

Testing freeze-in with Z' bosons

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Talk based on:

C. Cosme, M. Dutra, S. Godfrey, T. Gray; JHEP **arXiv:2104.13937**

BSM PANDEMIC Delta Series

November 2nd, 2021

Phenomenology **A**nd **N**etworking **D**espite **E**veryone **M**eandering
Inside **C**autiously

Outline

1. Introduction
2. Z' portal model of FIMP dark matter
3. Conclusions

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Introduction: Dark matter particles

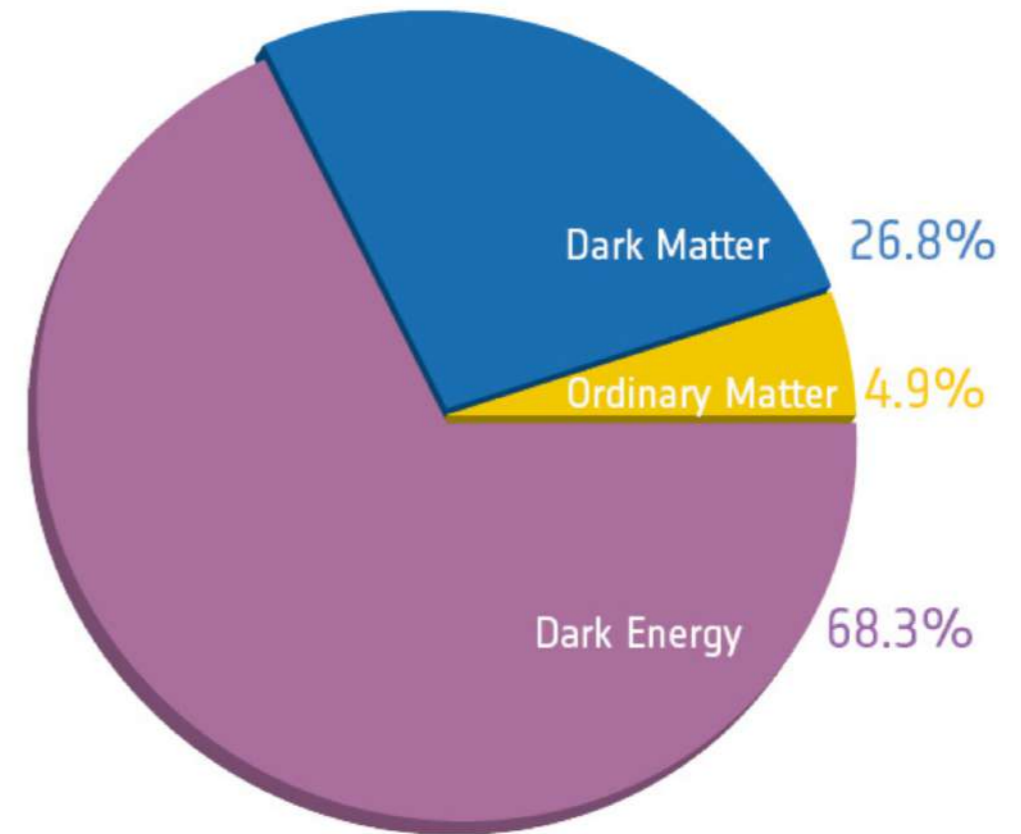
effectively NEUTRAL

NON-BARYONIC

WEAKLY INTERACTING

mostly COLD

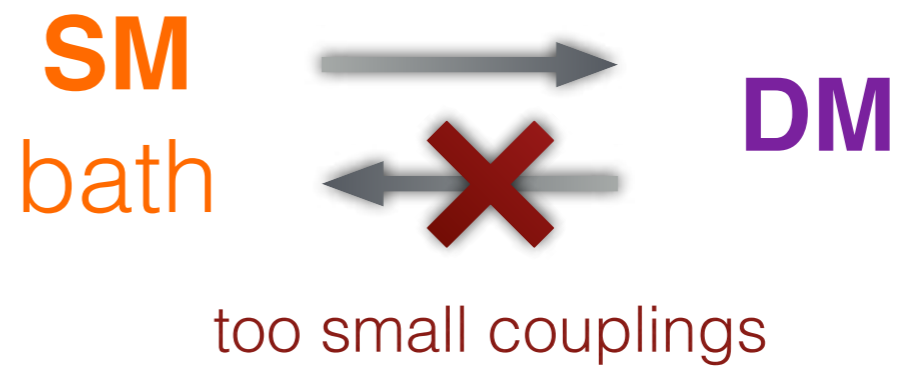
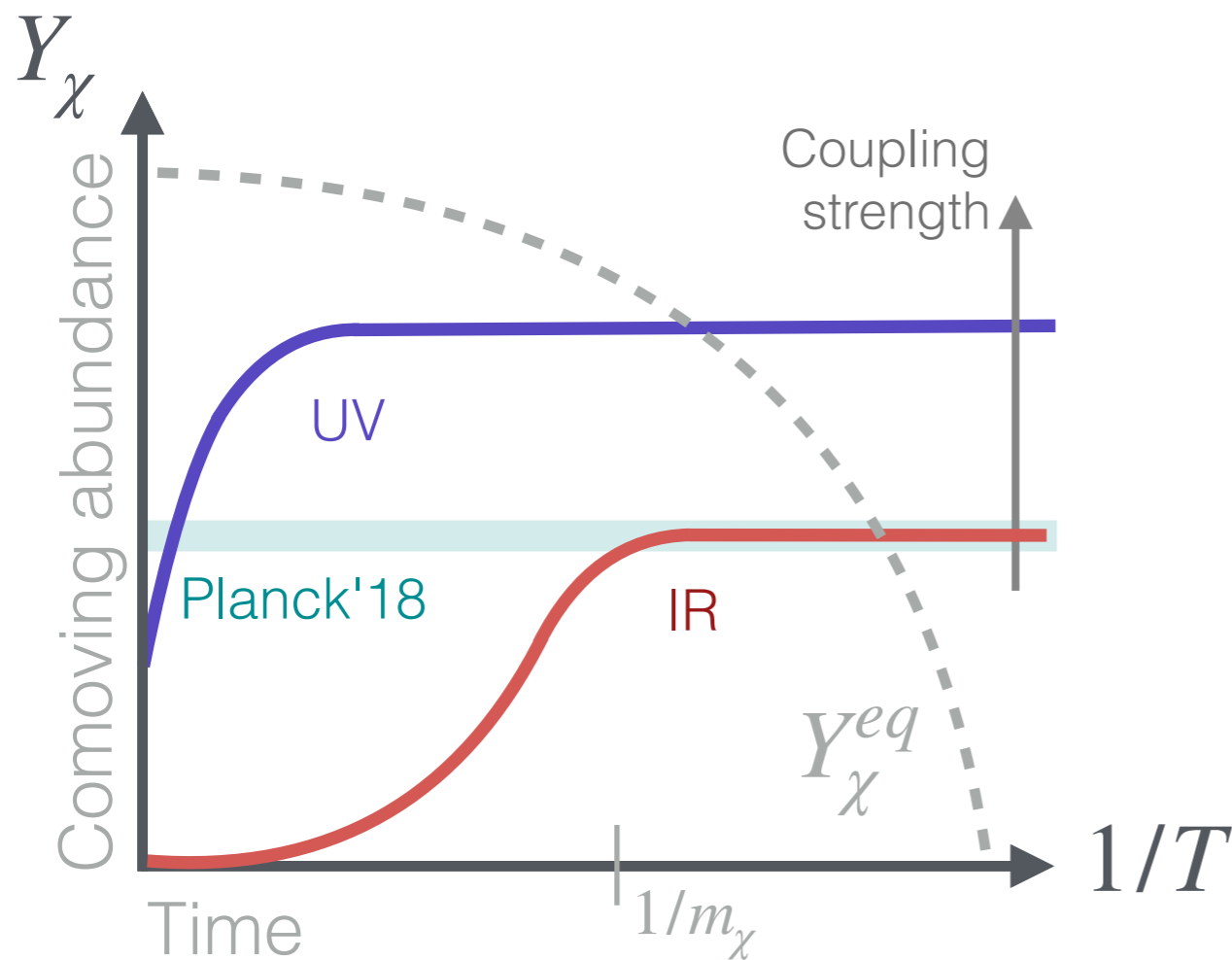
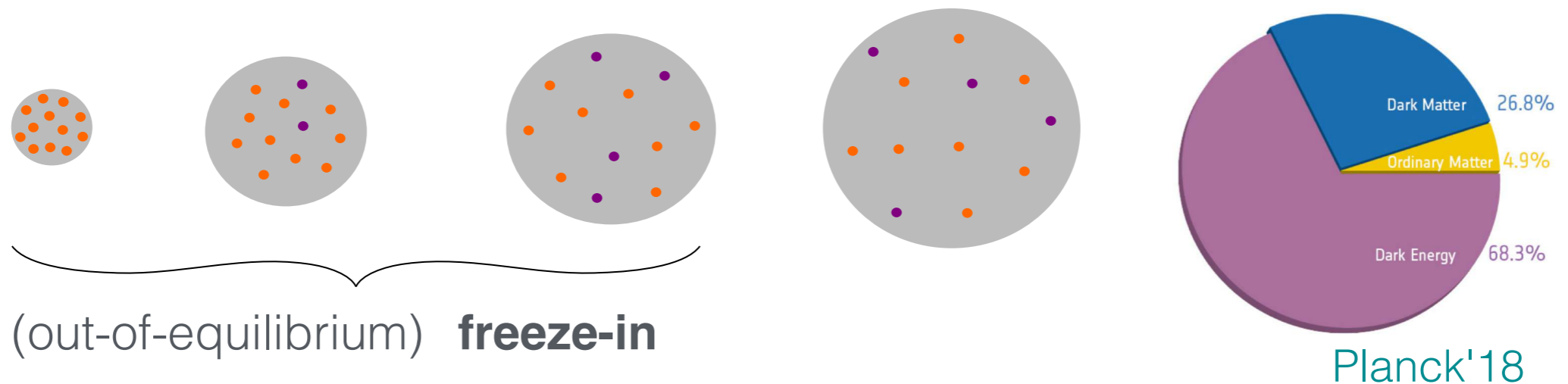
cosmologically STABLE



Planck'18

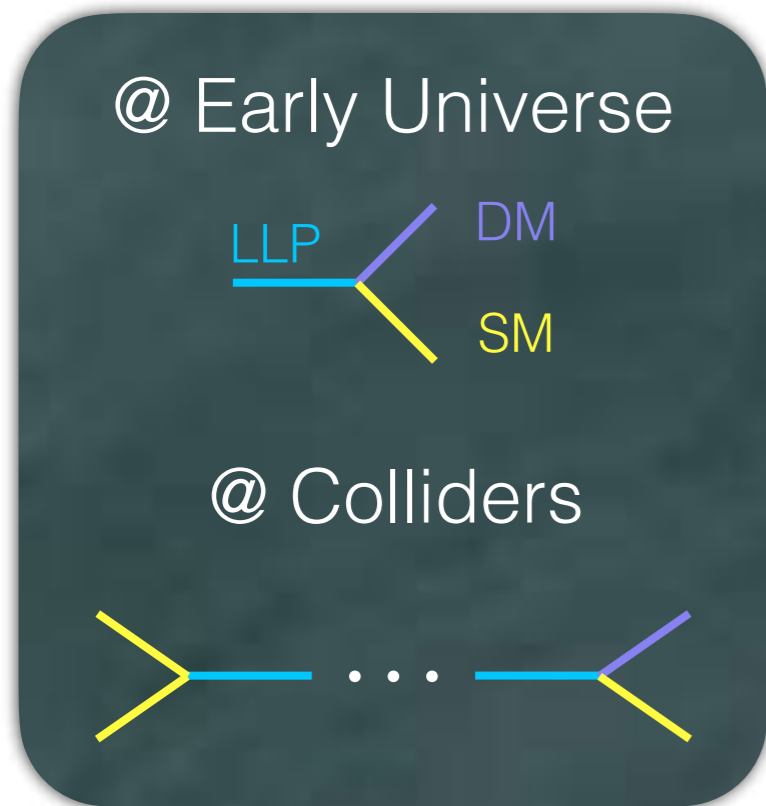
Introduction: The freeze-in mechanism

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



Introduction: Testing freeze-in

Colliders&Accelerators

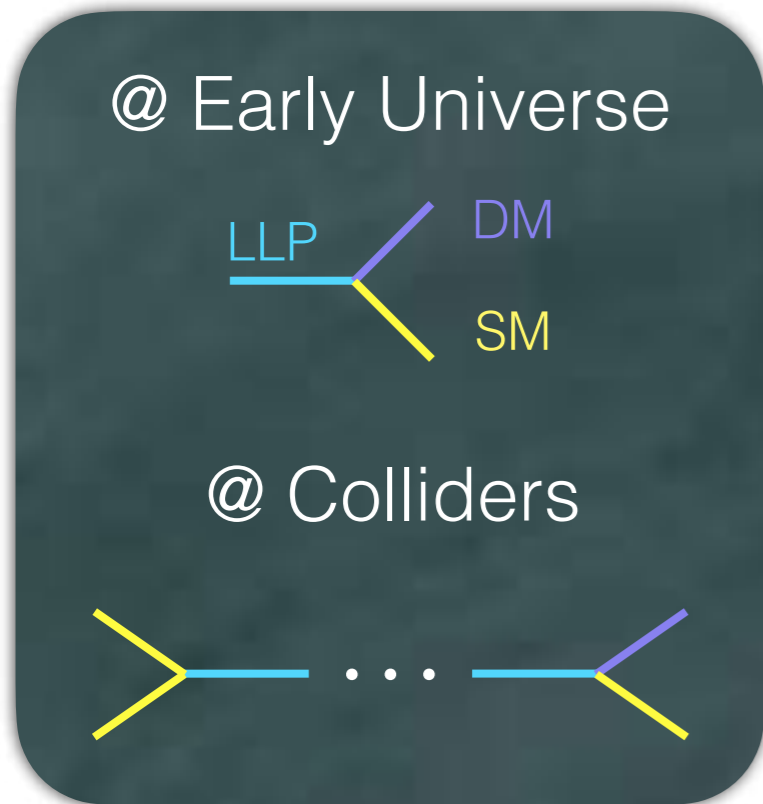


Models with long-lived particles

1506.07532
1611.09540
1805.04423
1811.05478
1908.11387

Introduction: Testing freeze-in

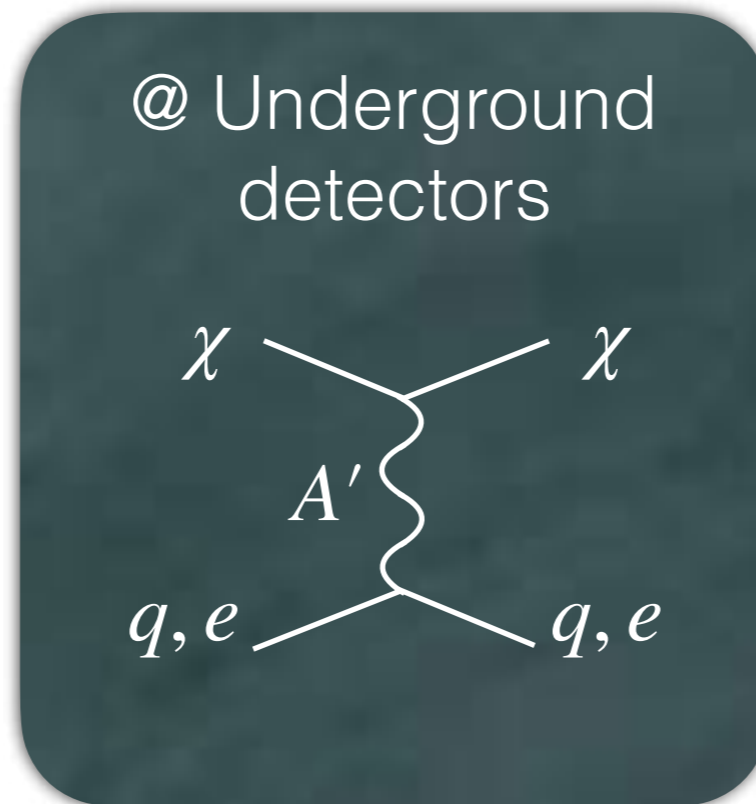
Colliders&Accelerators



Models with long-lived particles

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1611.09540
1805.04423
1811.05478
1908.11387

