

# PhenoBR 2021

24 - 25 de junho de 2021

Natal - RN

Evento online

## Colocando freeze-in à prova com bosons $Z'$

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Carleton University  
Ottawa, Canada

Palestra baseada em C. Cosme, M. Dutra, S. Godfrey, and T. Gray  
arXiv:2104.13937



**Carleton**  
UNIVERSITY



Arthur B. McDonald  
Canadian Astroparticle Physics Research Institute

24 de junho, 2021

# Visão geral

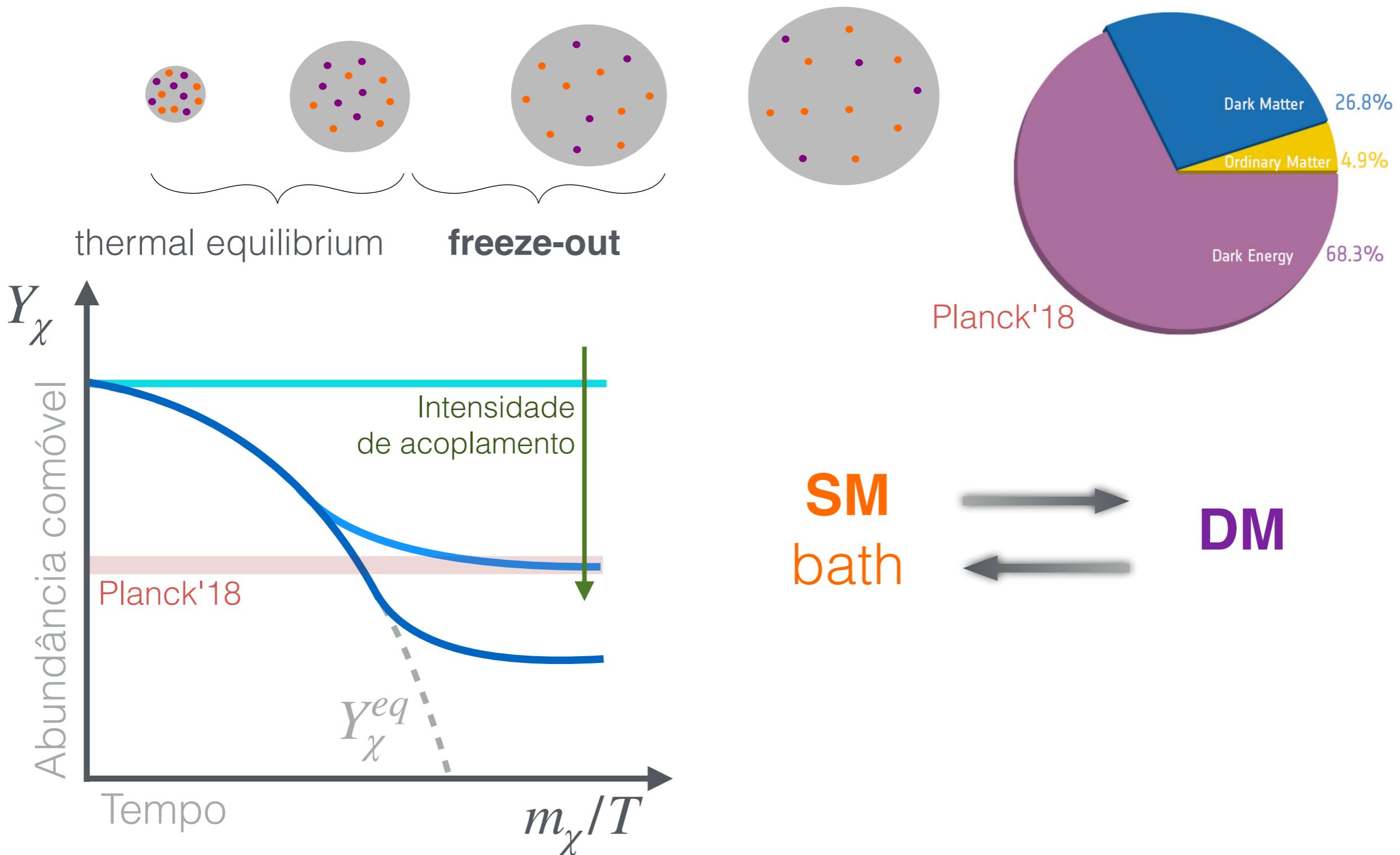
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1. Introdução
2. Portal  $Z'$  vetor e axial
3. Espaço de parâmetros viável
4. Conclusões

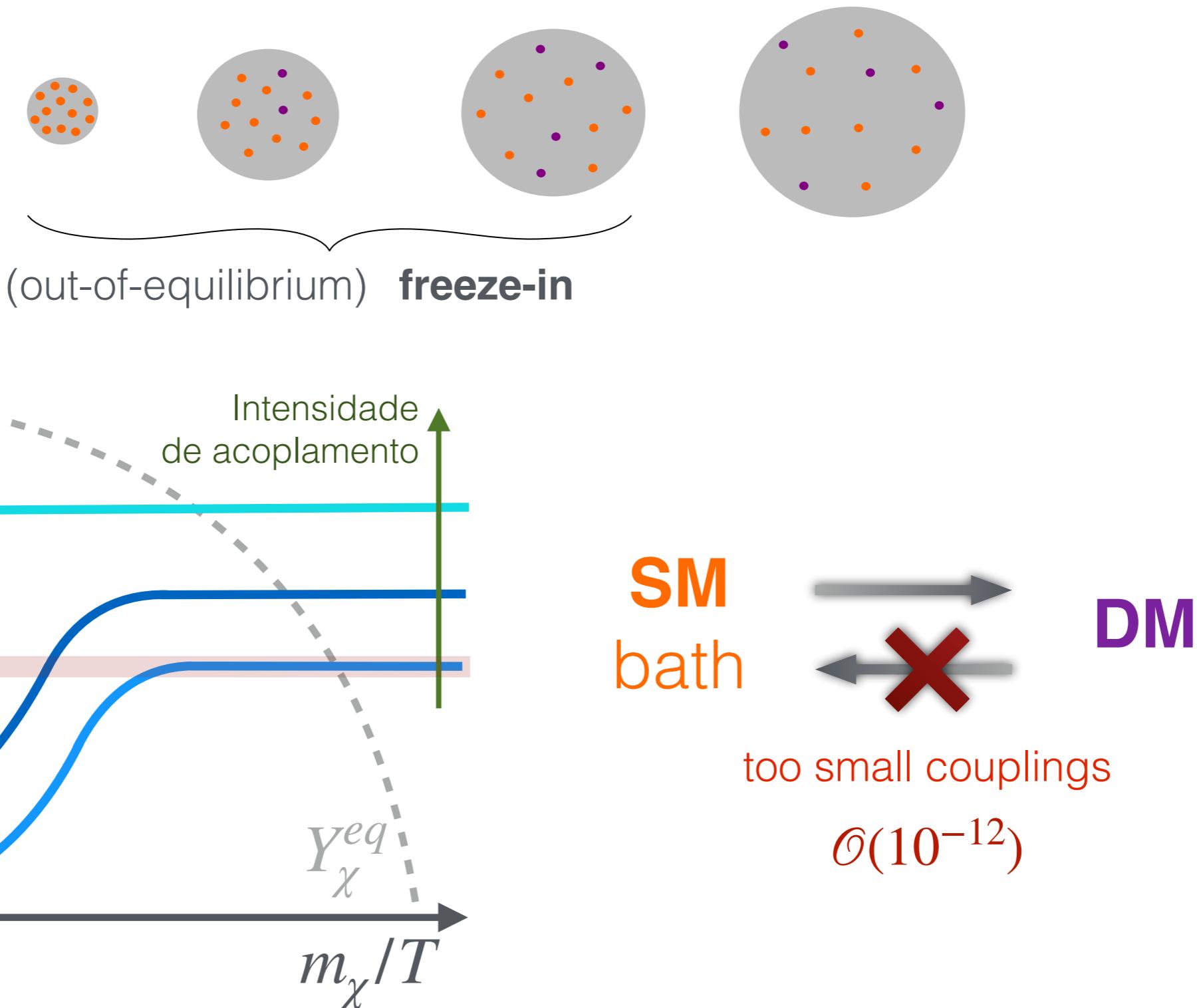
# Introdução: gerando matéria escura via "freeze-out"

