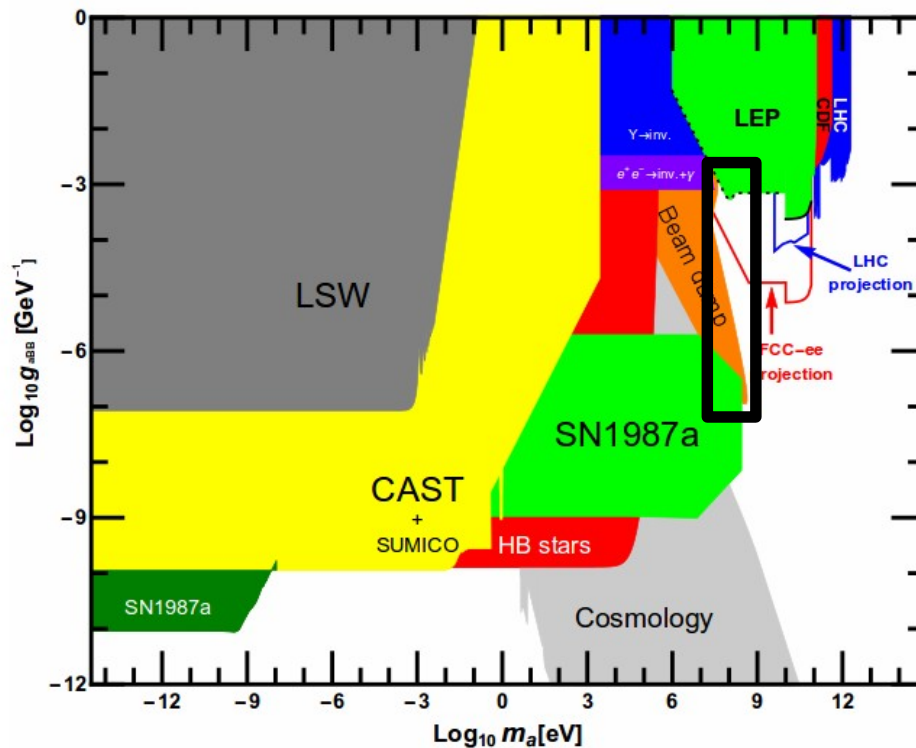
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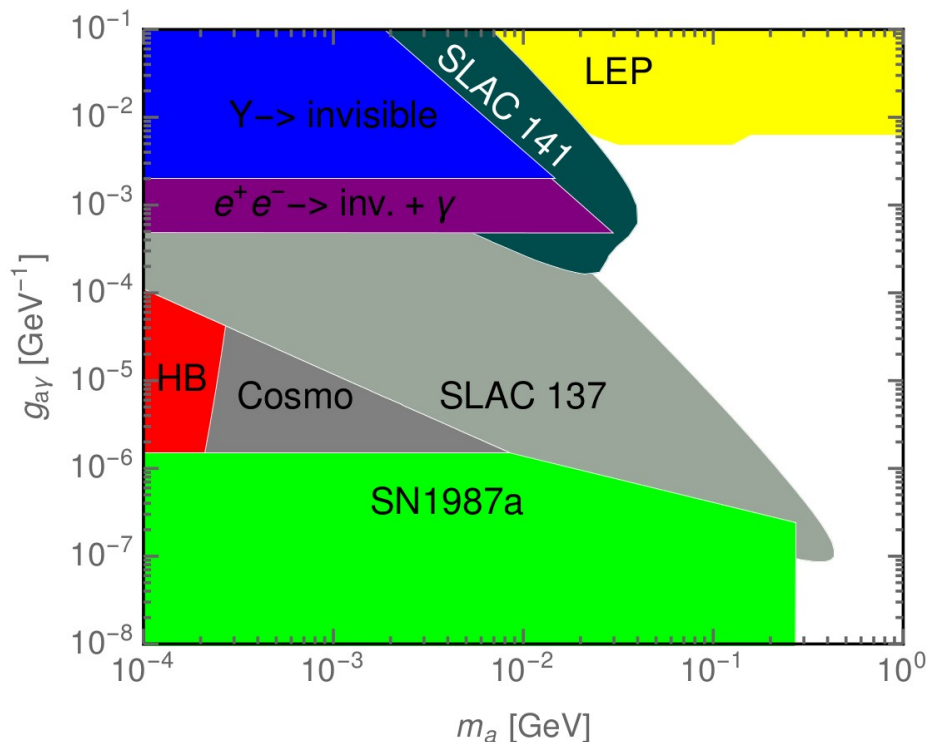
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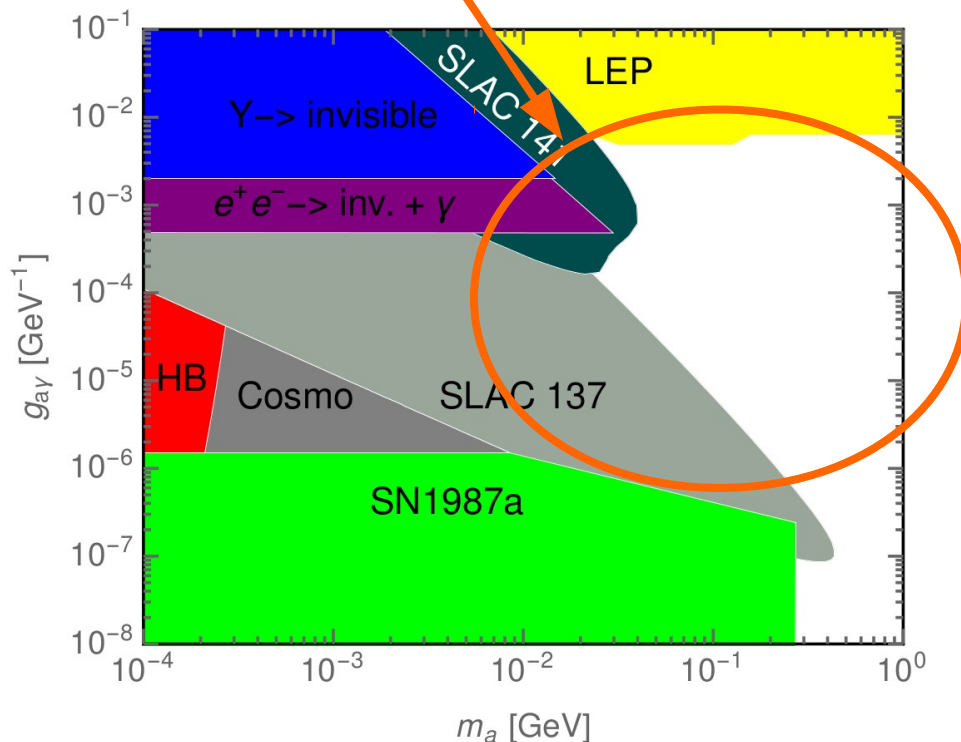