Direct detection

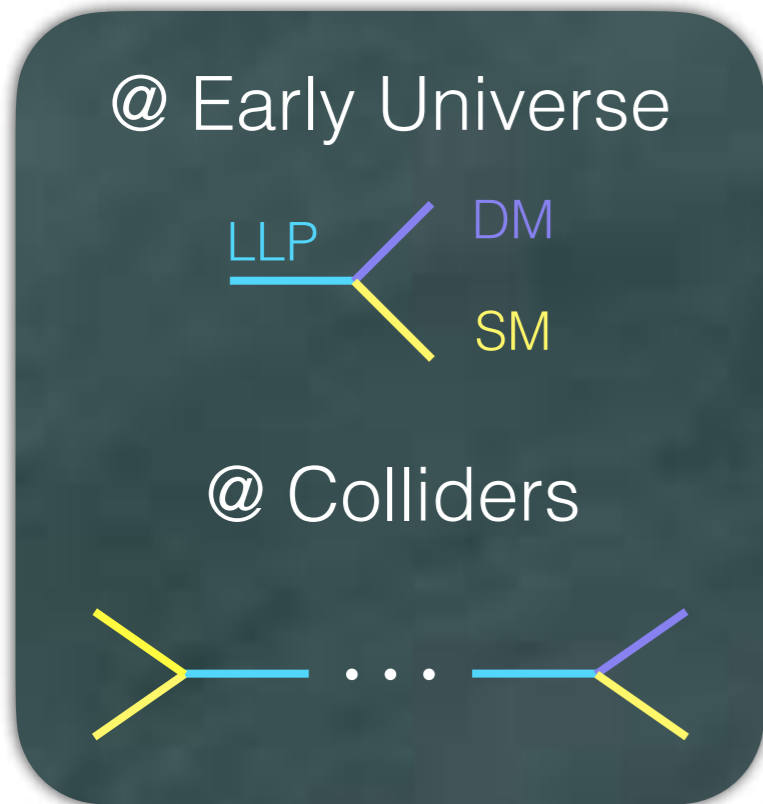


Models with light mediators

1807.05022
1908.09834
2006.15672

Introduction: Testing freeze-in

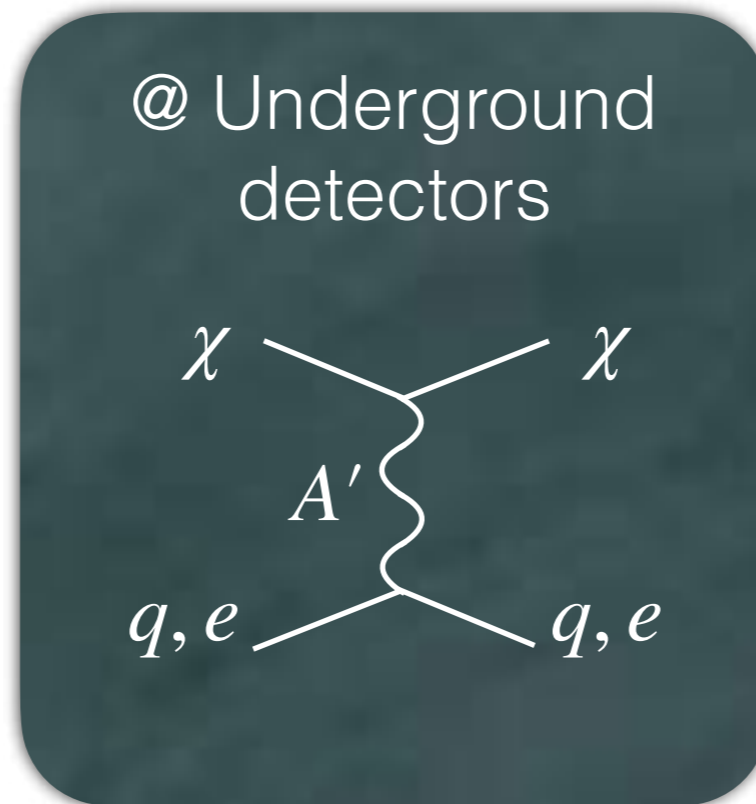
Colliders&Accelerators



Models with long-lived particles

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1611.09540
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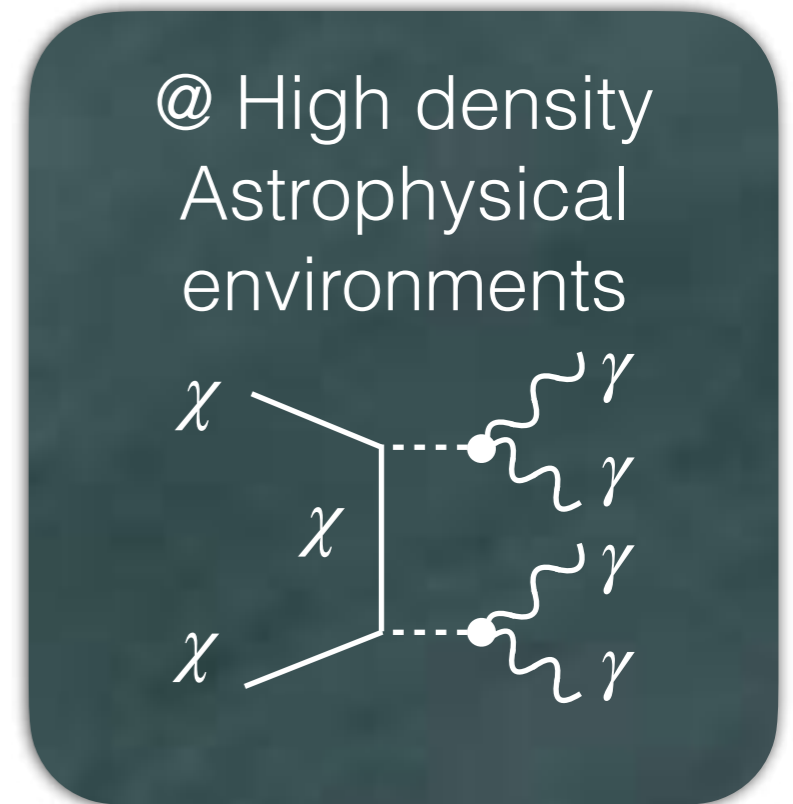
Direct detection



Models with light mediators

1807.05022
1908.09834
2006.15672

Indirect detection



Models with mediators effectively coupled to photons

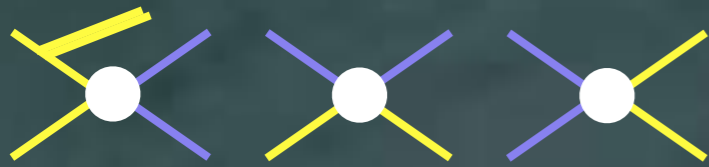
1710.02146
1907.07973

Introduction: Testing freeze-in

@ Early Universe

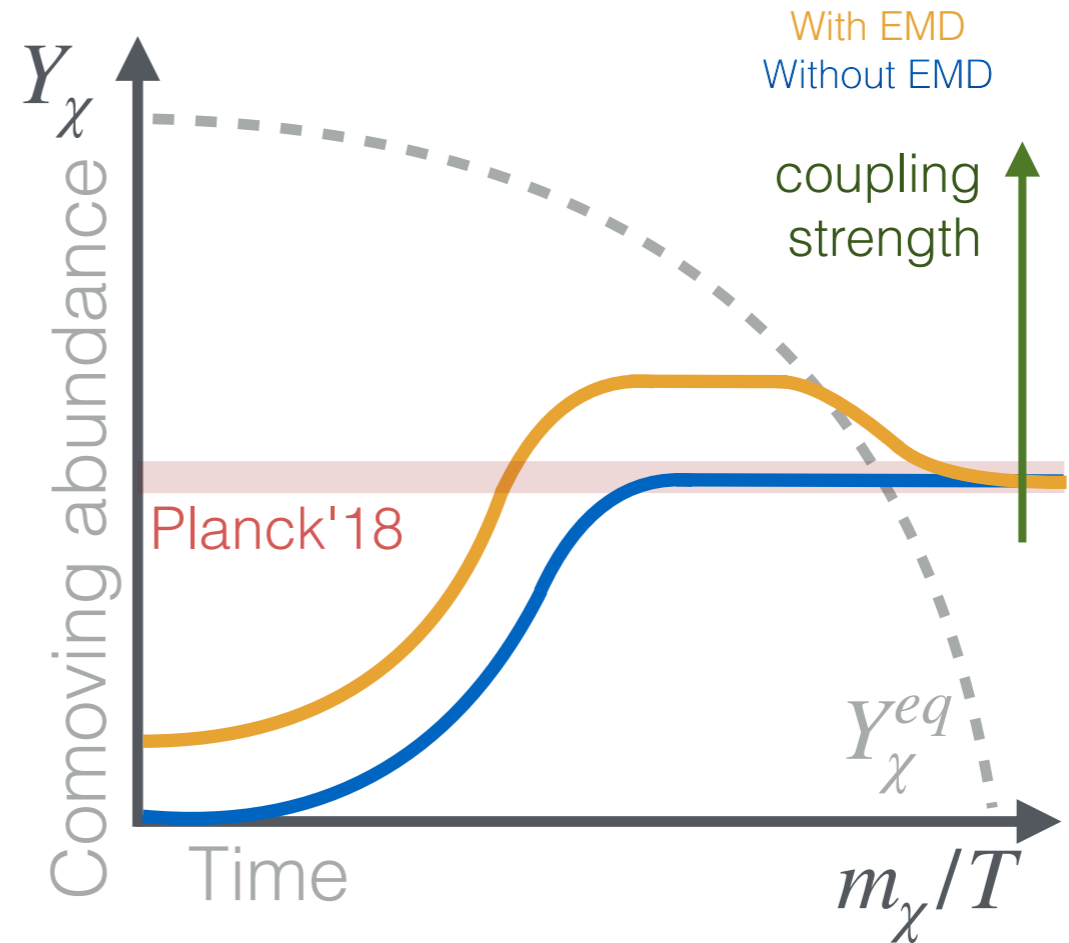


@ Colliders, DD, ID



Any particle physics model!

1506.07532
1803.08064
2003.01723



Early matter-dominated era



Larger couplings between FIMPs and SM particles

Outline

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2. Z' portal model of FIMP dark matter
3. Conclusions

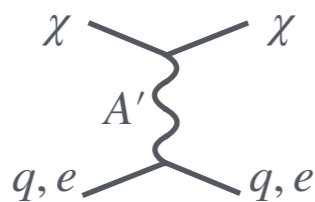
$U(1)$ extensions

- Extra $U(1)$ symmetries are present in many BSM scenarios

$$\mathcal{L} \supset \bar{\chi}_R \gamma^\mu D_\mu \chi_R + \bar{\chi}_L \gamma^\mu D_\mu \chi_L \quad \supset \quad \bar{\chi} \gamma^\mu \left(\underbrace{g_{Z'} \frac{q_{\chi_L} + q_{\chi_R}}{2}}_{V_\chi} - \underbrace{g_{Z'} \frac{q_{\chi_L} - q_{\chi_R}}{2}}_{A_\chi} \gamma_5 \right) \chi Z'_\mu$$

Pure vector $U(1)$ bosons

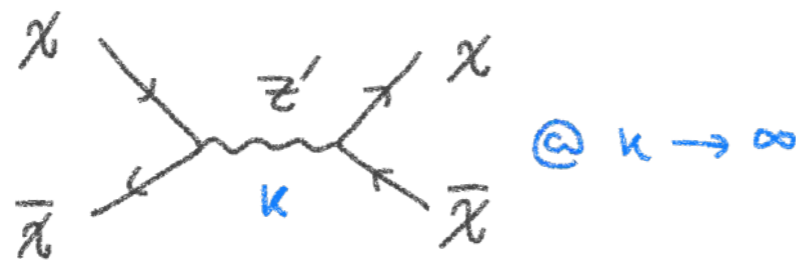
- Easily anomaly-free ($U(1)_{B-L}$, $U(1)_{L_\mu - L_\tau}$, etc)
- Direct detection of FIMPs and sub-GeV WIMP-like DM



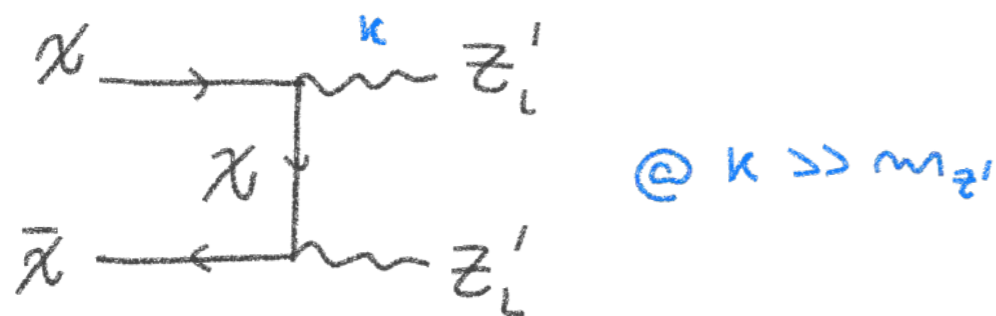
$U(1)$ extensions

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

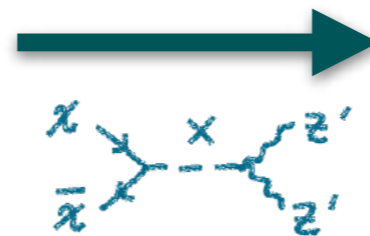
F. Kahlhoefer, K. Schmidt-Hoberg, T. Schweitzer, S. Vogl
arXiv:1510.02110



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



New particle restoring unitarity



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

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

$U(1)$ extensions

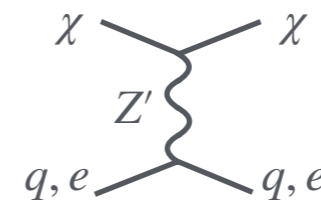
Pure axial $U(1)$ bosons

- Anomaly-free models are involved, but possible

A. Ismail, W. Keung, K. Tsao, J. Unwin
arXiv:1609.02188

- Interesting from a phenomenological point of view

**Spin-dependent
direct detection**



MeV anomalies



Y.Kahn, G.Krnjaic, S.Mishra-Sharma, T.Tait
arXiv:1908.09834

**GC γ -ray
excess**



D. Hooper
arXiv:1411.4079

¿ Can we have a testable freeze-in with axially coupled $U(1)$ bosons ?

Z' portal: The model

Testing freeze-in with axial and vector Z' bosons
 Catarina Cosme, MD, Steve Godfrey, and Taylor Gray
 arXiv:2104.13937

Visible sector

SM particles

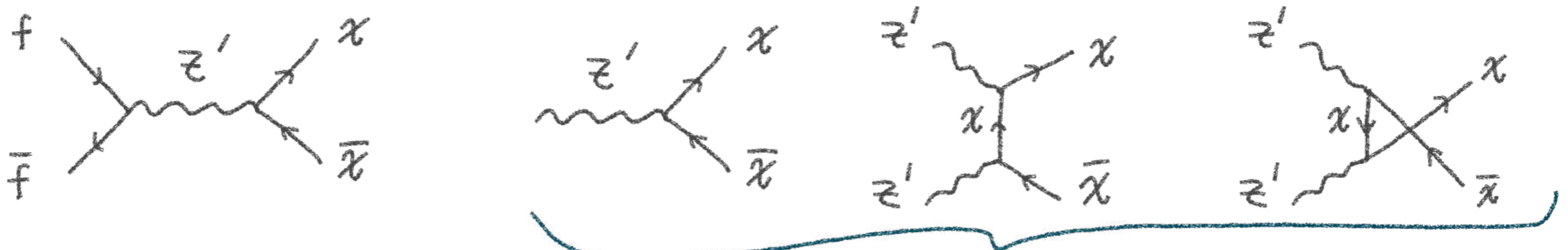
$U(1)'$ gauge boson: Z'

Dark sector

Dark fermion: χ

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

Processes contributing to freeze-in:

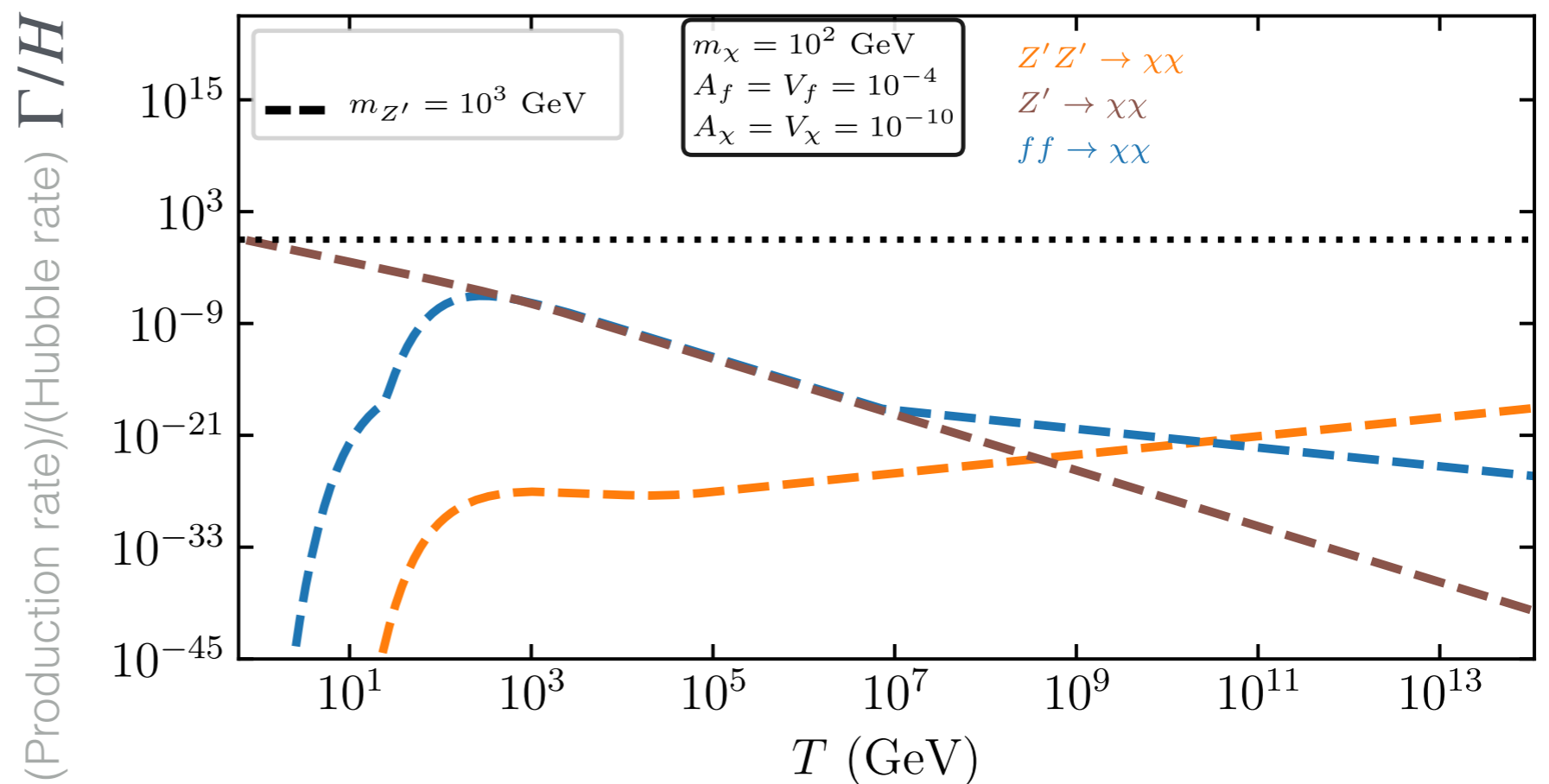
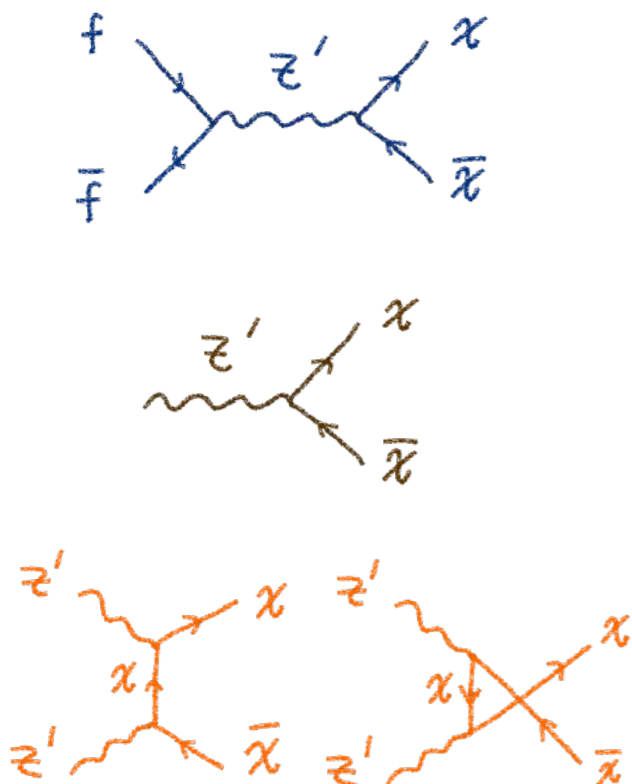