Evolução das weakly interacting massive particles (**WIMPs**) no universo primordial:



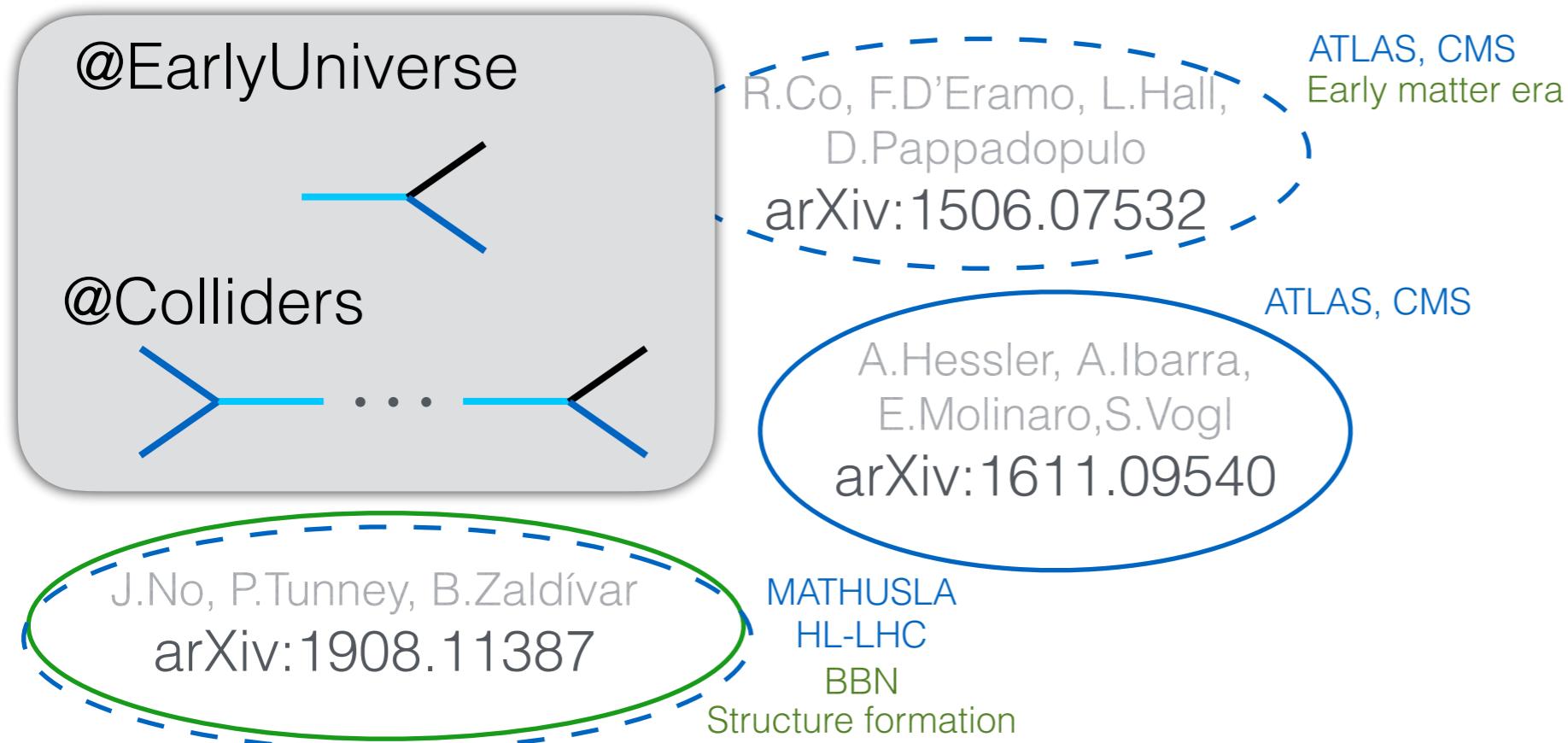
# Introdução: gerando matéria escura via "freeze-in"

Evolução das feebly interacting massive particles (**FIMPs**) no universo primordial:



# Introdução: como testar freeze-in?

Colliders&Accelerators    Astro&Cosmo



# Introdução: como testar freeze-in?

Colliders&Accelerators    Astro&Cosmo    Direct detection

@EarlyUniverse



@Colliders



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

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

ATLAS, CMS  
Early matter era

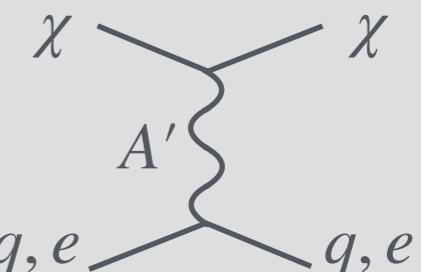
A.Hessler, A.Ibarra,  
E.Molinaro,S.Vogl  
arXiv:1611.09540

ATLAS, CMS

MATHUSLA  
HL-LHC  
BBN  
Structure formation

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

# Introdução: como testar freeze-in?

Colliders&Accelerators Astro&Cosmo Direct detection Indirect detection

@EarlyUniverse



@Colliders



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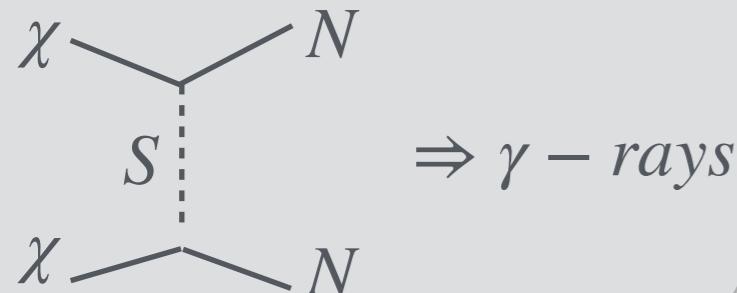
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ATLAS, CMS

Neutrino portal



Fermi-LAT & H.E.S.S.  
Early matter era

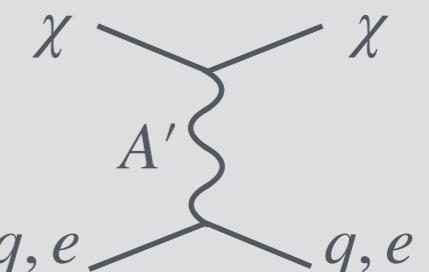
C.Cosme, M.Dutra,  
T.Ma, Y.Wu, L.Yang  
arXiv:2003.01723

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HL-LHC  
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# Portal $Z'$ vetor e axial

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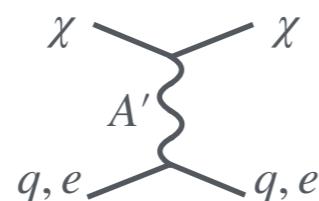
- \* Extra  $U(1)$  symmetries are present in many BSM scenarios
- \* Light BSM spin-1 bosons associated with extra  $U(1)$  symmetries:  
enhanced new physics signals  $\Rightarrow$  weakly interacting

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Dark photons

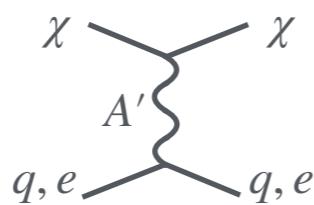


**FIMP direct detection, light DM**

# Portal $Z'$ vetor e axial

- \* Extra  $U(1)$  symmetries are present in many BSM scenarios
- \* Light BSM spin-1 bosons associated with extra  $U(1)$  symmetries: enhanced new physics signals  $\Rightarrow$  weakly interacting

