Dark Matter Self-Interactions.

From observations to particle physics

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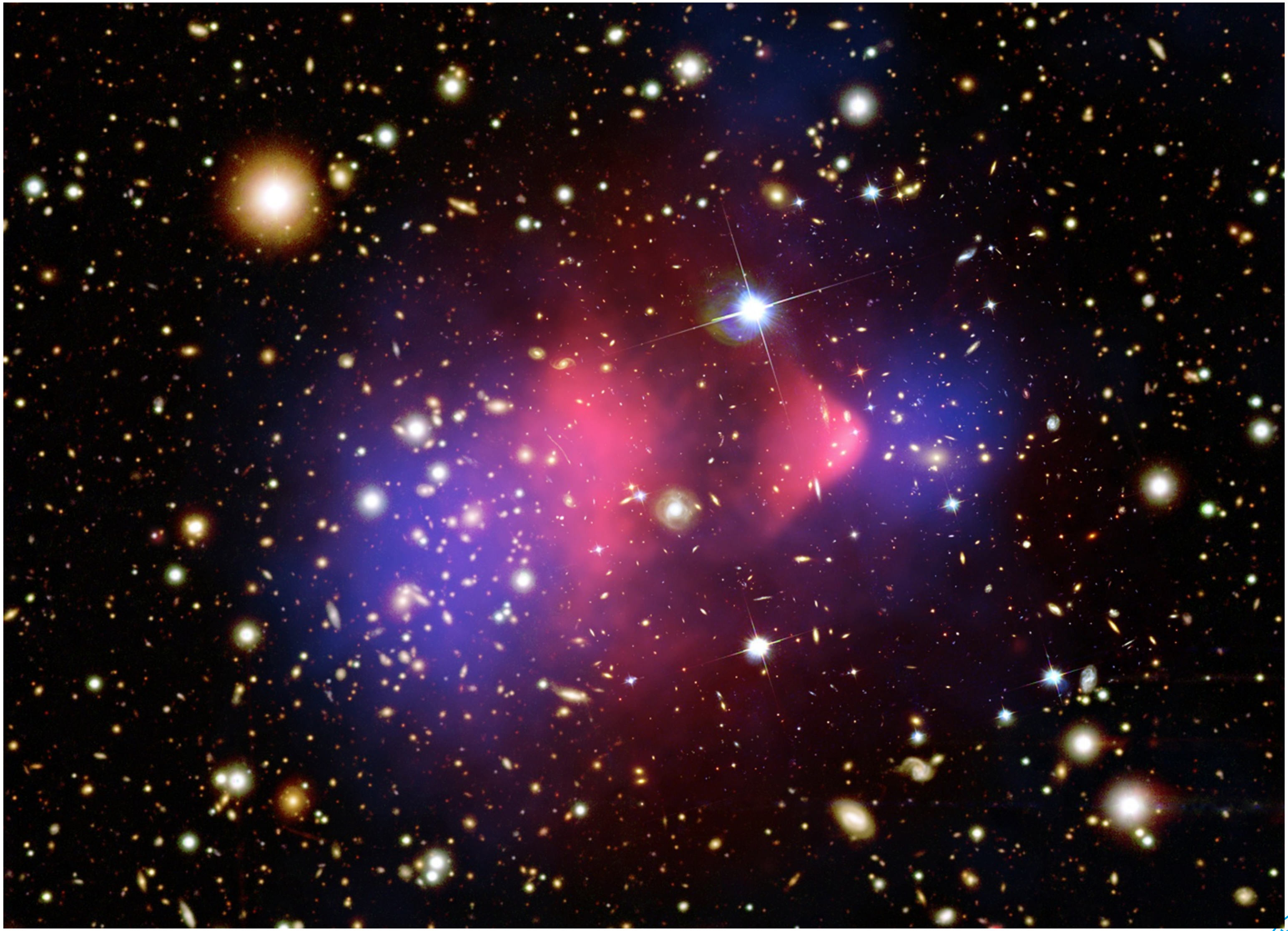
HELMHOLTZ ASSOCIATION

DESY

Outline

- Introduction: Motivation for self-interacting dark matter
- Part 1: How to study self-interactions in astrophysical systems
  - Using dark matter halos as particle colliders
  - Evaporation rates and drag forces
  - Velocity-dependent self-interactions from light mediators
- Part 2: How to search for light mediators in the laboratory
  - The case for pseudoscalar mediators
  - Constraints from proton beam-dump experiments
- Conclusions

The Bullet Cluster



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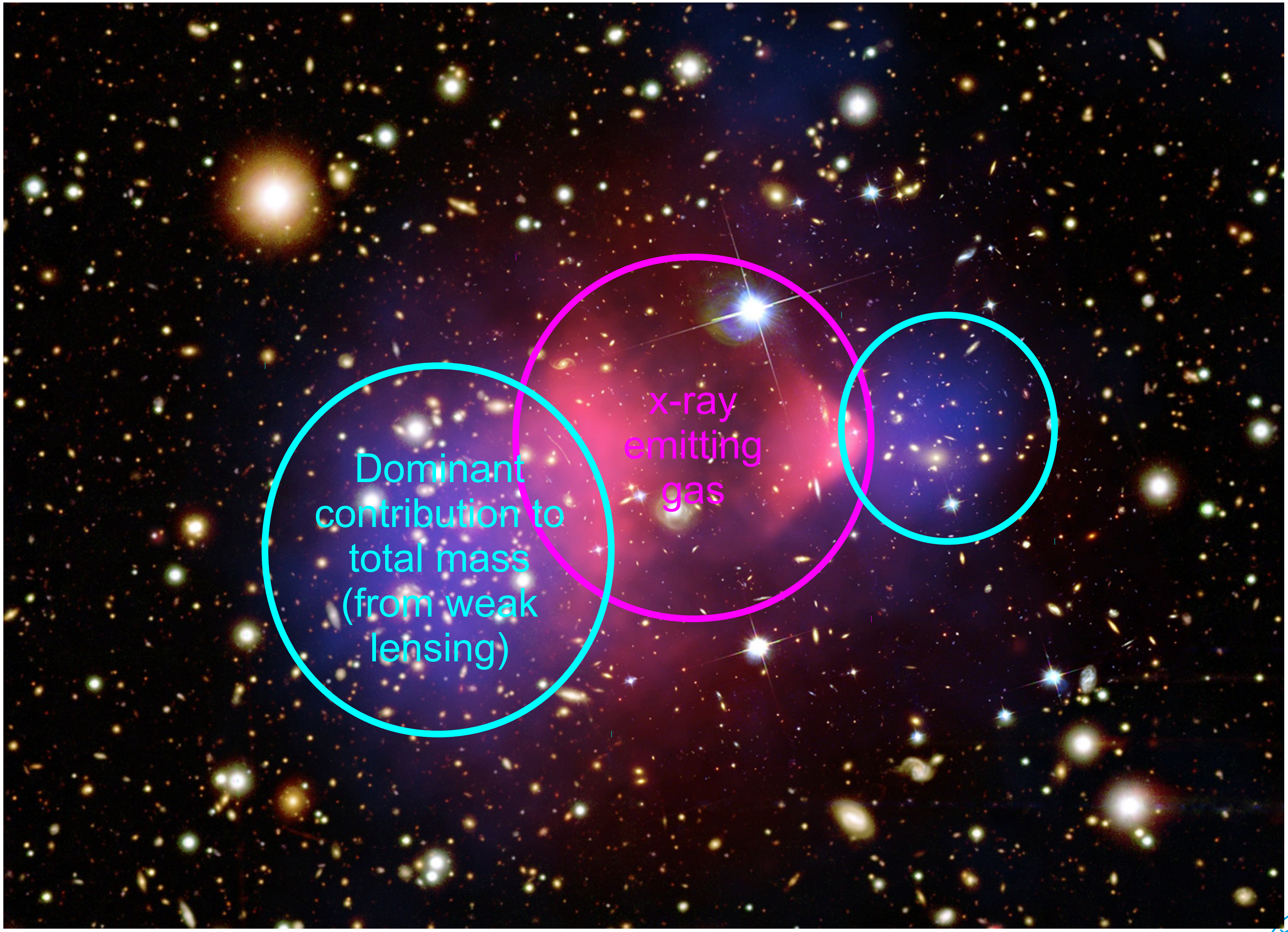
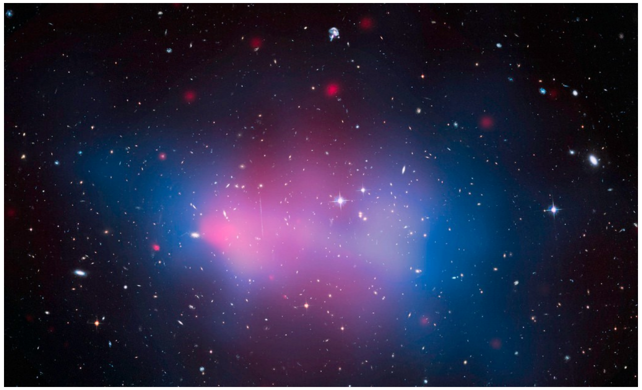


The Bullet Cluster

- Observations of the Bullet Cluster tell us that the dominant form of matter in galaxy clusters behaves very differently from baryonic gas:
  - No emission of x-ray radiation
  - No significant dissipation of energy
  - No loss of direction
- In fact, the dark matter behaves much more like the collisionless galaxies in the two galaxy clusters.
- Many similar observations in other major mergers

Abel 520



El Gordo

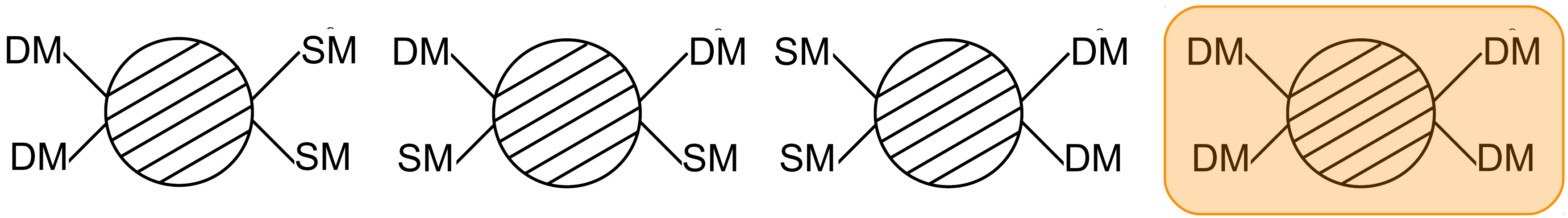
Baby Bullet

Collisionless dark matter?

- If DM consists of new elementary particles, collisions of galaxy clusters seem to imply that these particles would have small self-interactions.
- To obtain an approximate upper bound on the self-scattering cross section, we can calculate the projected (surface) DM density of a galaxy cluster.
- For the central region of the Bullet Cluster, we find $\Sigma \sim 0.3\ \mathrm{g/cm^2}$.
- In order for the majority of DM particles to travel from one end of the Bullet Cluster to the other without scattering, we require $\Sigma\sigma / m_x \lesssim 0.5$, and thus $\sigma / m_x \lesssim 1.5\ \mathrm{cm^2/g}$.
- Note that this is not at all a small cross section ($1.5\ \mathrm{cm^2/g} = 3$ barn/GeV). In fact, it is comparable to nucleon-nucleon scattering!

Self-interacting dark matter

- In order to be observable on astrophysical scales, DM self-interactions actually have to be very large.
- Nevertheless, even such large cross sections cannot be tested in the laboratory, so astrophysics gives us a completely different window to study DM properties.



- Any clear astrophysical evidence for DM self-scattering would rule out most of the popular DM models (WIMPs, axions, …).
- Instead: Point towards more complex dark sectors such as SIMPs

E.g. Hochberg et al., arXiv:1512.07917; Kamada et al., arXiv:1606.01628

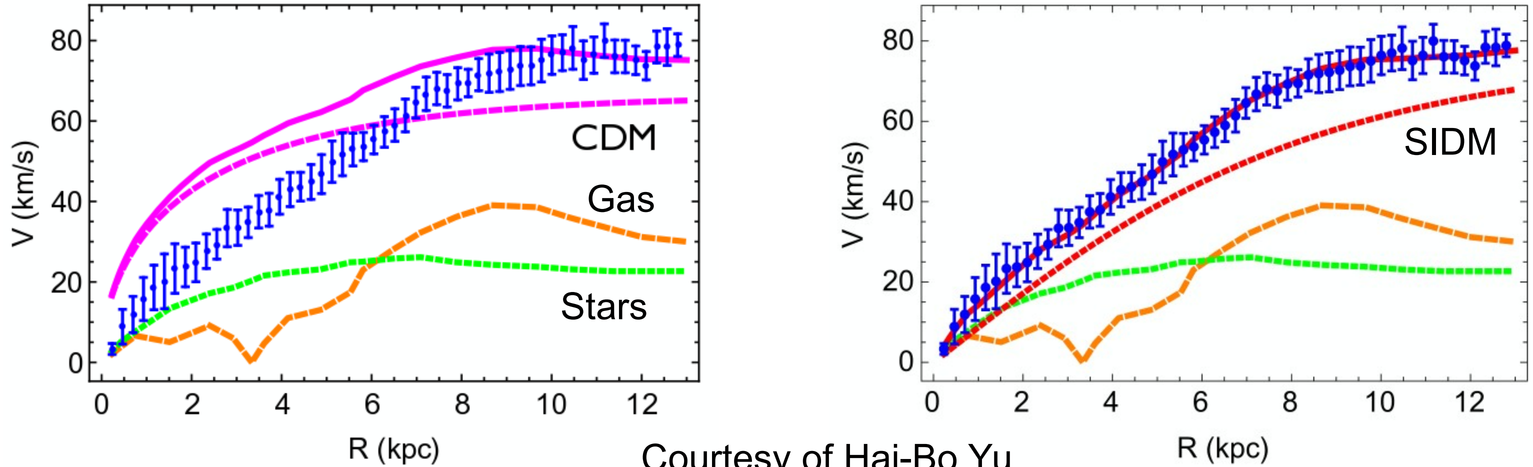
Hints for self-interacting dark matter?