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Large unexplored parameter region for relatively heavy ALPs

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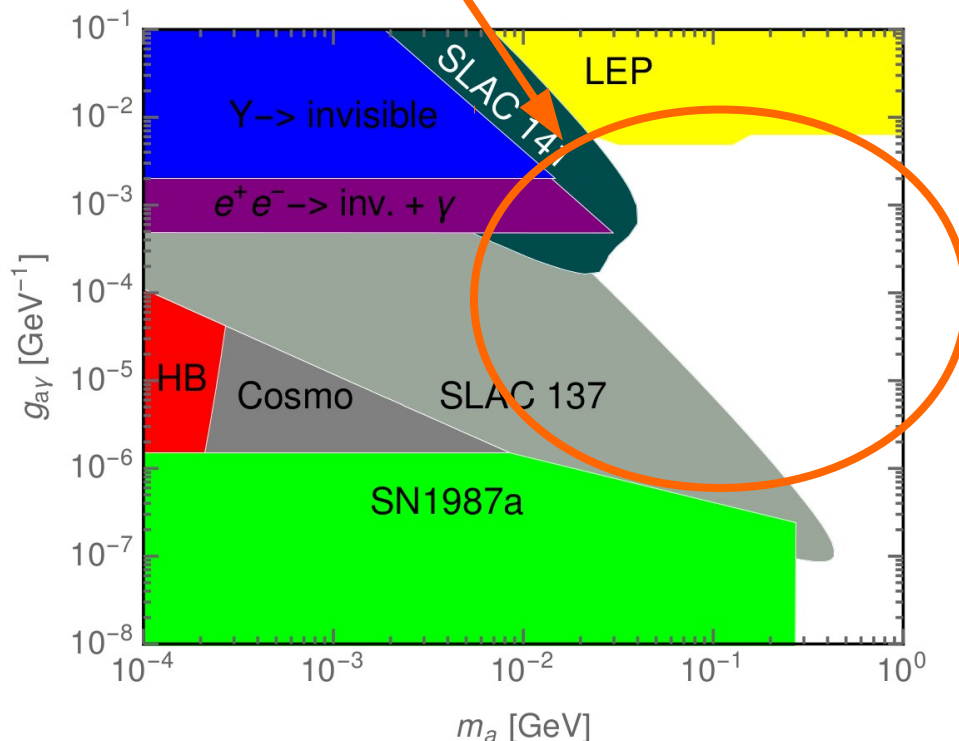


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The sensitivity of a given beam-dump experiment depends on:

- The production cross section for ALPs in the target.
- The probability for ALPs to travel through the absorber without decaying and then decay within the detector.
- This probability depends on the ALP decay length in the laboratory frame