Dark photons



FIMP direct detection, light DM

Axial  $U(1)$  bosons

MeV anomalies

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



GC  $\gamma$ -ray excess

D. Hooper  
arXiv:1411.4079

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

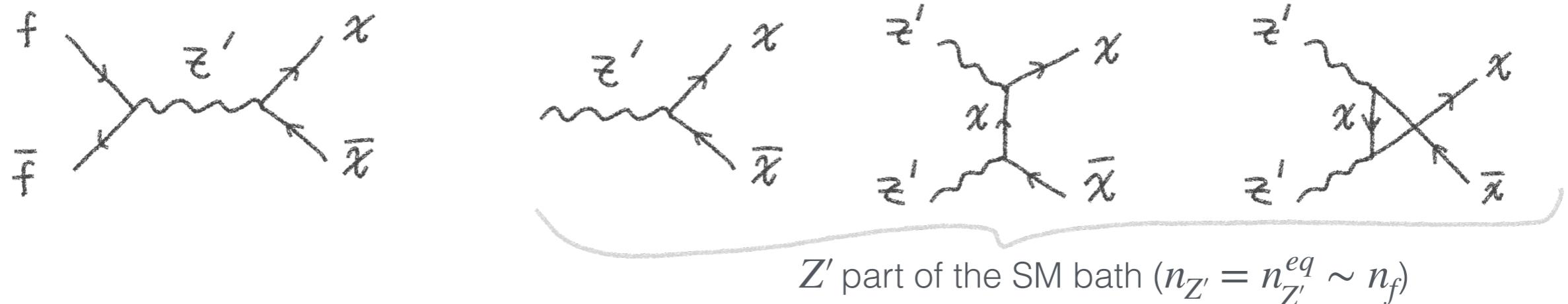
# Portal Z' vetor e axial

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

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

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

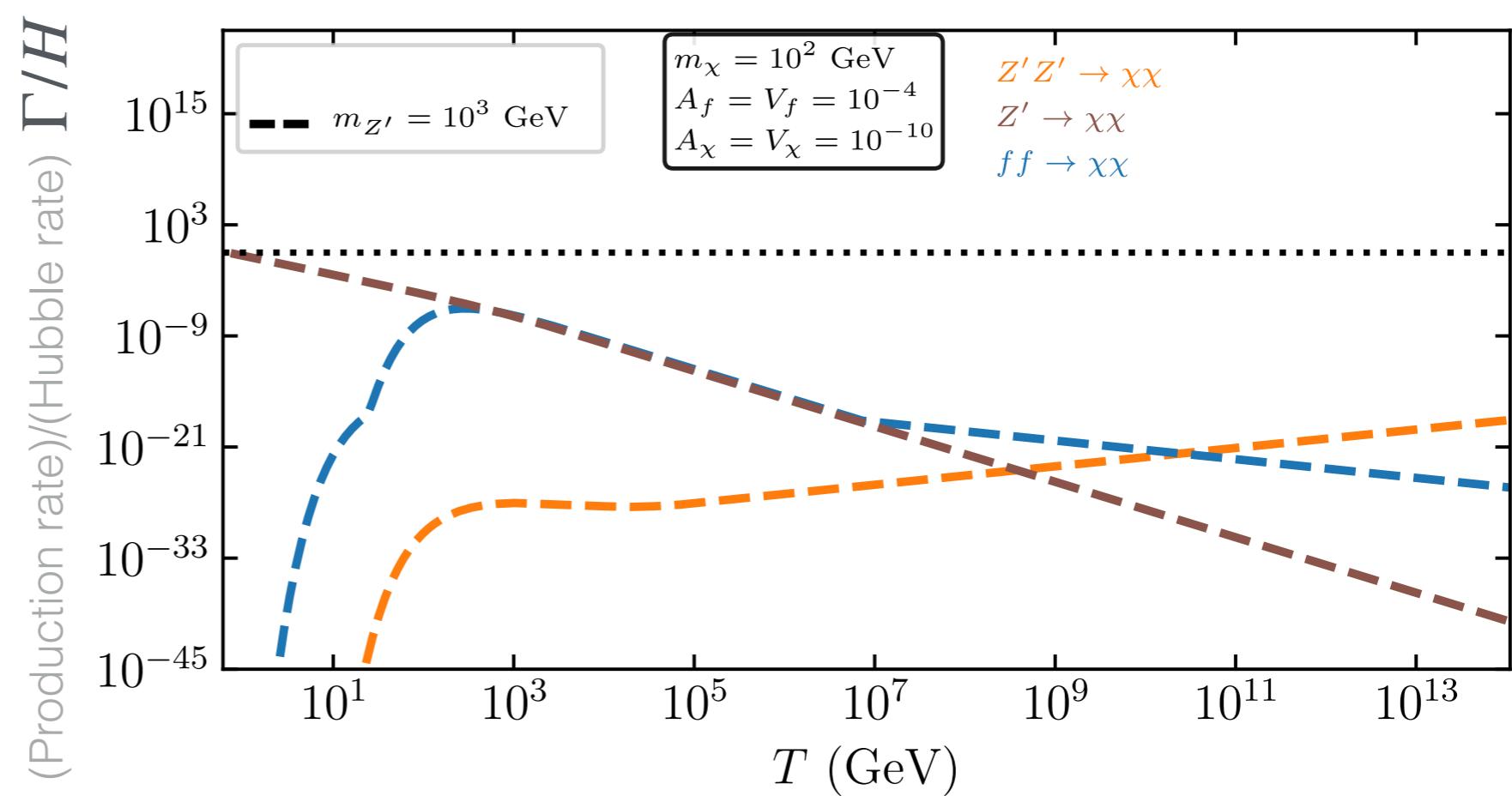
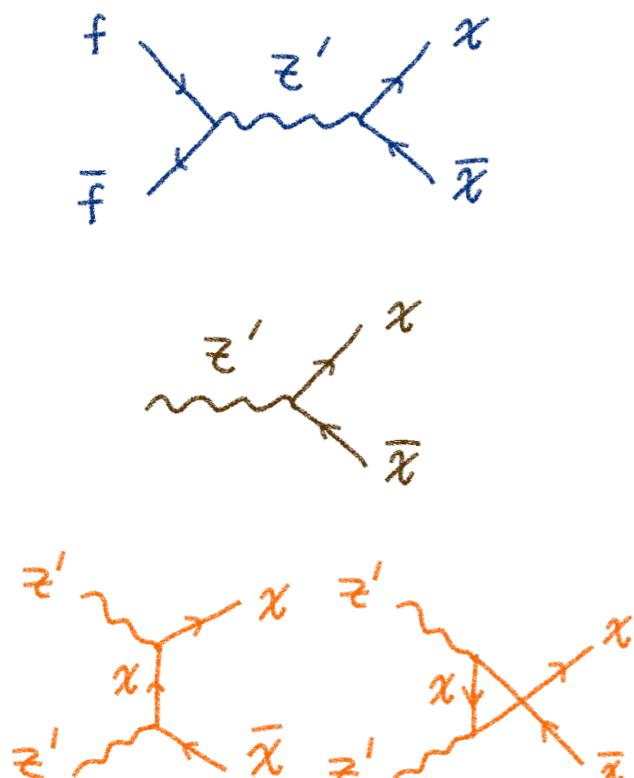
$$A_f = \frac{g_{Z'}}{2} (X_{f_L} - X_{f_R})$$



# Portal Z' vetor e axial

Catarina Cosme, MD, Steve Godfrey, and Taylor Gray  
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$$\Gamma_{s-ch} + \Gamma_{dec} + \Gamma_{t-ch} < H \Rightarrow \text{Freeze-in}$$

