Searches for axion-like particles at the intensity frontier

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BSM in direct, indirect and tabletop experiments
Weizmann Institute of Science, Israel
7 November 2017

Based on
and **arXiv:1709.00009** with Matthew J. Dolan, Torben Ferber, Christopher Hearty and Kai Schmidt-Hoberg

Emmy Noether-Programm
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Probing self-interacting WIMPs with low-threshold direct detection experiments

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The small-scale crisis of LCDM

- There are various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales:
  - Too-big-to-fail problem

    Boylan-Kolchin, Bullock, Kaplinghat: 1103.0007, 1111.2048
  - Missing-satellites problem

    Klypin et al.: astro-ph/9901240; Moore et al.: astro-ph/9907411
  - Cusp-vs-core problem

    Moore (1994); Flores, Primack: astro-ph/9402004
  - Diversity problem

    Tulin & Yu: arXiv:1705.02358

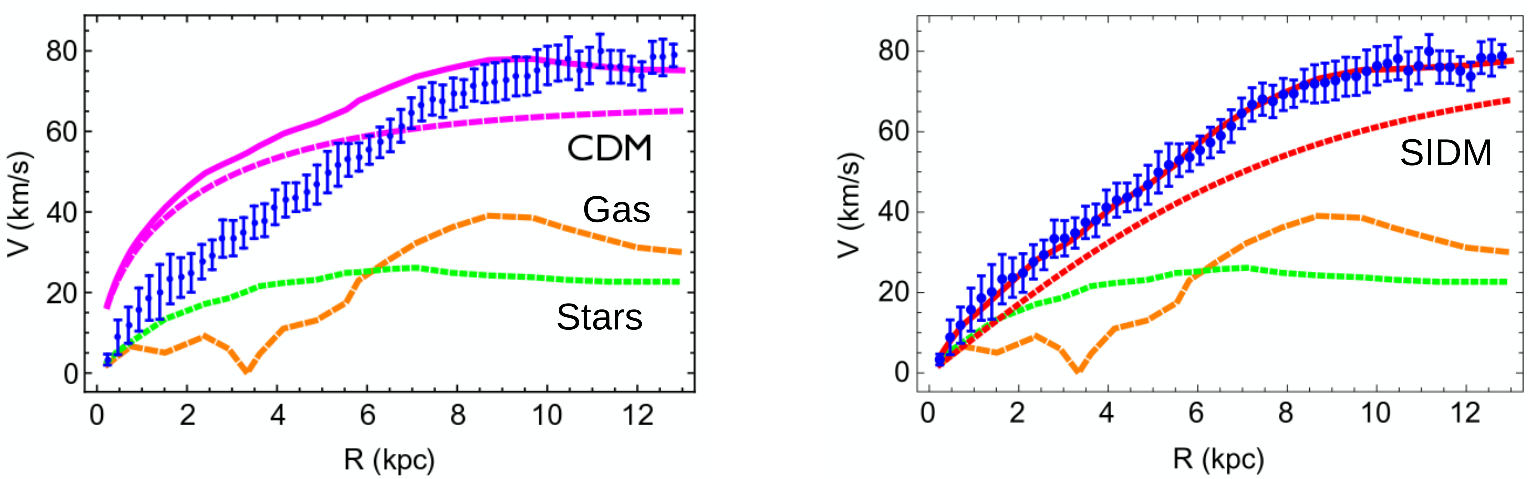
- The observational situation concerning the “small-scale crisis” is not yet clear
- Even if fully established, it remains unclear whether baryonic feedback can equally provide an explanation for missing satellites and cored dwarf galaxies

Self-interacting dark matter

- It is nevertheless intriguing that DM self-interactions may solve these problems.

  Spergel & Steinhard: astro-ph/9909386

  - Basic idea: In the central regions of DM halos, self-interactions can be sufficiently frequent to allow for energy transfer between DM particles.
  - This energy transfer will heat up DM particles that sit deep in the gravitational potential and create an isothermal core.



