Testing freeze-in with Z' bosons

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Ottawa, Canada

Talk based on C. Cosme, M. Dutra, S. Godfrey, and T. Gray
arXiv:2104.13937

Carleton University

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

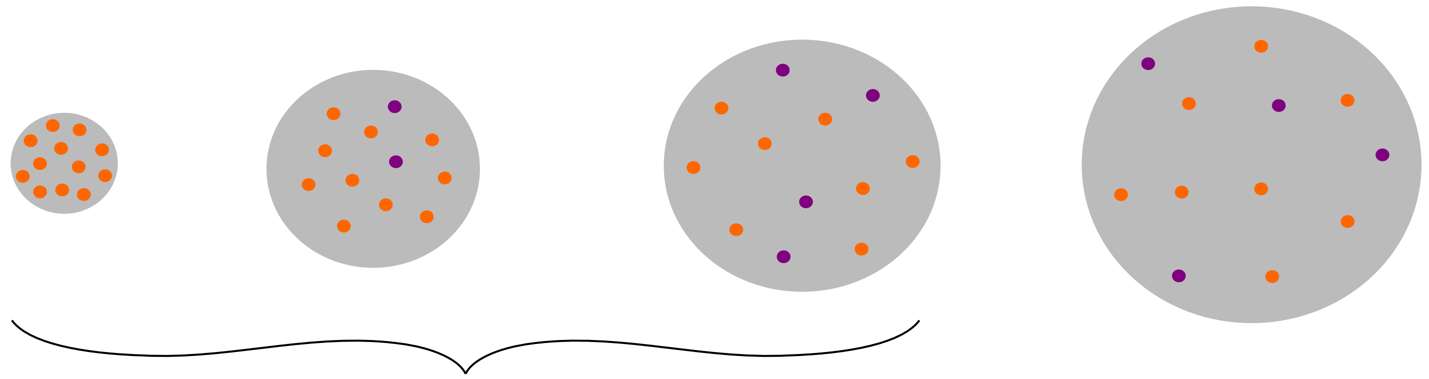
May 25, 2021

Overview

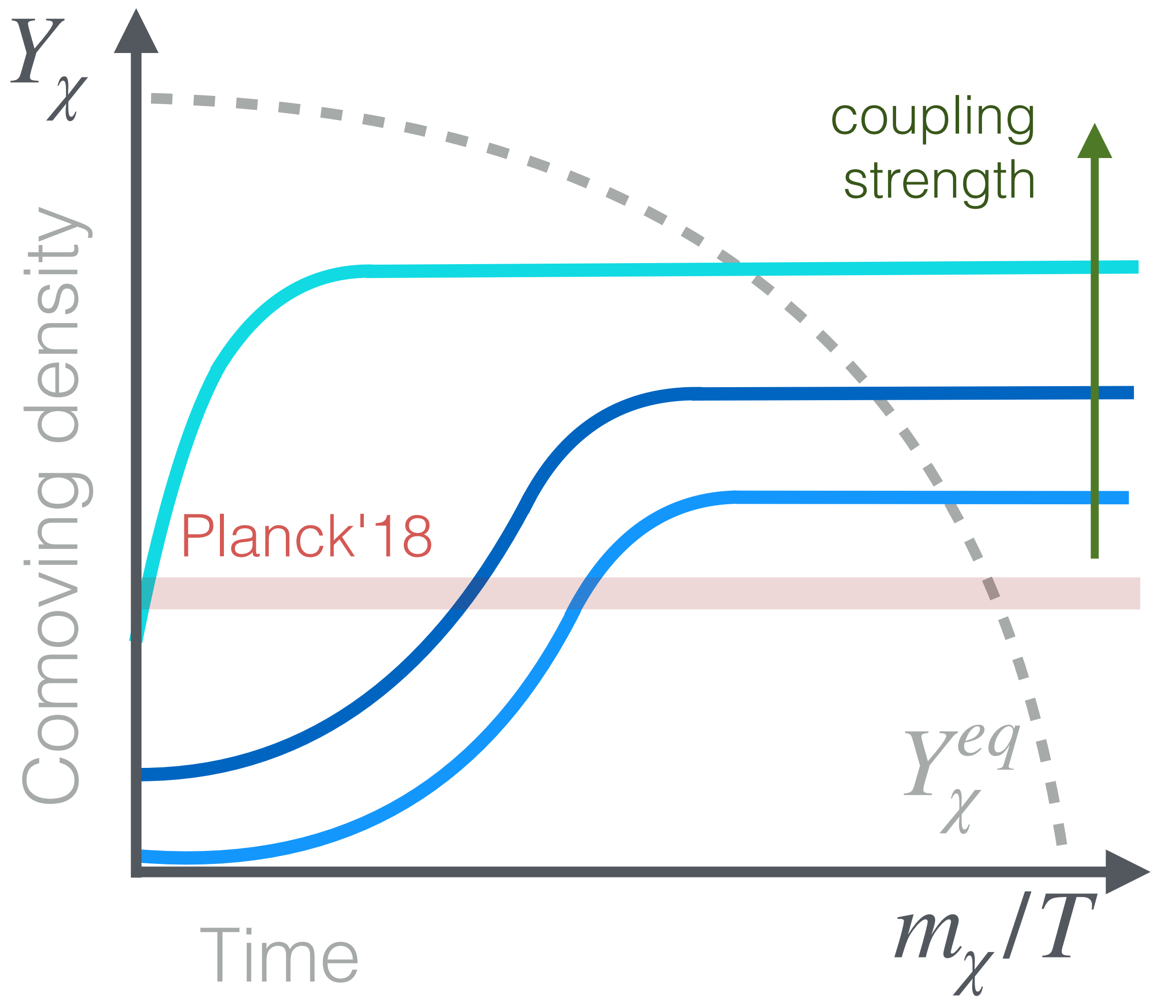
1. Introduction
2. Axial and vector Z' portal
3. Viable parameter space
4. Conclusions