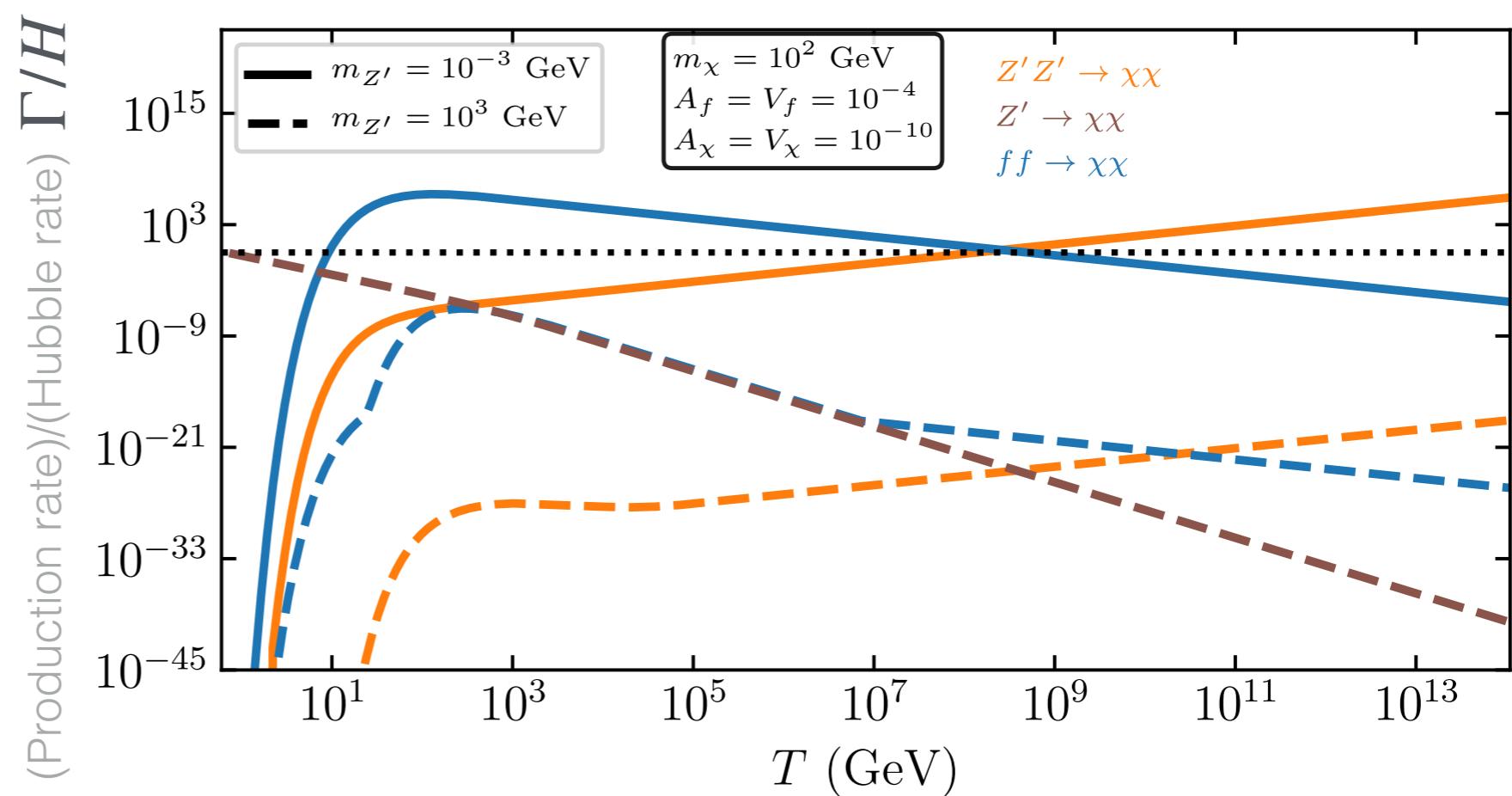
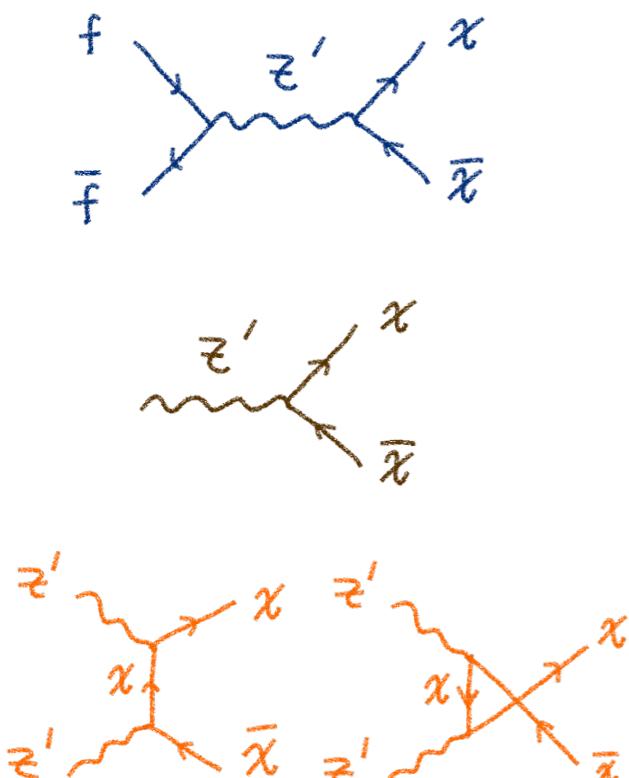


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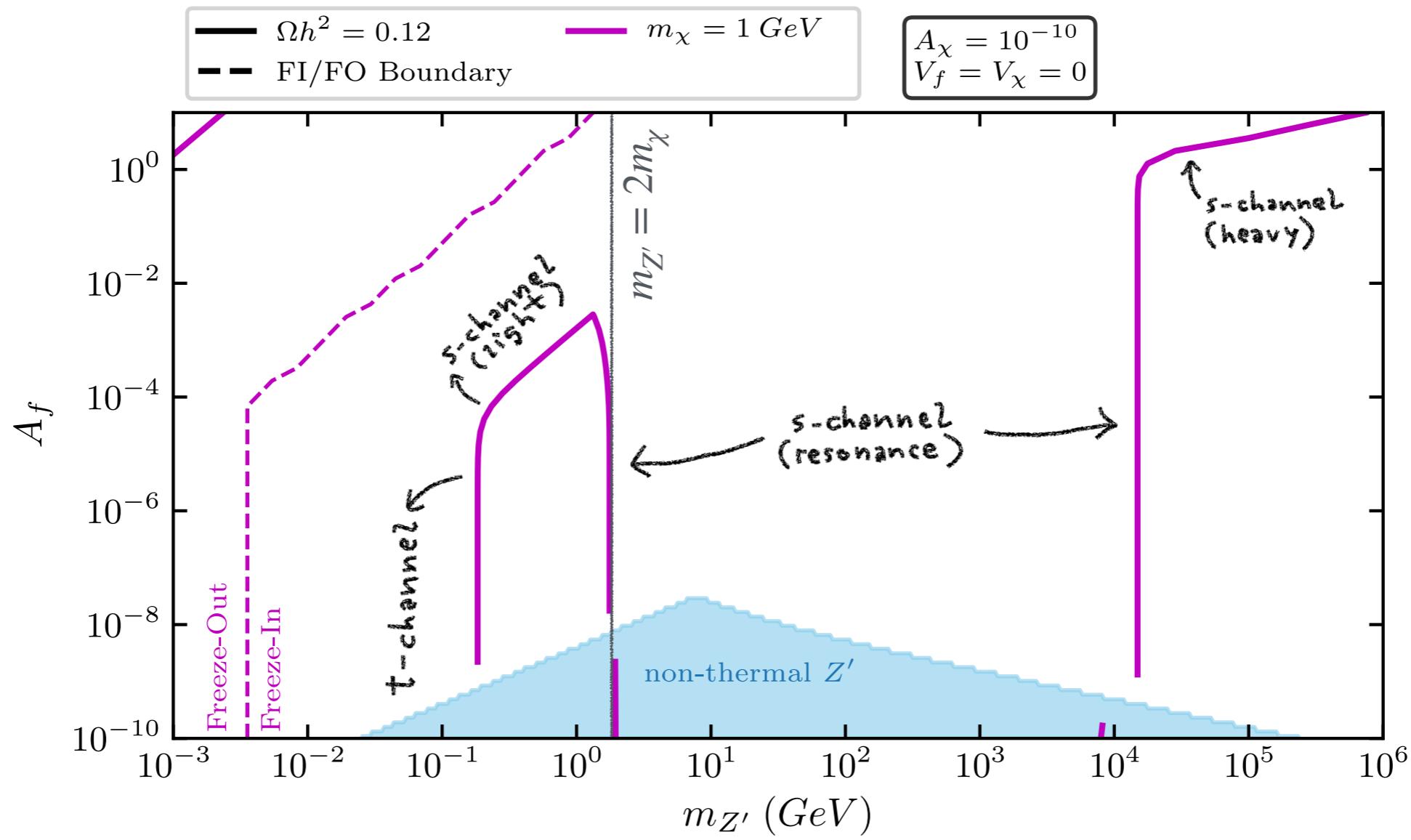
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$$\Gamma_{s-ch} + \Gamma_{dec} + \Gamma_{t-ch} < H \Rightarrow \text{Freeze-in}$$