- 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

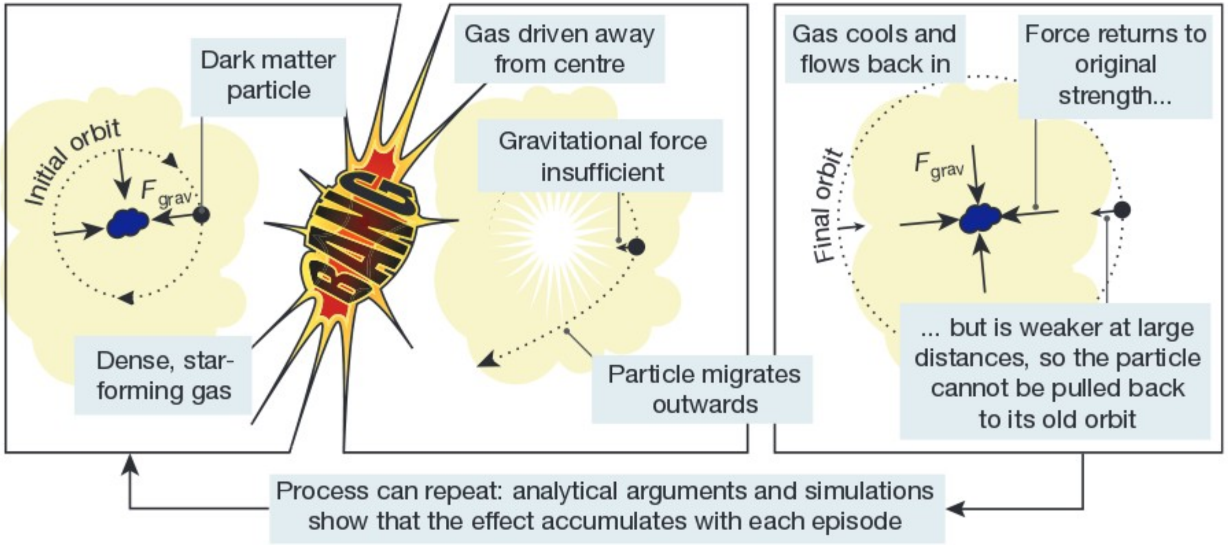


Courtesy of Hai-Bo Yu

Hints for self-interacting dark matter?

- The observational situation concerning the "small-scale crisis" is not yet clear. Maybe we just need to discover more Milky Way satellites (already many new discoveries in 2015 & 2016).
- Even if fully established, it remains unclear whether baryonic feedback can equally provide an explanation for missing satellites and cored dwarf galaxies.

Pontzen & Governato, Nature 506, 171–178 (2014)



Hints for self-interacting dark matter?

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

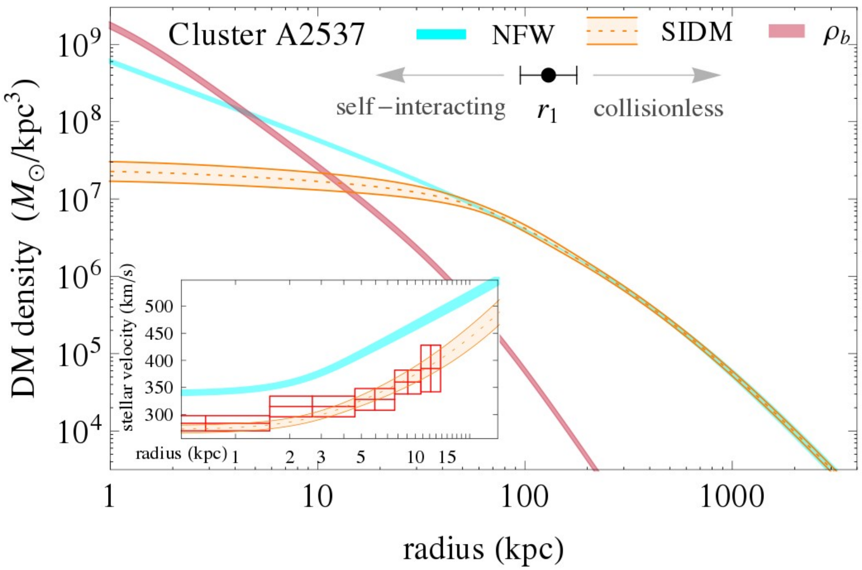
  Spergel & Steinhard: astro-ph/9909386

- 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.

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

Kaplinghat et al., arXiv:1508.03339



Two strategies for probing self-interactions

1) Study the effects of self-interactions on relaxed systems (halo morphology)

- Constant-density cores in galaxy clusters

  Yoshida et al., arXiv:astro-ph/0006134; Rocha et al., arXiv:1208.3025; Kaplinghat et al., arXiv:1508.03339

- Reduced ellipticity of galactic halos and galaxy cluster halos

  Miralda-Escude (2002); Feng et al., arXiv:0905.3039; Peter et al., arXiv:1208.3026

2) Use dark matter halos as particle colliders

- Major mergers

  Markevitch et al.: astro-ph/0309303; Randall et al.: 0704.0261; Kim et al., arXiv:1608.08630

- Infalling sub-halos

  Massey et al., arXiv:1007.1924, Harvey et al., arXiv:1305.2117, arXiv:1310.1731, arXiv:1503.07675

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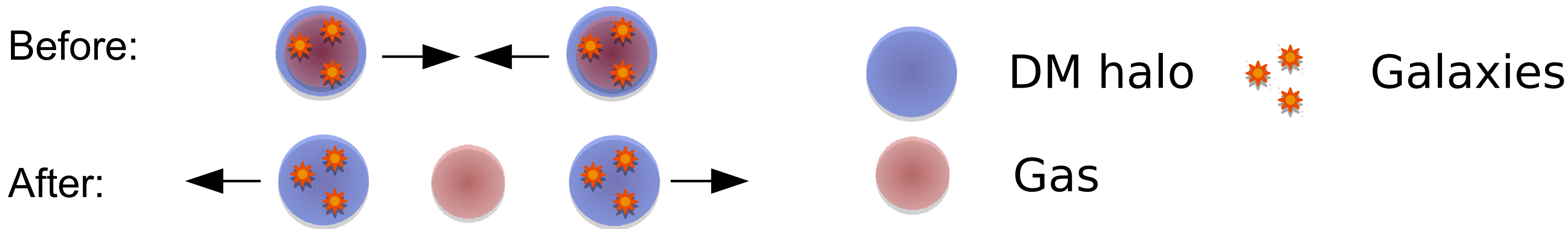
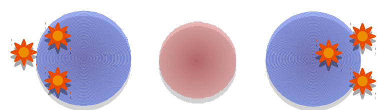
Major mergers

- In the absence of self-interactions we expect DM to behave exactly like collisionless stars and galaxies:

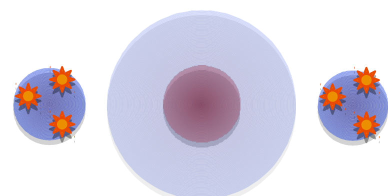


- To obtain constraints on DM self-interactions from major mergers, we have to understand how self-scattering would modify observations.

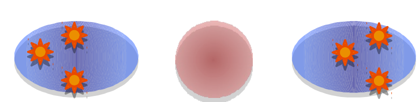
  - Does the DM halo slow down?



  - Does the DM halo evaporate?



  - Is the DM halo deformed?



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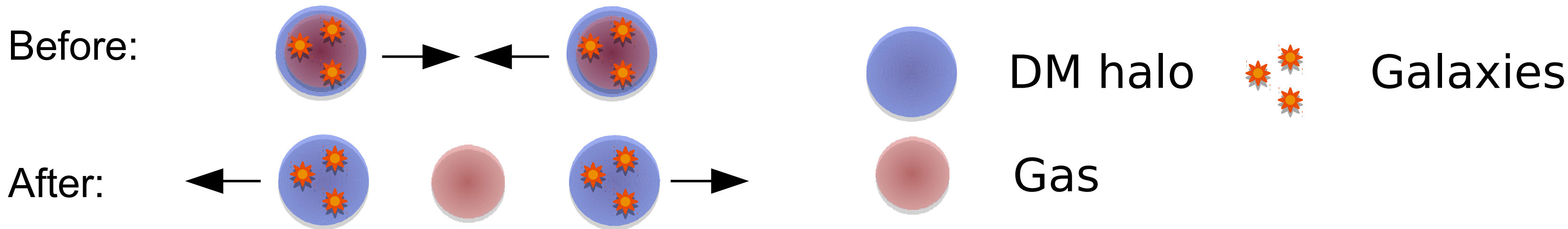

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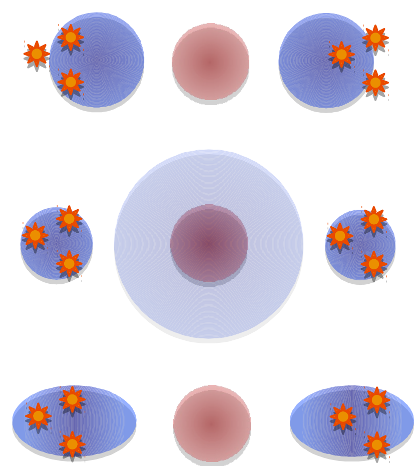
  - Does the DM halo slow down?
    - Galaxy-DM offset
  - Does the DM halo evaporate?
    - Mass-to-light ratio
  - Is the DM halo deformed?
    - Asymmetric halos



Major mergers

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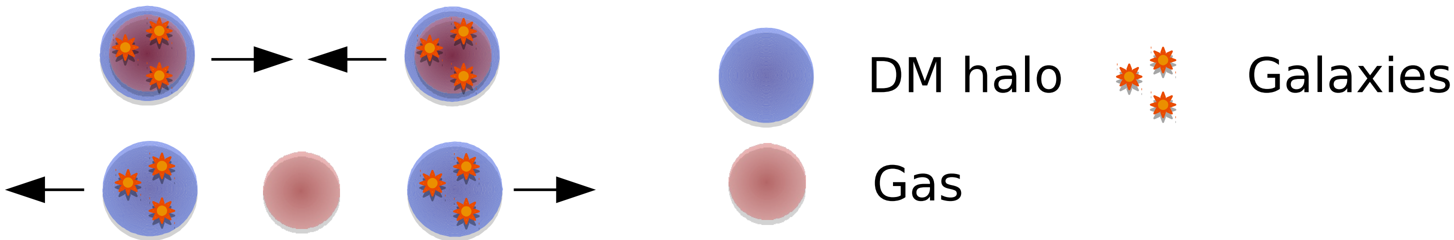
Before:

After:



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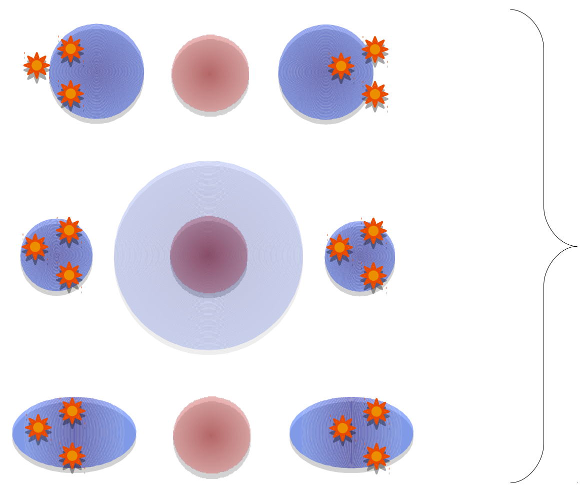
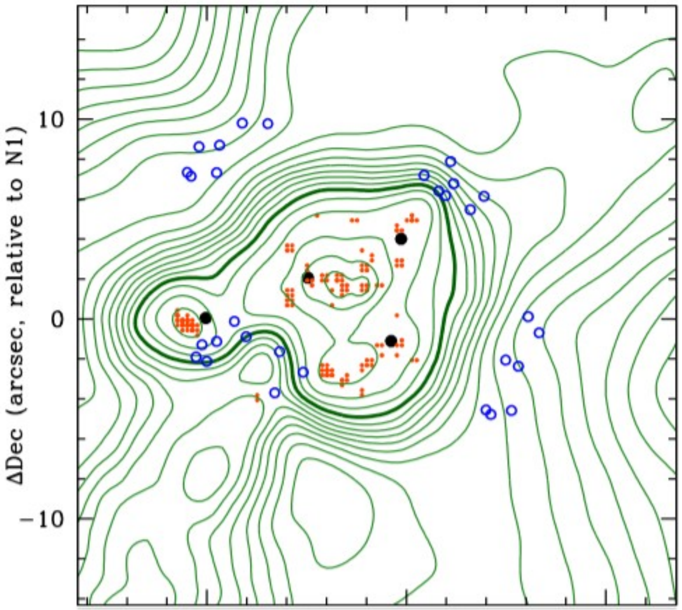


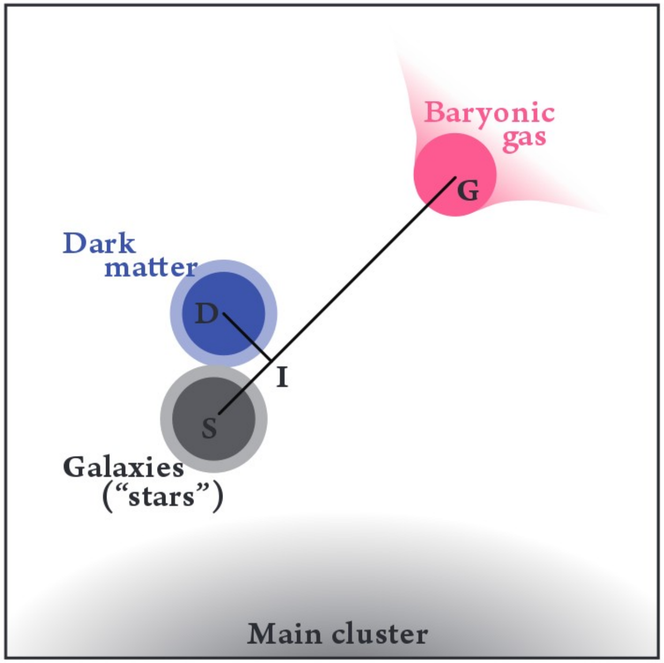
All of these can be searched for, but which one is the most promising?