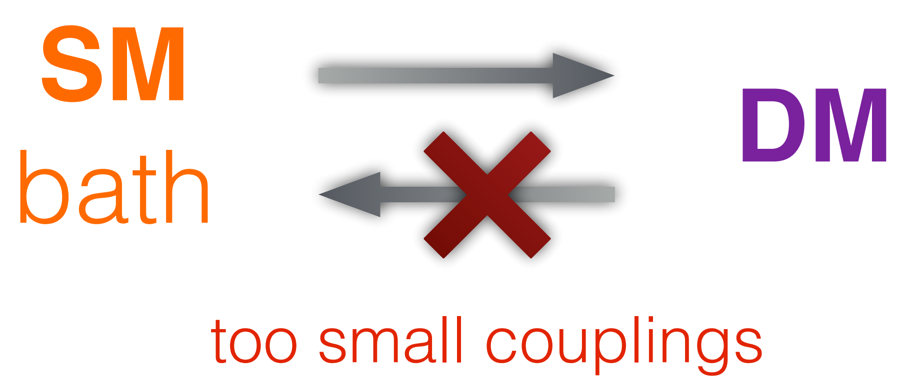
Introduction: freeze-in mechanism

Evolution of feebly interacting massive particles (**FIMPs**) in the early universe:



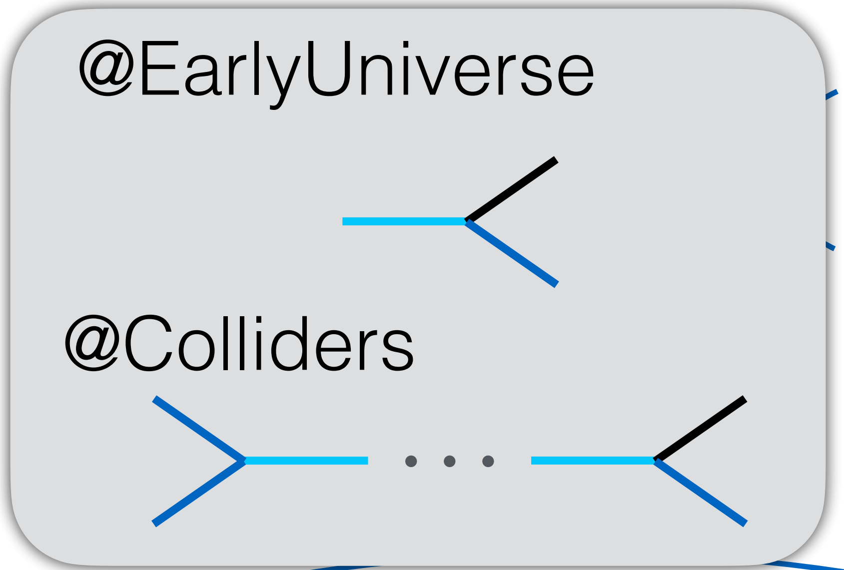
(out-of-equilibrium) **freeze-in**





Introduction: how can we test freeze-in?

Colliders&Accelerators Astro&Cosmo



R.Co, F.D'Eramo, L.Hall, D.Pappadopulo
arXiv:1506.07532

ATLAS, CMS
Early matter era

J.No, P.Tunney, B.Zaldívar
arXiv:1908.11387

MATHUSLA
HL-LHC
BBN
Structure formation

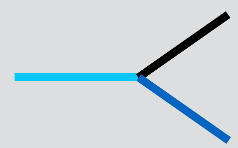
G.Bélanger, N.Desai, A.Goudelis, J.Harz, A.Lessa, J.No, A.Pukhov, S.Sekmen, D.Sengupta, B.Zaldívar, J.Zurita
arXiv:1811.05478

ATLAS, CMS

Introduction: how can we test freeze-in?

Colliders&Accelerators   Astro&Cosmo   Direct detection

@EarlyUniverse



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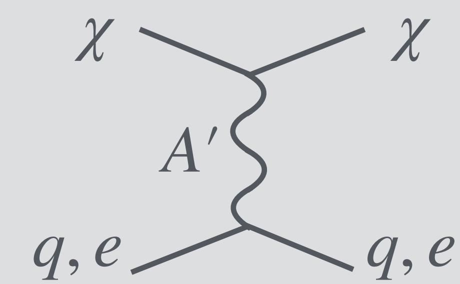
ATLAS, CMS

MeV-scale dark photon

$U(1)_{kin\ mix}, U(1)_{B-L}, \dots$



T.Hambye, M.Tytgat, J.Vandecasteele, L.Vanderheyden
arXiv:1807.05022

XENON1T
Self-interaction
Late decay

Fixed-target experiments
XENON1T

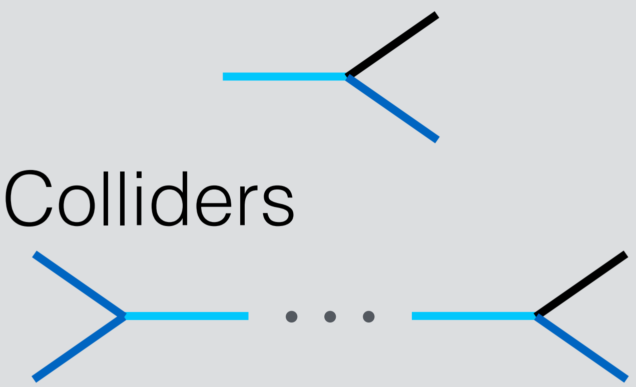
S.Heeba, F.Kahlhoefer
arXiv:1908.09834

Introduction: how can we test freeze-in?