$$l_a = \beta \gamma \tau \approx \frac{64\pi E_a}{g_{a\gamma}^2 m_a^4}$$

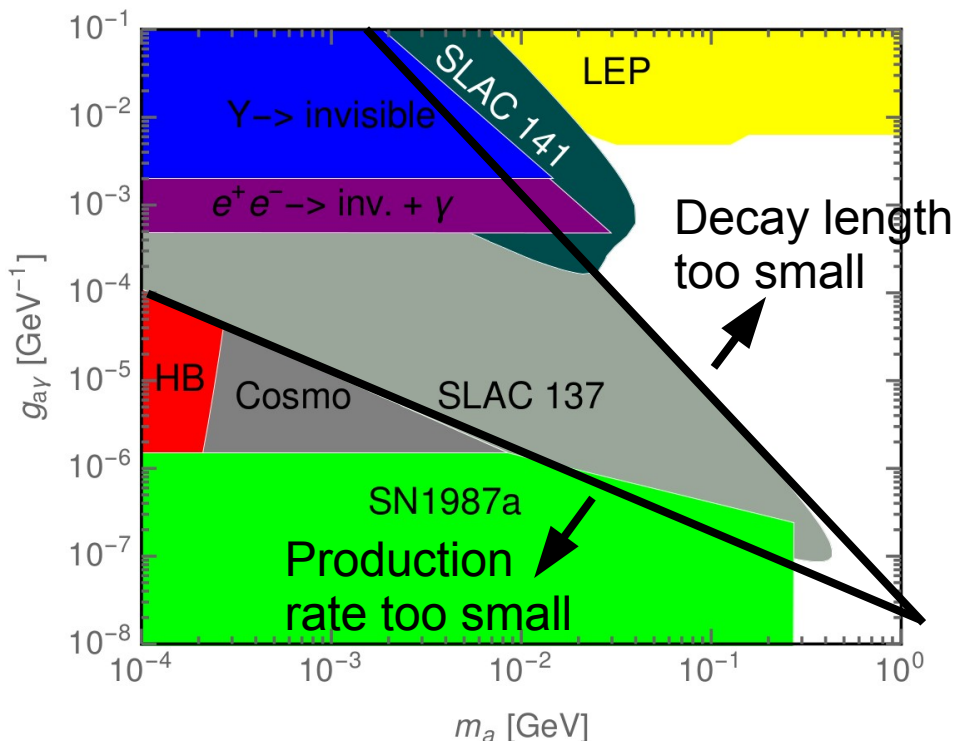


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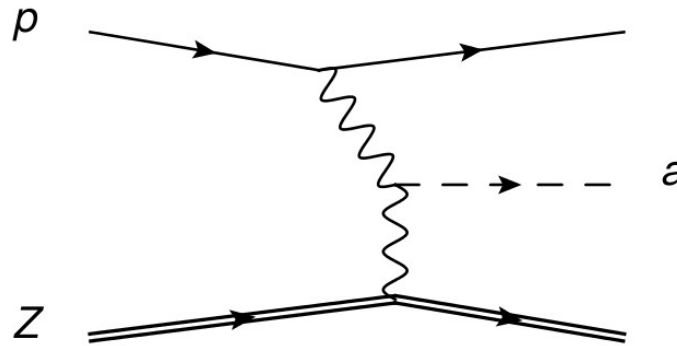
Proton beam-dump experiments

- For large couplings g_{Ay} the ALP production cross section is very large, but the ALP decay length is much smaller than the length of the absorber ($l_a \ll L$), so the number of observable ALP decays is exponentially suppressed.
- The most promising way to improve on existing bounds is to increase the beam energy, leading to larger ALP boost factors and hence larger decay lengths in the laboratory frame.
- Proton beam-dump experiments are the obvious choice for this purpose, as they combine a very high reaction rate with high centre-of-mass energy.
- However, proton beam-dumps are also complicated: In order to calculate experimental predictions, we have to deal with the composite nature of both the proton and the nucleus.



Primakoff production

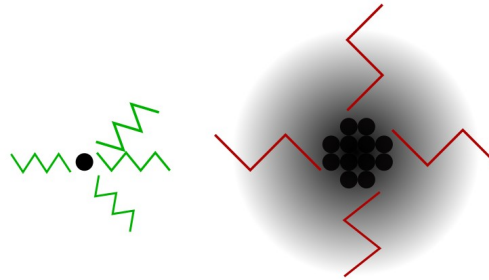
- Crucial observation: It is possible for GeV-scale ALPs to be produced from the fusion of two coherently emitted photons (Primakoff production).



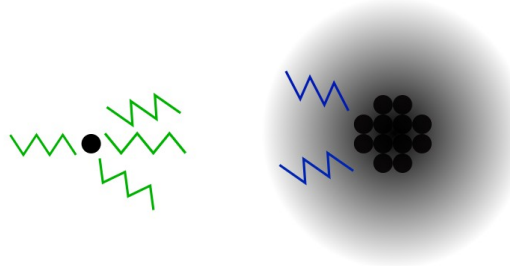
- Both the proton and the nucleus scatter elastically, so the interaction can be described using simple atomic form factors.
- Moreover, since the photon couples to the entire target nucleus, the ALP production cross section is enhanced proportional to Z^2 .
- Transverse momenta are very small, so cross sections are very strongly peaked in the forward direction.

How is this possible?

- > Both the proton and the ALP are surrounded by the virtual photons that make up the usual electric field of a charged particle.
- > In the respective rest frames, these photons are soft, i.e. they do not resolve the sub-structure of the proton/nucleus.



- > However, in the rest frame of the one particle, the photons emitted from the other particle are significantly blue-shifted.



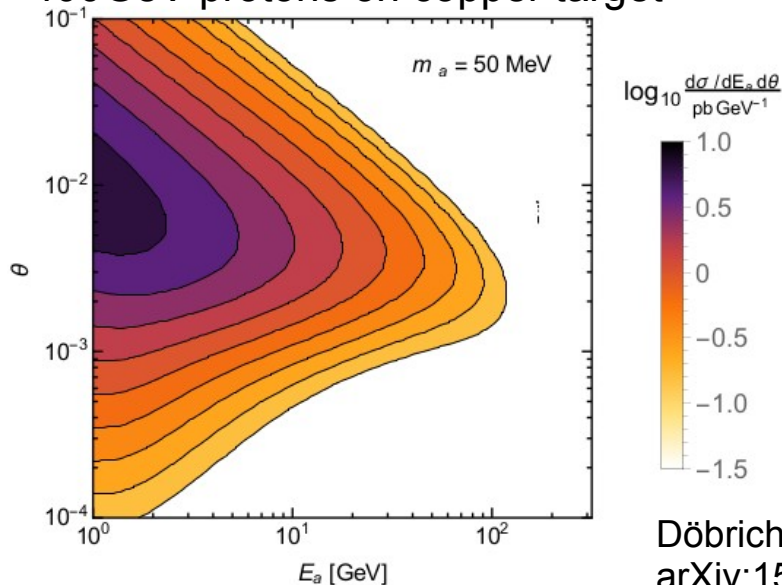
- > These photons provide enough energy to produce rather heavy ALPs.