Z' part of the SM bath ($n_{Z'} = n_{Z'}^{eq} \sim n_f$)

Z' portal: Out-of-equilibrium conditions

We consider both cases: χ thermalized and non-thermalized

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

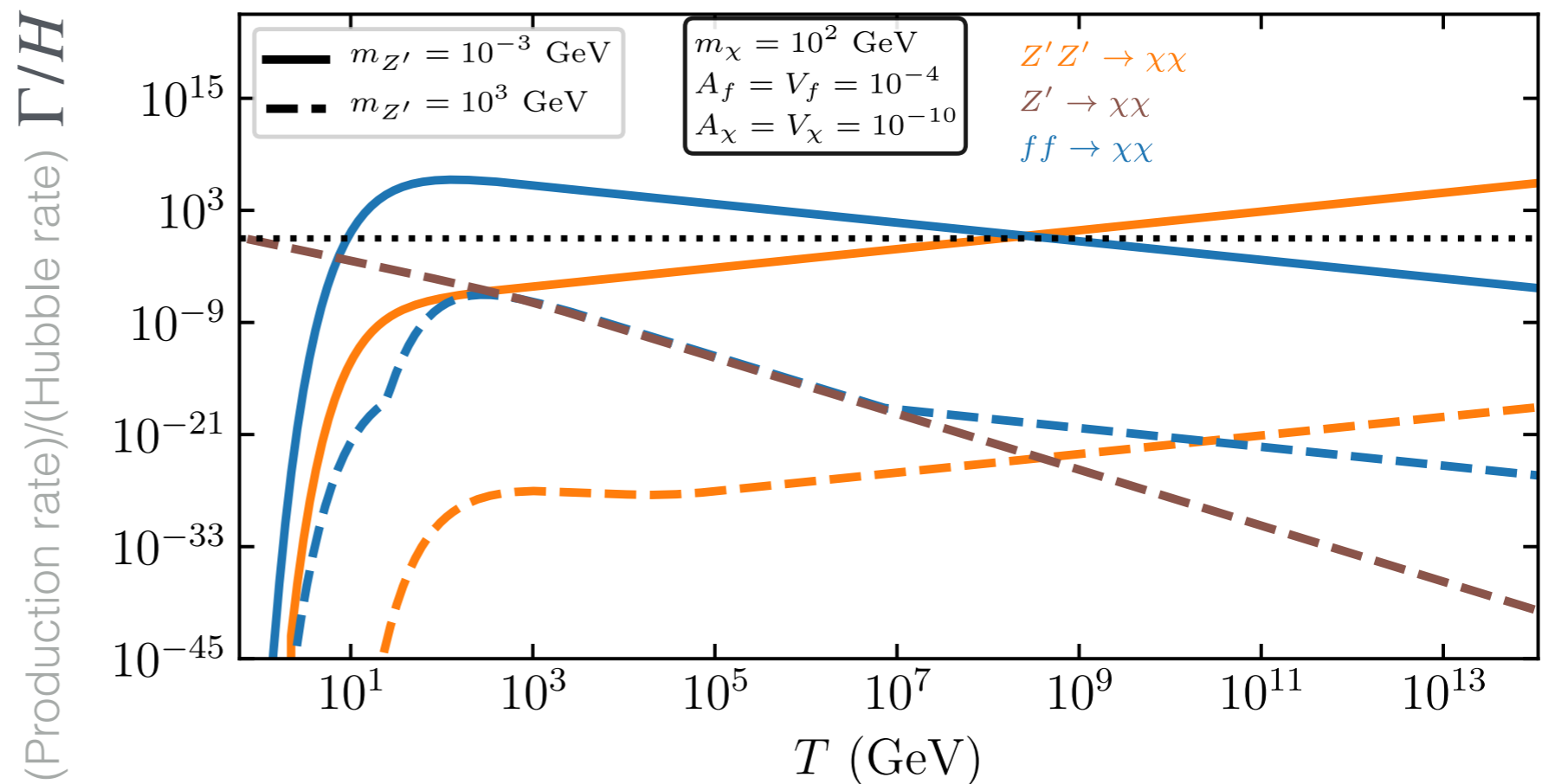
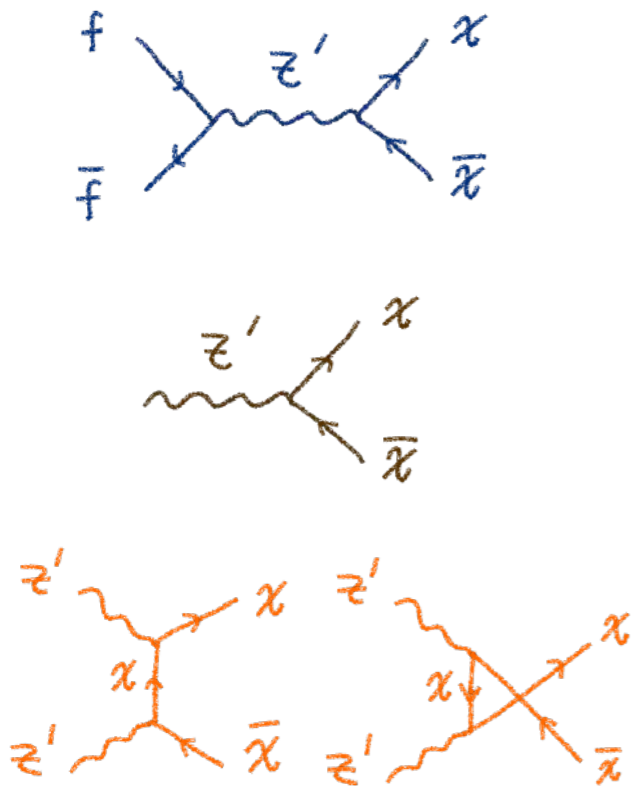


Z' portal: Out-of-equilibrium conditions

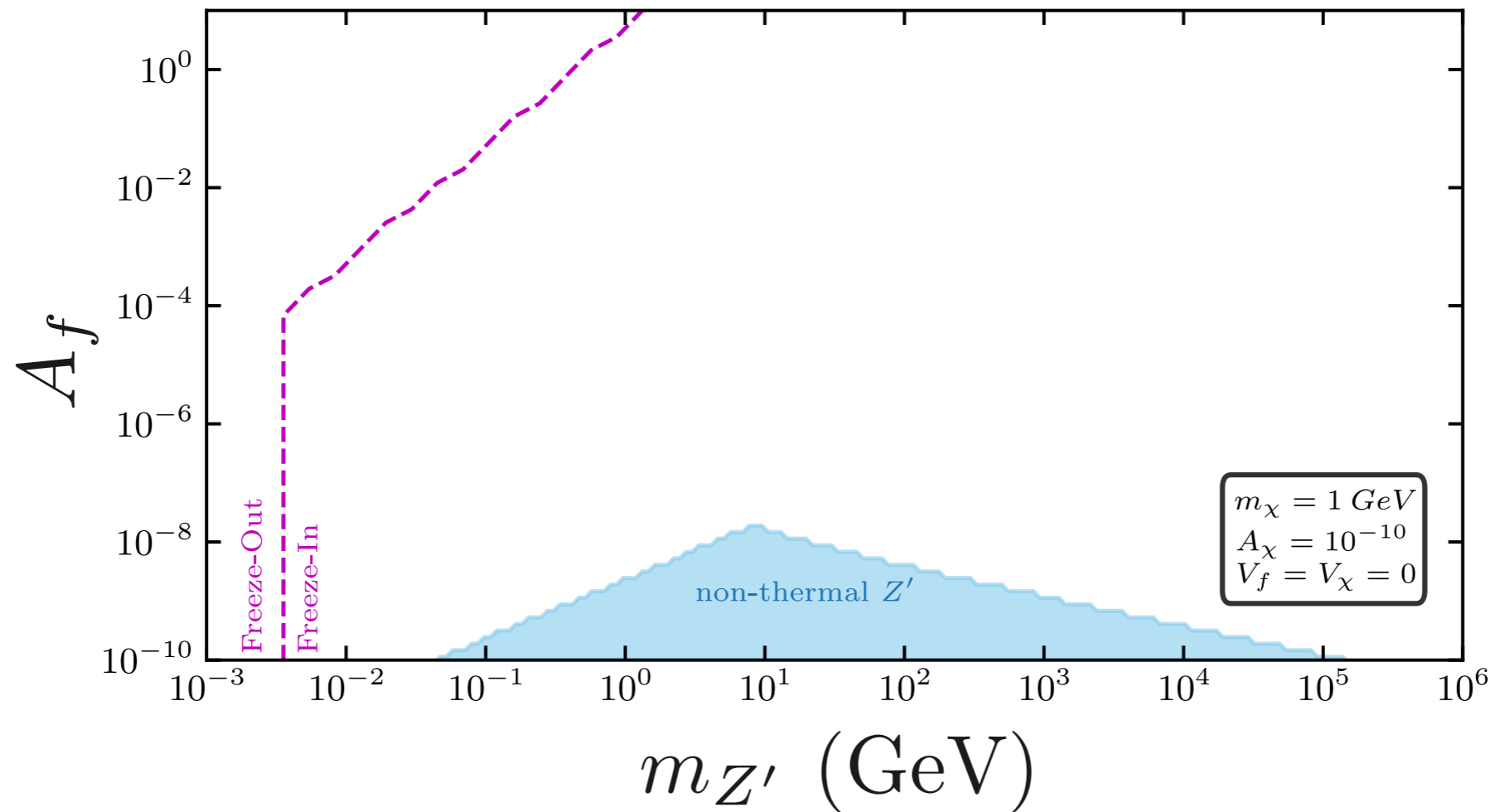
We consider both cases: χ thermalized and non-thermalized

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

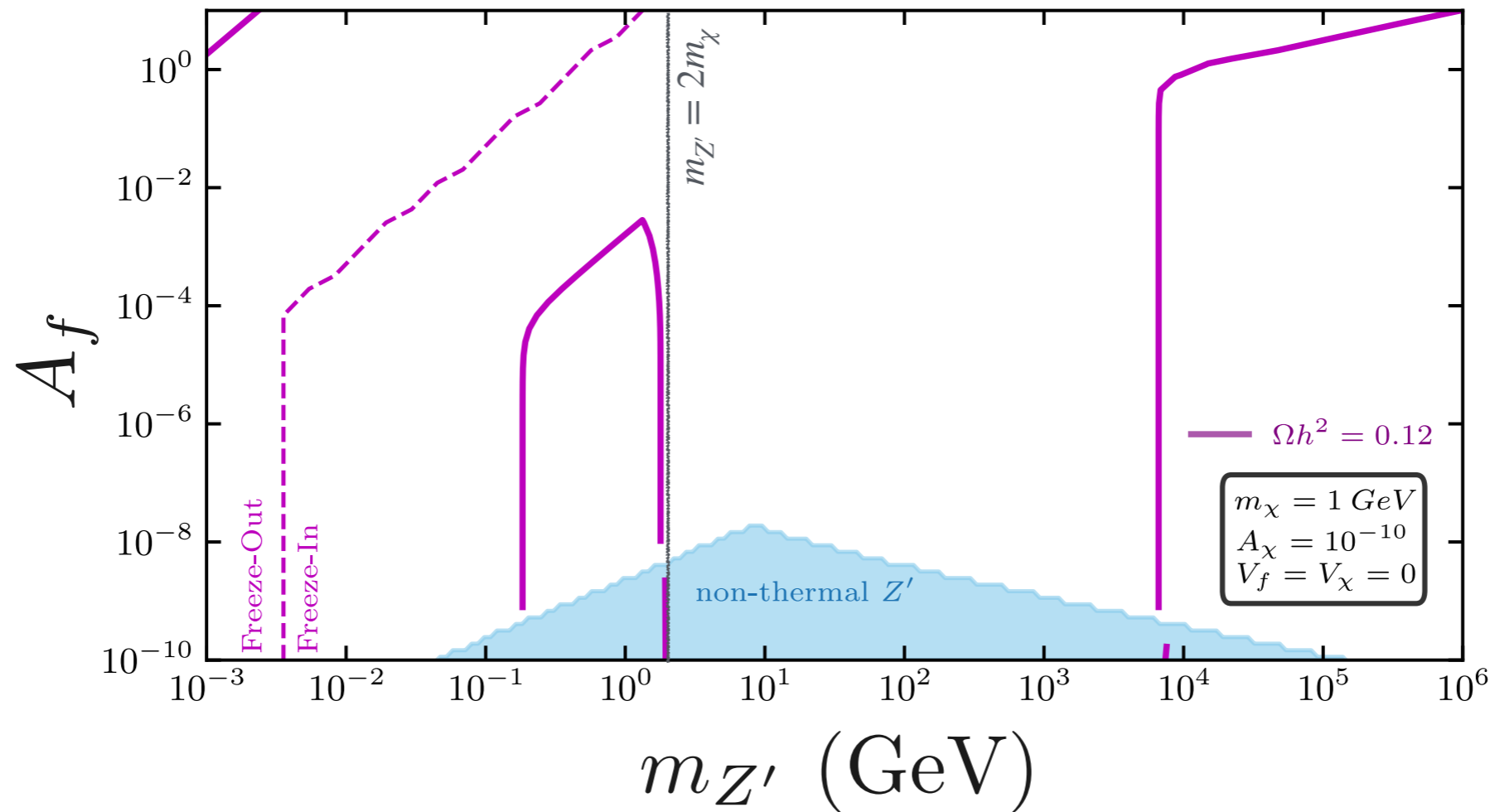
$$\Gamma_{s-ch, dec, t-ch} > H \Rightarrow \text{Freeze-out}$$



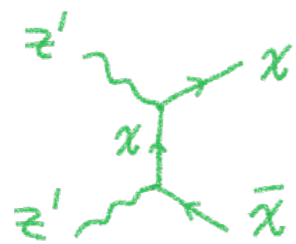
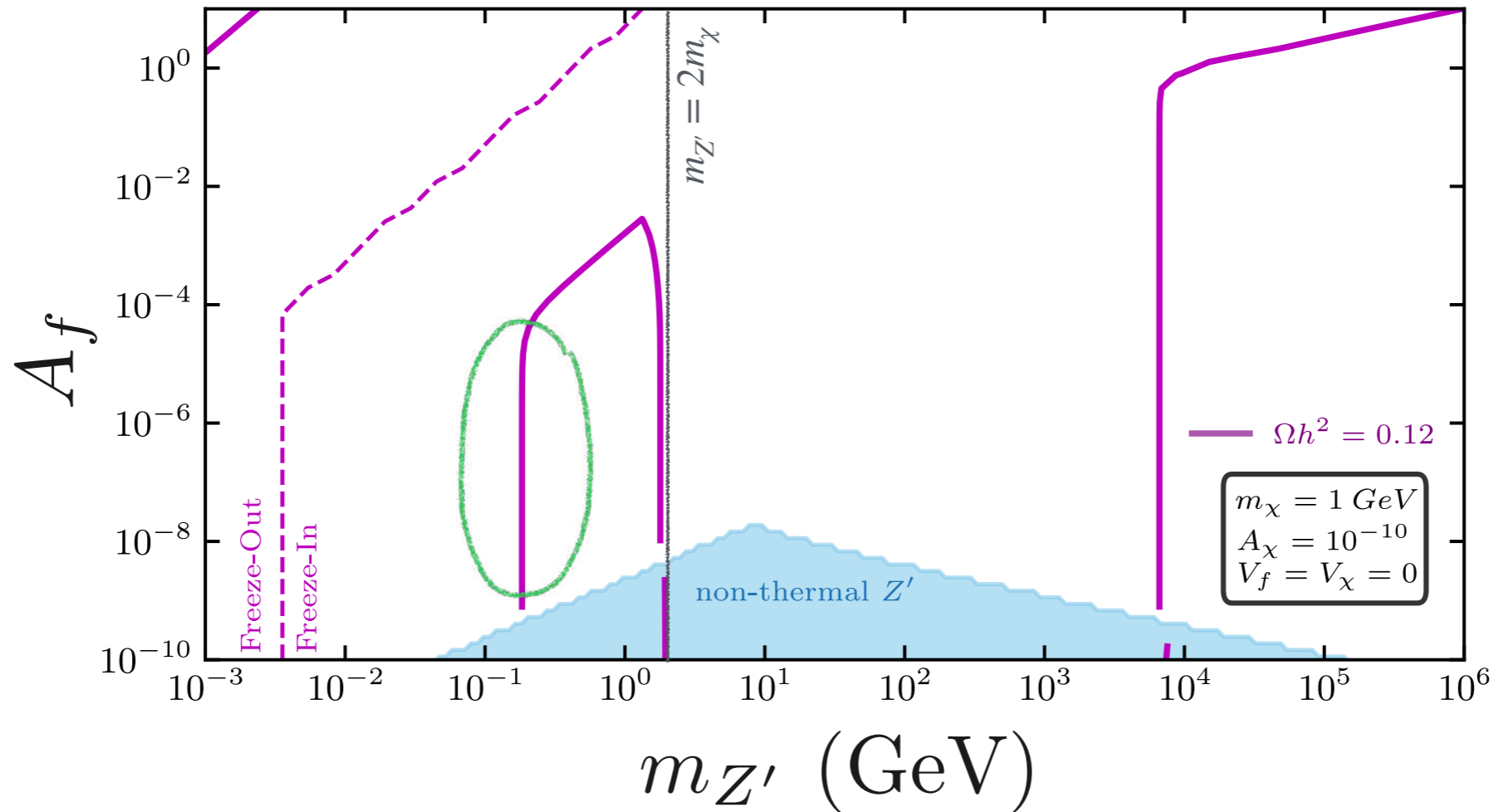
Z' portal: Relic density