Colliders&Accelerators Astro&Cosmo Direct detection Indirect detection

@EarlyUniverse

@Colliders



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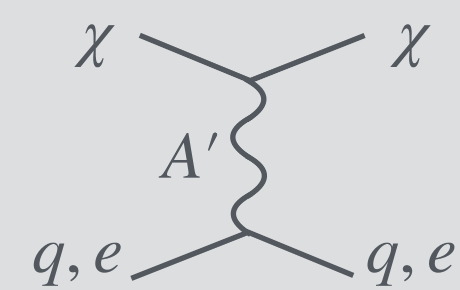
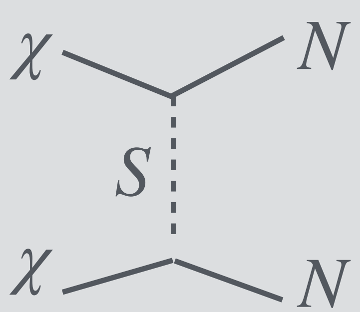


T.Hambye, M.Tytgat, J.Vandecasteele, L.Vanderheyden
arXiv:1807.05022
XENON1T
Self-interaction
Late decay

Neutrino portal



$\Rightarrow \gamma - rays$

Fermi-LAT & H.E.S.S.
Early matter era
C.Cosme, M.Dutra, T.Ma, Y.Wu, L.Yang
arXiv:2003.01723

Fixed-target experiments
XENON1T
S.Heeba, F.Kahlhoefer
arXiv:1908.09834

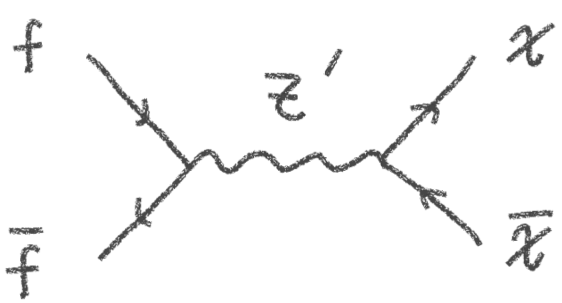
Axial and vector Z' portal

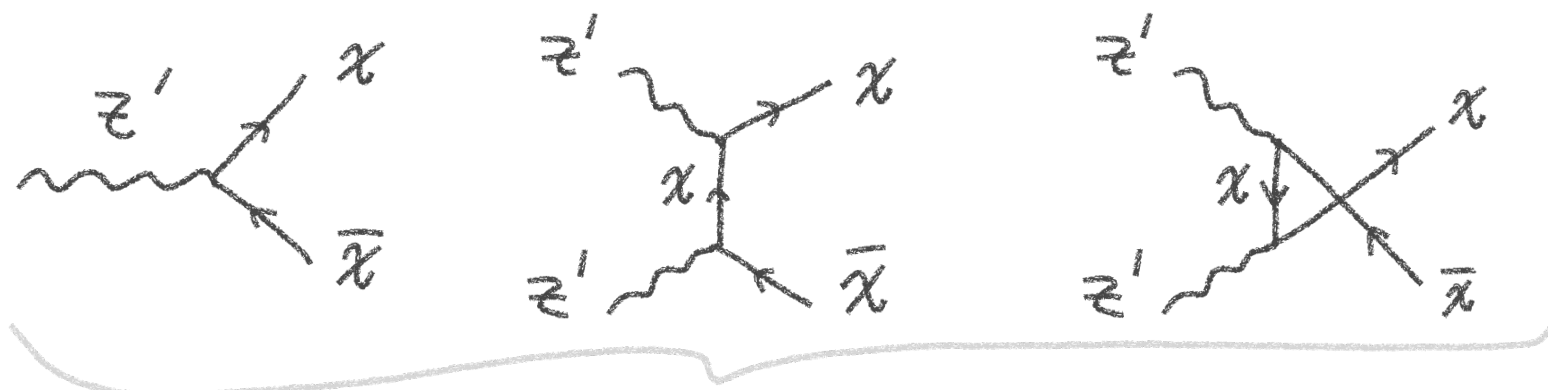
Catarina Cosme, MD, Steve Godfrey, and Taylor Gray
arXiv:2104.13937

$$\mathscr{L} \supset m_\chi \bar{\chi}\chi - \frac{m_{Z'}}{2} Z'_\mu Z'^\mu + \bar{\chi}\gamma^\mu (V_\chi - A_\chi \gamma_5)\chi Z'_\mu + \sum_f \bar{f}\gamma^\mu (V_f - A_f \gamma_5) f Z'_\mu$$