Sub-halos

- Similar considerations are relevant for (galactic) sub-halos falling into the central region of a galaxy cluster.
  - Do self-interactions simply destroy such halos?
  - Or does the halo remain intact but becomes separated from the stars?



Harvey et al., arXiv:1310.1731

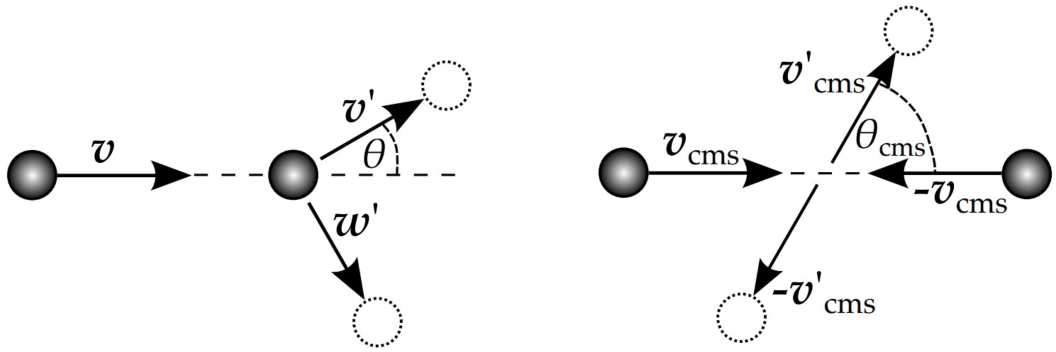


- Possible hints in Abel 3827

Massey et al., arXiv:1504.03388
FK et al., arXiv:1504.06576

The particle physics picture

- Let us consider the scattering of an incoming DM particle with velocity v on a DM particle at rest inside a DM halo.



- If after the collision both $v' > v_{\rm esc}$ and $w' > v_{\rm esc}$, the particles will both escape from the DM halo (immediate evaporation).

- Such an *expulsive scattering* occurs whenever the scattering angle in the centre-of-mass frame is sufficiently close to 90 degrees:

$$\frac{2\,v_{\rm esc}^2}{v_0^2} - 1 < \cos\theta_{\rm cms} < 1 - \frac{2\,v_{\rm esc}^2}{v_0^2}$$

- Bullet Cluster: $50° \lesssim \theta_{\rm cms} \lesssim 130°$

Evaporation rates

- The evaporation rate is then given by

$$R_{\rm imd} = \frac{\rho_2}{m_{\rm DM}} v_0 \int {\rm d}\phi_{\rm cms} \int_{2\,v_{{\rm esc},1}/v_0^2-1}^{1-2\,v_{{\rm esc},1}/v_0^2} {\rm d}\cos\theta_{\rm cms} \frac{{\rm d}\sigma}{{\rm d}\Omega_{\rm cms}}$$

- The halo fraction lost to evaporation is

$$\frac{\Delta N_{\rm imd}}{N} = 1 - \exp\left[-\frac{\Sigma_2\,\sigma\,f}{m_{\rm DM}}\right]$$

$$f = \frac{\int_{2\,v_{{\rm esc},1}/v_0^2-1}^{1-2\,v_{{\rm esc},1}/v_0^2} {\rm d}\Omega_{\rm cms}\ ({\rm d}\sigma/{\rm d}\Omega_{\rm cms})}{\int {\rm d}\Omega_{\rm cms}\ ({\rm d}\sigma/{\rm d}\Omega_{\rm cms})}$$

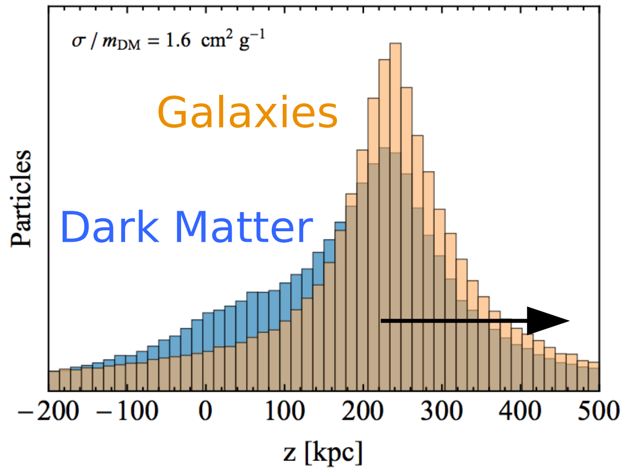
(fraction of expulsive collisions)

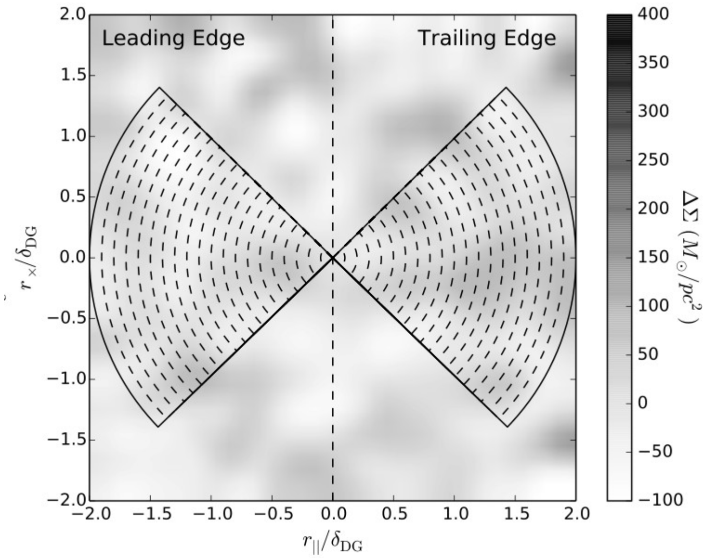
Isotropic scattering

- If the scattering of DM particles is isotropic (e.g. from contact interactions), we expect f to me large (in the Bullet Cluster, around 60% of collisions are expulsive).
- To be consistent with observations, we then must require that self-interactions are rare, i.e. a significant fraction of DM particles do not experience scattering.
- The particles that do scatter will form a tail in the backward direction.

First attempts to search for such tails: Harvey et al., arXiv:1610.05327

FK et al., arXiv:1308.3419





Frequent self-interactions

- A second possibility to satisfy constraints on the evaporation rate is to have frequent self-interactions,

$$\Sigma_2 \, \sigma / m_{\rm DM} \gg 1$$

  but a small fraction of expulsive collisions:

$$f \ll 1$$

- To achieve this goal, the overwhelming majority of collisions must have small momentum transfer (i.e. small scattering angles).
- In other words, we are interested in cross-sections that peak for $\theta_{\rm cms} \to 0$.
- Well-known example: Rutherford scattering

Frequent self-interactions

- Frequent self-interactions lead to the deceleration of DM halos moving through a background density, which can be described by an effective drag force:

$$\frac{F_{\text{drag}}}{m_{\text{DM}}} = \frac{\tilde{\sigma}}{4\,m_{\text{DM}}}\rho\, v_0^{2m}$$

- For velocity-independent self-interaction cross sections one finds m = 1.

- However, a strong angular dependence typically also requires a strong velocity dependence, because the cross section can depend on the angle only via the two Mandelstam variables $t = -2\, m_{DM} v_{cms}^2\,(1 - \cos\theta)$ and $u = -2\, m_{DM} v_{cms}^2\,(1 + \cos\theta)$.

- E.g. for Rutherford scattering:

$$\frac{d\sigma}{d\Omega} \approx \alpha'^2 \frac{s(t+u)^2}{(t\,u)^2} = \frac{\alpha'^2}{m_{\text{DM}}^2\, v_{\text{cms}}^4\,(1-\cos^2\theta_{\text{cms}})^2}\,,$$

and therefore m = -1.

Frequent self-interactions

- Implementing frequent self-interactions into numerical simulations remains an open problem.
- The two main approaches are:
  - Averaging out the angular dependence and implementing only the velocity dependence of the self-scattering cross section

    Zavala et al., arXiv:1211.6426; Vogelsberger et al., arXiv:1405.5216

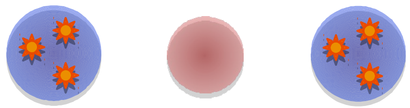
    - Probably a good approximation for nearly isotropic systems close to equilibrium.
  - Implementing an effective drag force which captures the net effect of many DM collisions

    FK et al., arXiv:1308.3419; FK et al., arXiv:1504.06576

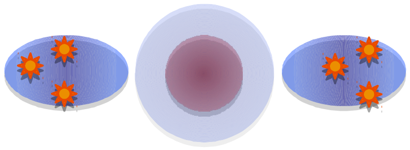
    - More suitable for systems with a strong directionality such as mergers.
- For a velocity-dependent cross section, the largest effects are expected on the scale of dwarf spheroidals, while constraints from galaxy clusters are typically weak.

Particle physics meets astrophysics

- No self-interactions:

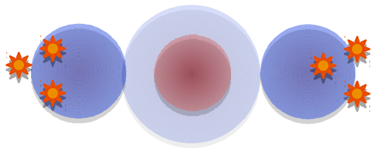


- Rare self-interactions:



Search for asymmetric halos!

- Frequent self-interacations



Search for galaxy-DM offset!

- Also some degree of evaporation - measure mass-to-light ratios?
  - Requires assumptions on the initial mass-to-light ratio of the system
  - May be biased by galaxies escaping from the (reduced) gravitational potential

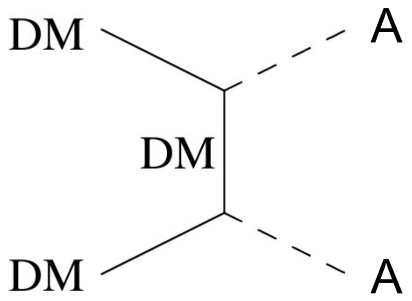
Conclusions part I

- Astrophysical systems provide the only known way of potentially probing DM self-scattering.
- In particular, observations of major mergers may enable us to constrain or discover self-interacting DM, provided we know what exactly to look for.
- Observational constraints on evaporation rates tell us that the rate of isotropic scattering must be low.
- Frequent self-interactions are possible if the angular dependence of the scattering ensures that there is only a small fraction of expulsive collisions.
- In the latter case we also expect a velocity dependence of the scattering cross section and therefore larger effects on smaller scales (e.g. cores in dwarf galaxies).
- Astrophysical observations may help us to understand the particle physics properties of dark matter.

How to obtain frequent self-interactions

- Frequent self-interactions with strong velocity dependence arise naturally if the mediator of the DM self-interaction is light compared to the DM mass.

- Attractive extra feature: Relic abundance set by dark sector freeze-out



- To avoid overclosing the Universe, the mediator needs to be unstable and decay into SM states.

- There are important constraints on such decays from primordial nucleosynthesis:
  - Lifetime should be smaller than a few seconds.
  - This gives a lower bound on the coupling of the new state to SM particles.