ALP production cross section

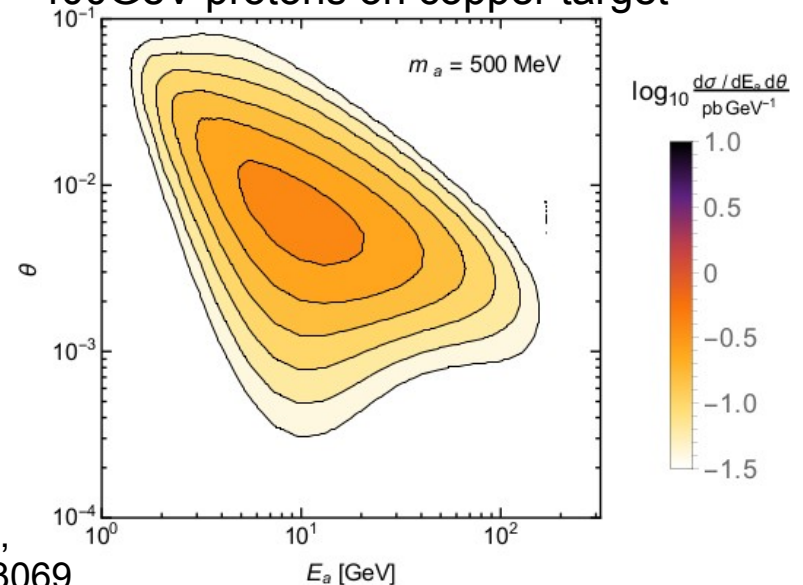
- We start from the Weizsaecker-Williams approximation to obtain an equivalent photon spectrum $\gamma(x)$.
- This formalism is then extended to include non-zero transverse momenta, which are necessary to calculate angular distributions.

$$\gamma(x, q_t^2) = \frac{\alpha}{2\pi} \frac{1 + (1-x)^2}{x} \left[\frac{q_t^2}{(q_t^2 + x^2 m^2)^2} D(q^2) + \frac{x^2}{2} C(q^2) \right]$$

400GeV protons on copper target

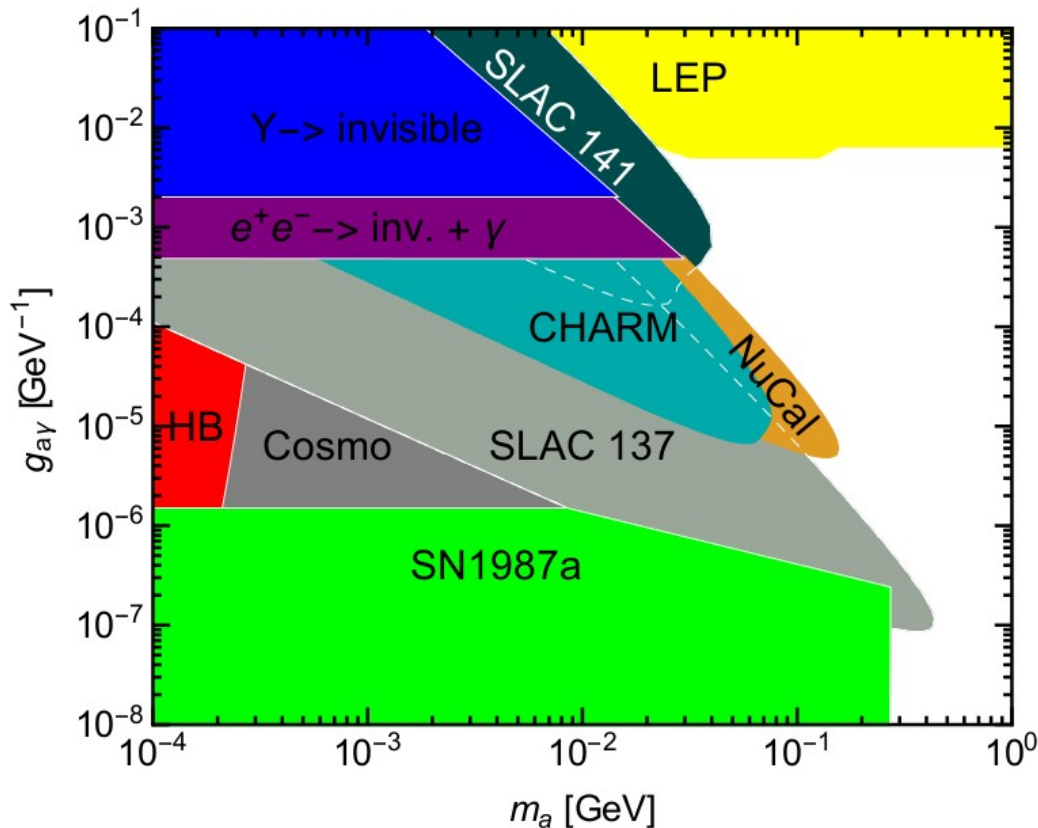
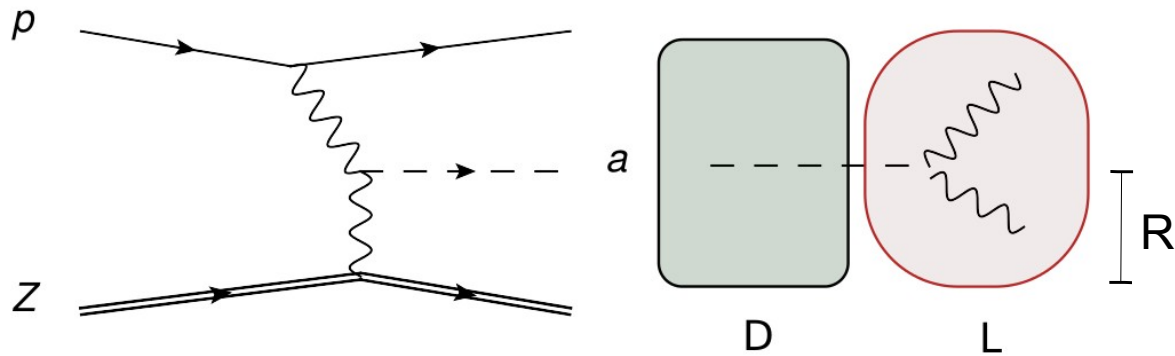