$$V_f = \frac{g_{Z'}}{2}(X_{f_L} + X_{f_R})$$

$$A_f = \frac{g_{Z'}}{2}(X_{f_L} - X_{f_R})$$



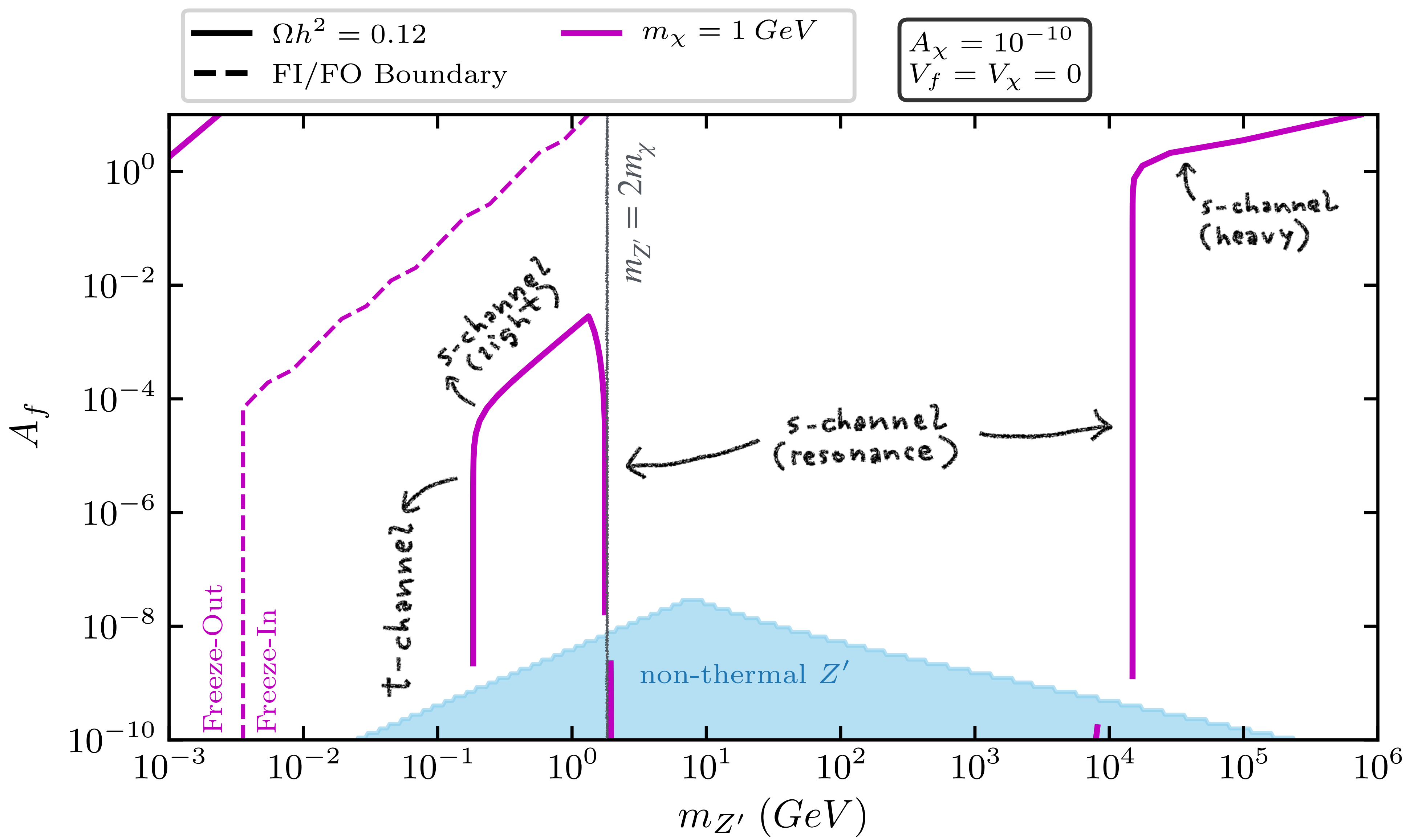


Z' part of the SM bath ($n_{Z'} = n_{Z'}^{eq} \sim n_f$)

$$\Gamma_{s-ch} + \Gamma_{dec} + \Gamma_{t-ch} < H \Rightarrow \text{ Freeze-in}$$

$$\Gamma_{s-ch,\, dec,\, t-ch} > H \Rightarrow \text{ Freeze-out}$$

Viable parameter space: relic density



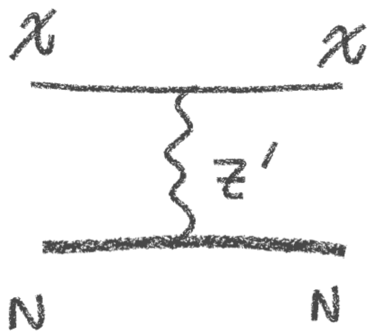
- Smaller (larger) m_χ requires smaller (larger) $m_{Z'}$

Catarina Cosme, MD, Steve Godfrey, and Taylor Gray
arXiv:2104.13937

Viable parameter space: constraints

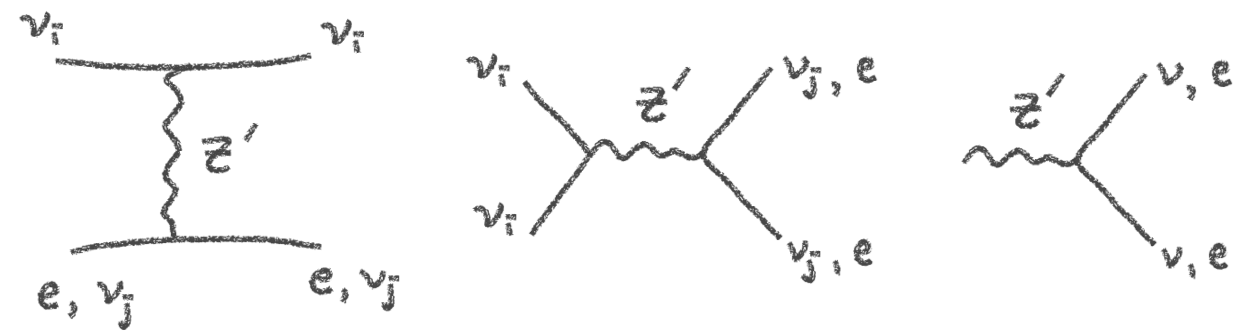
Direct detection

XENON1T



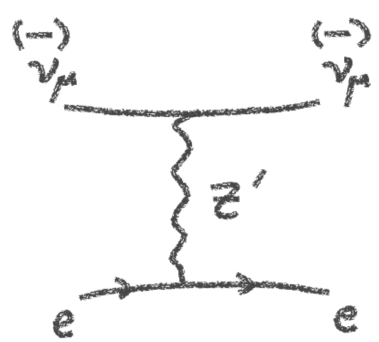
Astro&Cosmo

Big Bang nucleosynthesis



Colliders&Accelerators

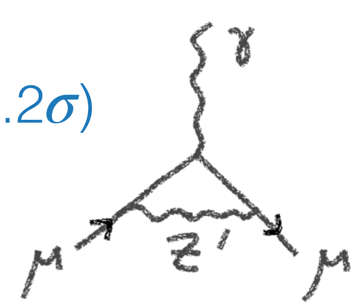
Neutrino-electron scattering



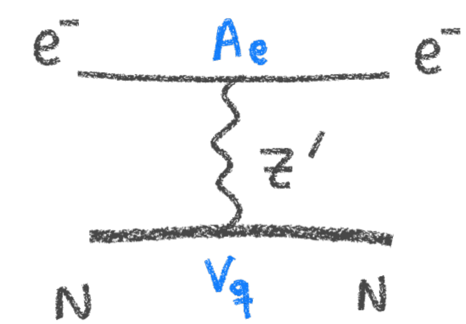
Leptonic anomalous magnetic moments

$(g-2)_\mu$

FNAL+BNL (4.2σ)