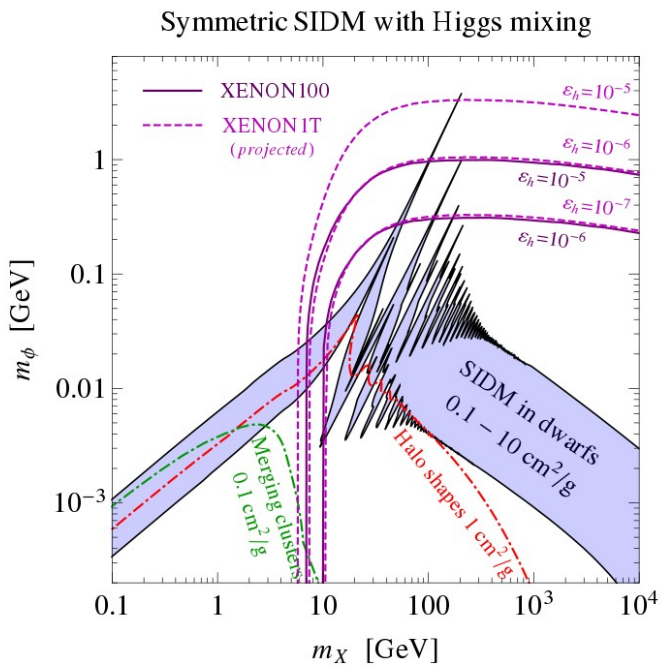
Direct detection constraints

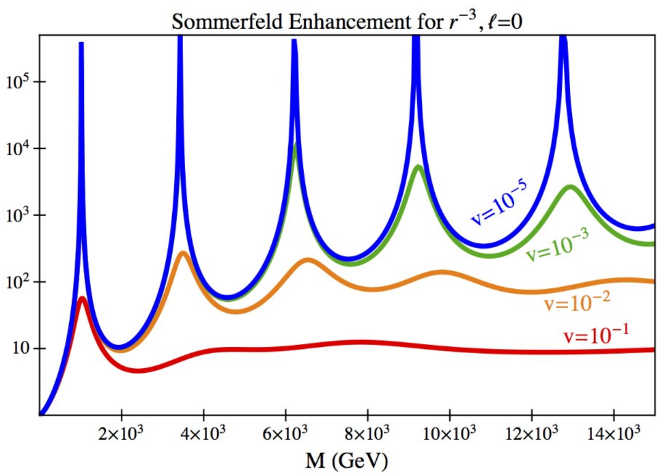
- For scalar mediators, the coupling strength required to ensure decay before BBN is in significant tension with direct detection experiments.

Kaplinghat et al., arXiv:1310.7945

- For pseudoscalar mediators, on the other hand event rates in direct detection experiments are strongly suppressed.

Boehm et al., arXiv:1401.6458





- For pseudoscalar mediators tree-level self-scattering has no strong dependence on the scattering angle and velocity.
- This changes, however, once non-perturbative effects are included.

Bellazzini et al., arXiv:1307.1129

The pseudoscalar portal

- Light pseudoscalars, in particular axions and axion-like particles (ALPs), are also well-motivated from a theoretical perspective.
- 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

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

and dimension-5 couplings to gauge bosons

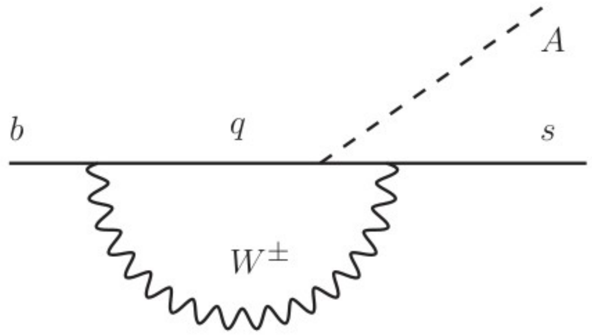
$$-\frac{1}{4} g_{\phi\gamma} \phi F^{\mu\nu} \tilde{F}_{\mu\nu} \qquad g_{\phi\gamma} \sim \frac{\alpha}{2\pi f_A}$$

- Here we take the ALP mass as a free parameter (enhanced by strong dynamics in a hidden sector).

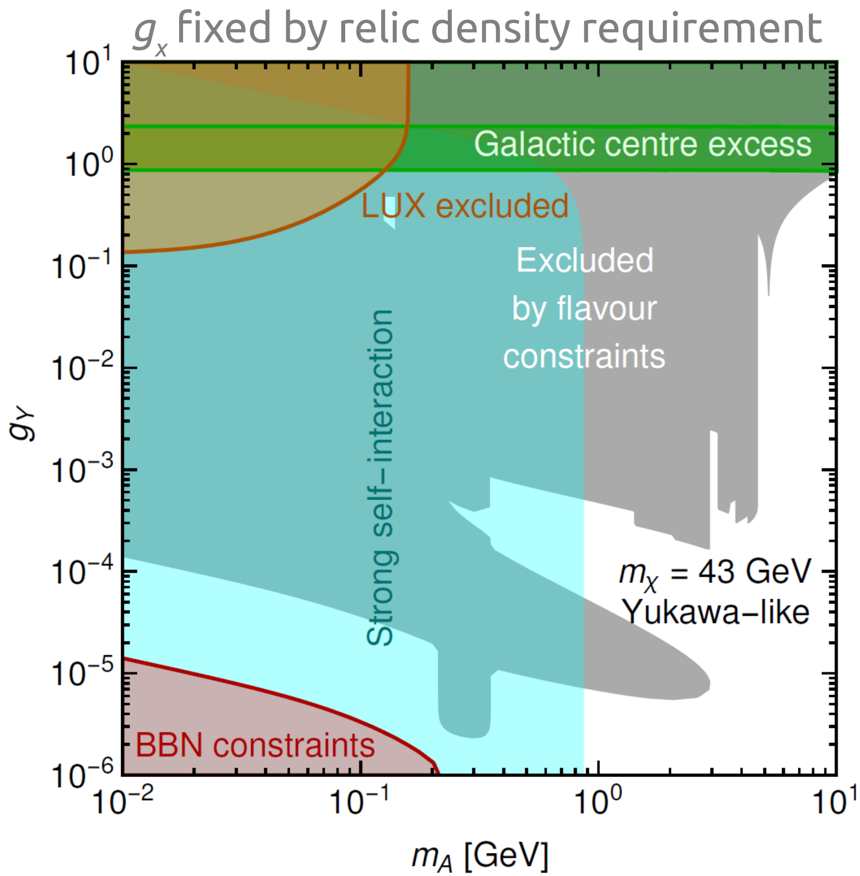
Fukuda et al., arXiv:1504.06084

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

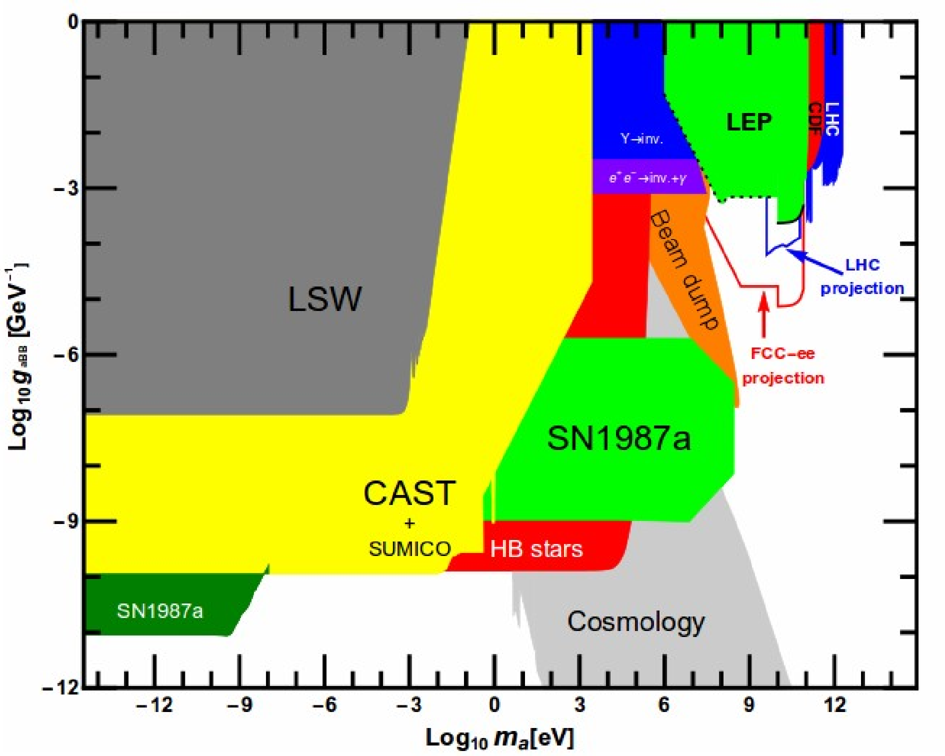


- Some remaining parameter space for very small masses and couplings.

ALP-photon coupling

- The focus of the rest 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

$$-\frac{1}{4} g_{a\gamma}\, a\, F^{\mu\nu} \tilde{F}_{\mu\nu}$$



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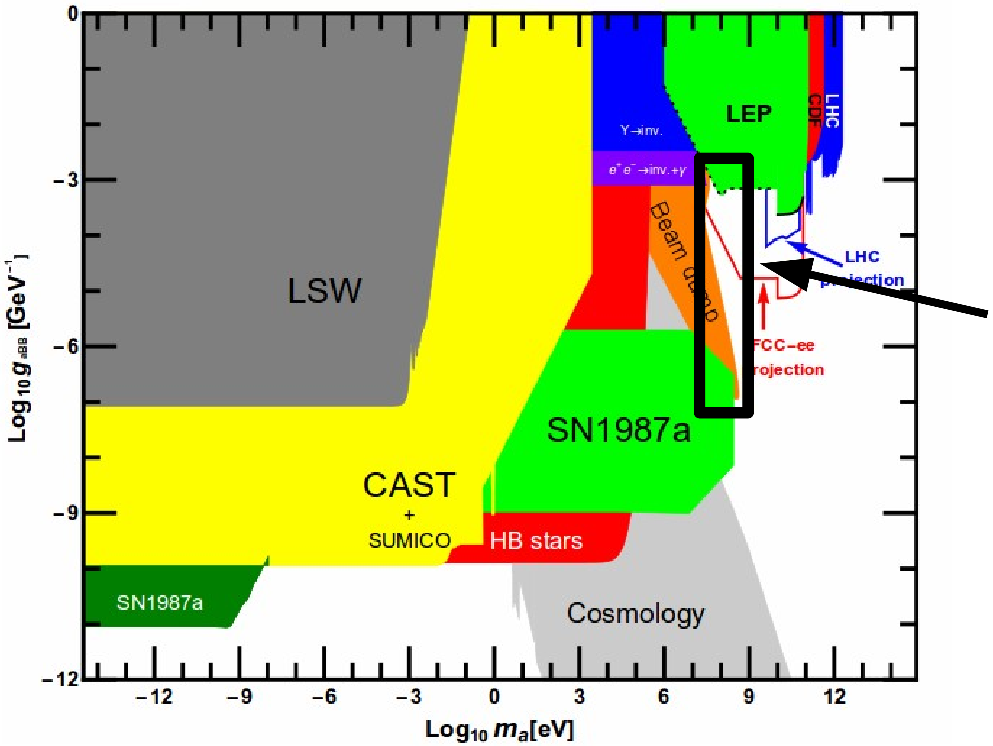

Interesting mass region for self-interactions

- Heavy enough to decay
- Light enough to boost self-interactions

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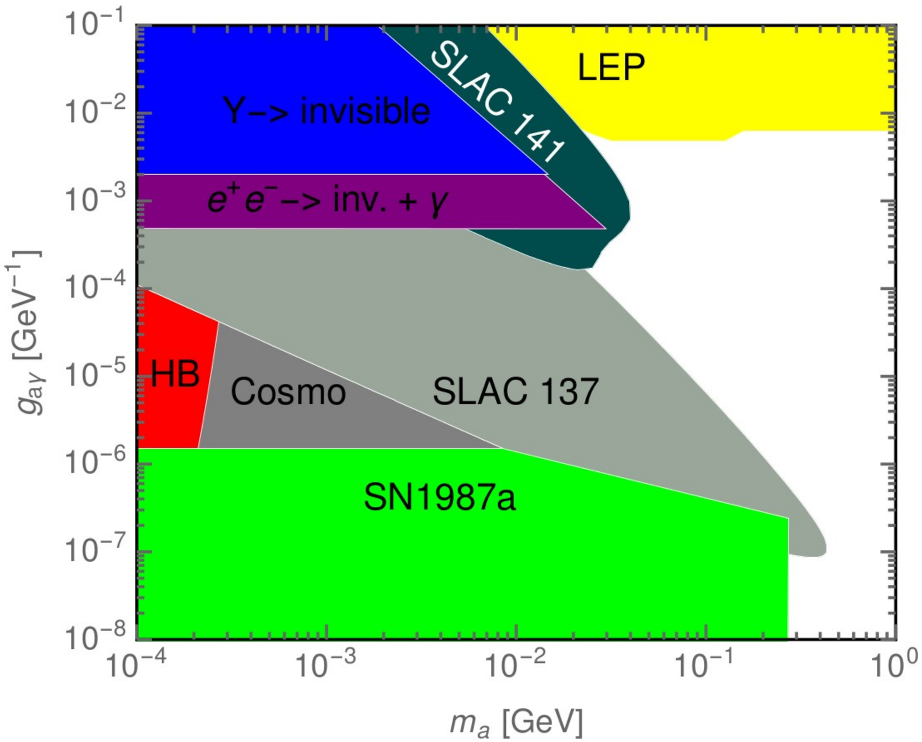

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Large unexplored parameter region for relatively heavy ALPs