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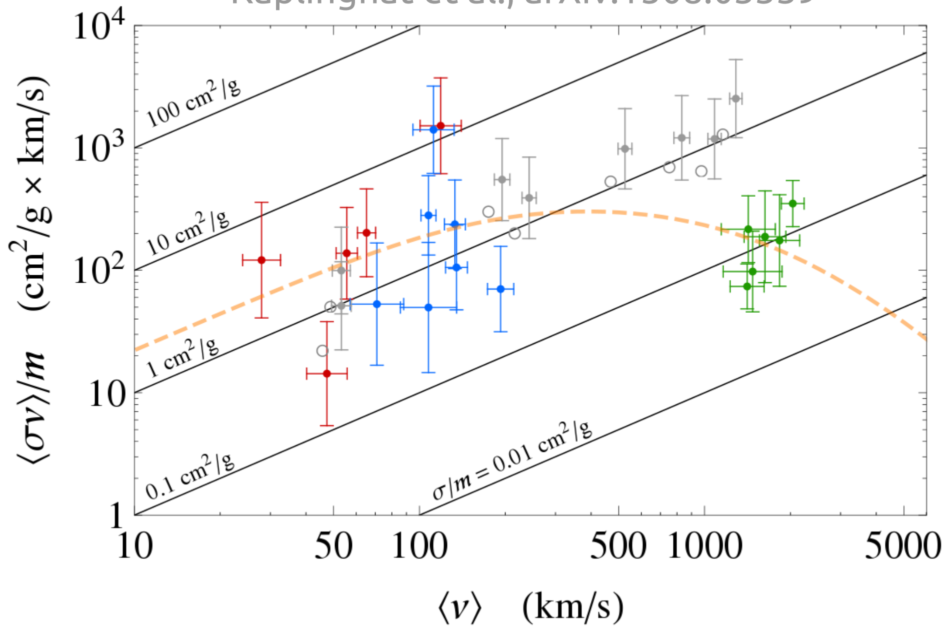
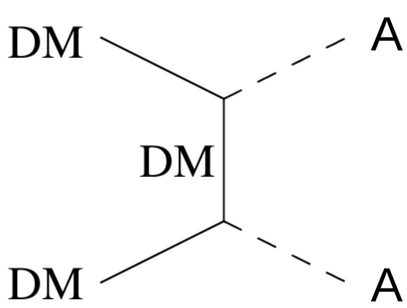
  - Moreover, sub-halos moving through a bigger DM halo will also heat up and potentially evaporate.

Self-interacting WIMPs

- Observations require larger self-interactions on dwarf galaxy scales than on cluster scales.
- Solution: Self-interactions from the exchange of a light mediator.
- Scattering with large momentum transfer is suppressed.

Kaplinghat et al., arXiv:1508.03339



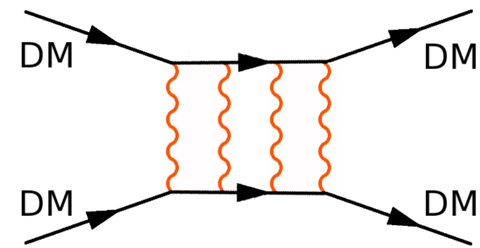


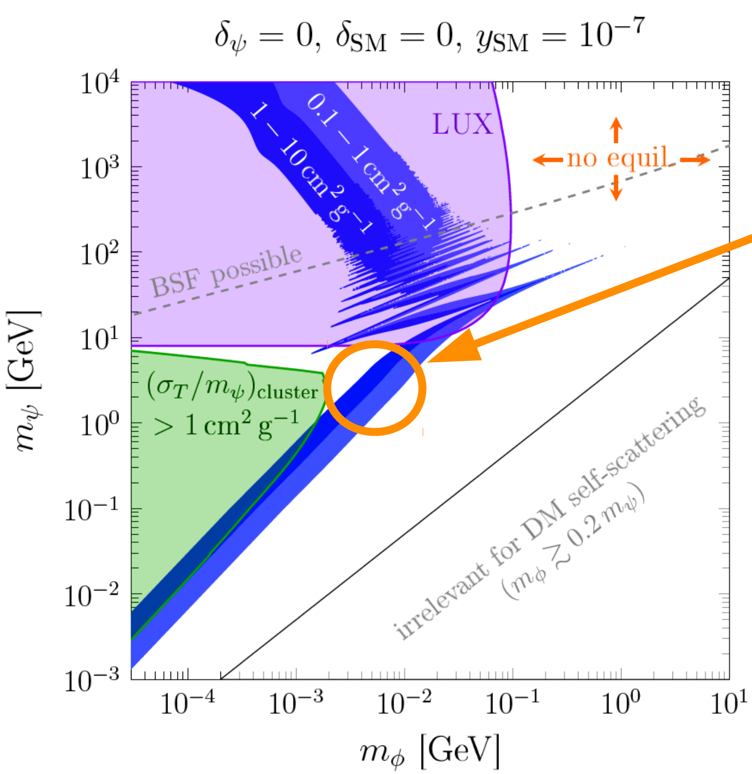
- The DM particle can obtain its relic abundance via annihilations into pairs of mediators (dark sector freeze-out).
- Self-interacting WIMPs!

Probing self-interacting WIMPs

- DM self-interactions are enhanced by non-perturbative effects (multiple mediator exchange).