Z' portal: Relic density



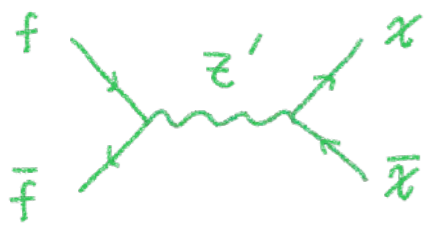
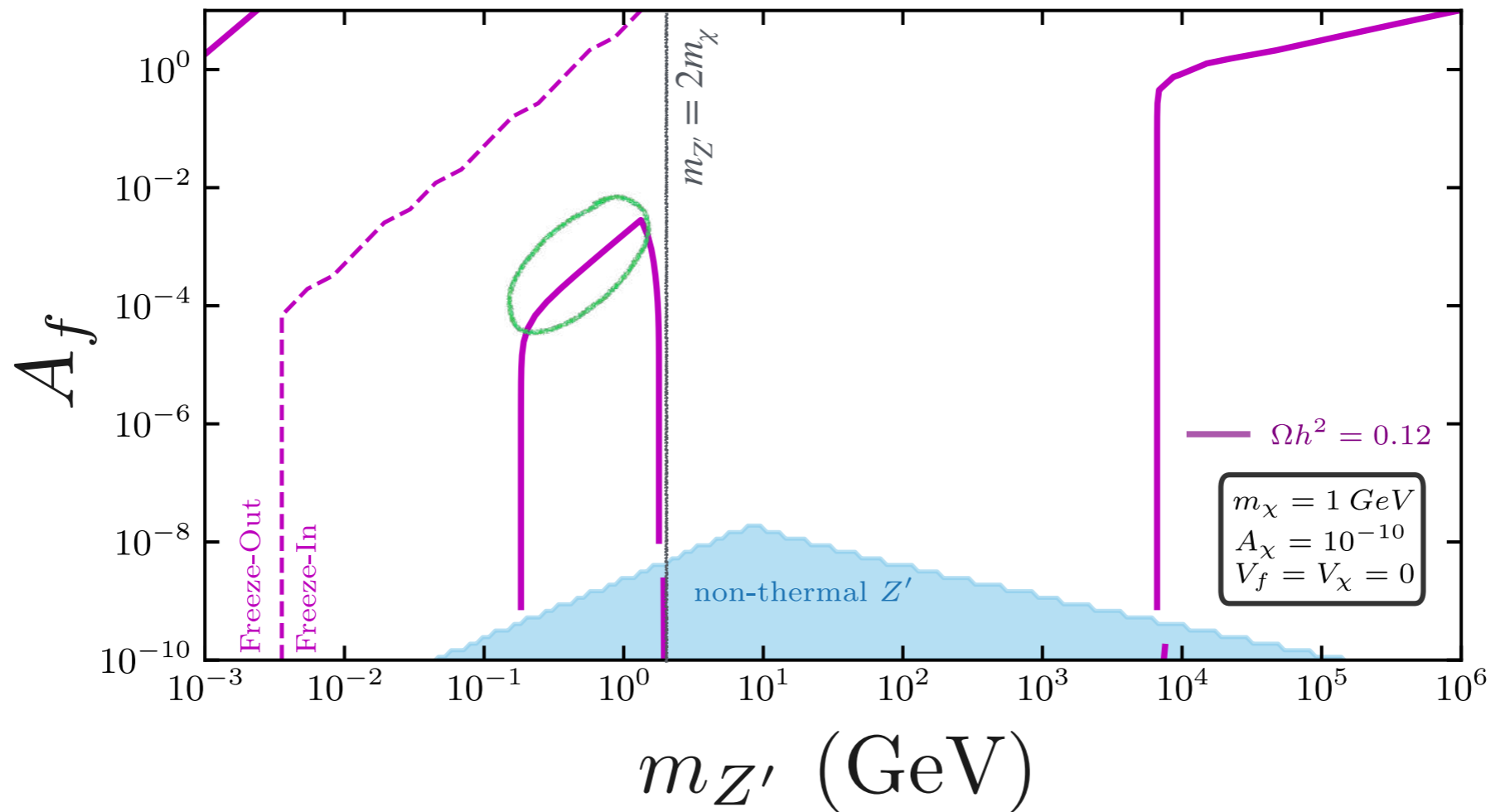
Z' portal: Relic density



$$\Omega_\chi^0 h^2 \sim 0.12 \left(\frac{m_\chi}{1\text{GeV}} \right)^3 \left(\frac{0.2\text{GeV}}{m_{Z'}} \right)^4 \left(\frac{A_\chi}{10^{-10}} \right)^4 \left(\frac{T_{RH}}{10^{14}\text{GeV}} \right)$$

- The t-channel is a **UV freeze-in process**

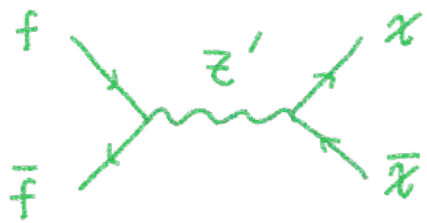
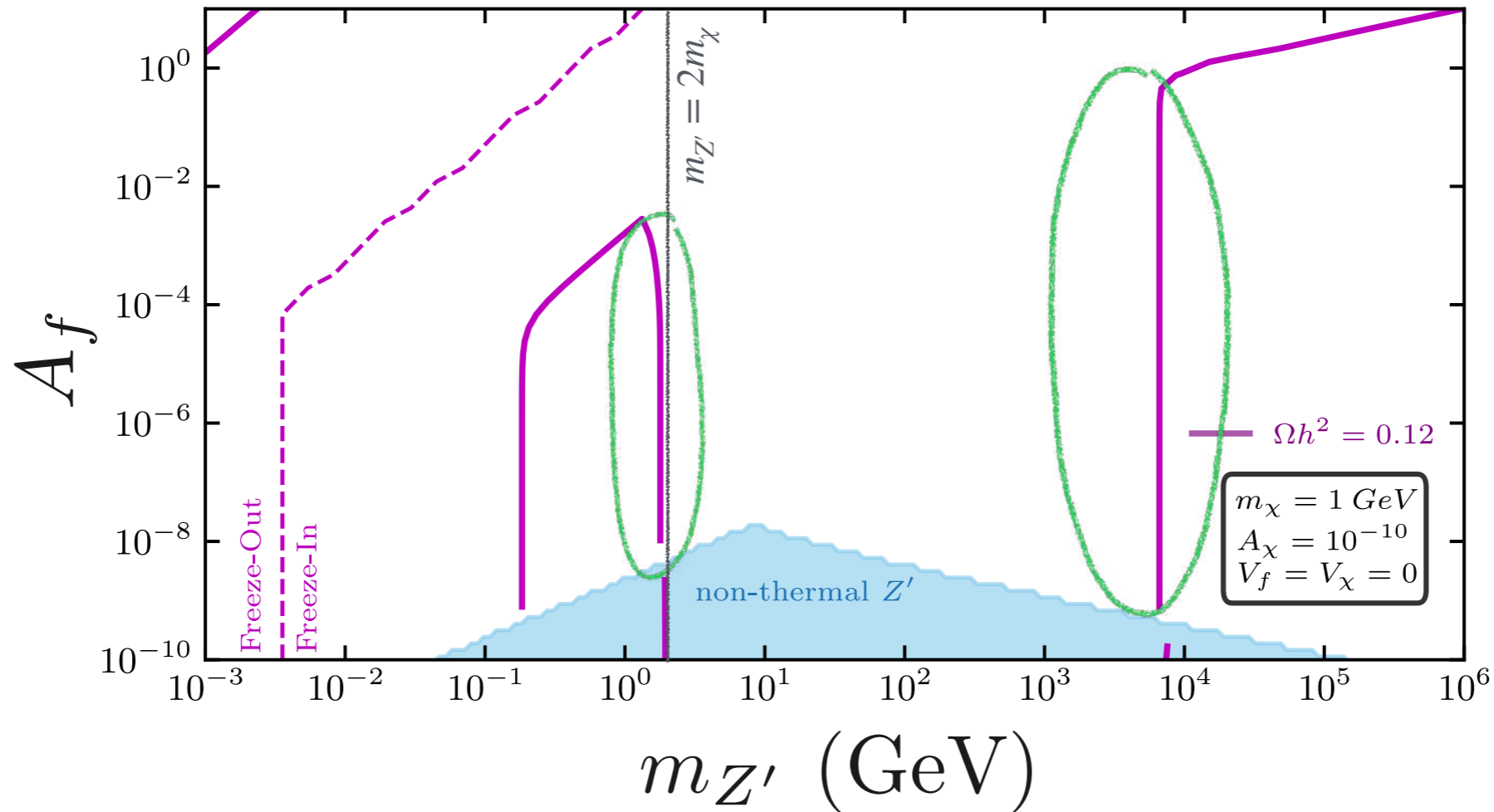
Z' portal: Relic density



$$\Omega_\chi^0 h^2 \propto \sum_f \frac{m_\chi}{\max(m_f, m_\chi)} \left[v_f^2 (V_\chi^2 + A_\chi^2) + A_f^2 \left(V_\chi^2 + A_\chi^2 \left(1 + \frac{12m_\chi^2 m_f^2}{m_{Z'}^4} \right) \right) \right]$$

- The **light Z' regime of the s-channel** is independent of $m_{Z'}$ in the absence of axial couplings

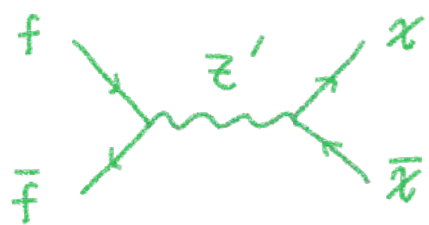
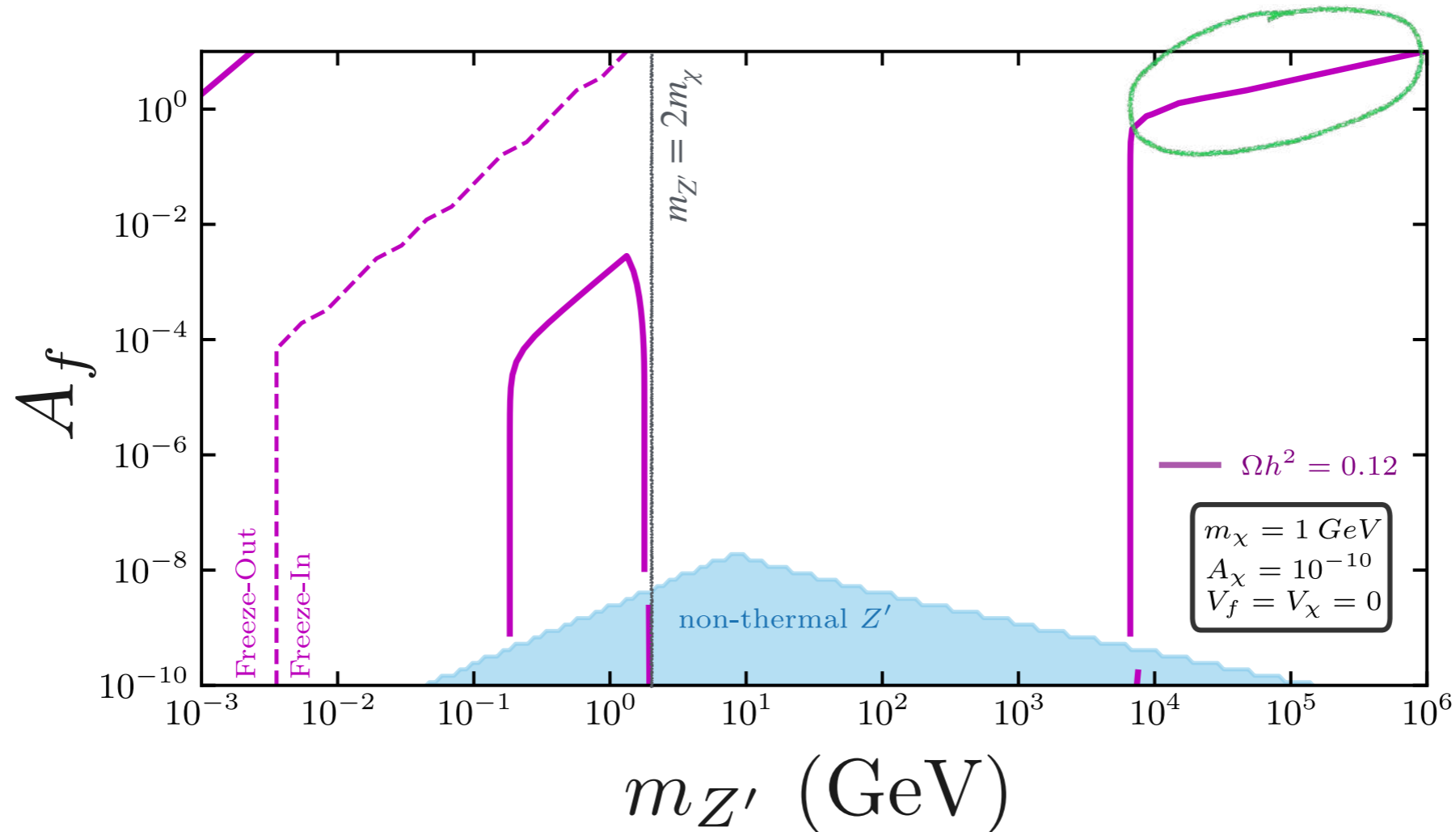
Z' portal: Relic density



$$\Omega_\chi^0 h^2 \propto \frac{m_\chi}{m_{Z'}} \frac{A_\chi^2 A_f^2(\dots)}{A_\chi^2(\dots) + \sum_f A_f^2(\dots)}$$

- The **resonant Z' regime** of the s-channel is independent of A_f for $A_f^2 \gtrsim A_\chi^2$ and can dominate the FI contours even for $m_{Z'} \gg m_\chi$

Z' portal: Relic density



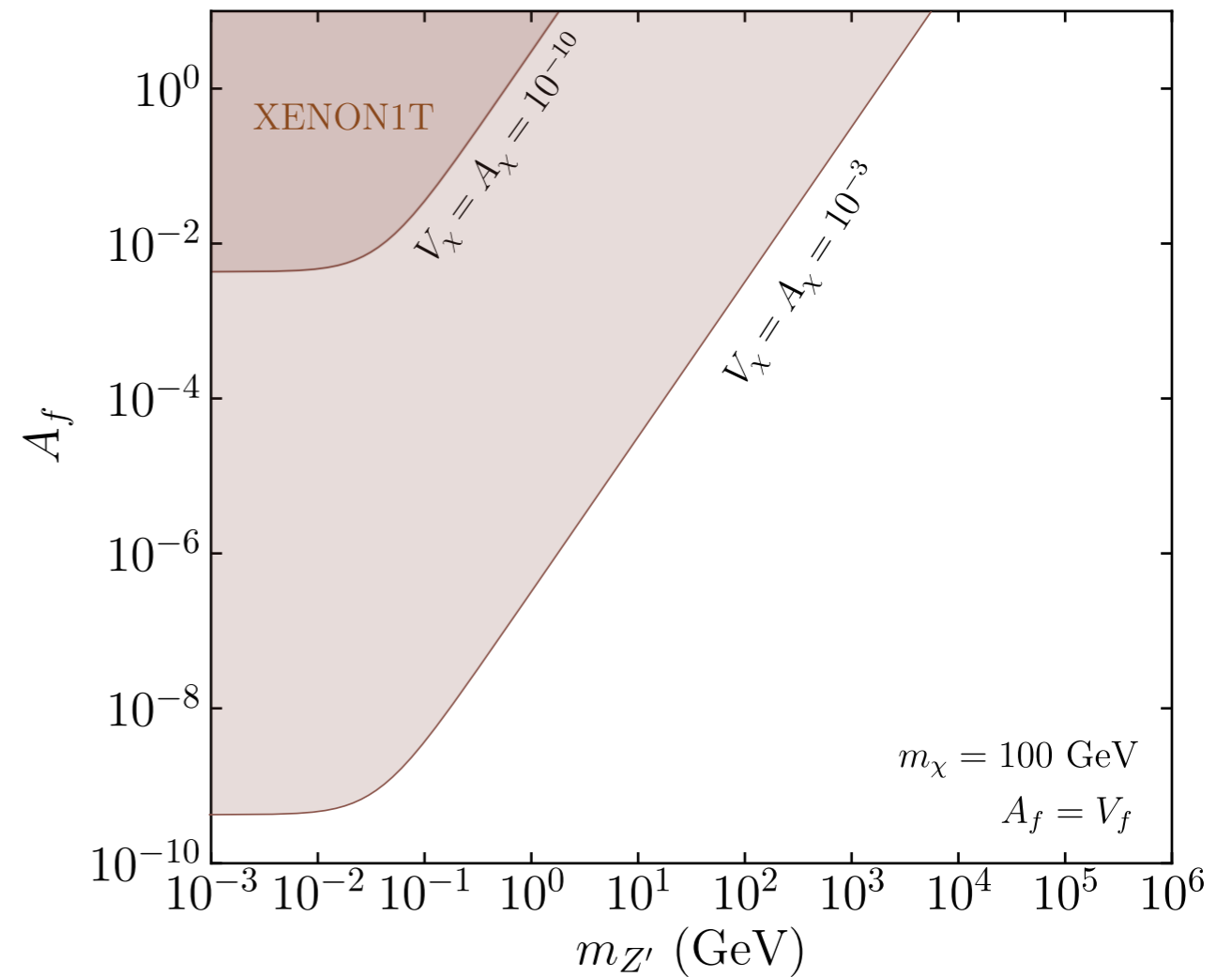
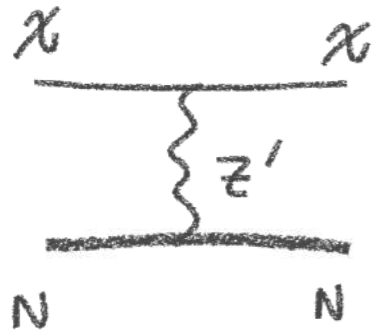
$$\Omega_{\chi}^0 h^2 \propto (V_{\chi}^2 + A_{\chi}^2)(V_f^2 + A_f^2) \times \begin{cases} \frac{m_{\chi}}{m_{Z'}} & \text{if } m_{Z'} < T_{RH} \\ \frac{m_{\chi} T_{RH}^3}{m_{Z'}^4} & \text{if } m_{Z'} > T_{RH} \end{cases}$$