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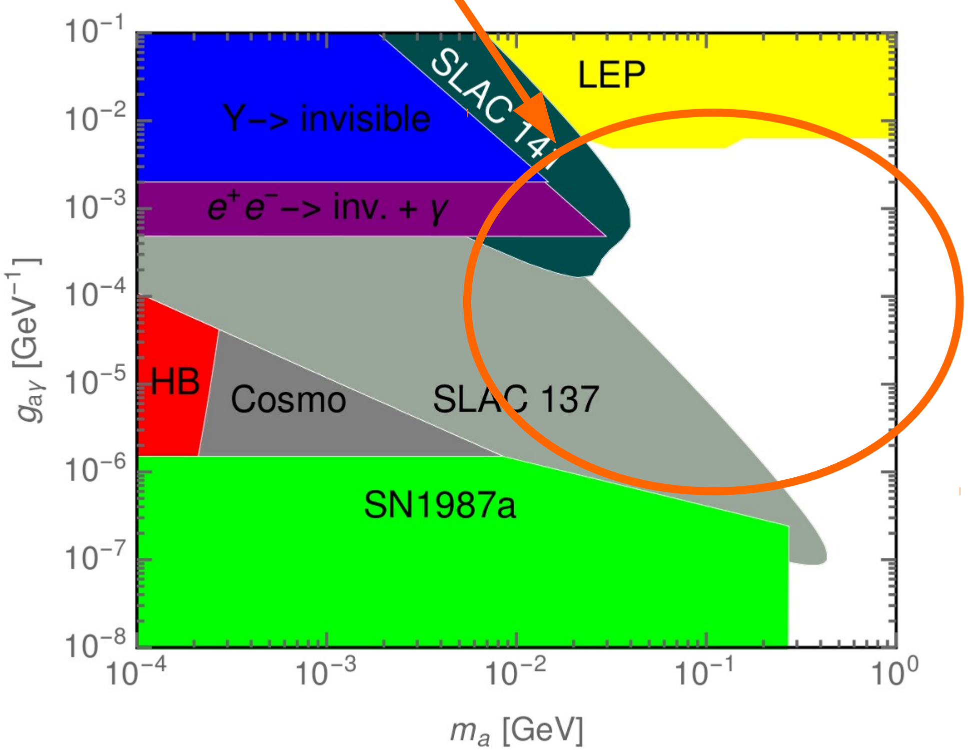

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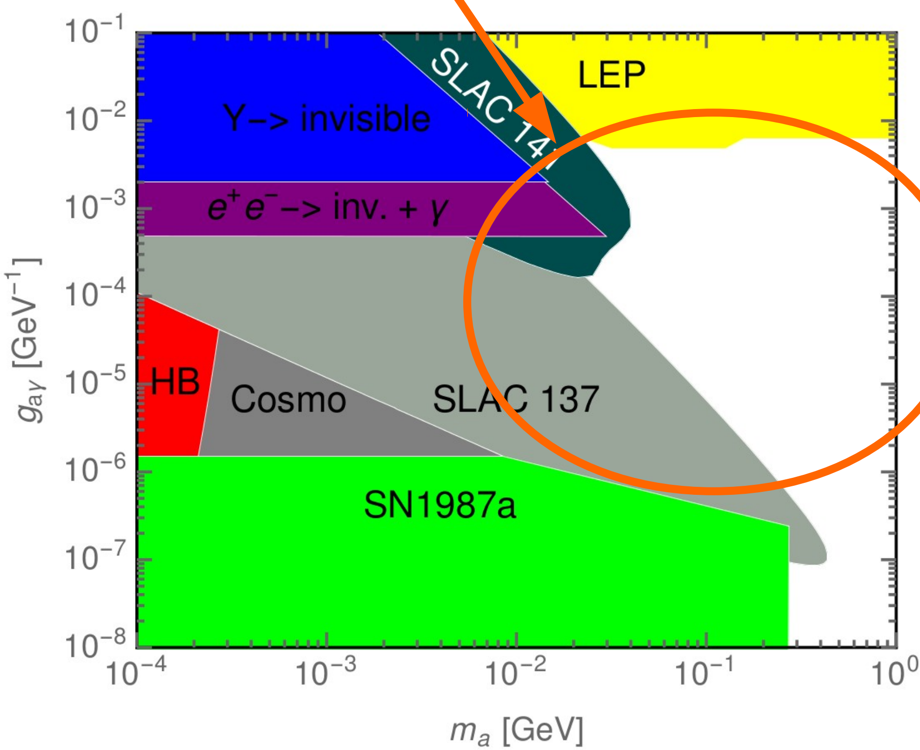

The sensitivity of a given beam-dump experiment depends on:

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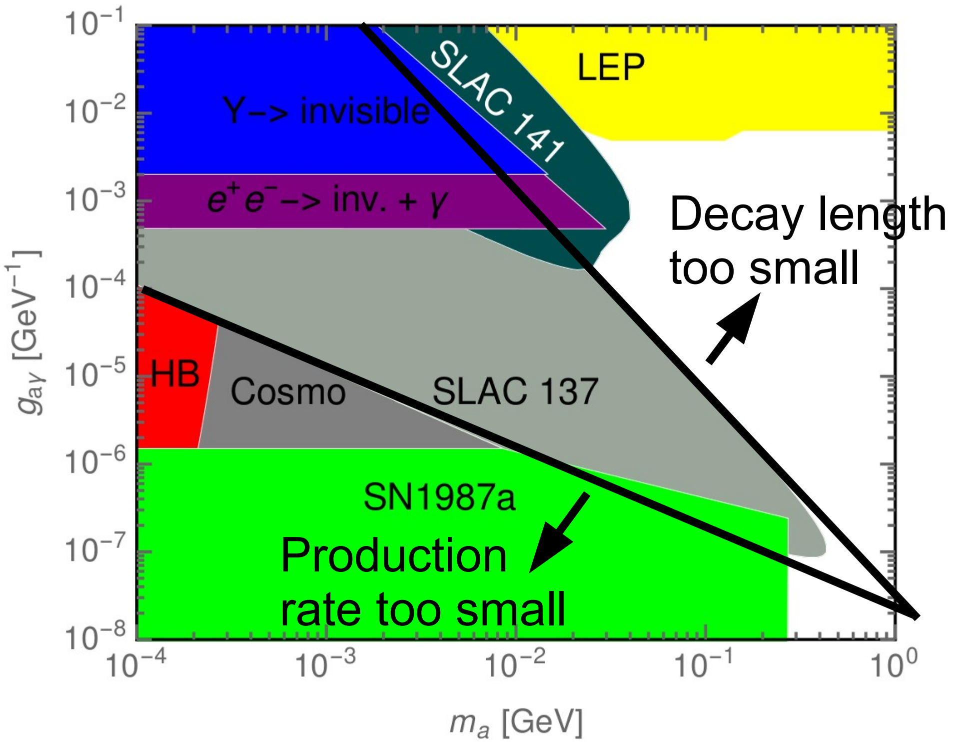
- The focus of this talk will be on the case where the interactions between ALPs and the Standard Model (and hence ALP decays) are dominated by the effective ALP-photon coupling

$$-\frac{1}{4}\, g_{a\gamma}\, a\, F^{\mu\nu}\, \tilde{F}_{\mu\nu}$$



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

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

Proton beam-dump experiments

- For large couplings $g_{A\gamma}$ the ALP production cross section is very large, but the ALP decay length is much smaller than the length of the absorber ($l_a << L$), so the number of observable ALP decays is exponentially suppressed.

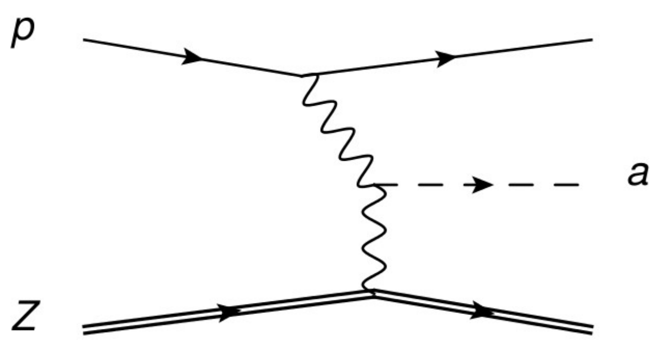
- The most promising way to improve on existing bounds is to increase the beam energy, leading to larger ALP boost factors and hence larger decay lengths in the laboratory frame.

- 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).

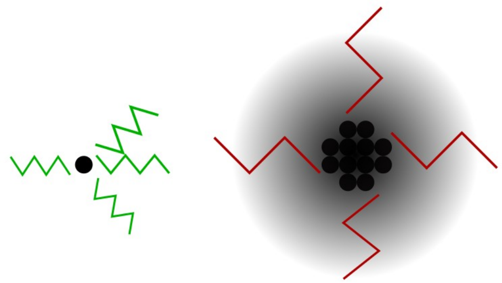


- Both the proton and the nucleus scatter elastically, so the interaction can be described using simple atomic form factors.
- Moreover, since the photon couples to the entire target nucleus, the ALP production cross section is enhanced proportional to Z^2.
- Transverse momenta are very small, so cross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

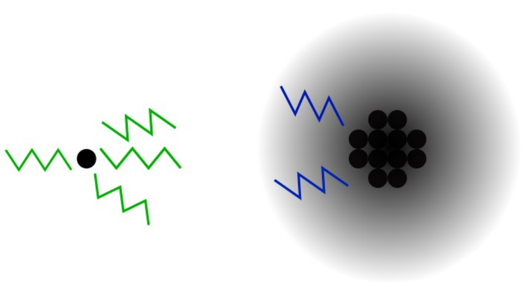
How is this possible?

- 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.



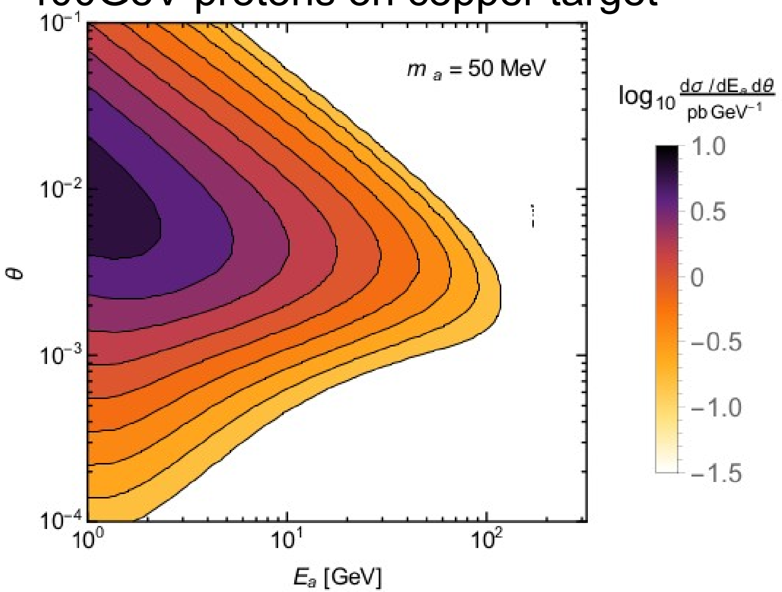
- These photons provide enough energy to produce rather heavy ALPs.

ALP production cross section

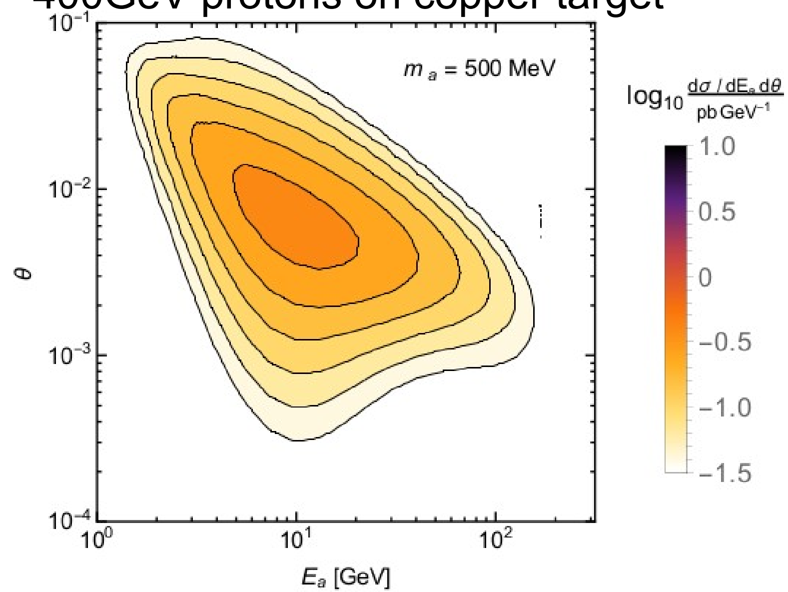
- We start from the Weizsaecker-Williams approximation to obtain an equivalent photon spectrum γ(x).
- This formalism is then extended to include non-zero transverse momenta, which are necessary to calculate angular distributions.