Feng, Kaplinghat, Yu: arXiv:0905.3039
Buckley & Fox: arXiv:0911.3898
Loeb & Weiner: arXiv:1011.6374



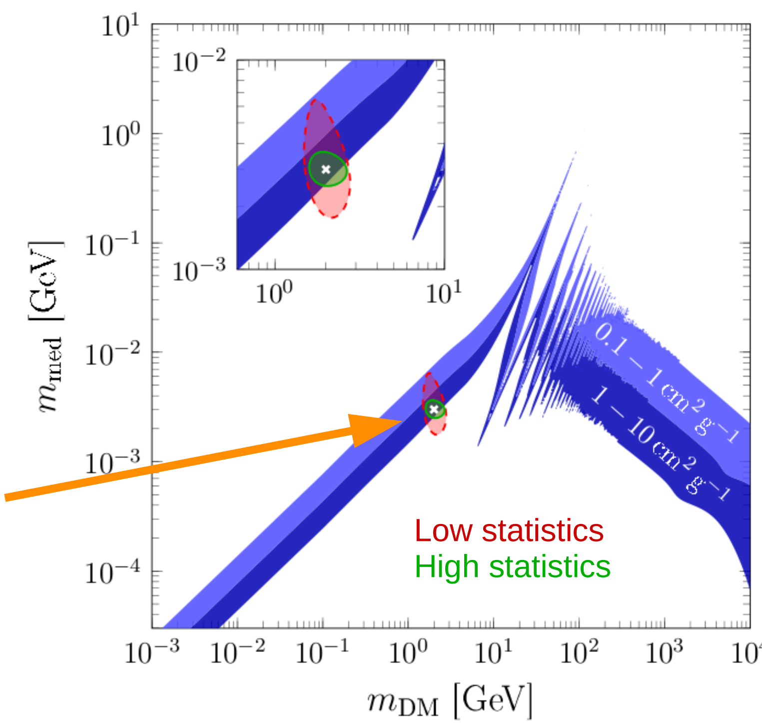


FK et al., arXiv:1704.02149.

Allowed parameter space!*

* Possible tension with BBN due to long-lived mediators.

Can be probed with future low-threshold direct detection experiments!



FK et al., arXiv:1707.08571

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No (convincing) signal in spite of spectacular improvements in sensitivity

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Solution 1

DM is lighter and/or much more weakly interacting than usually assumed (axions, sterile neutrinos, FIMPs, ...)

- Try different strategies of DM direct detection
  - Lower thresholds
  - Electron scattering
  - Axion haloscopes

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Solution 2

DM decouples from ordinary matter in the non-relativistic limit (momentum-suppressed interactions)

- Direct detection inefficient
- Need to produce (relativistic) DM particles in order to obtain observable signals

Theory motivation

- Momentum-suppressed interactions are a generic prediction if DM interacts via a pseudoscalar mediator (i.e. axions or axion-like particles)

- Such pseudoscalar mediators arise from the spontaneous breaking of an (approximate) global symmetry (so-called Goldstone bosons)

- Axions and axion-like particles (ALPs) occur in many SM extensions
  - Solutions to the strong CP problem — Weinberg (1978), Wilzcek (1978)
  - String compactifications — Arvanitaki et al., arXiv:0905.4720, Cicoli et al., arXiv:1206.0819,
  - Supersymmetry breaking — Bellazzini et al., arXiv:1702.02152
  - Relaxion mechanism — Graham et al., arXiv:1504.07551, Flacke et al., arXiv:1610.02025

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Renewed interest for axions in the MeV range

- Axion mass generated in a hidden sector ("dark QCD")

  Agrawal & Howe, arXiv:1710.04213; Hook, arXiv:1411.3325; Fukuda et al., arXiv:1504.06084

- Axion-pion mixing suppressed by accidental cancellations

  Alves & Weiner, arXiv:1710.03764

ALPs coupled to gauge bosons

- Let's focus on the following interactions:

$$\mathcal{L} = \frac{1}{2}\partial^\mu a\,\partial_\mu a - \frac{1}{2}m_a^2\,a^2 - \frac{c_B}{4\,f_a}\,a\,B^{\mu\nu}\tilde{B}_{\mu\nu} - \frac{c_W}{4\,f_a}\,a\,W^{i,\mu\nu}\tilde{W}^i_{\mu\nu}$$

- Such interactions arise e.g. from new heavy non-coloured fermions
- After electroweak symmetry breaking, this becomes

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4}aF_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4}aZ_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4}aW_{\mu\nu}\tilde{W}^{\mu\nu}$$