400GeV protons on copper target



Döbrich et al.,
arXiv:1512.03069

Existing constraints from past experiments



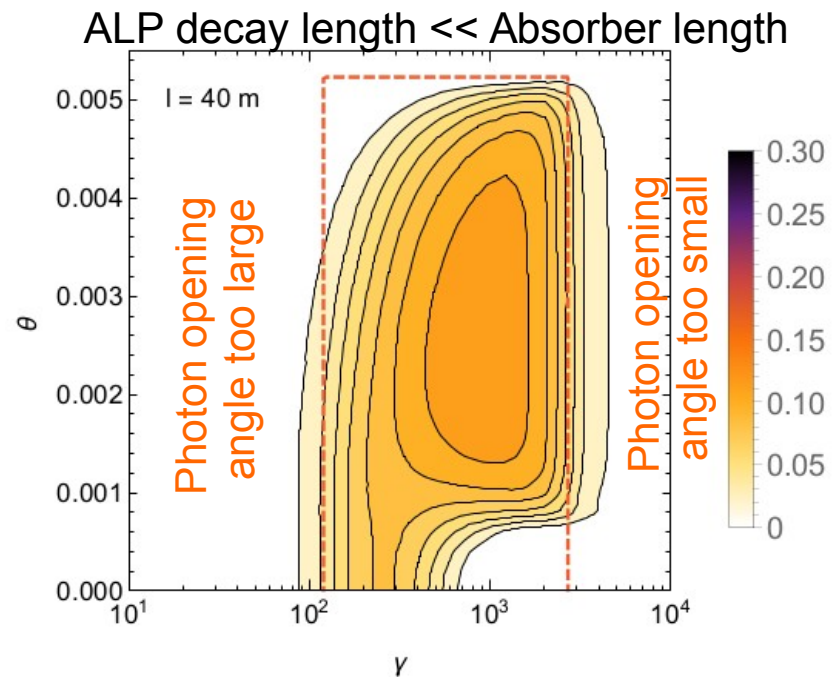
	CHARM	NuCal
E_{beam}	400 GeV	70 GeV
D	480 m	64 m
L	35 m	23 m
N_{pot}	2.4e18	1.7e18
Target	Copper	Iron
θ_{min}	7 mrad	0 mrad
θ_{max}	12 mrad	15 mrad

Döbrich et al.,
arXiv:1512.03069



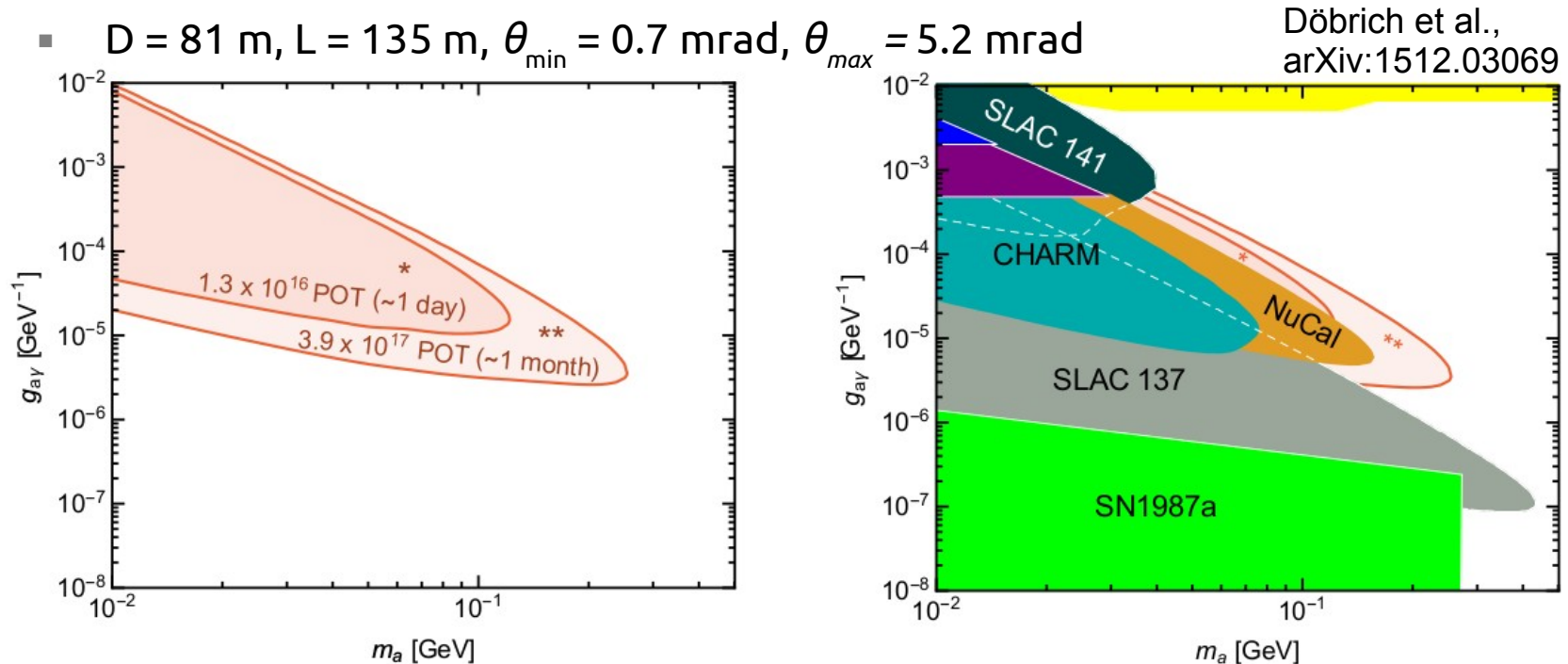
Probing further

- To extend the sensitivity further, we need new experiments
 - Higher beam energy (difficult)
 - Higher integrated intensity
 - Shorter absorber, longer decay volume
- However, all these modifications may lead to larger backgrounds.
- To isolate the ALP signal, we require that both photons produced in the ALP decay reach the detector (with sufficient separation).
- We calculate the resulting detector acceptance for such a signal from a toy Monte Carlo.