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



# Espaço de parâmetros viável: abundância relíquia

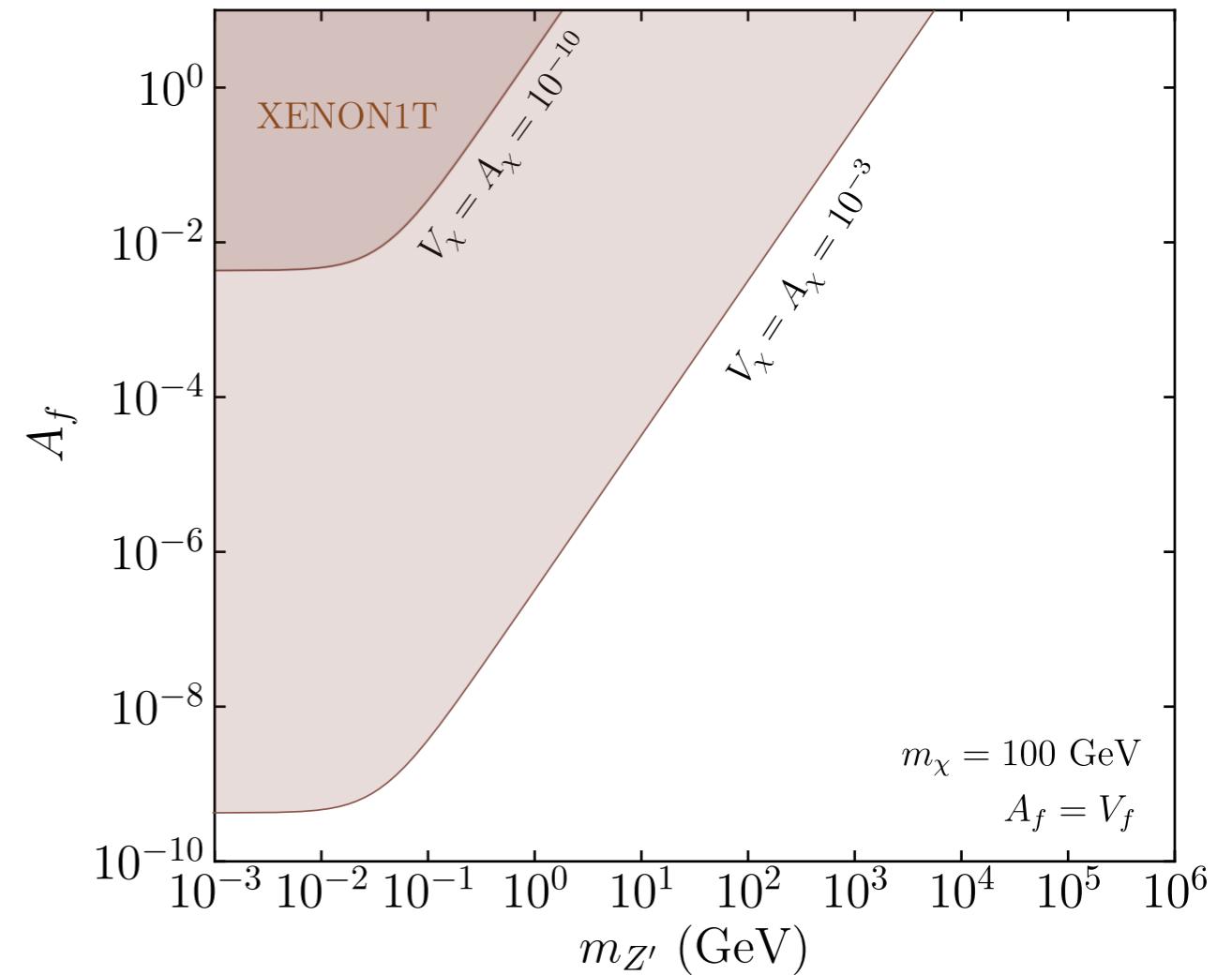
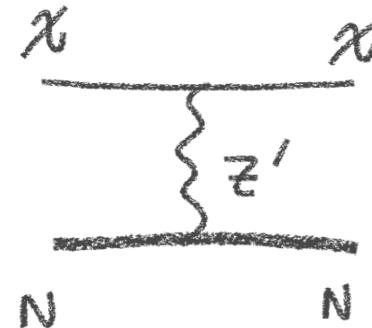


- Smaller (larger)  $m_\chi$  requires smaller (larger)  $m_{Z'}$

Catarina Cosme, MD, Steve Godfrey, and Taylor Gray  
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# Espaço de parâmetros viável: vínculos