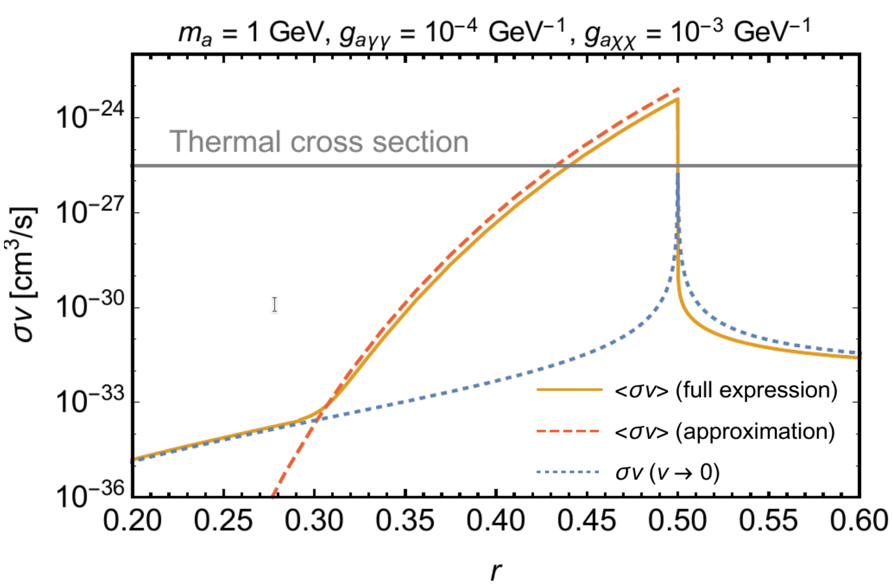
- Two interesting cases:
  - $c_B \sim c_W$: $g_{a\gamma Z} << g_{a\gamma\gamma}$ (photon couplings)
  - $c_B >> c_W$: $g_{a\gamma Z} \sim - g_{a\gamma\gamma}$ (hypercharge couplings)

ALPs and dark matter

- In addition to the couplings to gauge bosons, ALPs can also couple to dark matter:

$$\mathcal{L}_{\mathrm{DM}} = g_{a\chi\chi}\,\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\,\partial_{\mu}a$$

- Crucially, such derivative couplings are suppressed in the non-relativistic limit
  - No tension with direct detection experiments

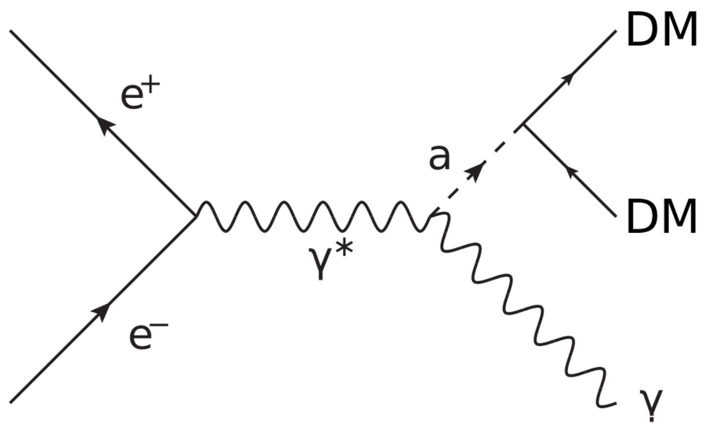


- Observed DM relic density can be reproduced if annihilations in the early Universe are resonantly enhanced
- For $r = m_\chi / m_a \sim 0.5$ this requires approximately $g_{a\gamma\gamma} \sim (10^{-5} - 10^{-4})$ GeV^{-1}
- Can we test such couplings in the laboratory?