- In our case, the **heavy regime of Z'** is an IR freeze-in process

Z' portal: Phenomenology

Direct detection

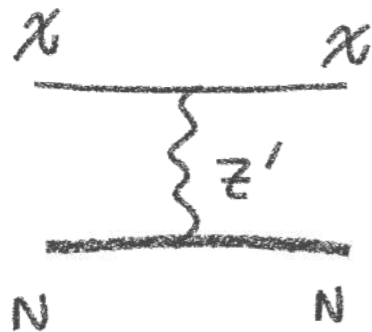
XENON1T



Z' portal: Phenomenology

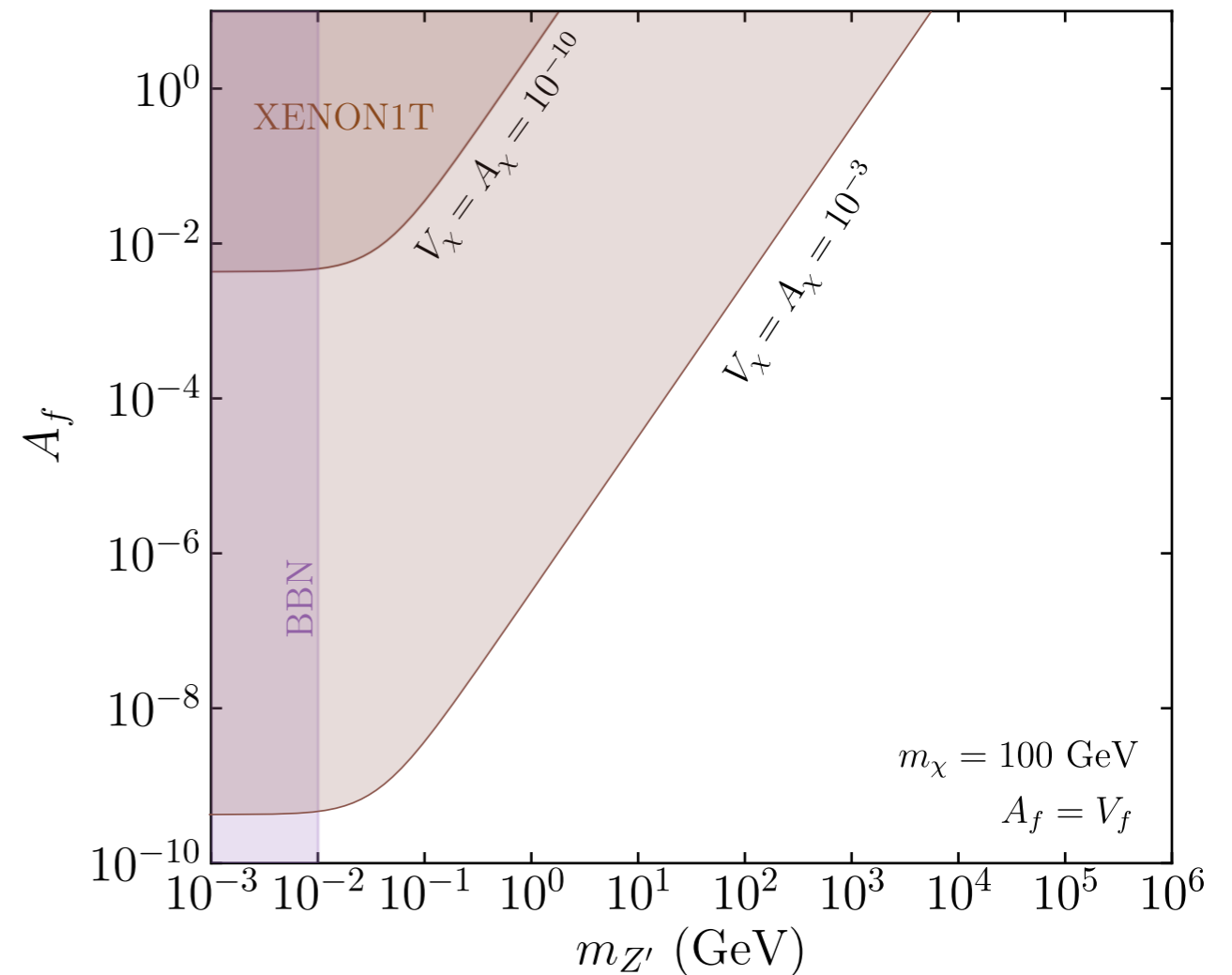
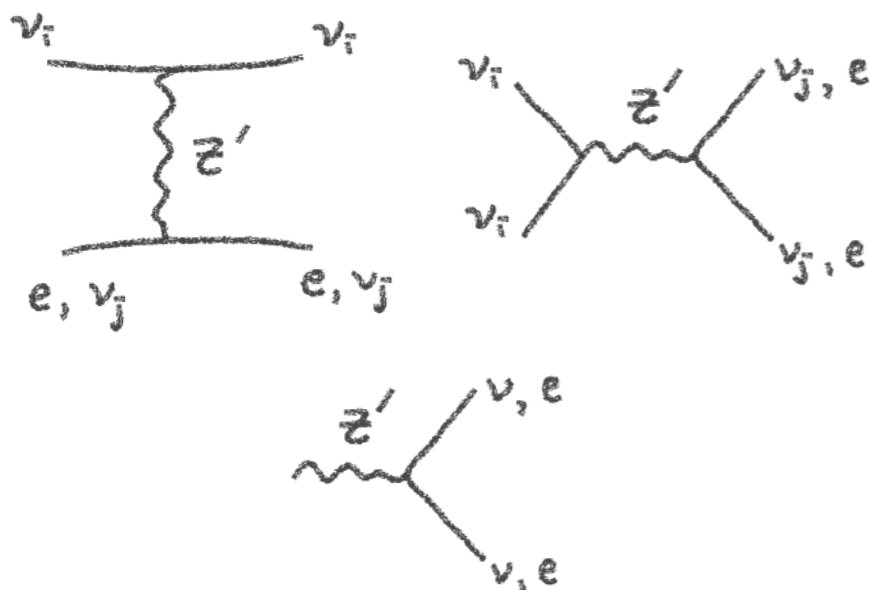
Direct detection

XENON1T



Astro&Cosmo

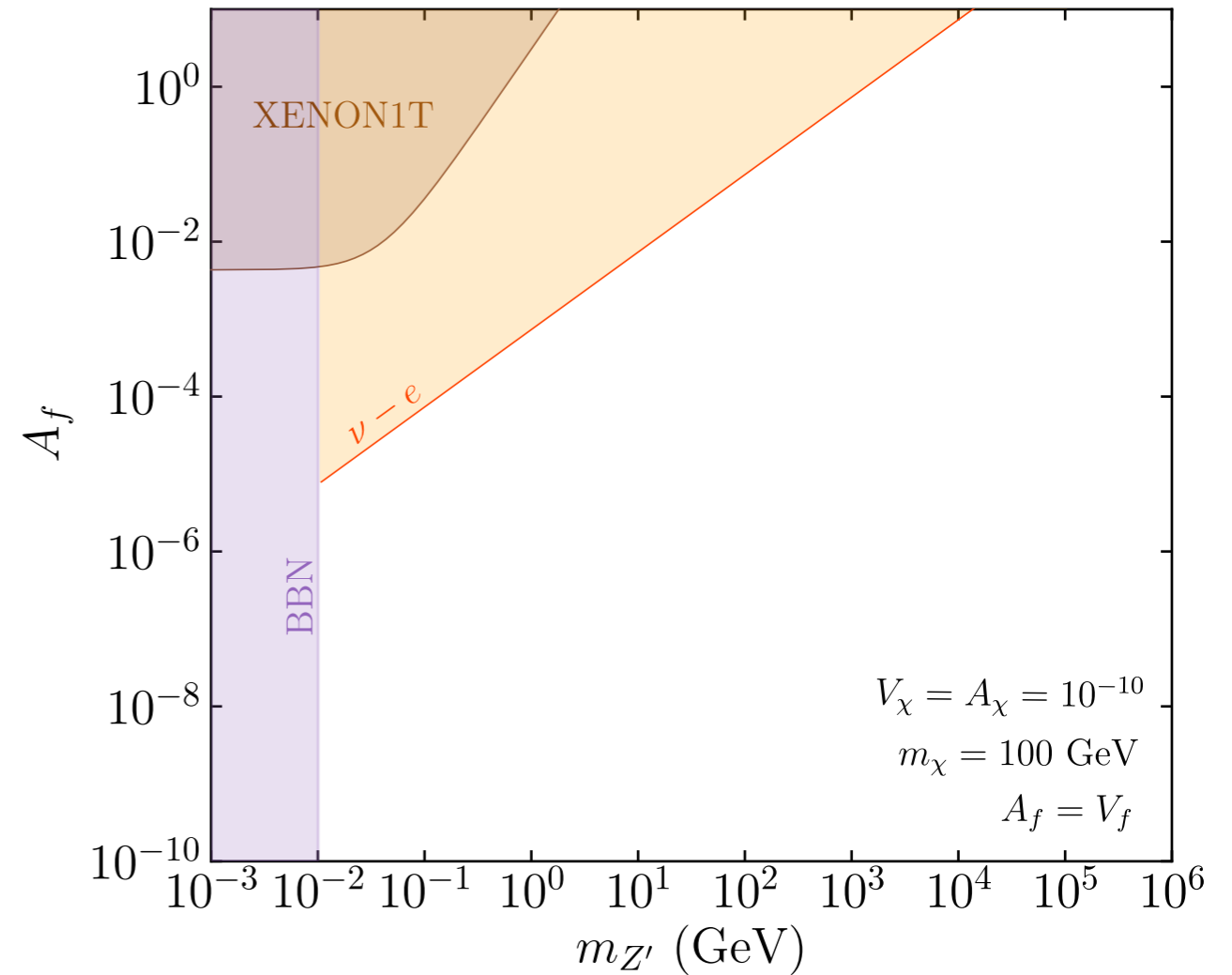
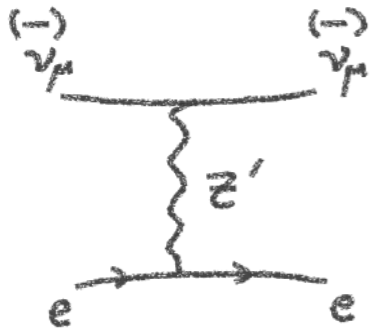
Big Bang Nucleosynthesis



Z' portal: Phenomenology

Colliders&Accelerators

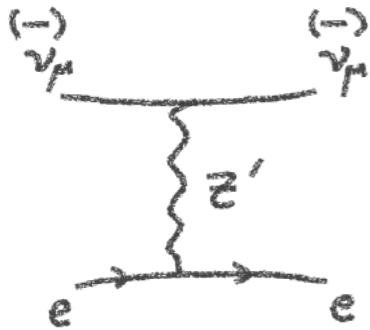
Neutrino-electron scattering



Z' portal: Phenomenology

Colliders&Accelerators

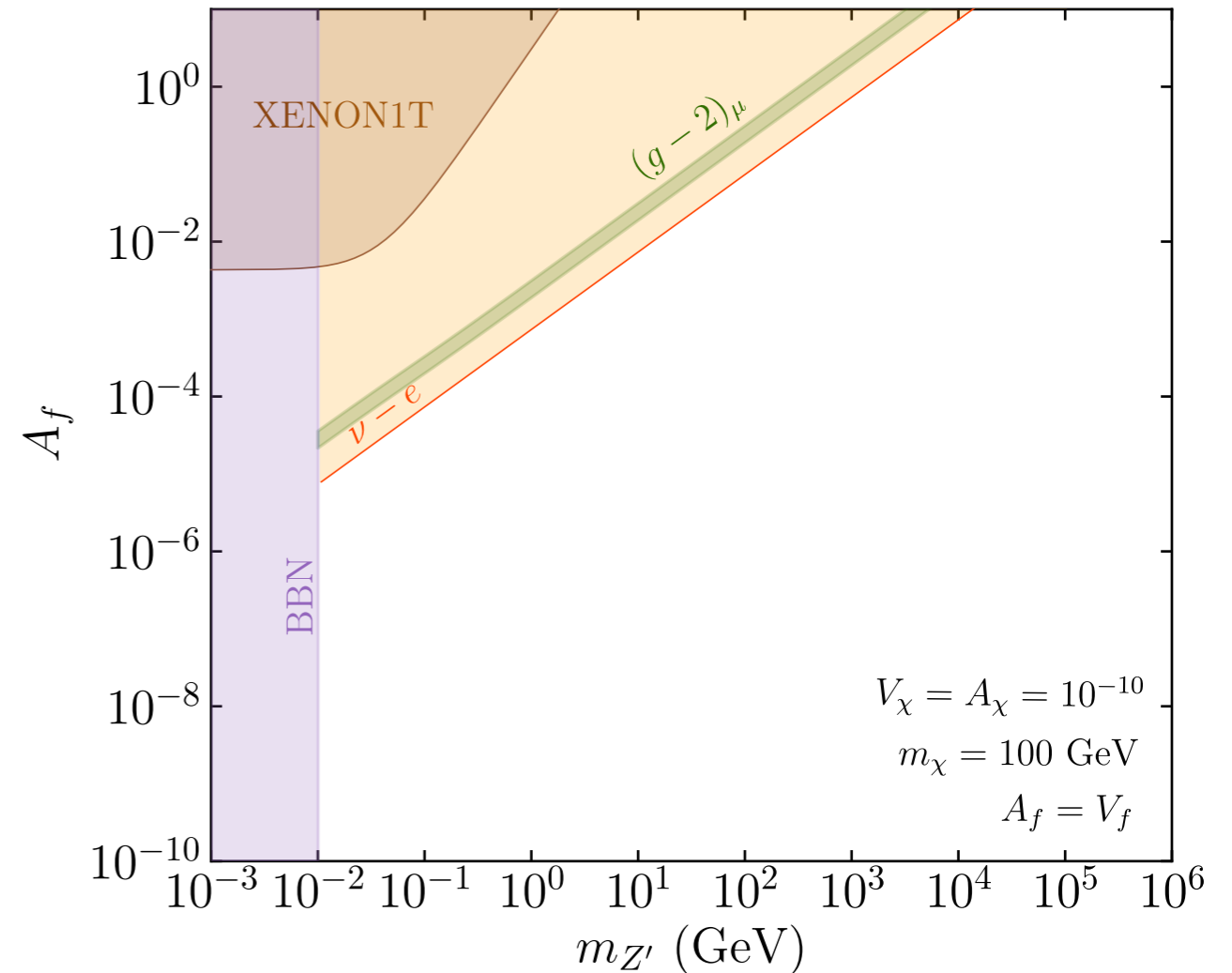
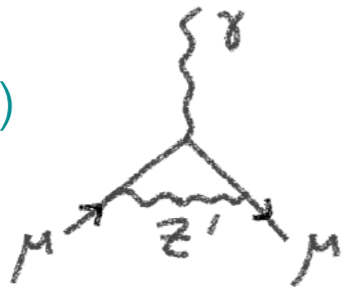
Neutrino-electron scattering



Leptonic anomalous magnetic moments

$$(g - 2)_\mu$$

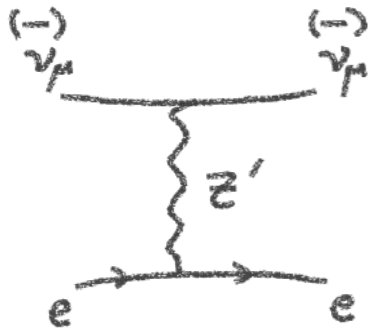
FNAL+BNL (4.2σ)



Z' portal: Phenomenology

Colliders&Accelerators

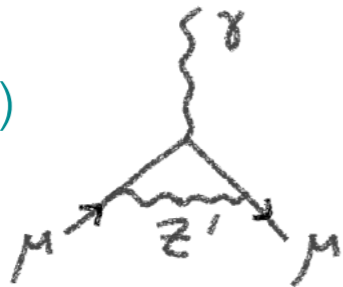
Neutrino-electron scattering



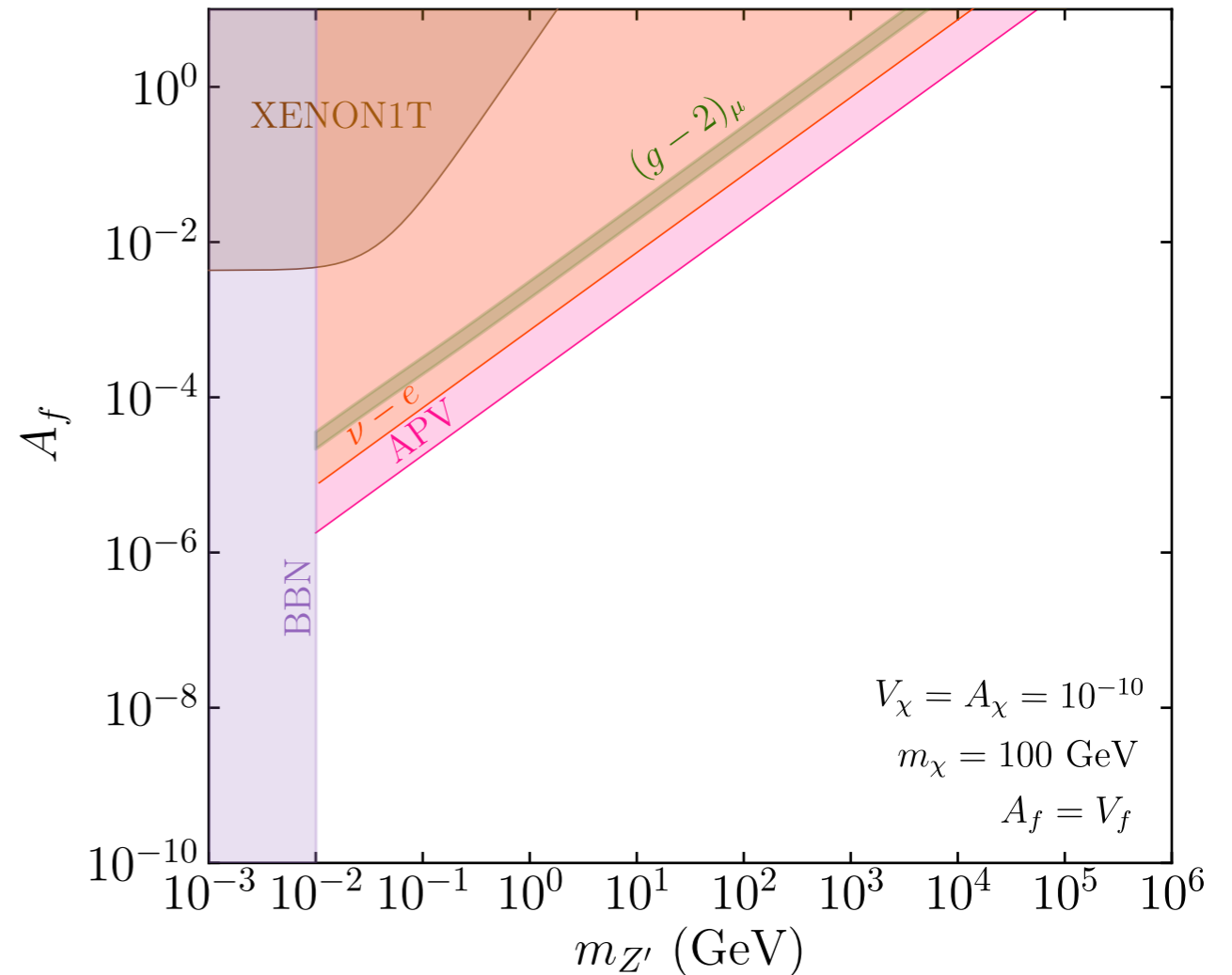
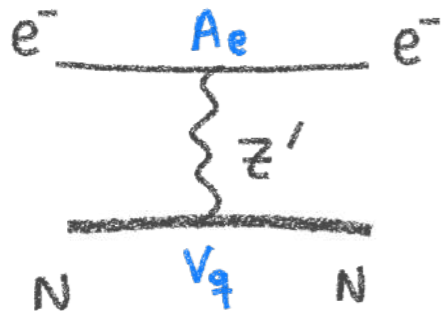
Leptonic anomalous magnetic moments

$$(g - 2)_\mu$$

FNAL+BNL (4.2σ)