Atomic parity violation



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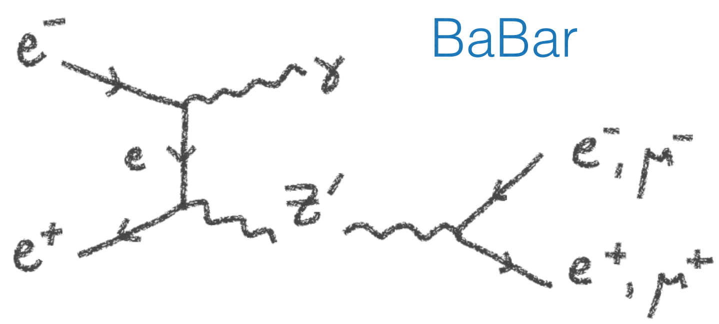
Viable parameter space: constraints

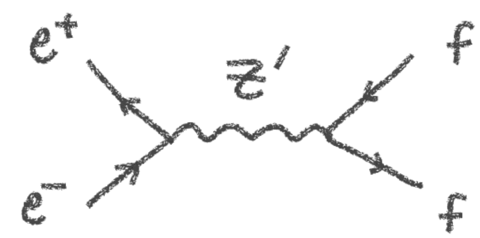
Colliders&Accelerators

Electron-positron collisions

BaBar

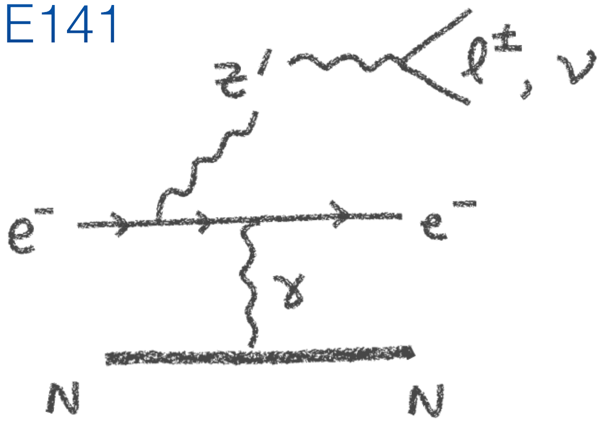


LEP-II



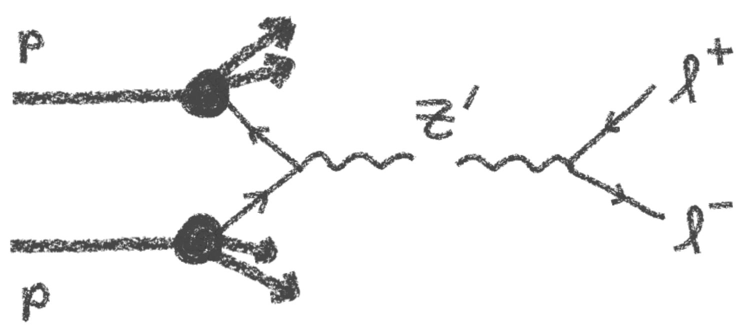
Electron beam-dump

SLAC E137
SLAC E141

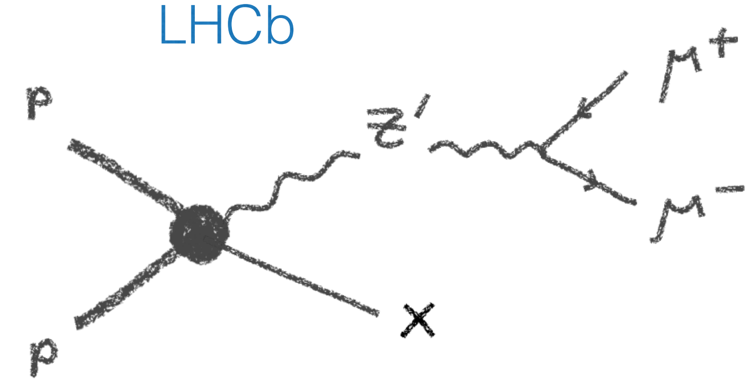


Proton-proton collisions

ATLAS



LHCb



Catarina Cosme, MD, Steve Godfrey, and Taylor Gray
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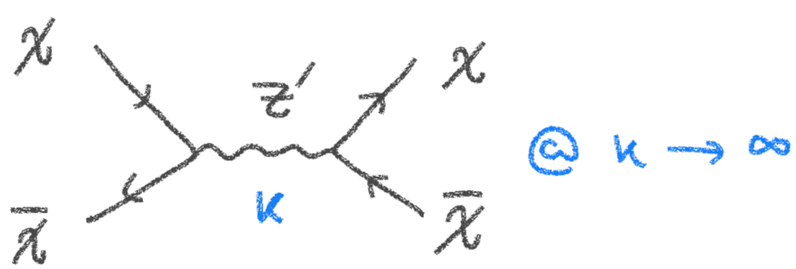
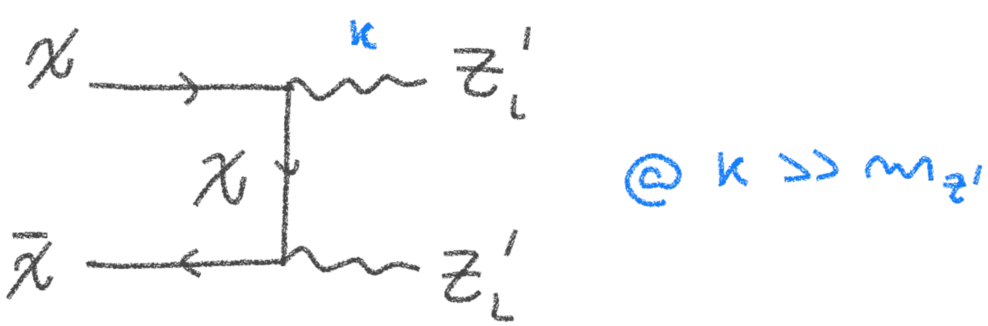
Viable parameter space: constraints