Direct detection  
XENON1T

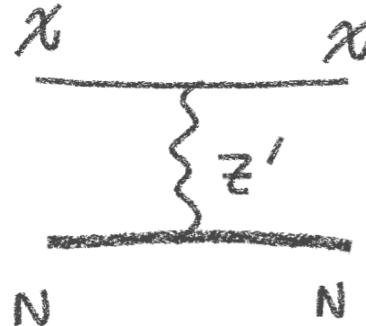


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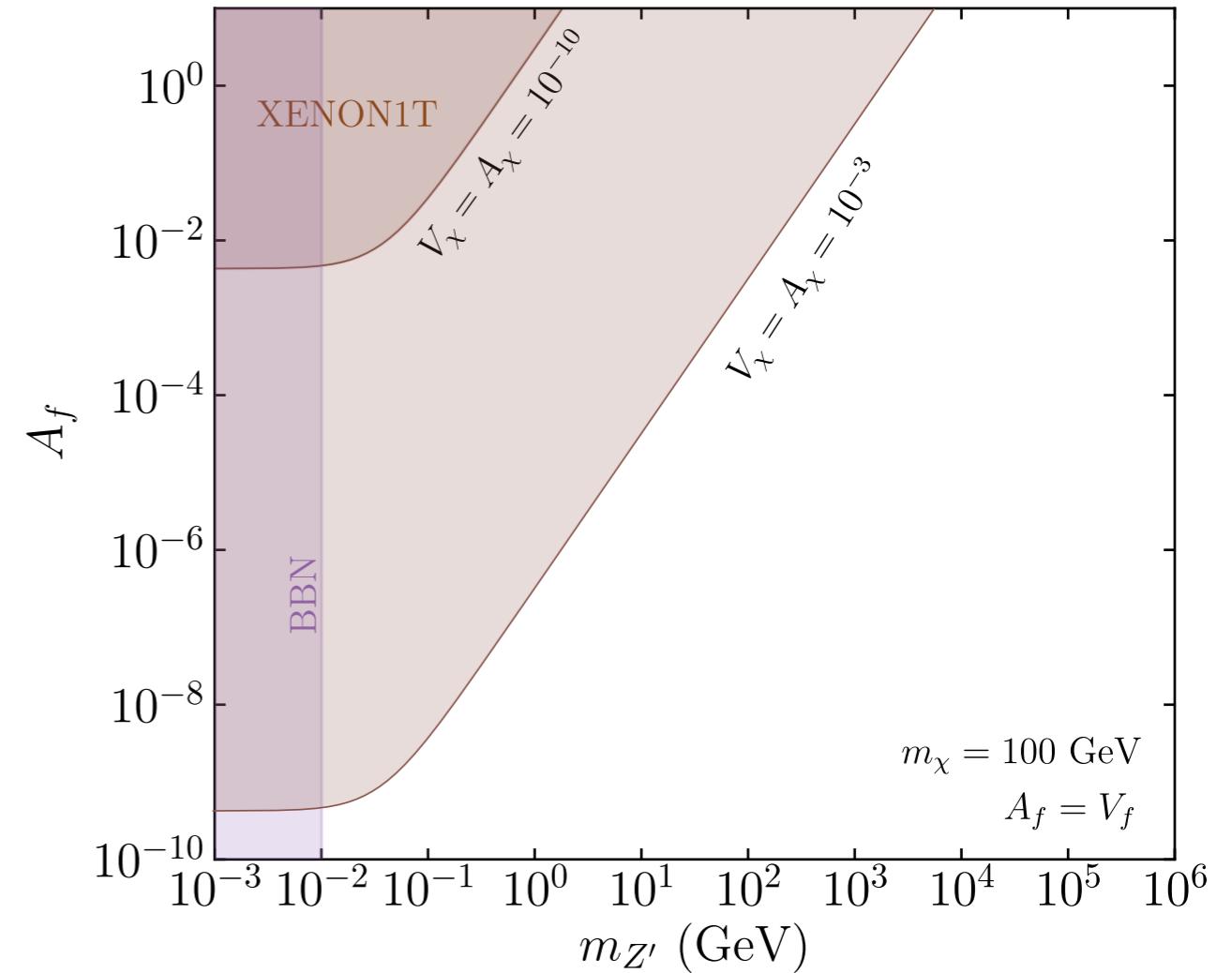
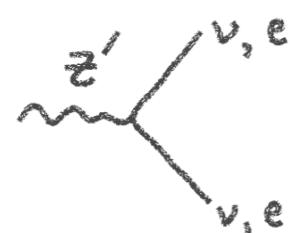
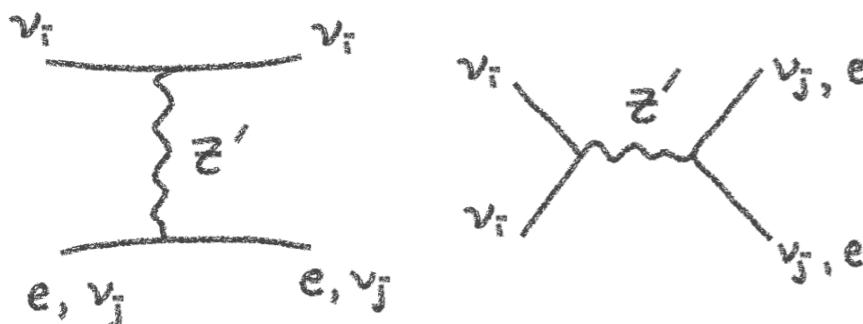
Direct detection

XENON1T



Astro&Cosmo

Big Bang nucleosynthesis

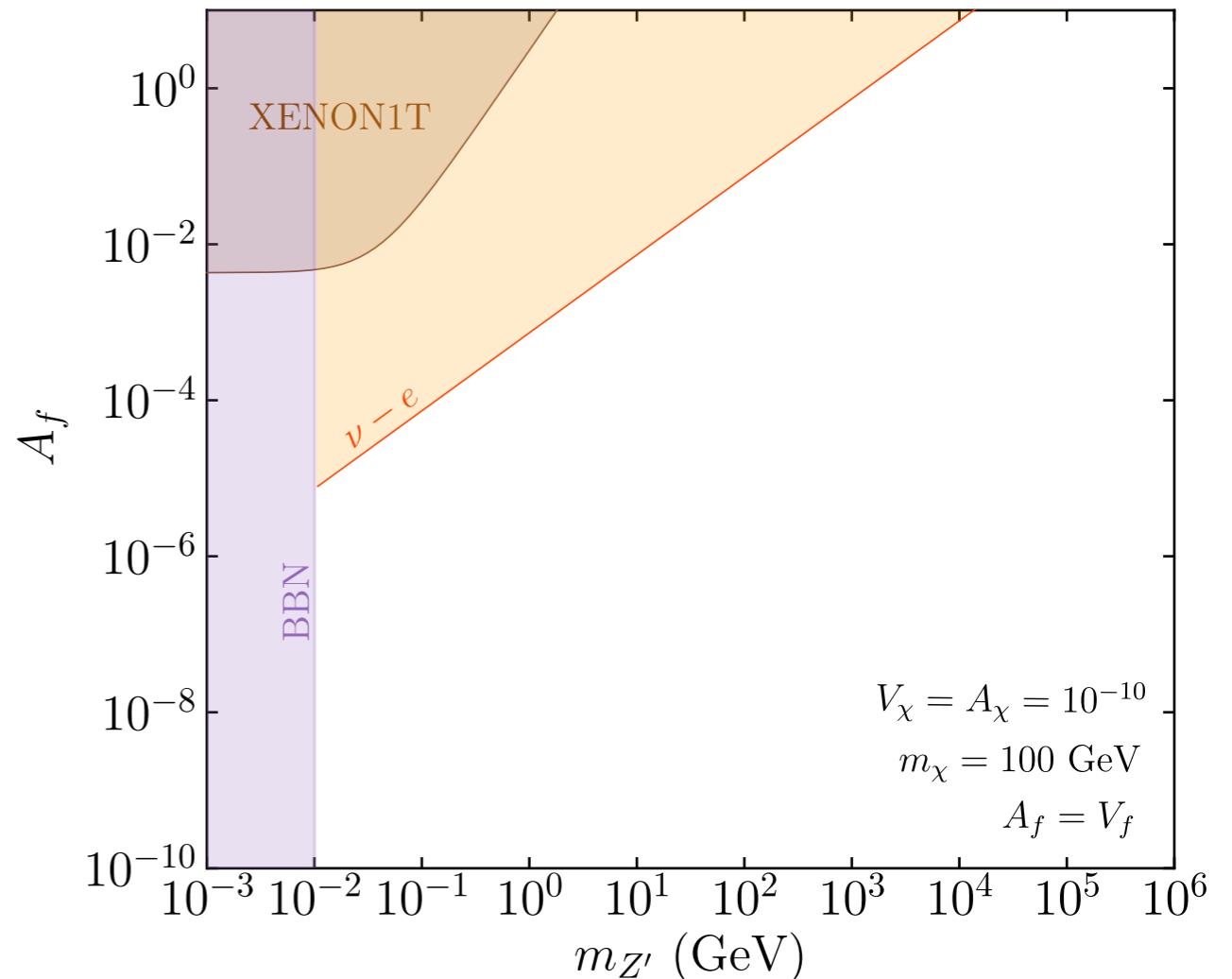
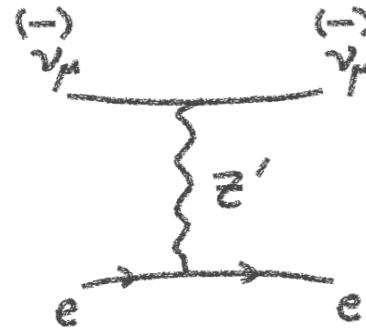