Dolan, FK et al., arXiv:1709.00009

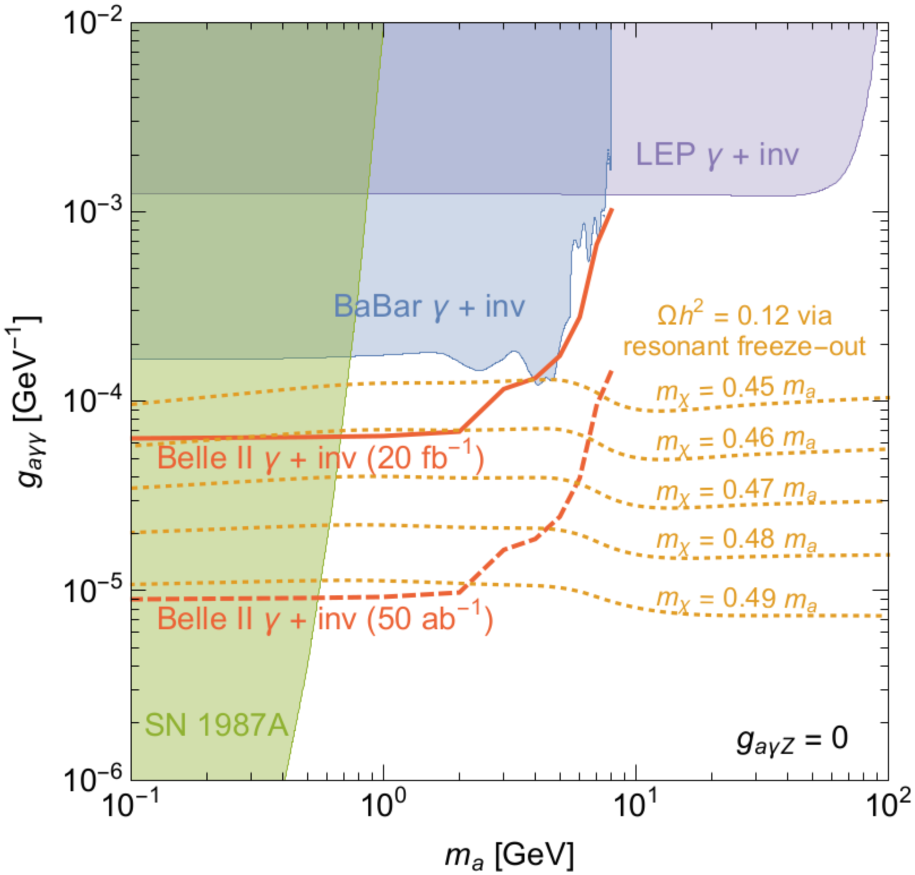
Single-photon searches at e^+e^- colliders

- For invisibly decaying ALPs a promising experimental signature is obtained if the ALP is emitted from a SM gauge boson
- One then obtains a high-p_T photon in association with missing energy.
- This signature has been searches for (e.g. in the context of hidden photons) at LEP and BaBar



- Significant improvements of sensitivity expected for Belle II.
  - Integrated luminosity of up to 50 ab^{-1} with a trigger on $E_\gamma >$ 1.8 GeV.
  - Dominant background from QED processes with undetected photons
  - Depends sensitively on detector geometry, which will be improved significantly in Belle II (more homogeneous calorimeter)

Belle II sensitivity for invisibly decaying ALPs



- LEP bound from a reanalysis of a mono-photon search at DELPHI
- BaBar bound from a reanalysis of a search for hidden photons

BaBar collaboration, arXiv:1702.03327

- SN 1987A bound from the length of the neutrino signal (bound on exotic energy loss mechanisms)

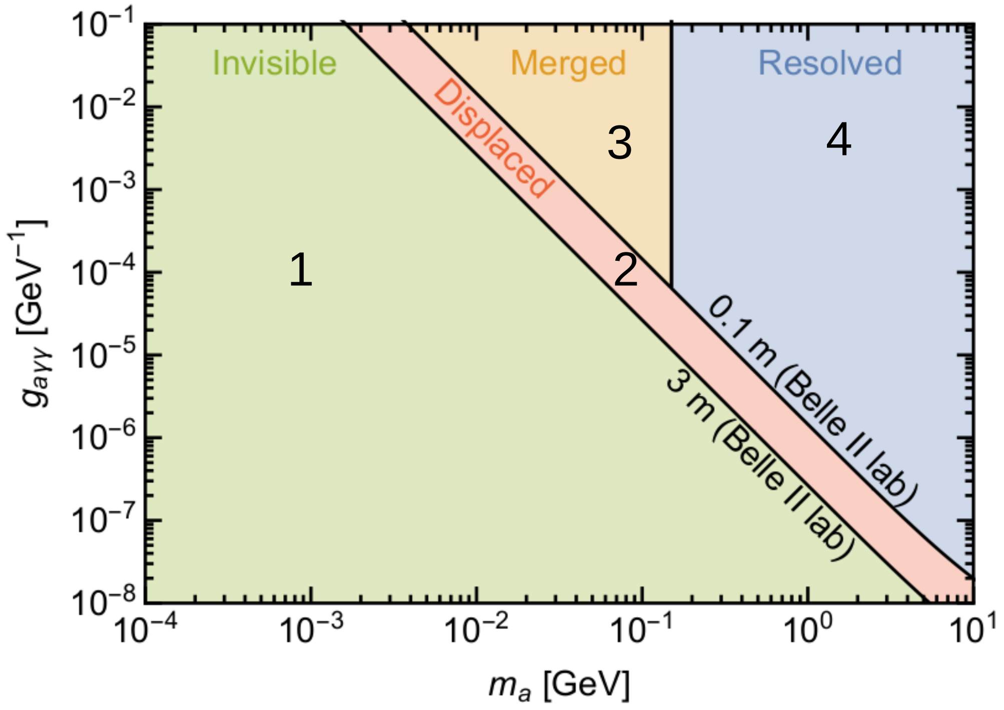
Jaeckel et al., arXiv:1702.02964

- Belle II has a unique potential to probe the parameter regions of particular interest

What about visibly decaying ALPs?