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

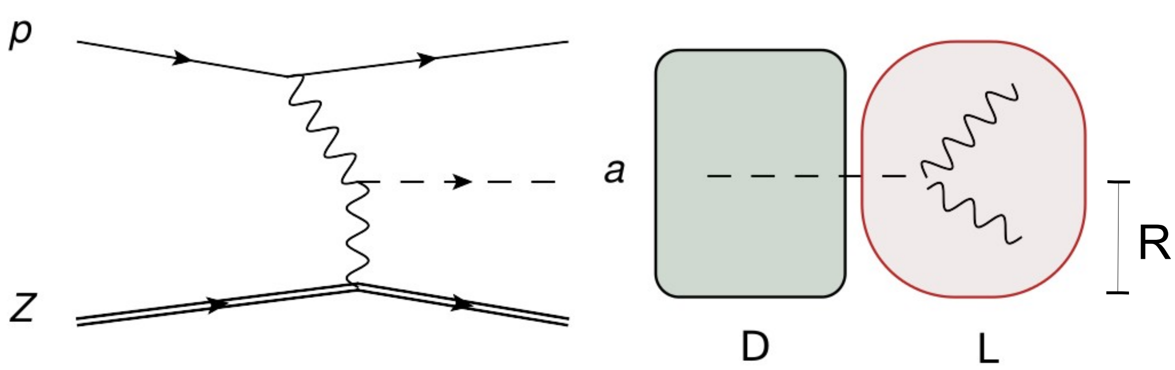
400GeV protons on copper target

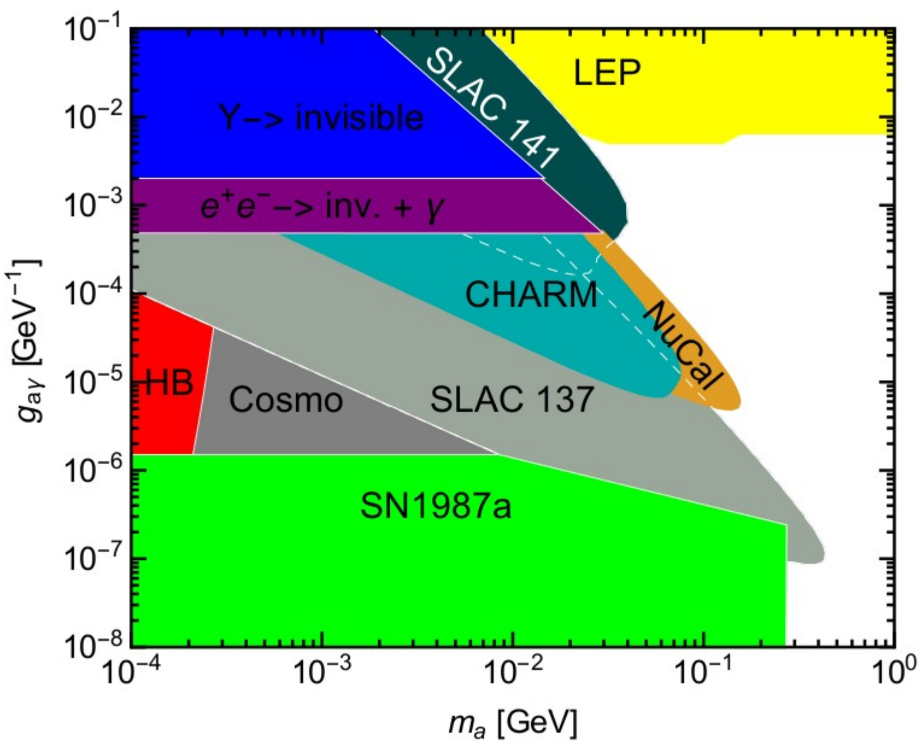


400GeV protons on copper target



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

Probing further

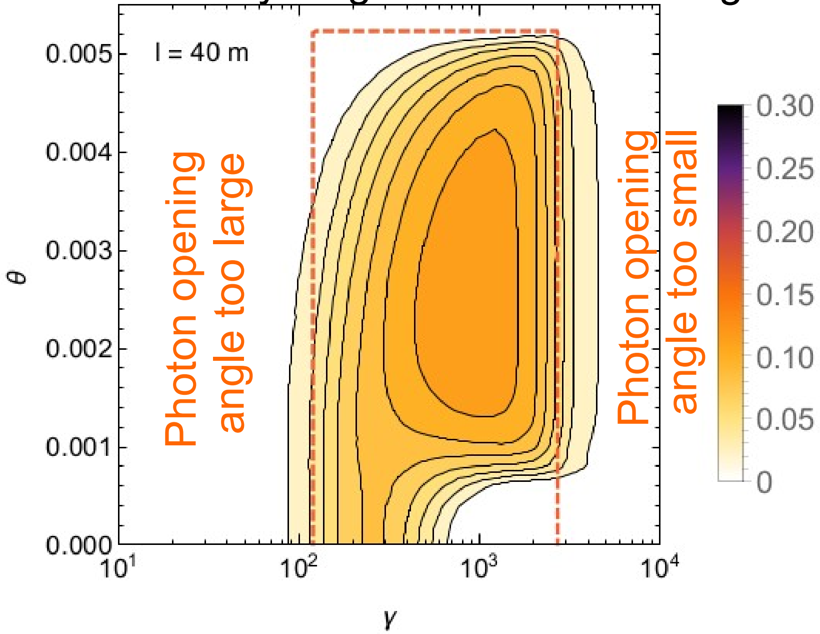
- To extend the sensitivity further, we need new experiments
  - Higher beam energy (difficult)
  - Higher integrated intensity
  - Shorter absorber, longer decay volume

- 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).

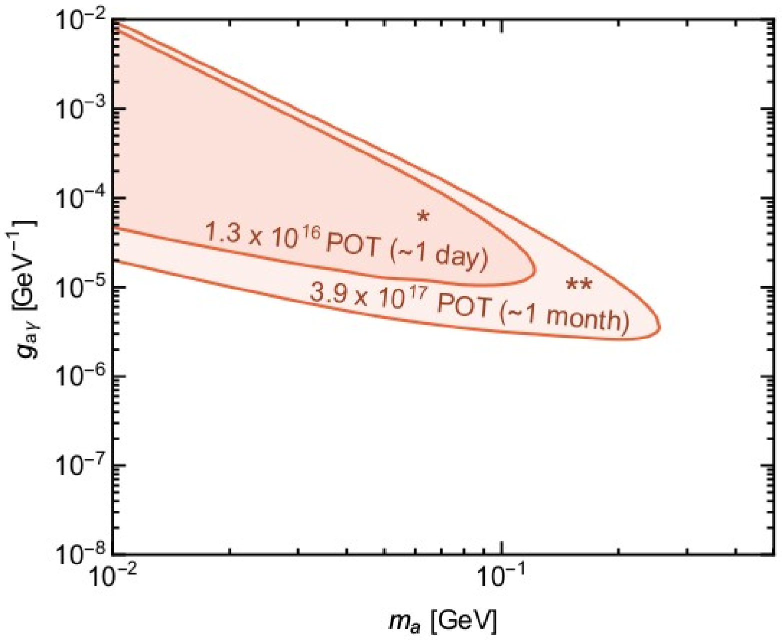
- We calculate the resulting detector acceptance for such a signal from a toy Monte Carlo.

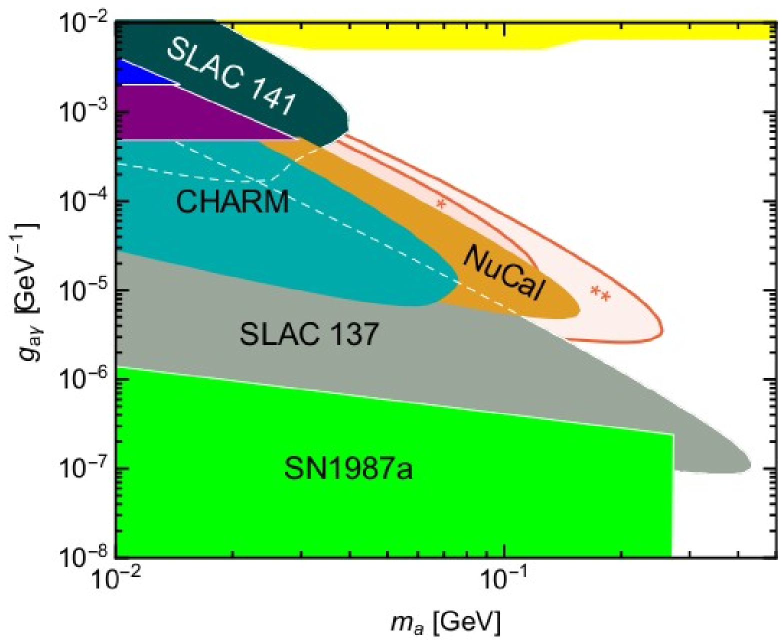
ALP decay length << Absorber length



Example: NA62

- NA62 in beam-dump mode: 400 GeV protons on a copper target
- Excellent sensitivity to photons in Liquid Krypton Calorimeter (LKr)
  - D = 81 m, L = 135 m, θ_{min} = 0.7 mrad, θ_{max} = 5.2 mrad

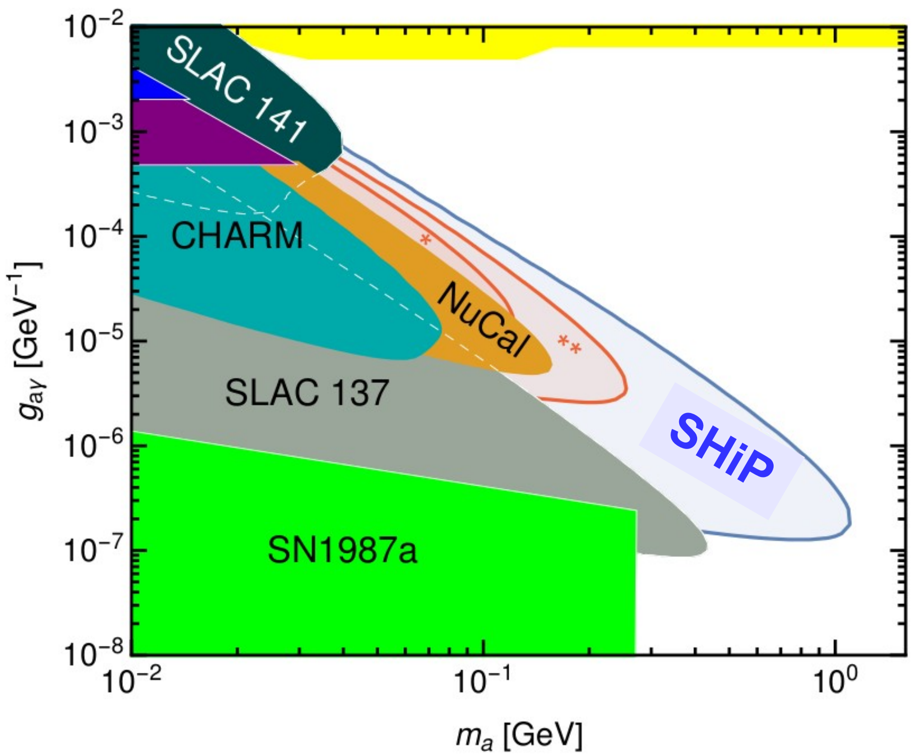




- NA62 can have about 1.3e16 protons on target per day.
- This data-taking period would already be enough to probe new parameter regions!

SHiP

- The proposed SHiP facility is optimised to search for hidden particles.
  - Up to 2e20 protons with energy 400 GeV on a molybdenum target
  - D = 70 m, L = 50 m
  - θ_{max} = 20 mrad (covers the peak of the ALP distribution)



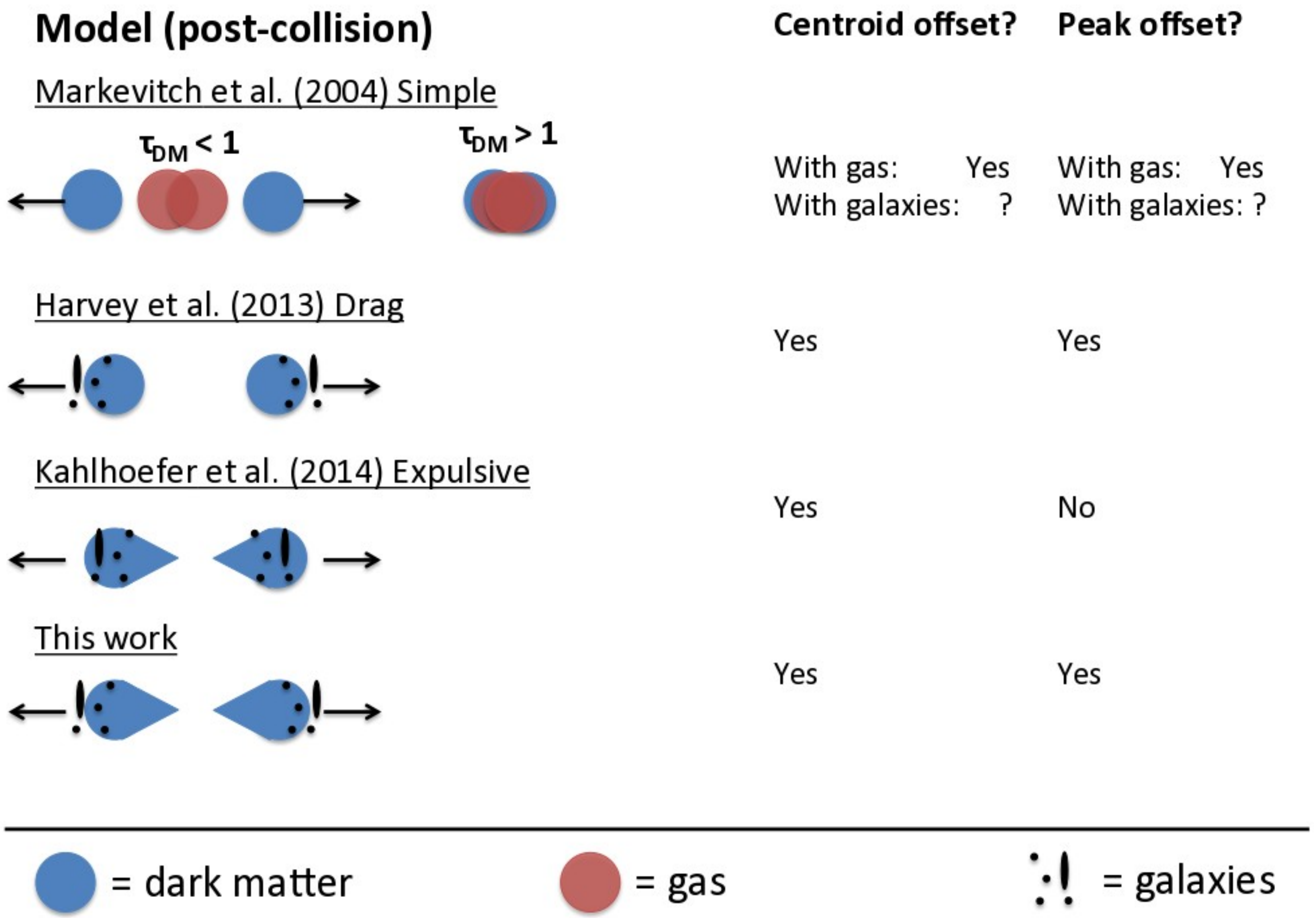
Conclusions part II

- A simple and attractive way to obtain large self-interactions with strong velocity dependence is to assume that DM interacts via a very light mediator.
- For scalar mediators it is difficult to satisfy all experimental (e.g. direct detection) and cosmological (e.g. BBN) constraints at the same time.
- Pseudoscalar mediators (such as axion-like particles) coupling the visible and dark sectors are an interesting alternative.
- The intensity frontier is a promising and rarely studied way to constrain these types of models and yields relevant and highly complementary information.
- For example, ALPs coupling dominantly to photons can potentially be explored at proton beam dump experiments, like the past NuCal, the present NA62 or the planned ShiP expeirments.