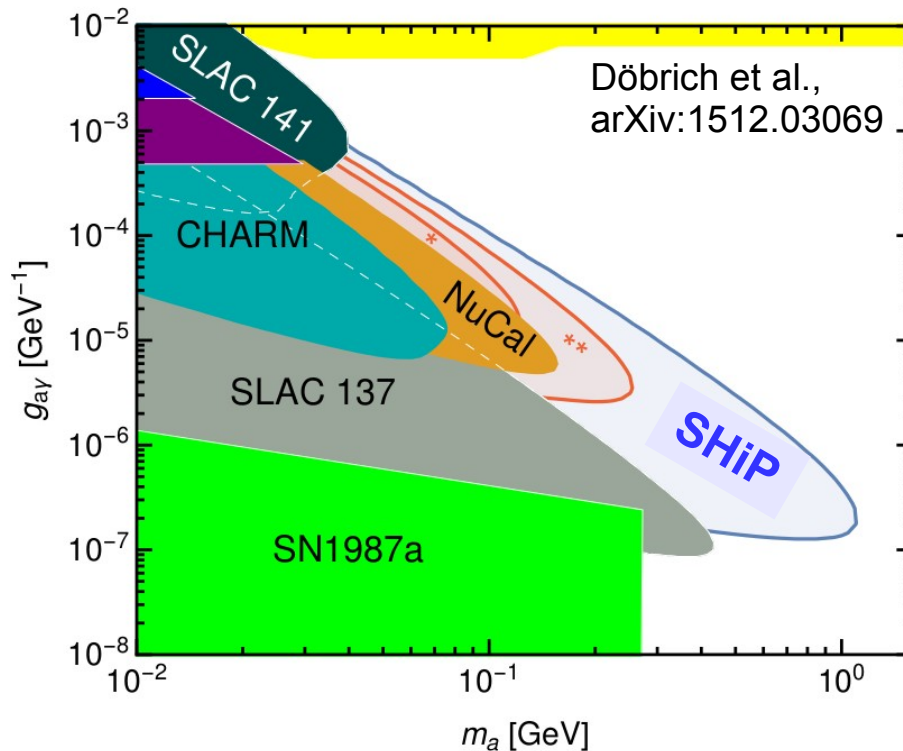
Example: NA62

- NA62 in beam-dump mode: 400 GeV protons on a copper target
- Excellent sensitivity to photons in Liquid Krypton Calorimeter (LKr)



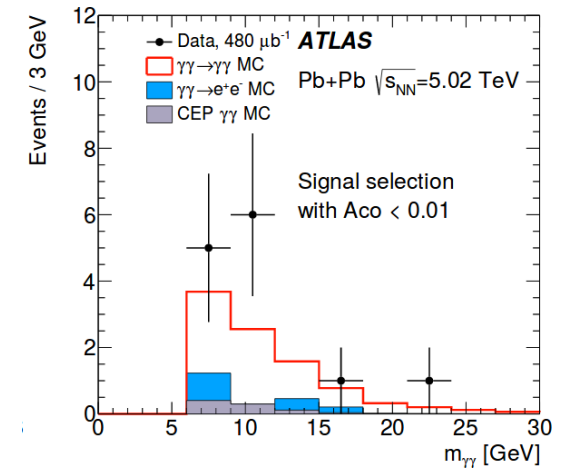
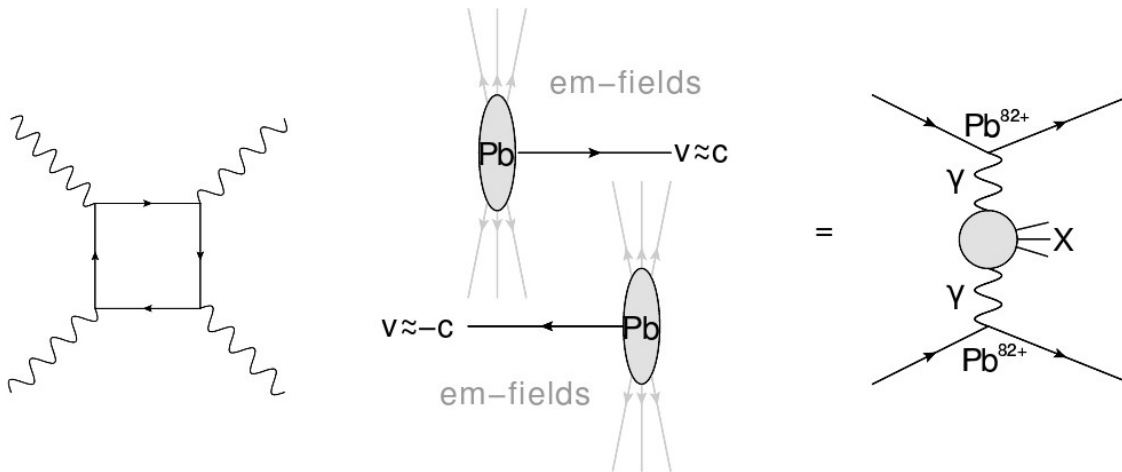
- NA62 can have about 1.3×10^{16} protons on target per day.
- This data-taking period would already be enough to probe new parameter regions!