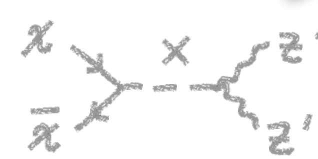
If $A_\chi \neq 0$, perturbative unitarity can be violated @ high energies



$$m_{Z'} \gtrsim \sqrt{2/\pi}\, A_\chi m_\chi$$



New particle restoring unitarity



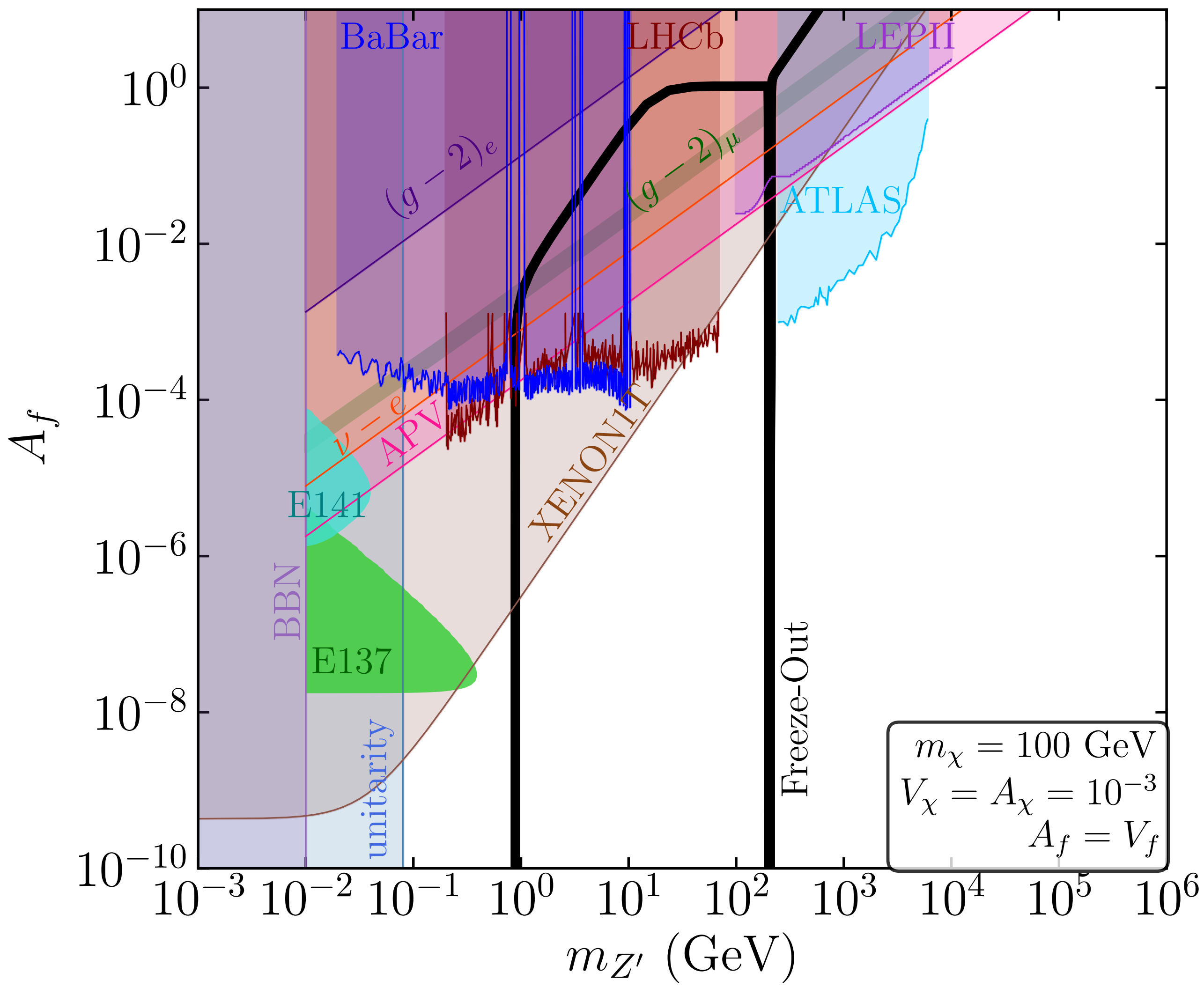
$$M_X < \frac{\pi}{A_\chi^2}\frac{m_{Z'}^2}{m_\chi}$$