Catarina Cosme, MD, Steve Godfrey, and Taylor Gray  
arXiv:2104.13937

# Espaço de parâmetros viável: vínculos

## Colliders&Accelerators

### Neutrino-electron scattering

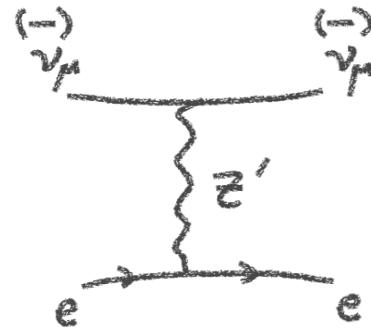


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# Espaço de parâmetros viável: vínculos

## Colliders&Accelerators

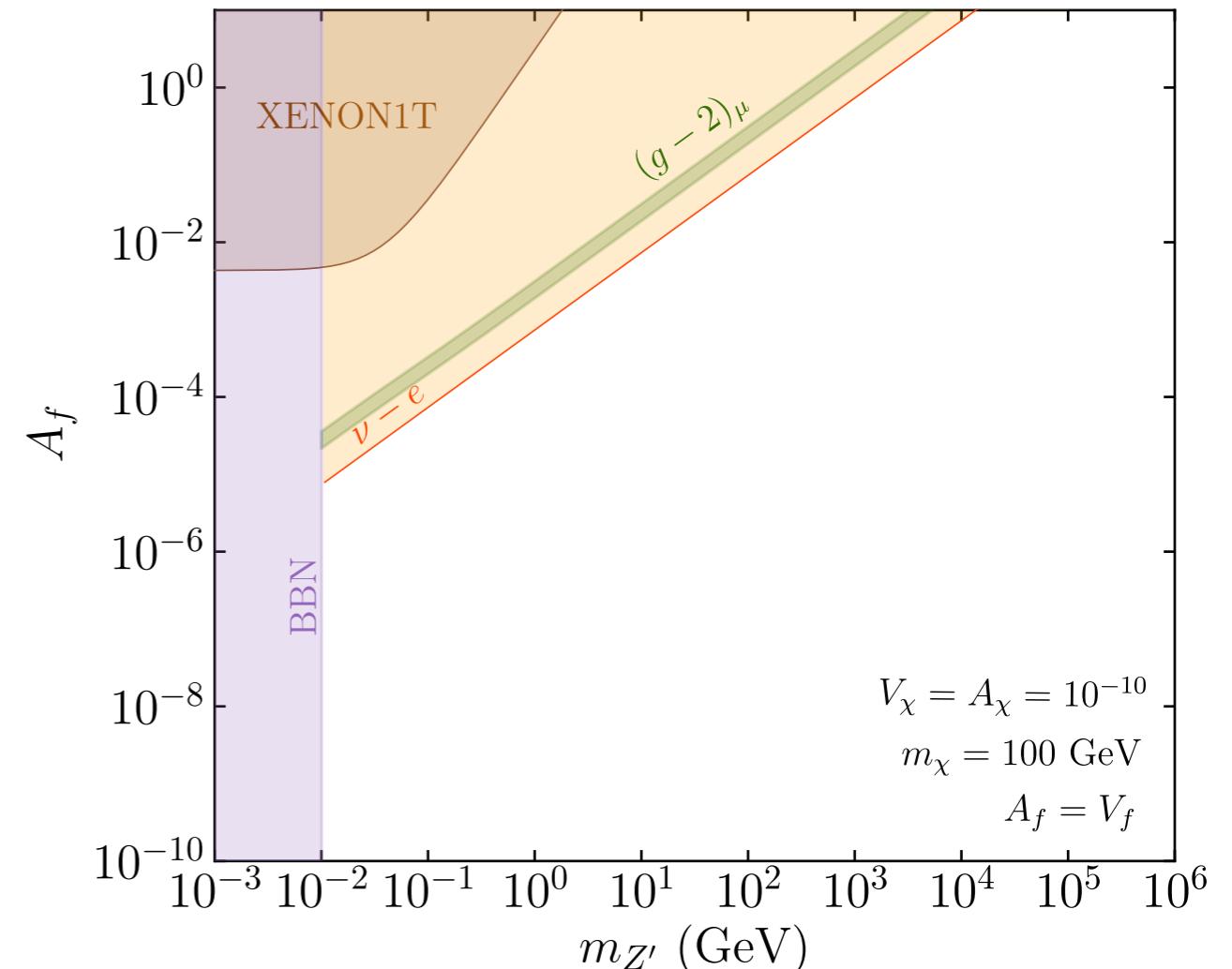
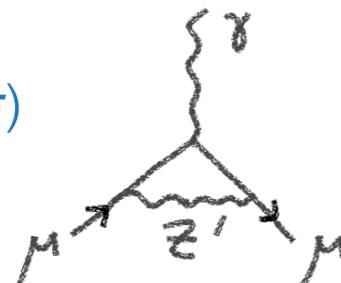
### Neutrino-electron scattering



### Leptonic anomalous magnetic moments

$(g - 2)_\mu$

FNAL+BNL ( $4.2\sigma$ )

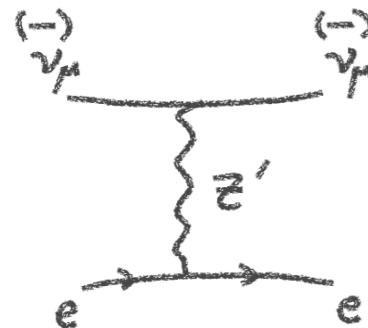


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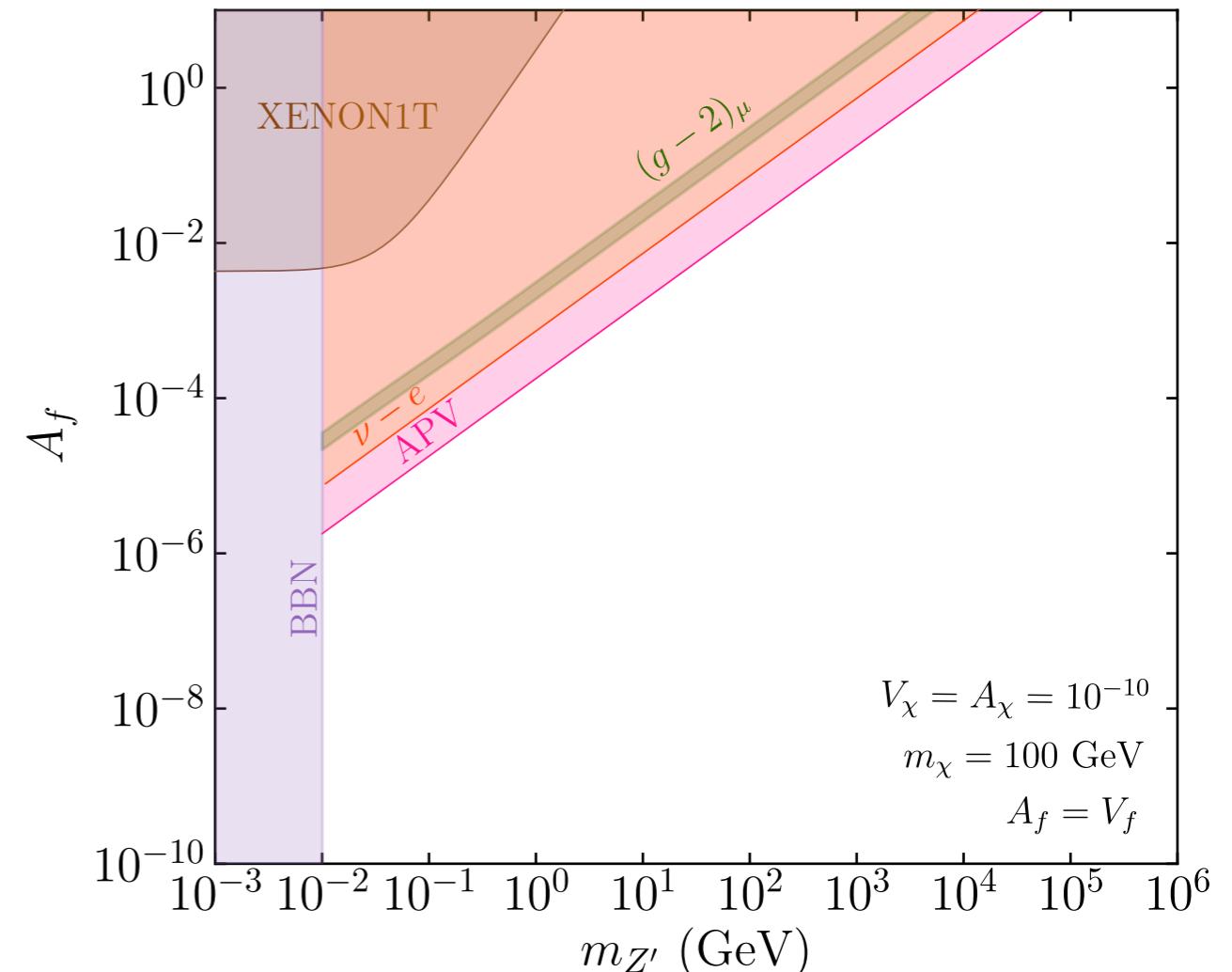
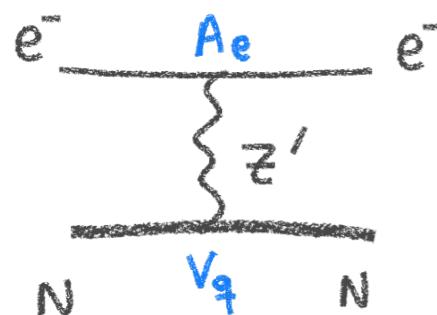
### Leptonic anomalous magnetic moments