- The answer depends on the ALP decay length relative to the size of the detector

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

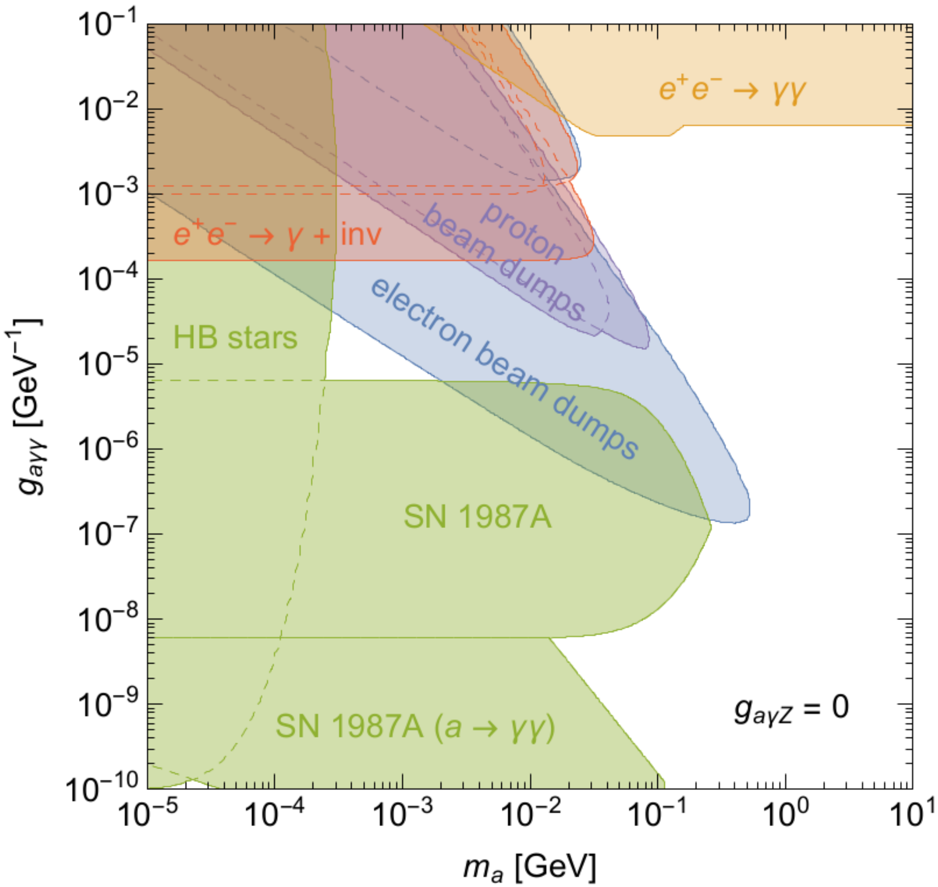


1) Small masses, small couplings
   - ALPs escape from the detector
   - Apparent missing energy
2) Medium masses, small couplings
   - ALPs decay from a displaced vertex
3) Medium masses, large couplings
   - Prompt decays, merged decay products
4) Large masses, large couplings
   - Prompt decays, resolved decay products