F.Kahlhoefer, K.Schmidt-Hoberg, T.Schwetz, S.Vogl
arXiv:1510.02110

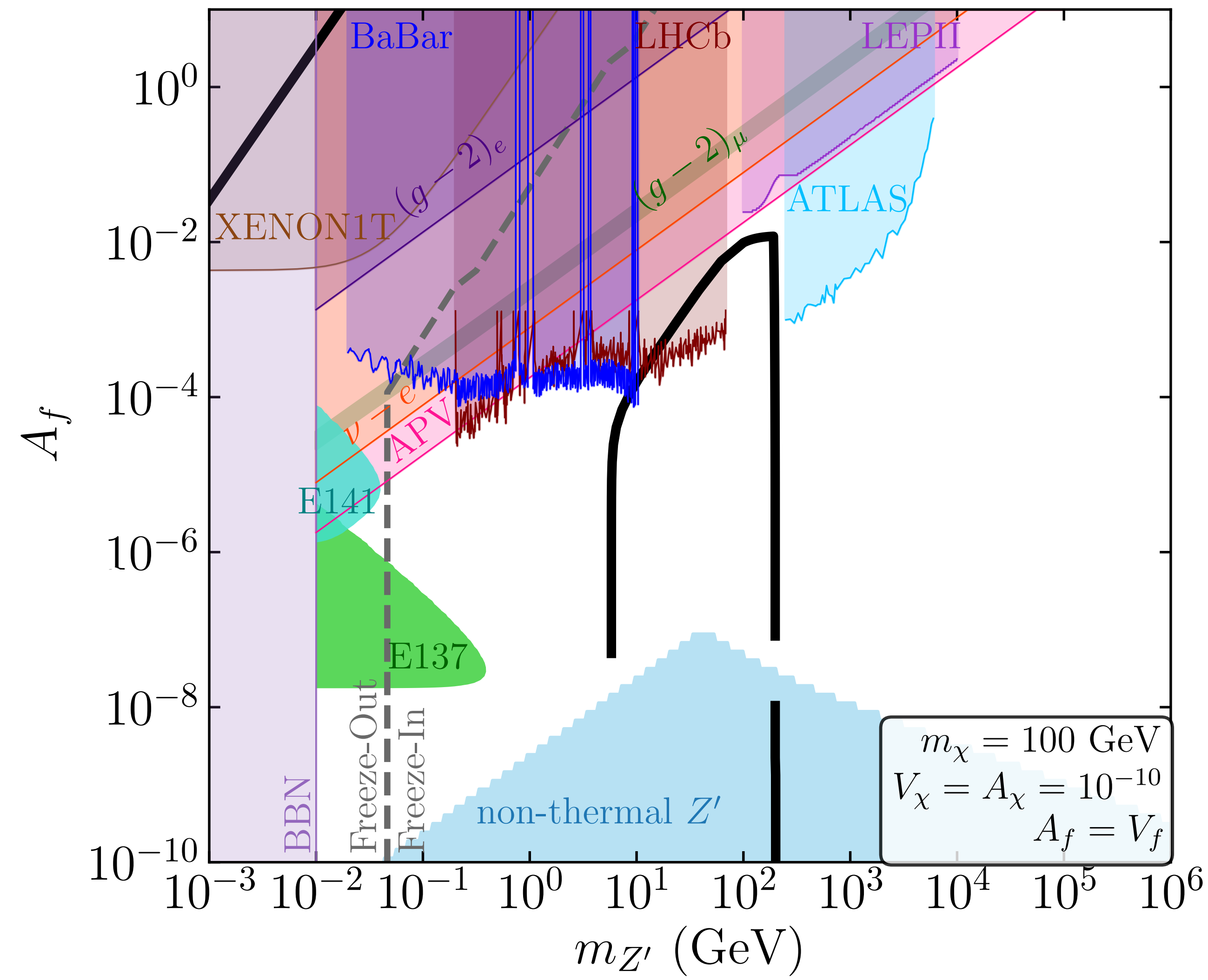
Simplified Z' portals are more natural in the freeze-in regime

Viable parameter space: results

axial and vector (FO)