Atomic parity violation

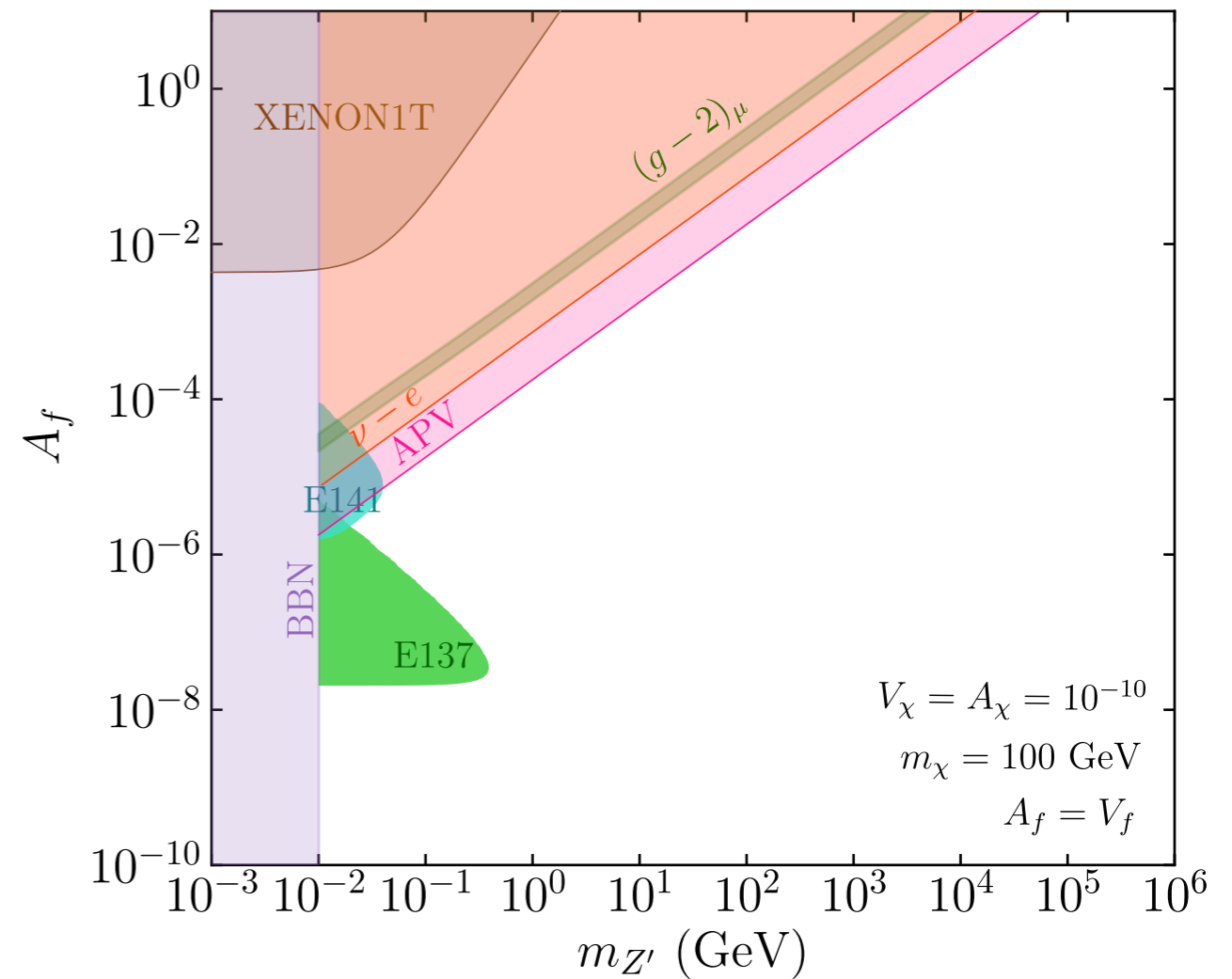
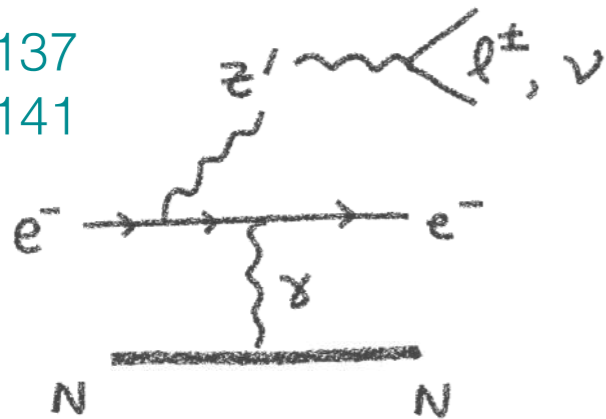


Z' portal: Phenomenology

Colliders&Accelerators

Electron beam-dump

SLAC E137
SLAC E141

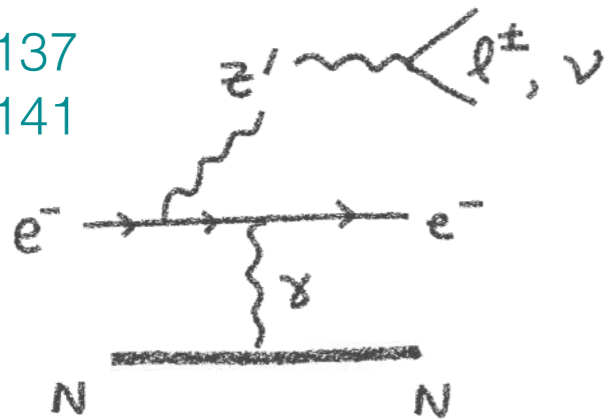


Z' portal: Phenomenology

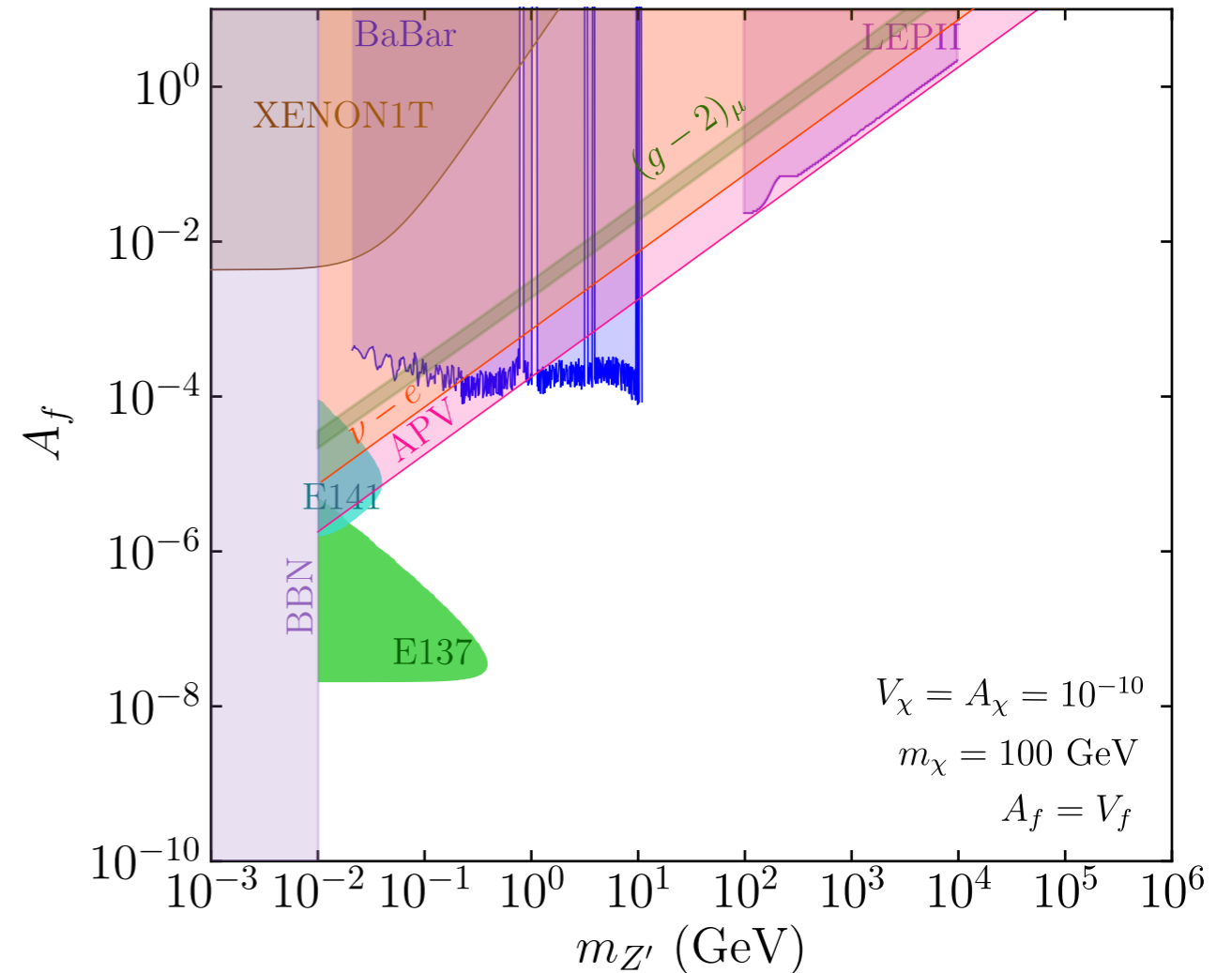
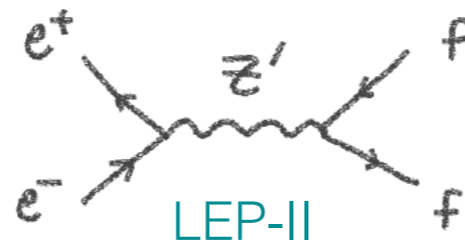
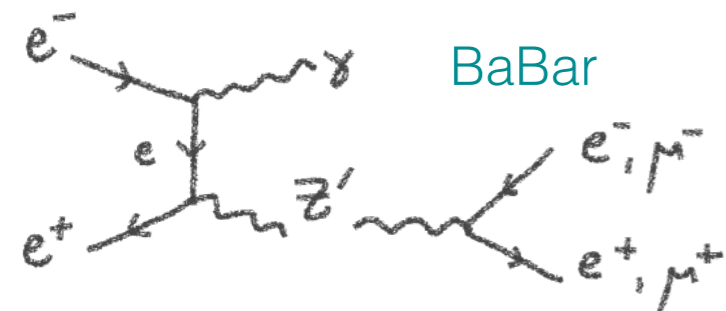
Colliders & Accelerators

Electron beam-dump

SLAC E137
SLAC E141



Electron-positron collisions

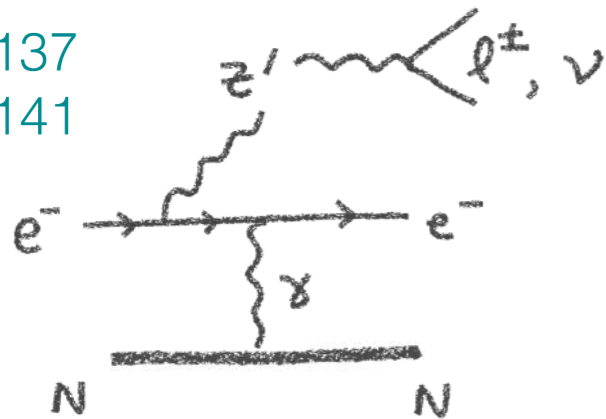


Z' portal: Phenomenology

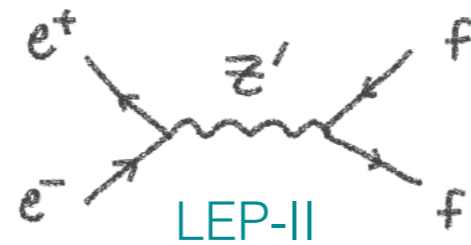
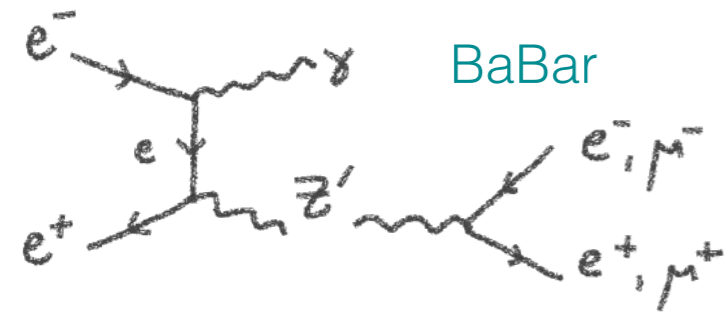
Colliders&Accelerators

Electron beam-dump

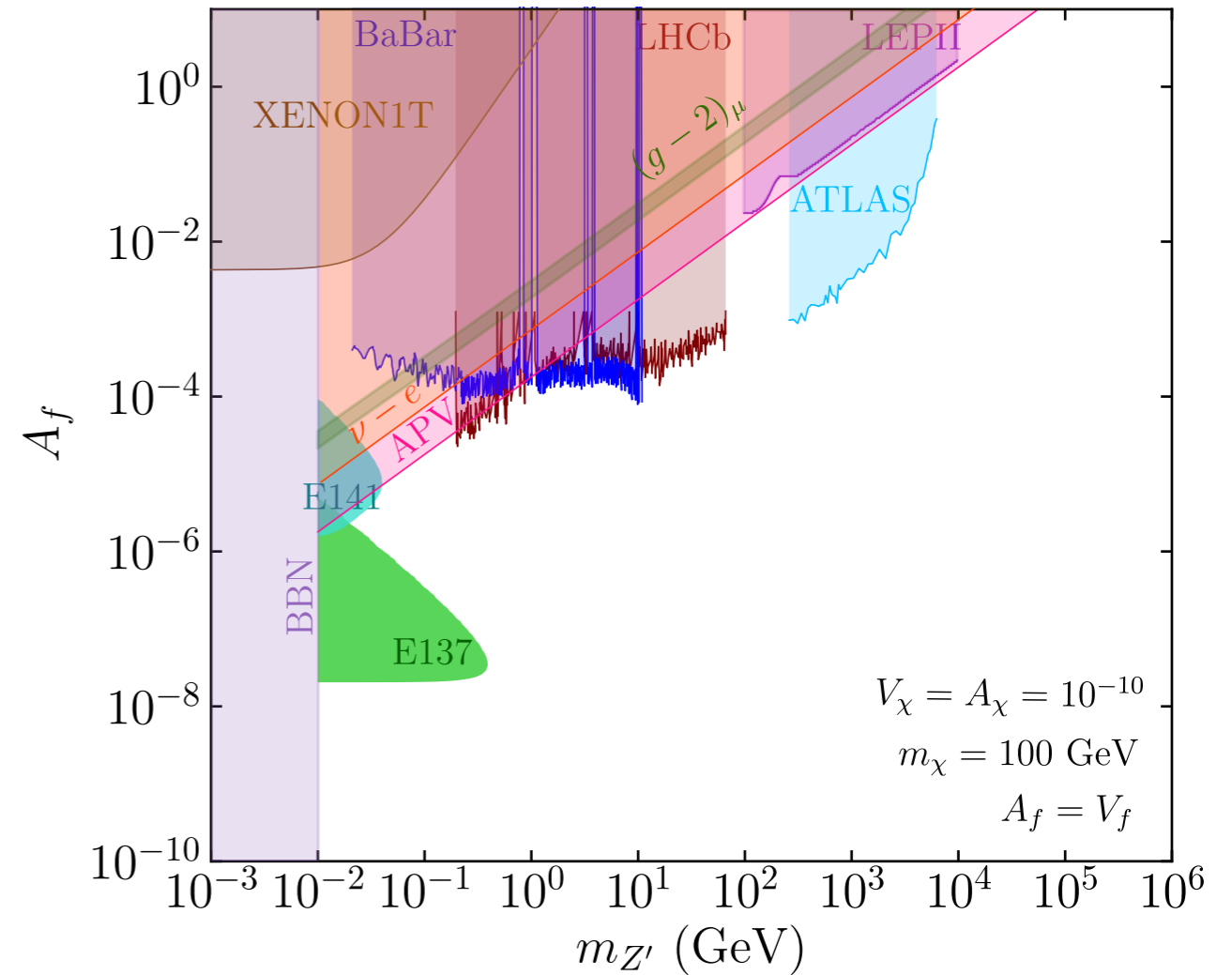
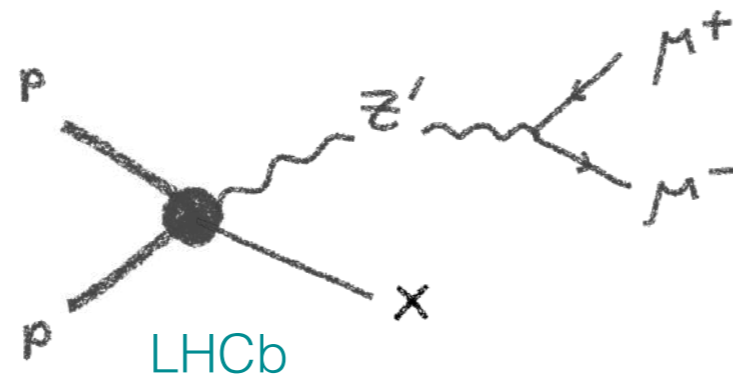
SLAC E137
SLAC E141