- The proposed SHiP facility is optimised to search for hidden particles.
 - Up to 2×10^{20} protons with energy 400 GeV on a molybdenum target
 - $D = 70$ m, $L = 50$ m
 - $\theta_{max} = 20$ mrad (covers the peak of the ALP distribution)



The Swiss Fitzcarraldo:
Driving a Ship into the Alps

Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC



SPIEGEL ONLINE

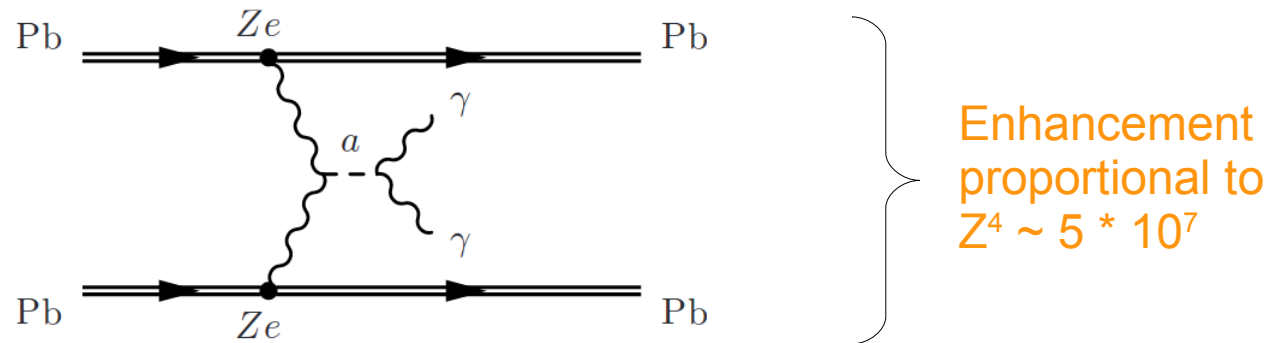
Extremes Experiment

Erstmals Kollision von Lichtteilchen beobachtet

Searching for axion-like particles with heavy-ion collision

- Can heavy-ion collisions be used to search for BSM physics?
- Yes! An axion-like particle in the 10–100 GeV mass range would appear as a resonance in the photon-photon invariant mass.

Knapen et al., arXiv:1607.06083



- One can again make use of the equivalent photon approximation to calculate the photon luminosity.
- New tool to include form factors and transverse momenta: STARlight

Klein et al., arXiv:1607.03838

Today's discovery is tomorrow's background

- Crucial observation: ALPs are produced almost exactly at rest

- The two photons are back-to-back:

$$|\Delta\phi - \pi| < 0.04$$

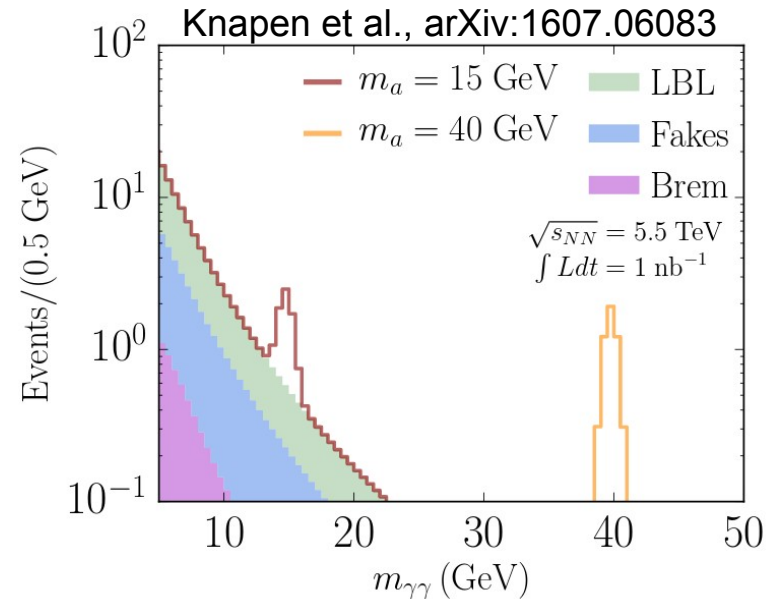
- Very little total transverse momentum:

$$|\vec{p}_{T\gamma_1} + \vec{p}_{T\gamma_2}| < 0.2 \text{ GeV}$$

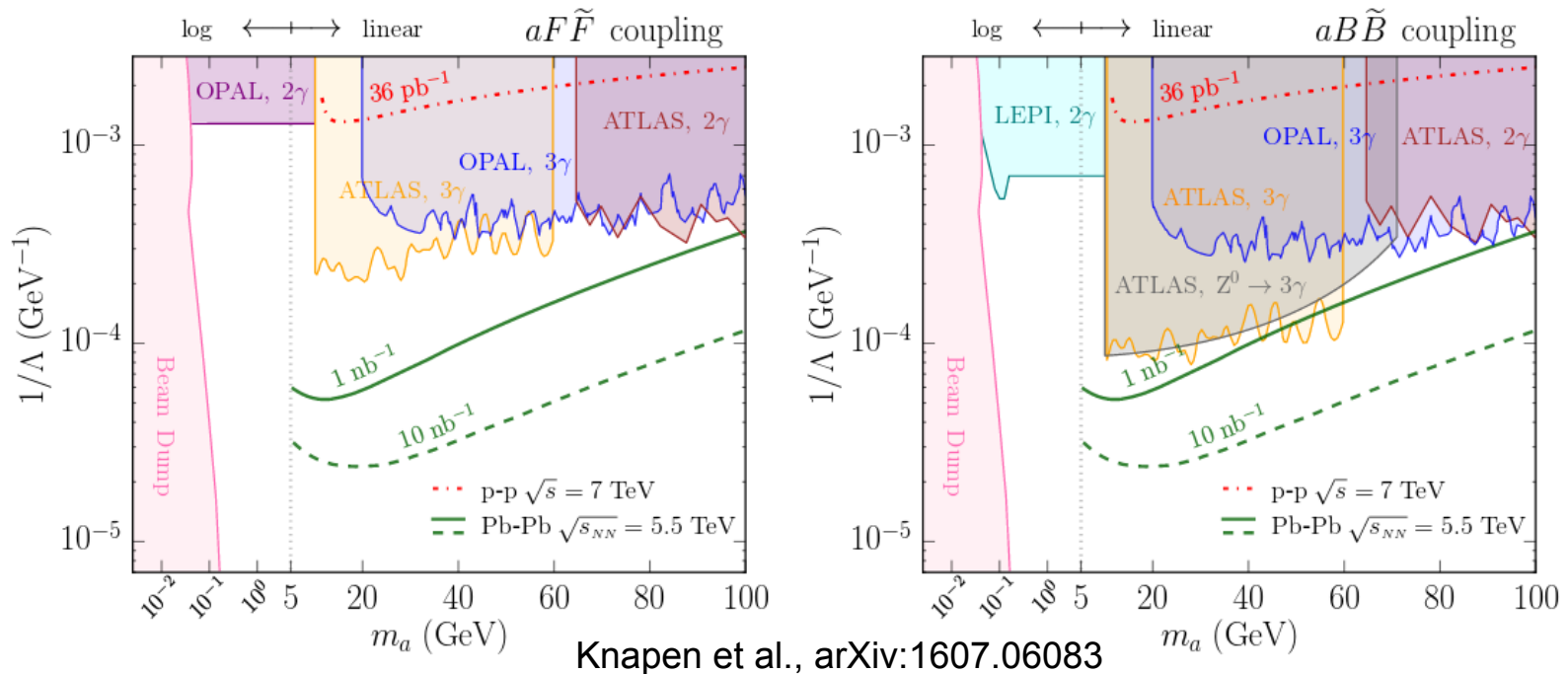
- Irreducible background from

- Light-by-light scattering
- Hadronic processes (e.g. $\pi^0\pi^0$ production)
- Bremsstrahlung

- Reducible background from electron misidentification



Expected sensitivity



- Search limited to $m_a > 5$ GeV due to photon trigger with $p_T > 2$ GeV.
- Optimum sensitivity for 10–20 GeV: Sensitive to $\Lambda \sim 10^4 - 10^5$ GeV.
- For higher masses: limited by photon luminosity

Final comment

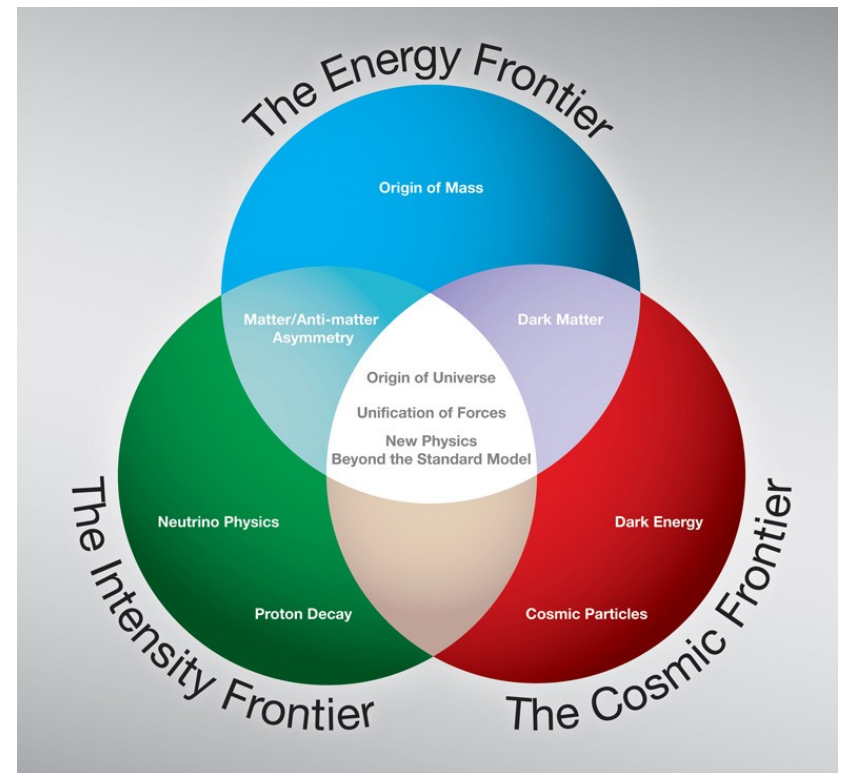
- $\Lambda \sim 10^4 - 10^5$ GeV is not a very large number!
- Coupling to photons is only induced at the loop-level, so really the vertex should be written as $\alpha / (4\pi\Lambda)$, requiring $\Lambda < 100$ GeV.
- For related model-building issues, consult your favourite paper on the 750 GeV diphoton ~~excess~~ disappointment.



A. Strumia

Conclusions

- Low-mass BSM physics can potentially be probed with existing and near-future experiments with comparably low effort, providing a complementary window to what is covered by high-energy accelerators.
- ALPs (i.e. pseudoscalar mediators) coupling the visible and dark sectors are interesting from model-building and phenomenological perspectives.
- ALP-fermion couplings are strongly constrained by measurements of rare decays and flavour-changing processes.
- ALP-photon couplings can be tested with beam-dump experiments and heavy ion collisions.



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Thanks!