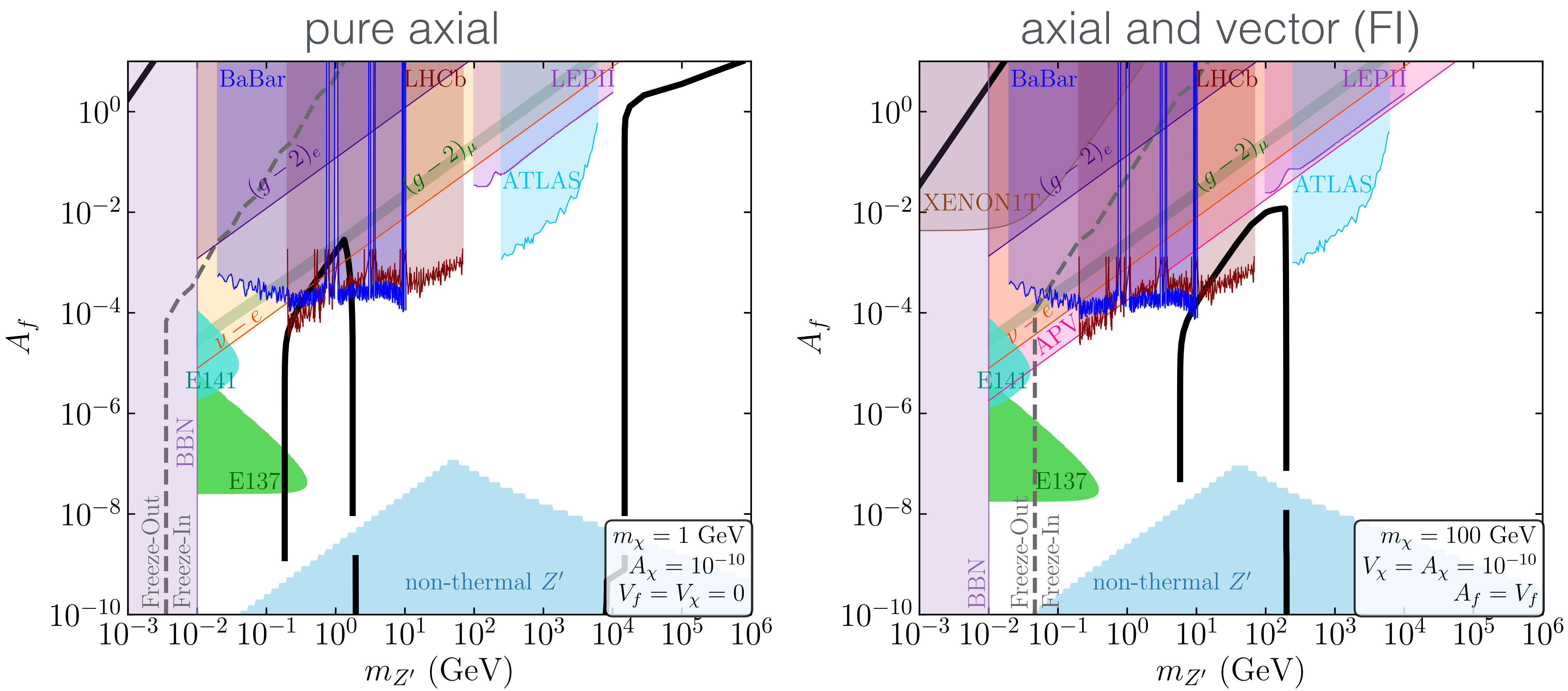


axial and vector (FI)



- FO: only $m_{Z'} \sim 2m_\chi$ and (if $A_{f/\chi} \neq 0$) $m_{Z'} \ll m_\chi$ regions are viable
- Smaller V/A_χ requires larger V/A_f
- FI: tested with colliders, APV, $\nu - e$ scatt., and beam-dump experiments for m_χ in the range of ~100 MeV - 100 GeV!

Viable parameter space: results

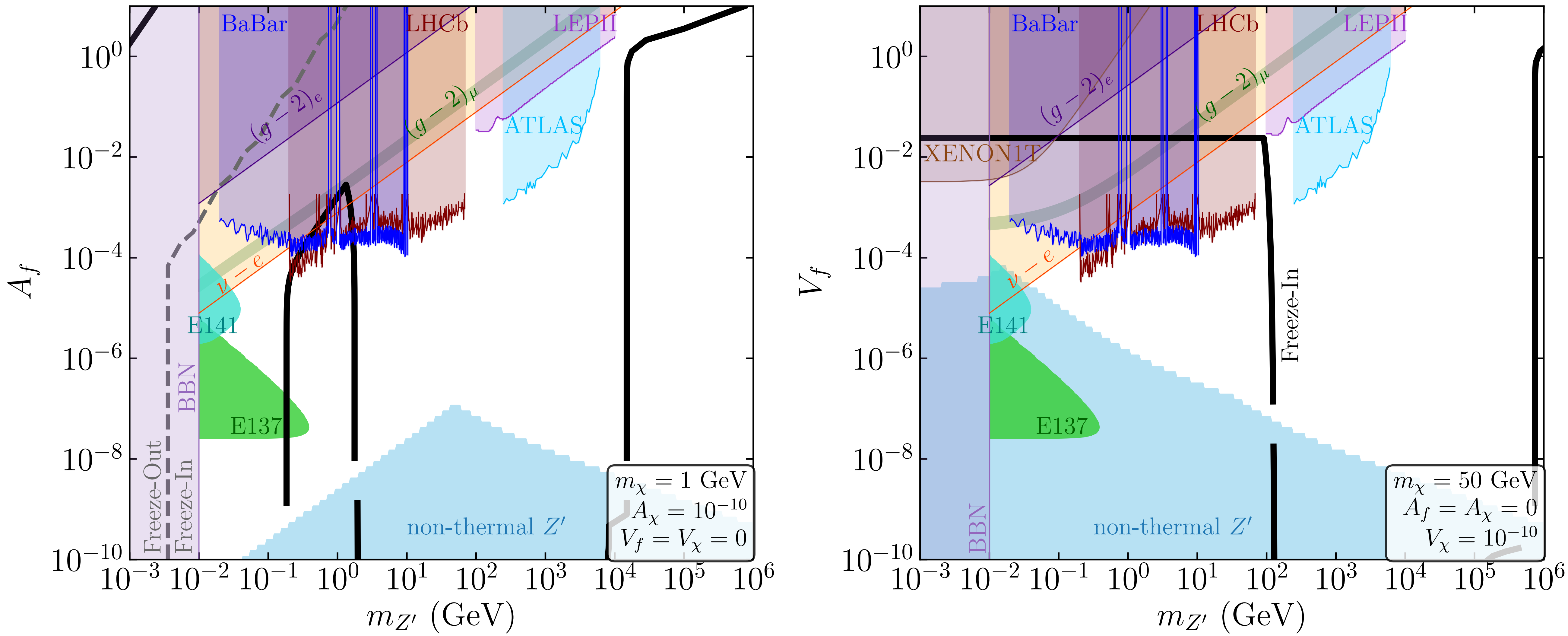


- Similar relic and boundary contours for pure axial and axial-vector cases, with FI still testable!

Viable parameter space: results

pure axial

pure vector



- Without axial couplings, the SM-DM interactions are weaker. In this case:
  - Thermalization is more difficult
  - Only s-channels set the relic density
  - FIMPs become testable by direct detection
  - For larger V_χ, FI is also testable at beam dump experiments

Conclusions

- Z' bosons with both vector and axial couplings to SM fermions can mediate interactions with both WIMPs and FIMPs

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- WIMPs are only viable for $m_\chi \sim m_{Z'}/2$ and (if $A_{f/\chi} \neq 0$) $m_\chi \gg m_{Z'}$

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- WIMPs are only viable for $m_\chi \sim m_{Z'}/2$ and (if $A_{f/\chi} \neq 0$) $m_\chi \gg m_{Z'}$

- Most of the experiments we have considered can already test FIMPs, especially for $m_\chi > m_{Z'}/2$

Thank you!