Electron-positron collisions



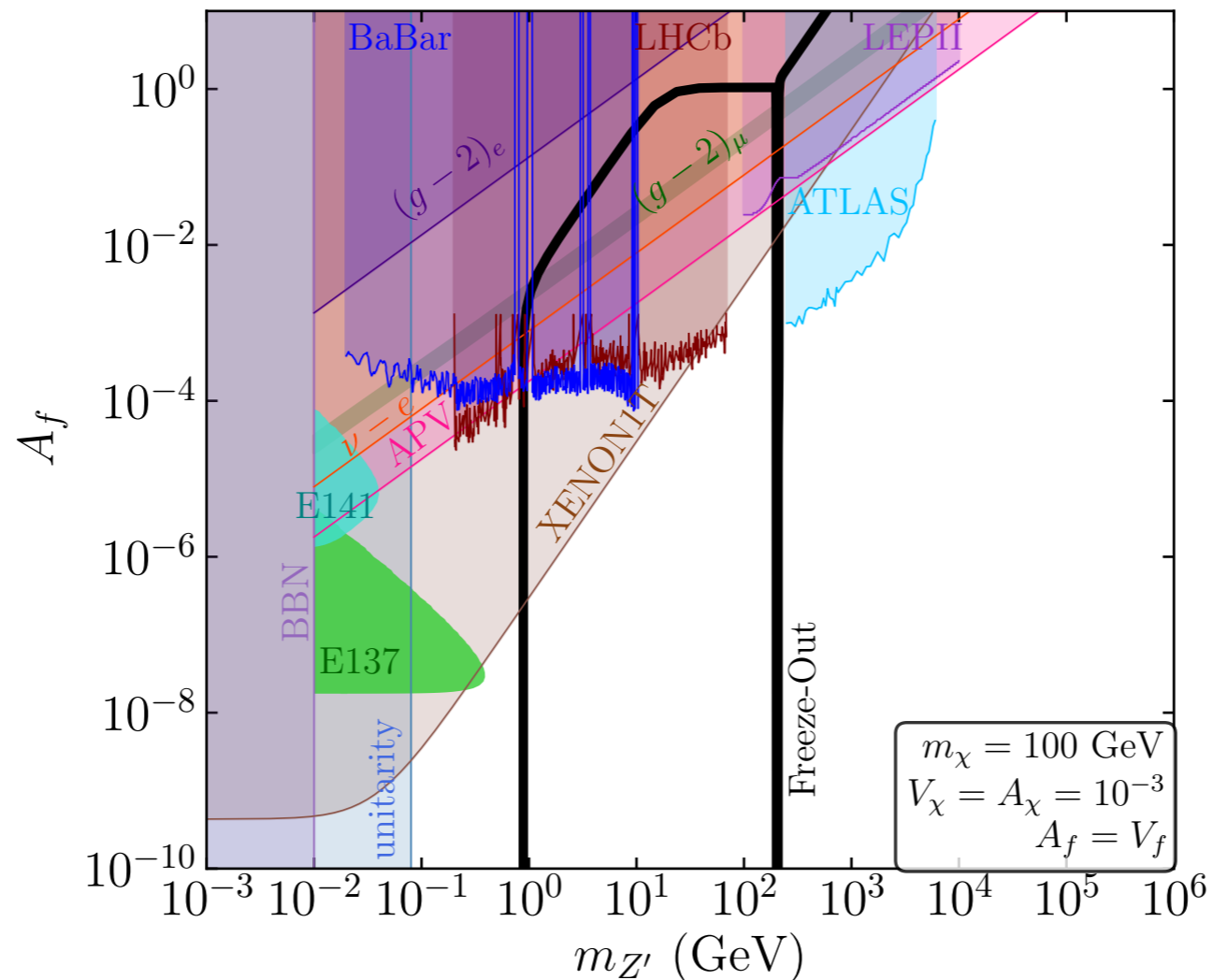
Proton-proton collisions



$V_x = A_x = 10^{-10}$
 $m_x = 100 \text{ GeV}$
 $A_f = V_f$

Z' portal: Viable parameter space

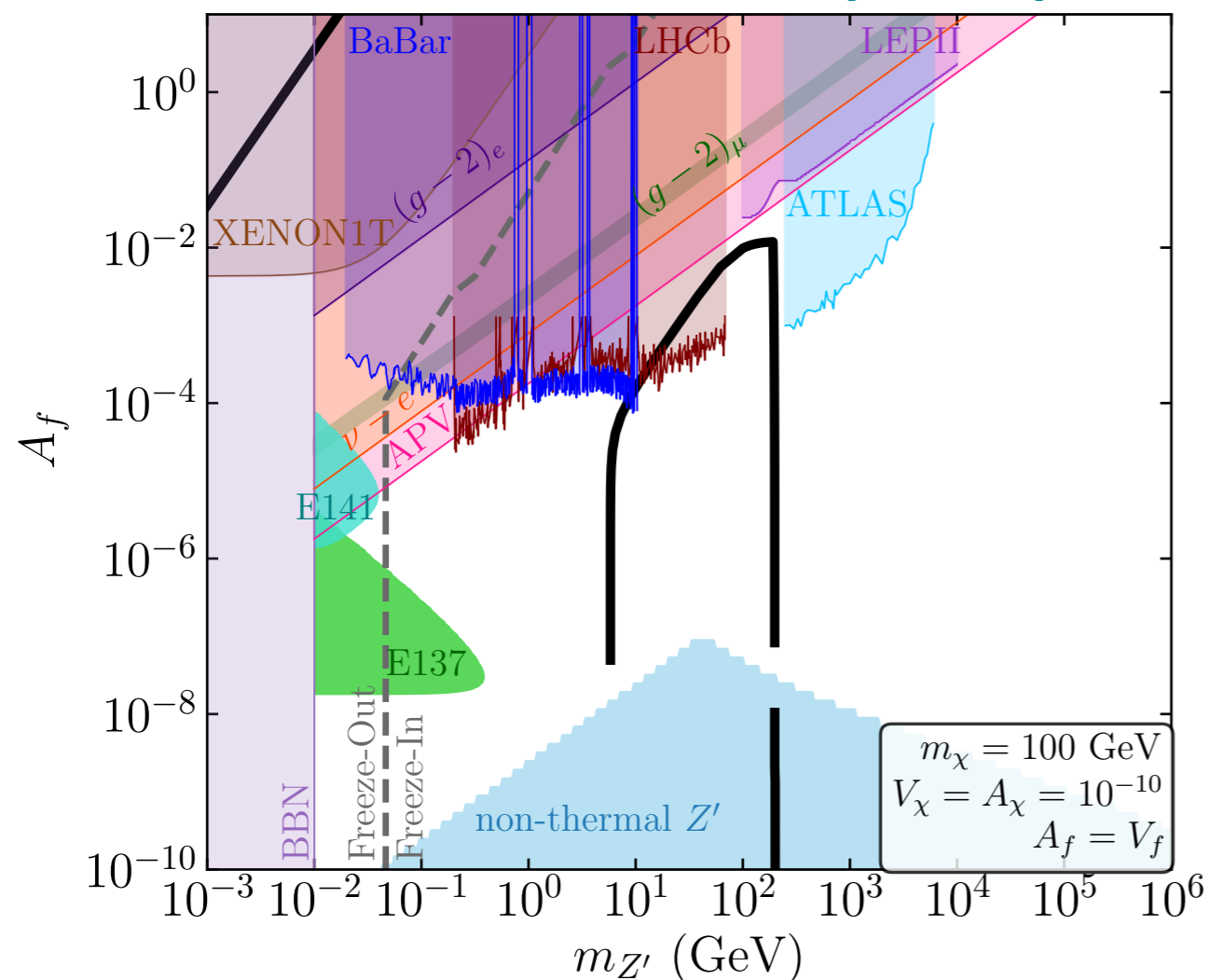
axial and vector (FO)



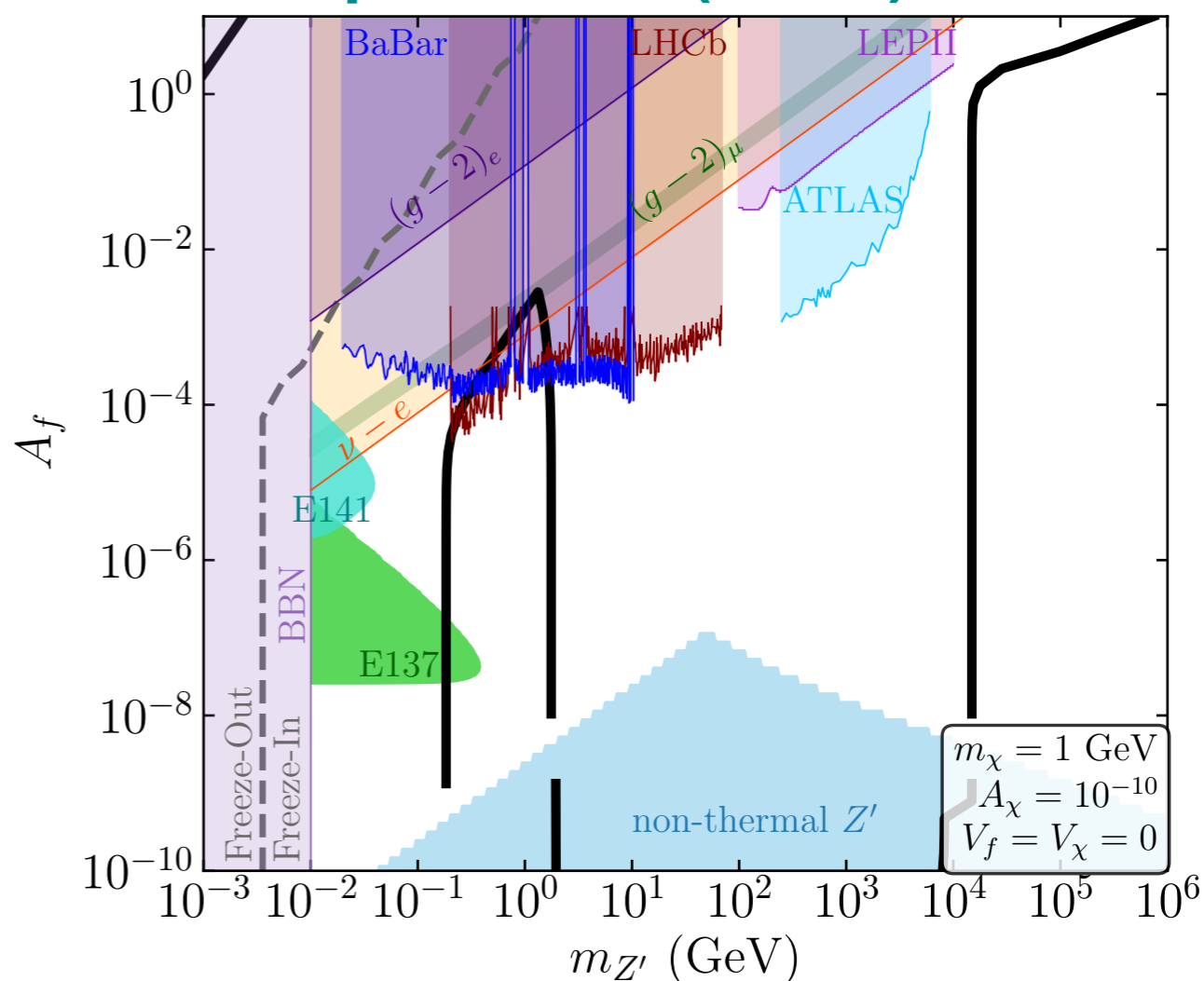
- $m_{Z'} \sim 2m_\chi$ and $m_{Z'} \ll m_\chi$ (if $A_{f/\chi} \neq 0$) \longrightarrow freeze-out still alive!
- Smaller V_χ, A_χ (no DM signals...) \longrightarrow Larger V_f, A_f for $\Omega h^2 = 0.12$

Z' portal: Viable parameter space

axial and vector (FO/FI)

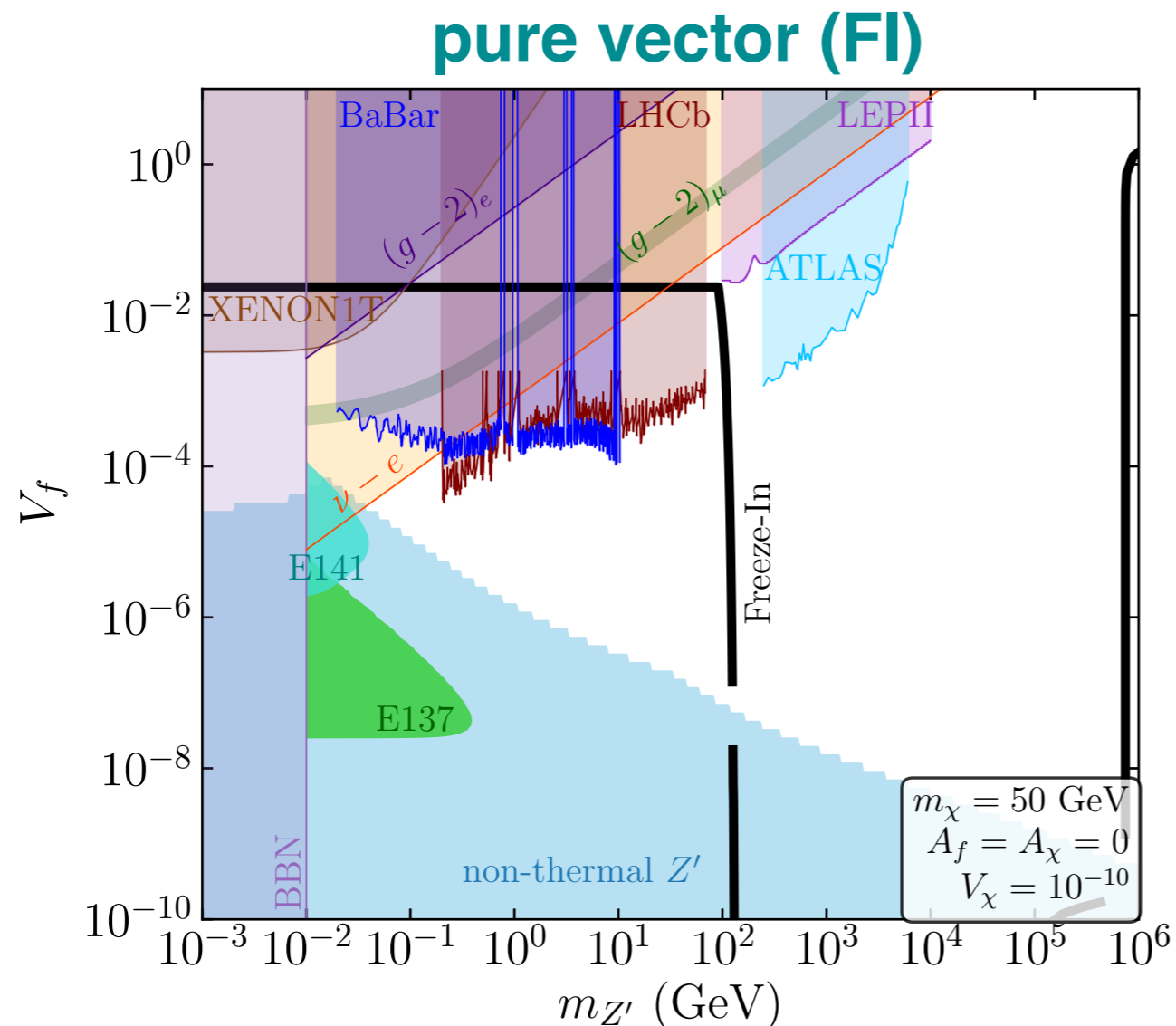


pure axial (FO/FI)



- Smaller $V_\chi, A_\chi \longrightarrow$ **freeze-in tested** by colliders, APV, $\nu - e$ scatt., and beam-dump experiments for m_χ in the range of ~ 100 MeV - 100 GeV!

Z' portal: Viable parameter space



No axial couplings
 ↓
 Weaker SM-DM interactions

- Thermalization is more difficult
- Only s-channels set the relic density → light regime independent of $m_{Z'}$
 → FIMPs tested @ direct detection
- Larger V_{χ} → FIMPs tested @ beam-dump (smaller V_f needed)

Outline

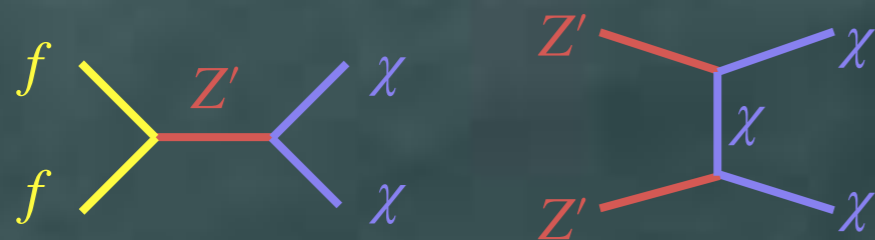
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Conclusions

- The freeze-in is an appealing mechanism for dark matter genesis, and is testable in a few scenarios
- The parameter space in which the freeze-in can populate the universe with the right amount of DM in the context of a generic Z' portal is already being tested by many experiments!



@ Early Universe



@ DD, $\nu - e^-$, APV, colliders, e^- BD



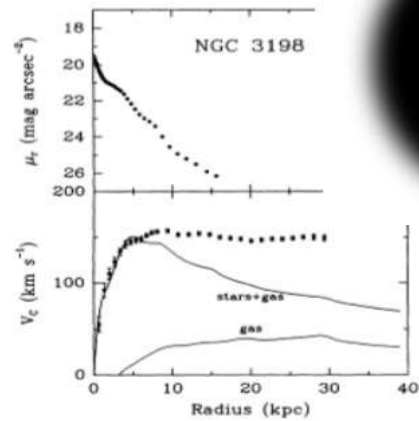
→ different realizations of axially coupled Z' portals are relevant for the phenomenology of both WIMPs and FIMPs

Thank you!