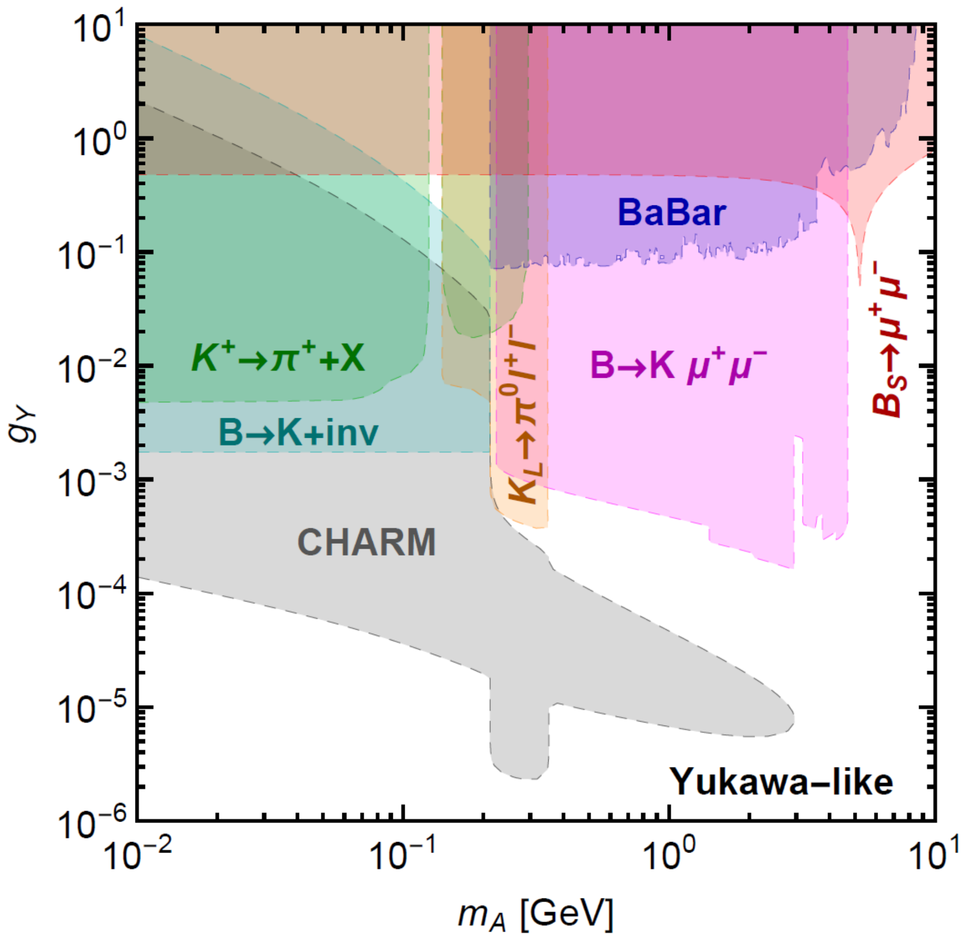
Backup

The reality is (always) more complicated

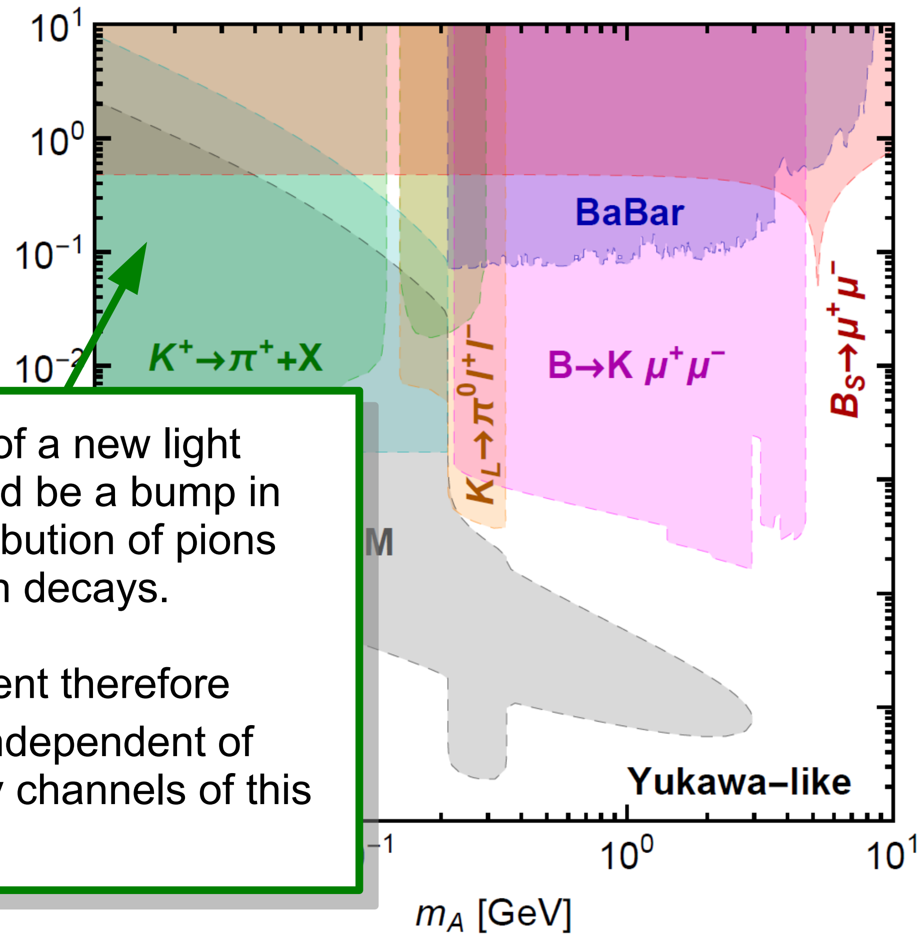
- A recent paper by Kim et al. (arXiv:1608.08630) showed that drag effects can also play a role for isotropic scattering.



Experimental results

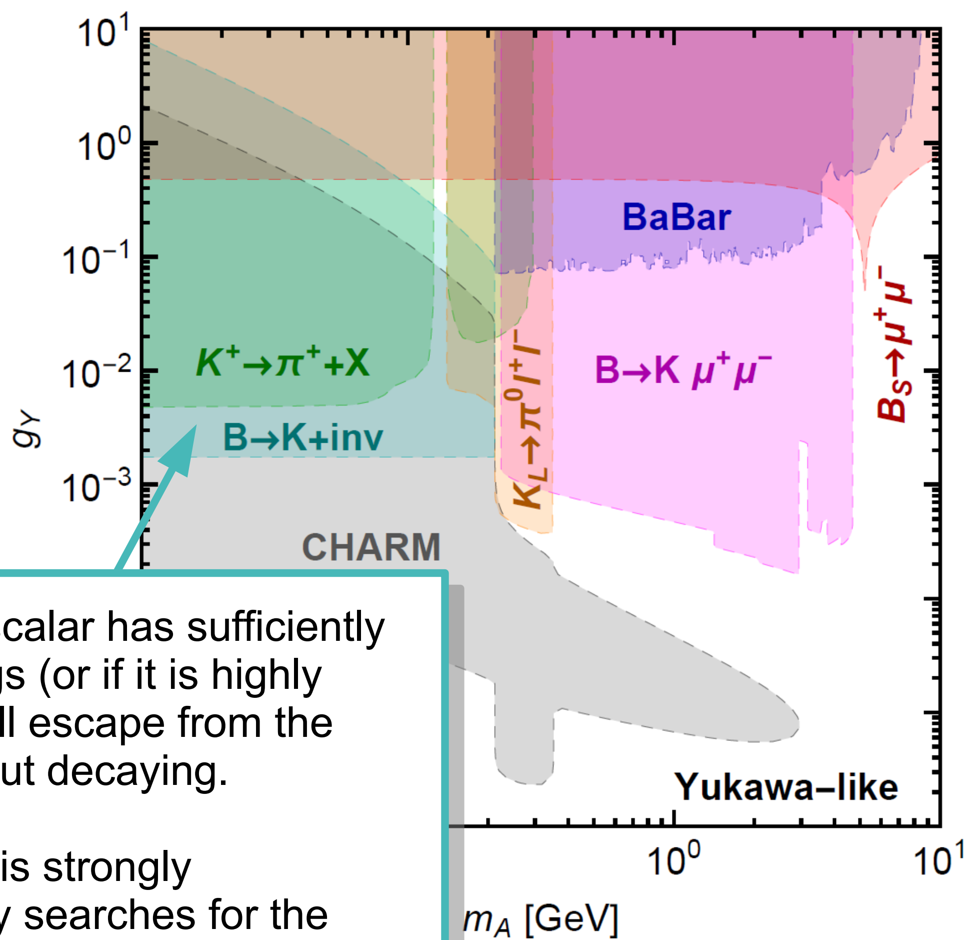


Experimental results



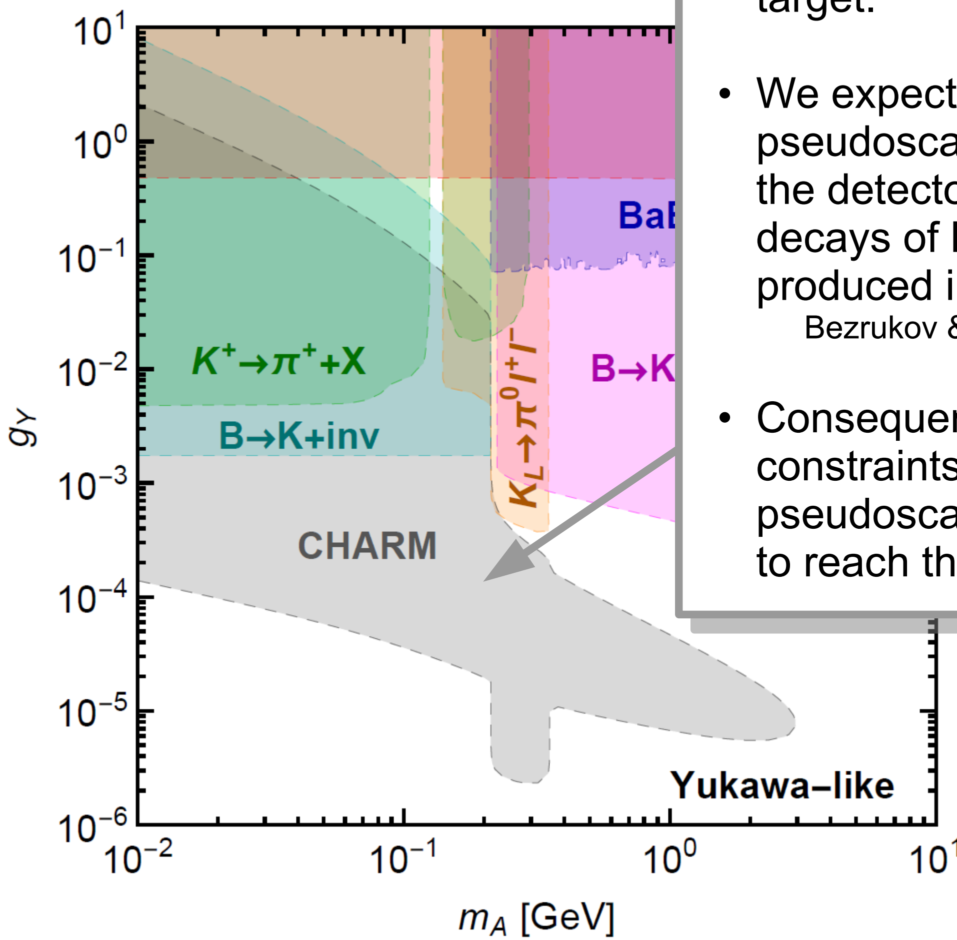
- In the presence of a new light state there should be a bump in momentum distribution of pions produced in kaon decays.
- The $K_{\mu 2}$ experiment therefore places bounds independent of the further decay channels of this new state.