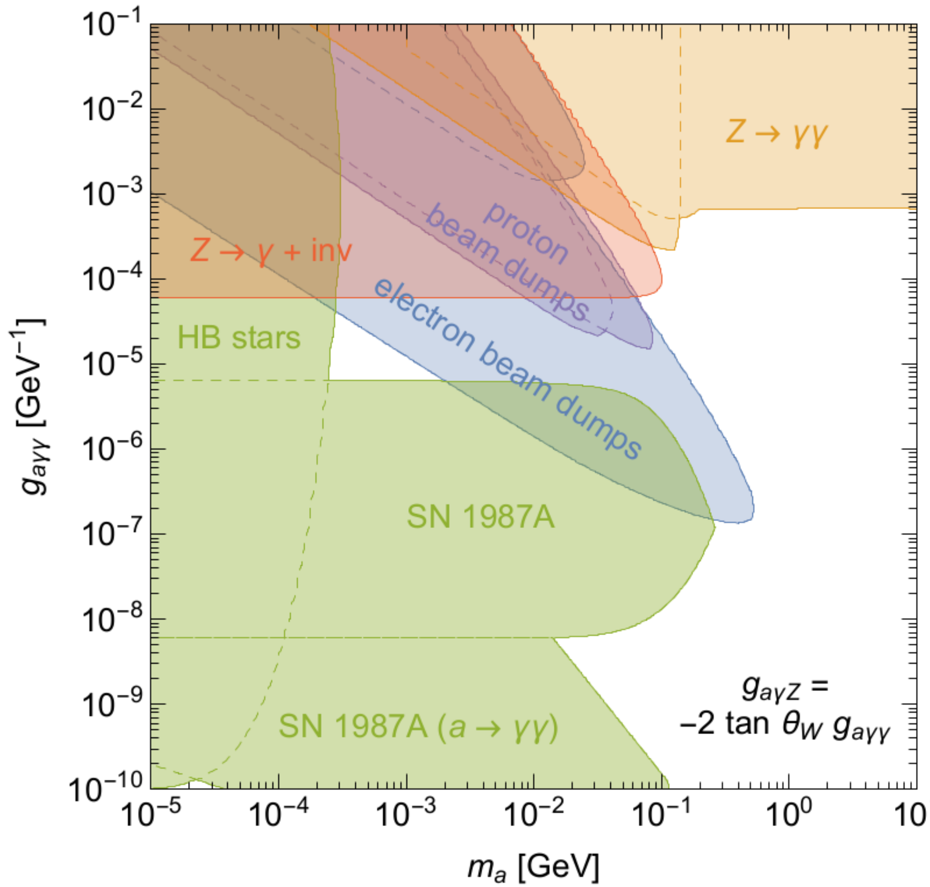
Existing constraints

(These plots update the constraints from Masso & Toldra, arXiv:hep-ph/9503293, arXiv:hep-ph/9702275)

ALPs coupling to photons

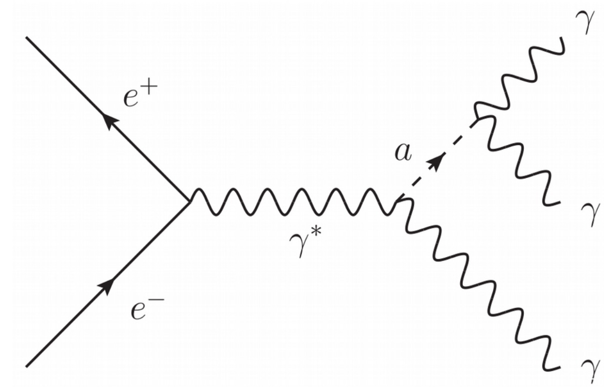


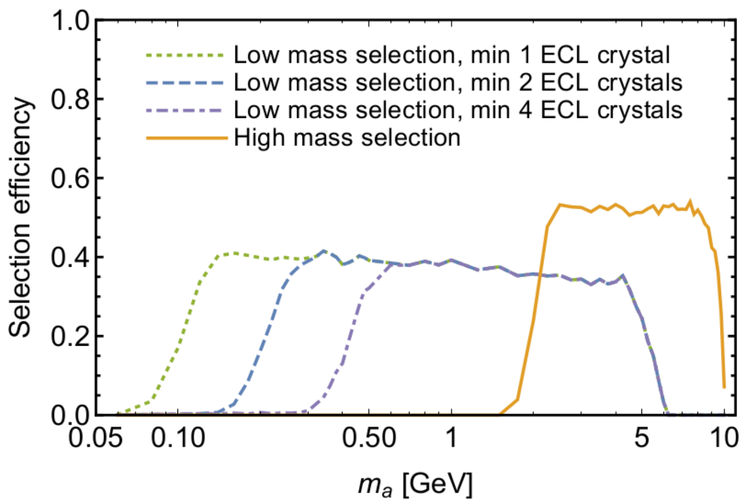
ALPs coupling to hypercharge



Belle II sensitivity for visibly decaying ALPs

- Belle II ideally suited for exploring resolved regime (all three photons reconstructed)