BACKUP SLIDES

Introduction: Evidence for dark matter particles

Rotation curves



effectively
NEUTRAL

NON-BARYONIC

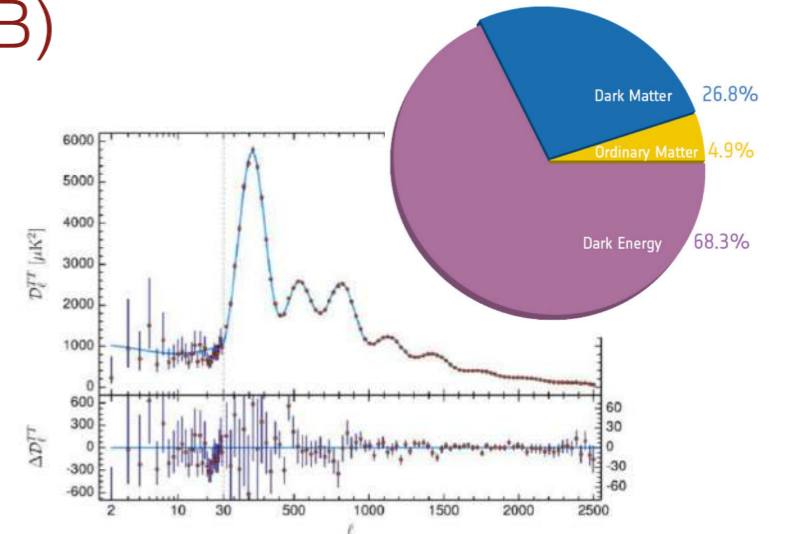
WEAKLY
INTERACTING

mostly
COLD

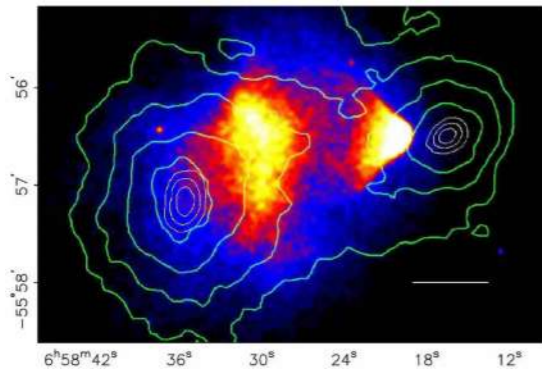
27%
of the cosmic energy
today

cosmologically
STABLE

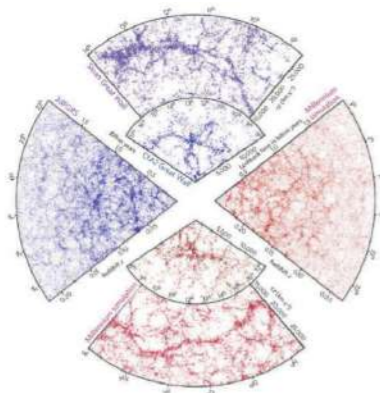
Cosmic Microwave Background (CMB)



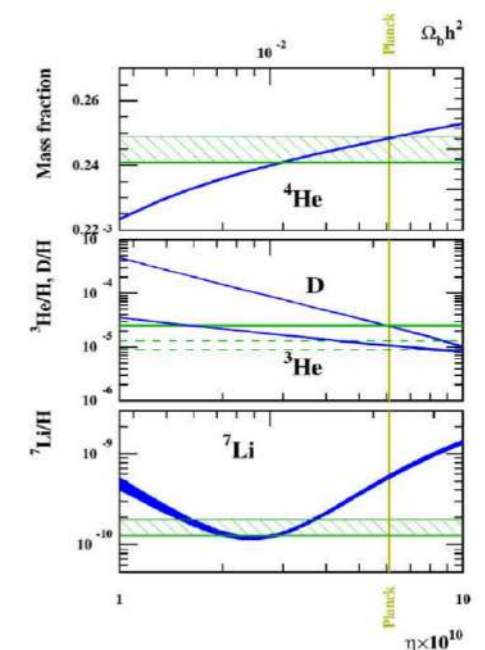
Merging clusters



Structure formation

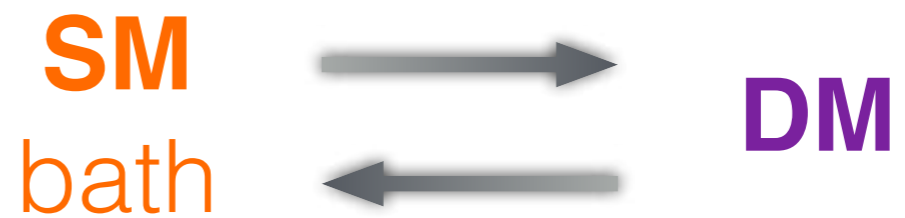
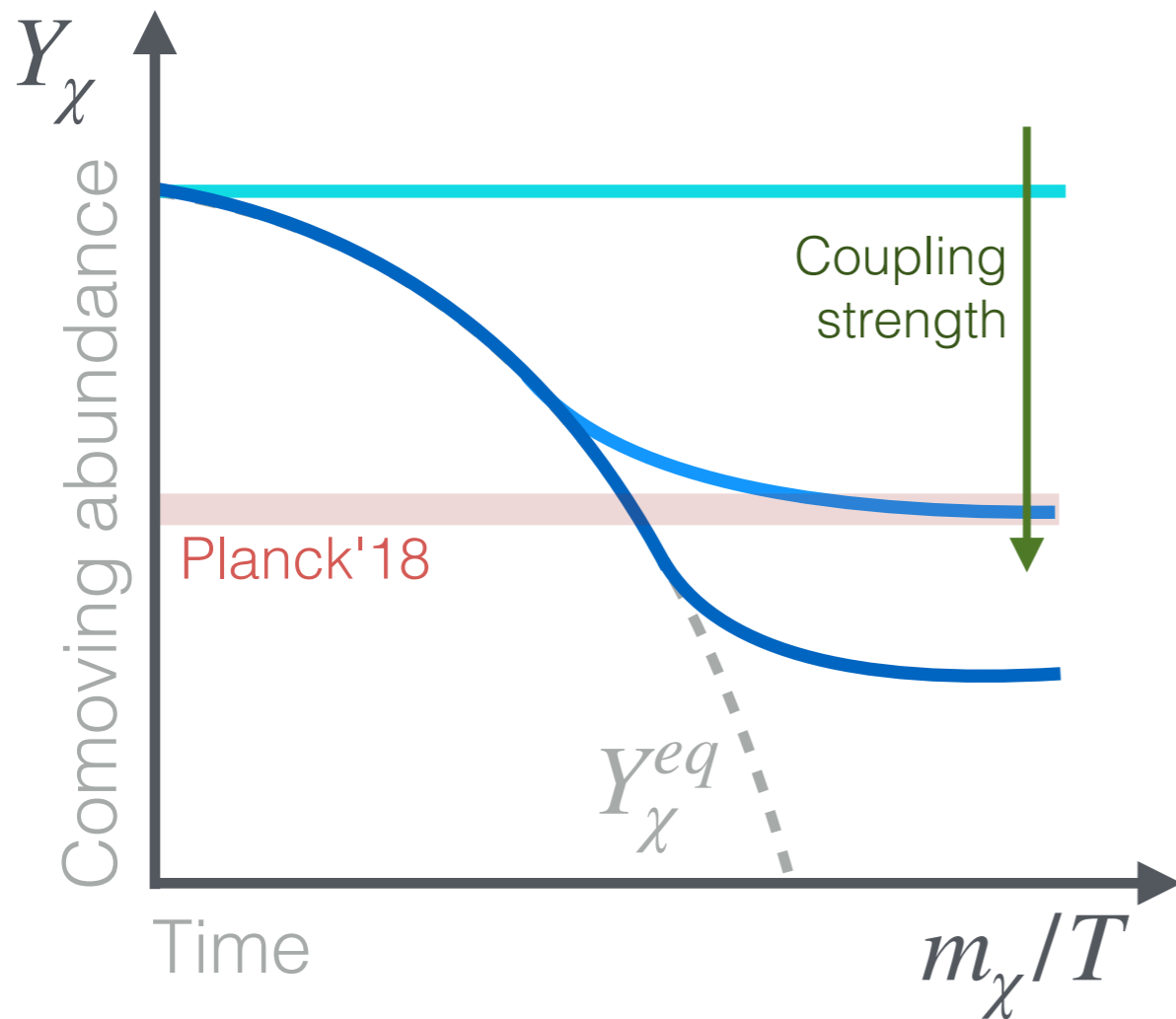
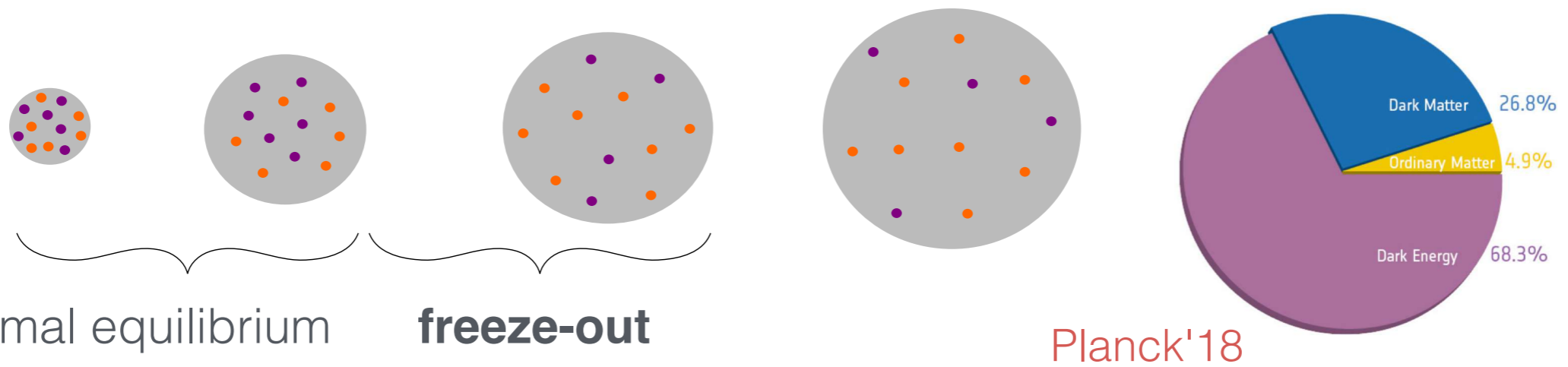


Big Bang Nucleosynthesis (BBN)

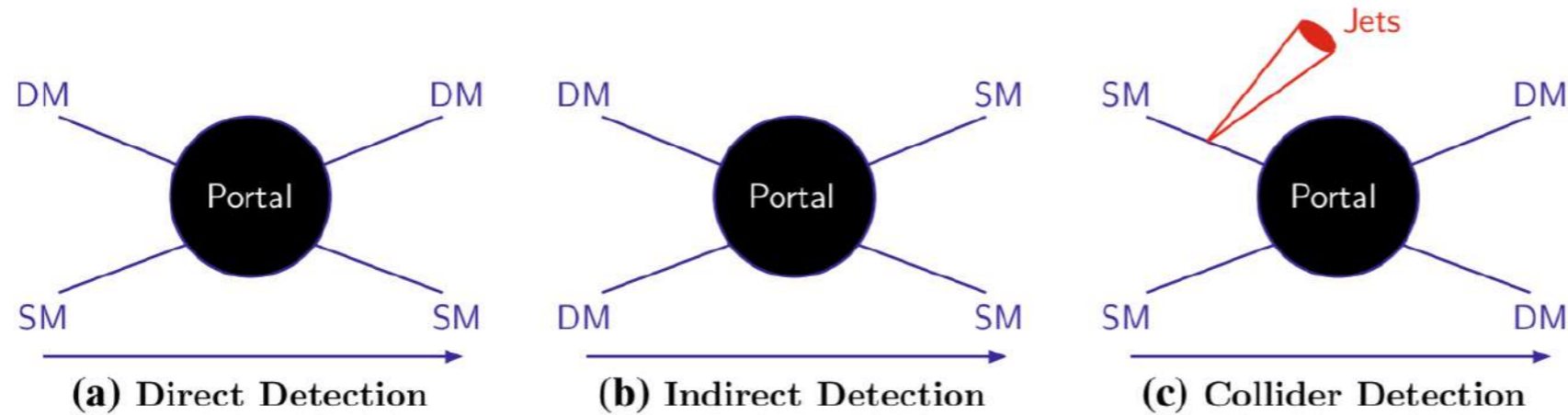


Introduction: DM genesis - the freeze-out

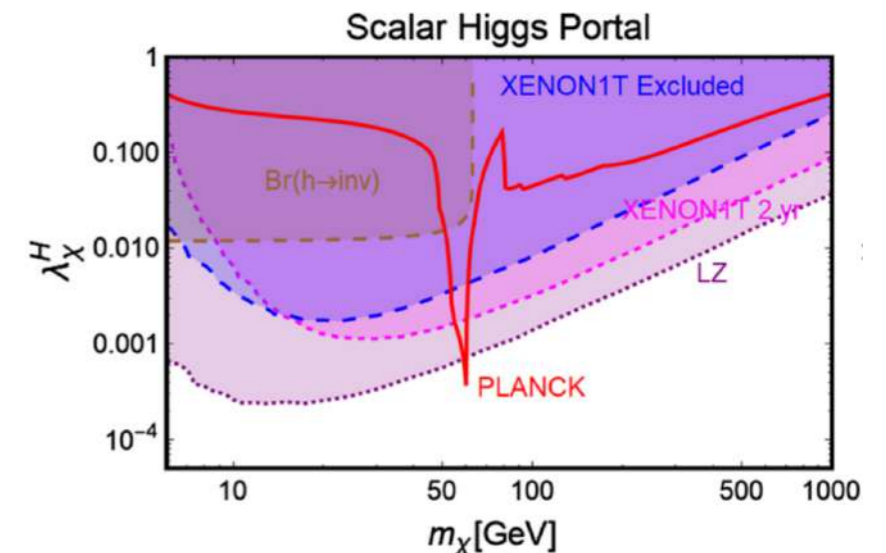
Evolution of weakly interacting massive particles (**WIMPs**) in the early universe:



Introduction: Testing freeze-out



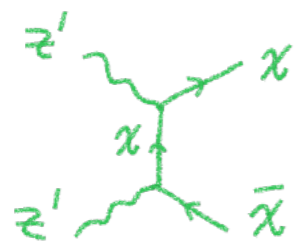
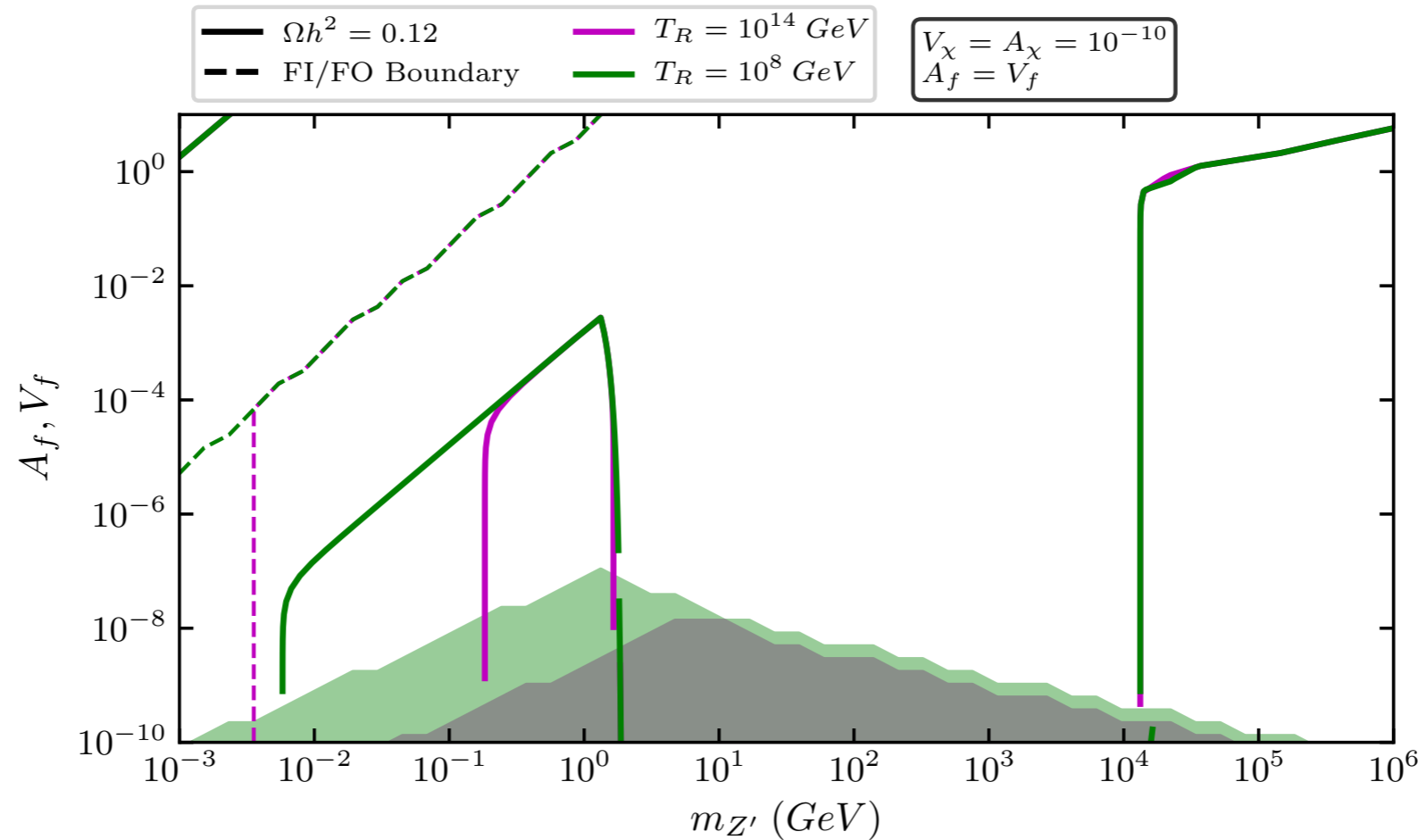
- Simplified portals of WIMP dark matter are typically in tension with bounds from direct detection and collider experiments
- The **rich phenomenology** of WIMPs has not been fully explored yet!



The waning of the WIMP? A review of models, searches, and constraints

G. Arcadi, MD, P. Ghosh, M. Lindner, Y. Mambrini, M. Pierre, S. Profumo, F. Queiroz
arXiv:1703.07364

Z' portal: Correct relic density via freeze-in



$$\Omega_\chi^0 h^2 \sim 0.12 \left(\frac{m_\chi}{1\text{GeV}} \right)^3 \left(\frac{0.2\text{GeV}}{m_{Z'}} \right)^4 \left(\frac{A_\chi}{10^{-10}} \right)^4 \left(\frac{T_{RH}}{10^{14}\text{GeV}} \right)$$

- The t-channel is a **UV freeze-in process**