Experimental results



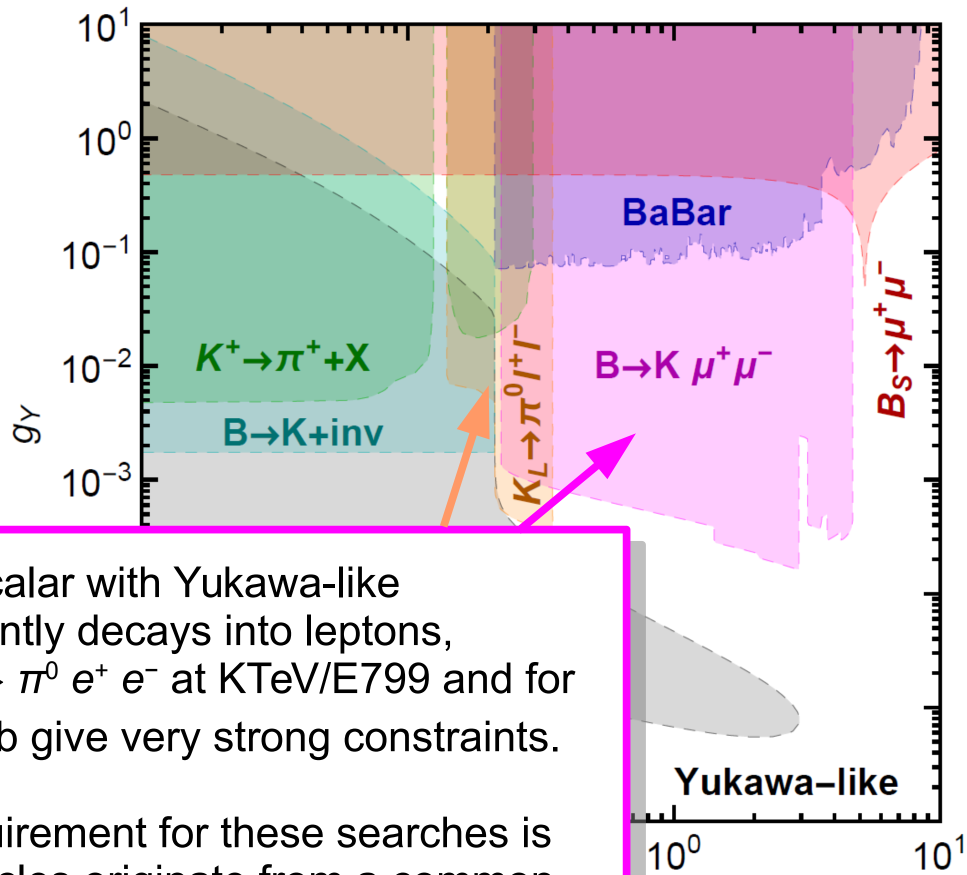
- If the pseudoscalar has sufficiently small couplings (or if it is highly boosted), it will escape from the detector without decaying.
- This scenario is strongly constrained by searches for the rare decay $B^0 \rightarrow K_S$ + inv at CLEO.

Experimental results



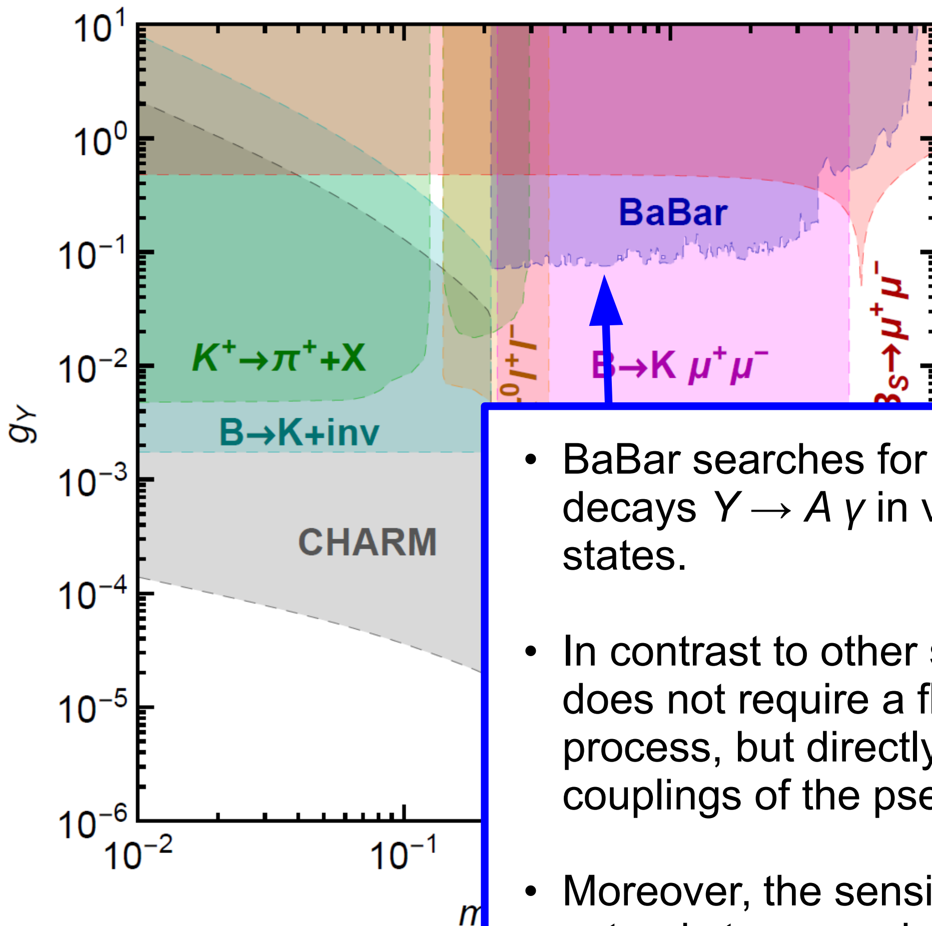
- CHARM is a proton beam-dump experiment with a detector placed 500m away from the target.
- We expect a large flux of pseudoscalars in the direction of the detector resulting from the decays of kaons and B-mesons produced in the target.
  Bezrukov & Gorbunov, arXiv:0912.0390
- Consequently we obtain strong constraints in the case that the pseudoscalar lives long enough to reach the detector.

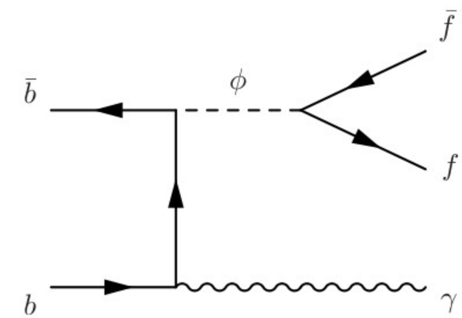
Experimental results



- Since a pseudoscalar with Yukawa-like couplings dominantly decays into leptons, searches for $K_L \to \pi^0 e^+ e^-$ at KTeV/E799 and for $B \to K\, l^+ l^-$ at LHCb give very strong constraints.
- An important requirement for these searches is that all three particles originate from a common vertex. These searches are therefore not sensitive for the case that the pseudoscalar decays from a displaced vertex.

Experimental results





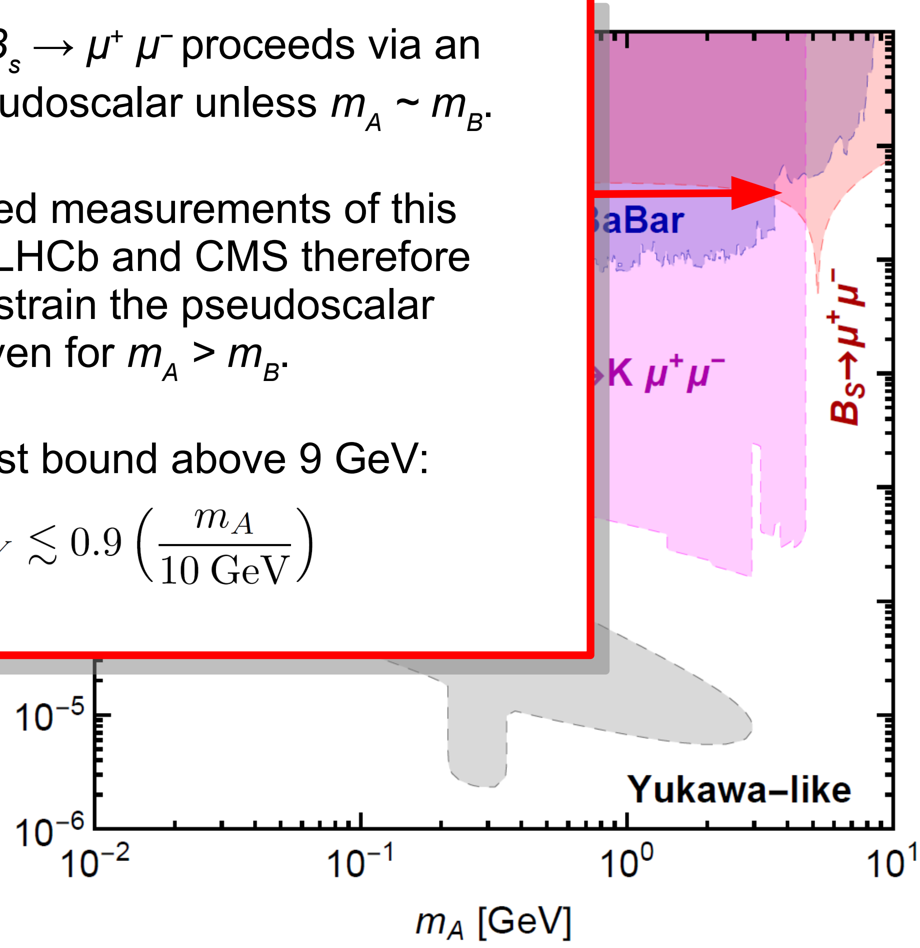
- BaBar searches for radiative Upsilon decays $Y \to A\,\gamma$ in various different final states.
- In contrast to other searches, this decay does not require a flavour-changing process, but directly probes the tree-level couplings of the pseudoscalar.
- Moreover, the sensitivity of this search extends to approximately 9 GeV.

Experimental results

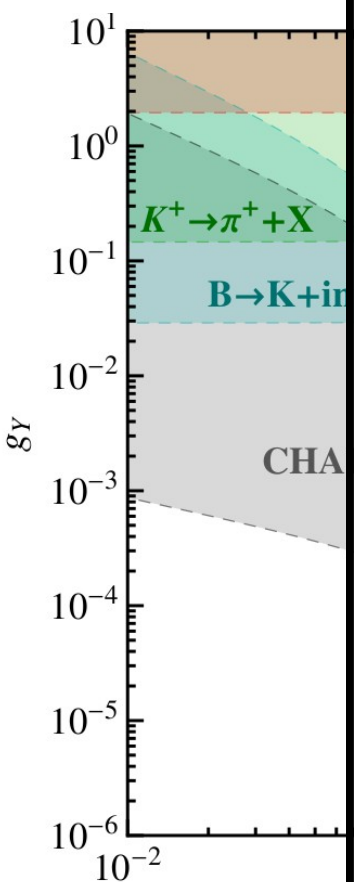
- The decay $B_s \to \mu^+ \mu^-$ proceeds via an off-shell pseudoscalar unless $m_A \sim m_B$.
- The combined measurements of this decay from LHCb and CMS therefore allow to constrain the pseudoscalar couplings even for $m_A > m_B$.

→ The strongest bound above 9 GeV:

$$g_Y \lesssim 0.9 \left(\frac{m_A}{10\ \text{GeV}}\right)$$



Experimental results



Channel	Experiment	Mass range [MeV]	Ref.	Relevant for
$K^+ \to \pi^+ + \text{inv}$	E949	0–110	[70]	Long lifetime*
		150–260	[71]	Long lifetime*
	E787	0–110 & 150–260	[72]	Long lifetime
$K^+ \to \pi^+\pi^0 \to \pi^+\nu\bar{\nu}$	E949	130–140	[73]	Long lifetime*
$K^+ \to \pi^+ e^+e^-$	NA48/2	140–350	[74]	Leptonic decays
$K_L \to \pi^0 e^+e^-$	KTeV/E799	140–350	[75]	Leptonic decays*
$K^+ \to \pi^+ \mu^+\mu^-$	NA48/2	210–350	[76]	Leptonic decays
$K_L \to \pi^0 \mu^+\mu^-$	KTeV/E799	210–350	[77]	Leptonic decays*
$K_L \to \pi^0 \gamma\gamma$	KTeV	40–100 & 160–350	[78]	Photonic decays*
$K_L \to \pi^0\pi^0 \to 4\gamma$	KTeV	130–140	[79]	Photonic decays*
$K^+ \to \pi^+ A$	$K_{\mu 2}$	10–130 & 140–300	[80]	All decay modes*
$B^0 \to K_S^0 + \text{inv}$	CLEO	0–1100	[81]	Long lifetime*
$B \to K\,\ell^+\ell^-$	BaBar	30–3000	[82]	Leptonic decays
	BELLE	140–3000	[83]	Leptonic decays
	LHCb	220–4690	[84]	Leptonic decays*
$B \to X_s\,\mu^+\mu^-$	BELLE	210–3000	[85]	Leptonic decays
$b \to s\,g$	CLEO	$m_A < m_B - m_K$	[86]	Hadronic decays*
$B_s \to \mu^+\mu^-$	LHCb/CMS	all masses	[87, 88]	Lepton couplings*
$\Upsilon \to \gamma\,\tau^+\tau^-$	BaBar	3500–9200	[89]	Leptonic decays*
$\Upsilon \to \gamma\,\mu^+\mu^-$	BaBar	212–9200	[90]	Leptonic decays*
$\Upsilon \to \gamma + \text{hadrons}$	BaBar	300–7000	[91]	Hadronic decays*
$K,\ B \to A + X$	CHARM	0–4000	[92]	Leptonic and photonic decays*

Many other searches considered.
Focus on the most constraining here.