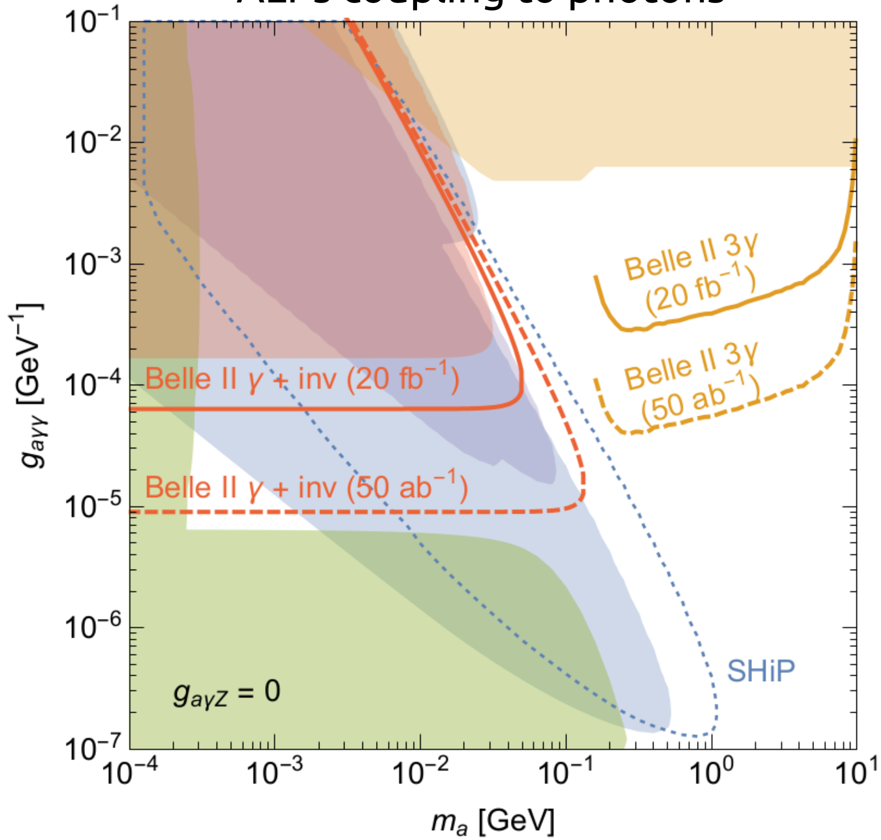


- To resolve the two photons from the ALP decay, we require a separation of at least two crystal in the electromagnetic calorimeter
- This yields a good selection efficiency for ALP masses above 200 MeV

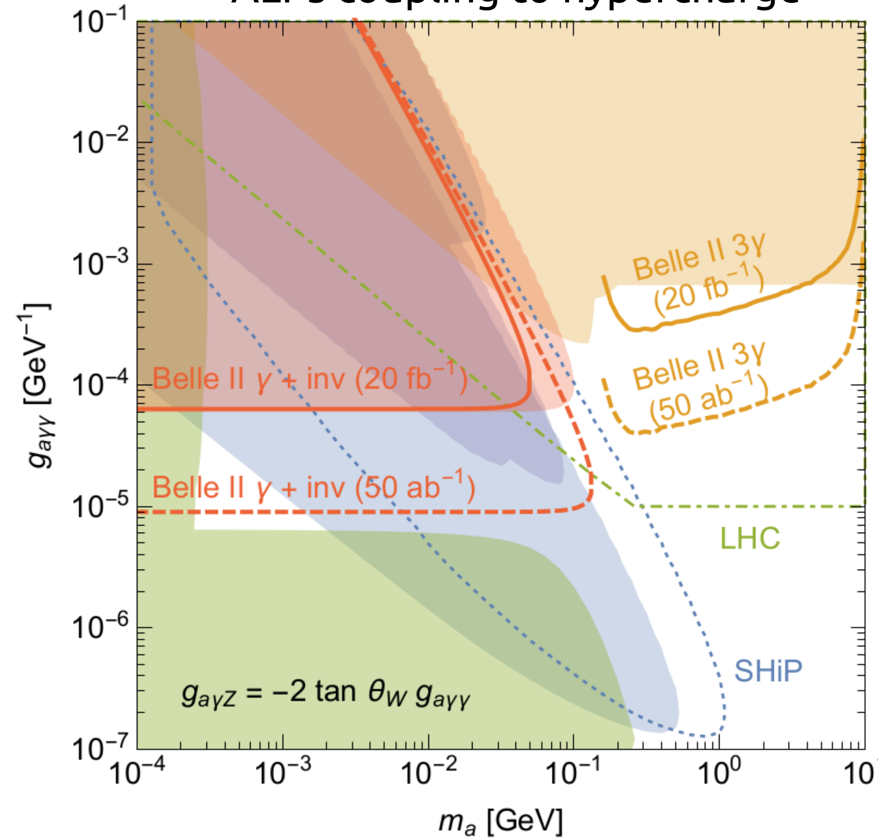
- Discrimination from the dominant QED backgrounds can be achieved by searching for a peak in the di-photon invariant mass

Projected sensitivities: Summary

ALPs coupling to photons



ALPs coupling to hypercharge



Important complementarity between Belle II, LHC and SHiP, as well as between visible and invisible decay modes!

Conclusions

- Searches for axion-like particles in the MeV to GeV range are a promising and exciting new direction for particle physics
- Single-photon searches at Belle II can explore both invisibly decaying ALPs (e.g. DM mediators) and long-lived ALPs
- Belle II searches for three resolved photons can cover wide ranges of new ALP parameter space
- Initial data sets (20 fb^{-1}) will already be sufficient to set world-leading limits in both cases
- Let’s go and discover ALPs!