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### Atomic parity violation



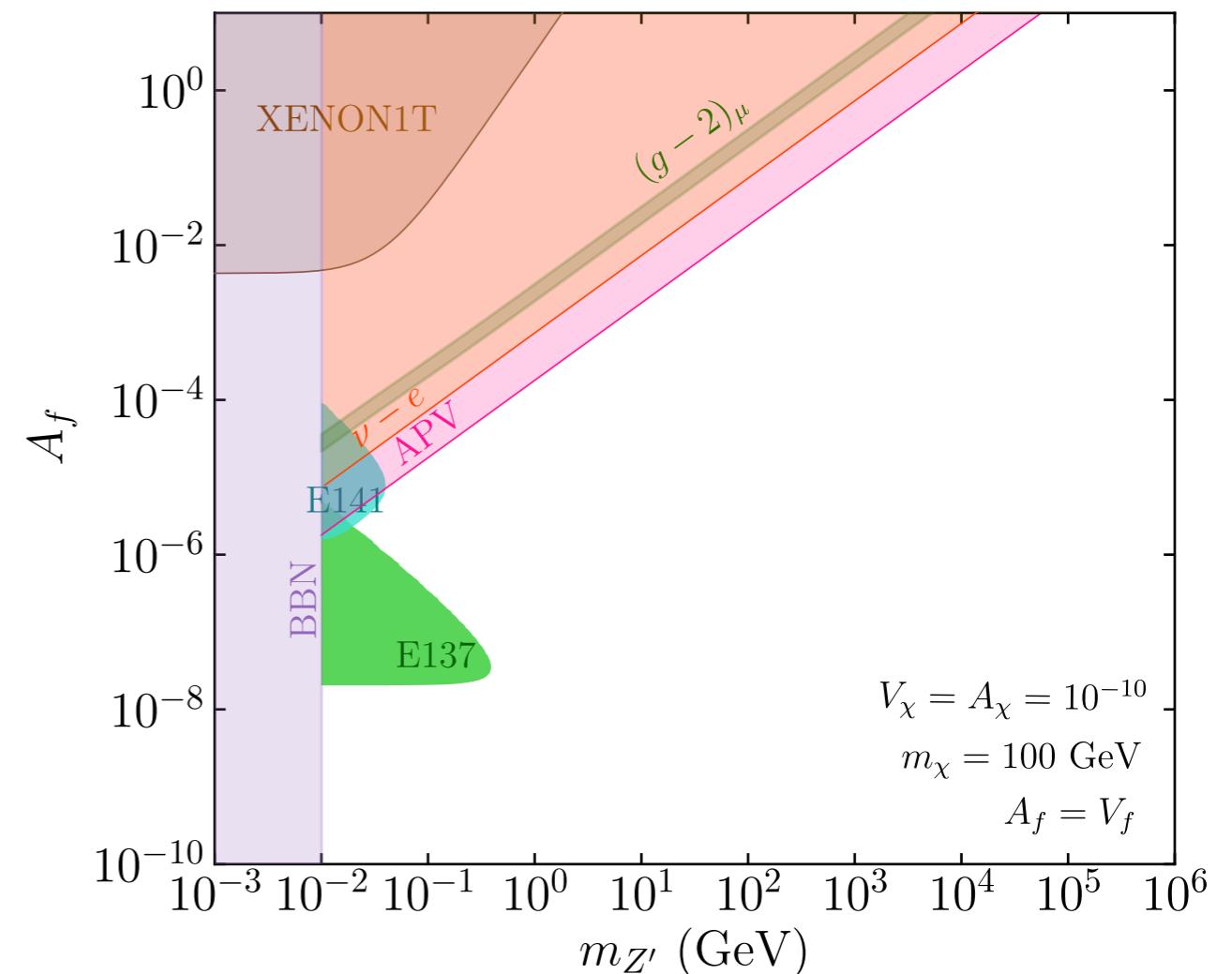
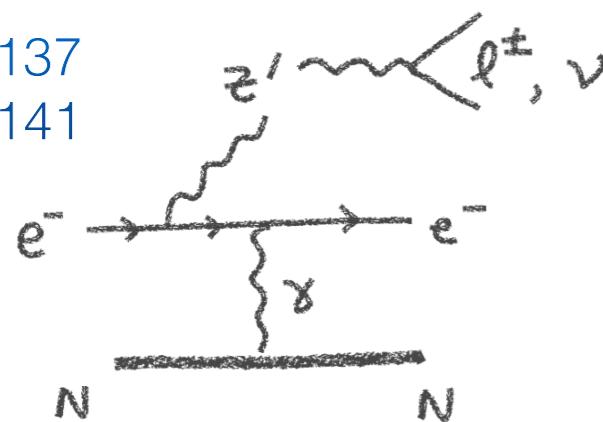
Catarina Cosme, MD, Steve Godfrey, and Taylor Gray  
arXiv:2104.13937

# Espaço de parâmetros viável: vínculos

## Colliders&Accelerators

### Electron beam-dump

SLAC E137  
SLAC E141



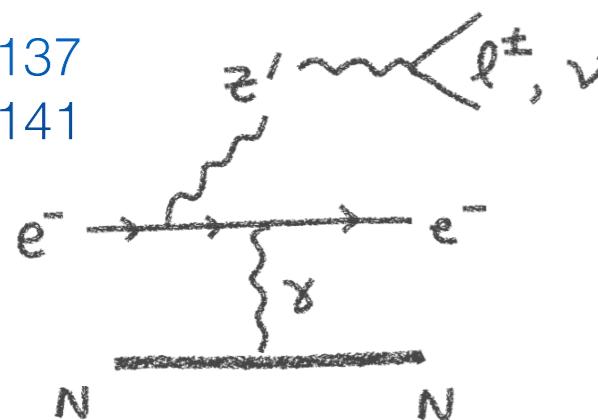
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# Espaço de parâmetros viável: vínculos

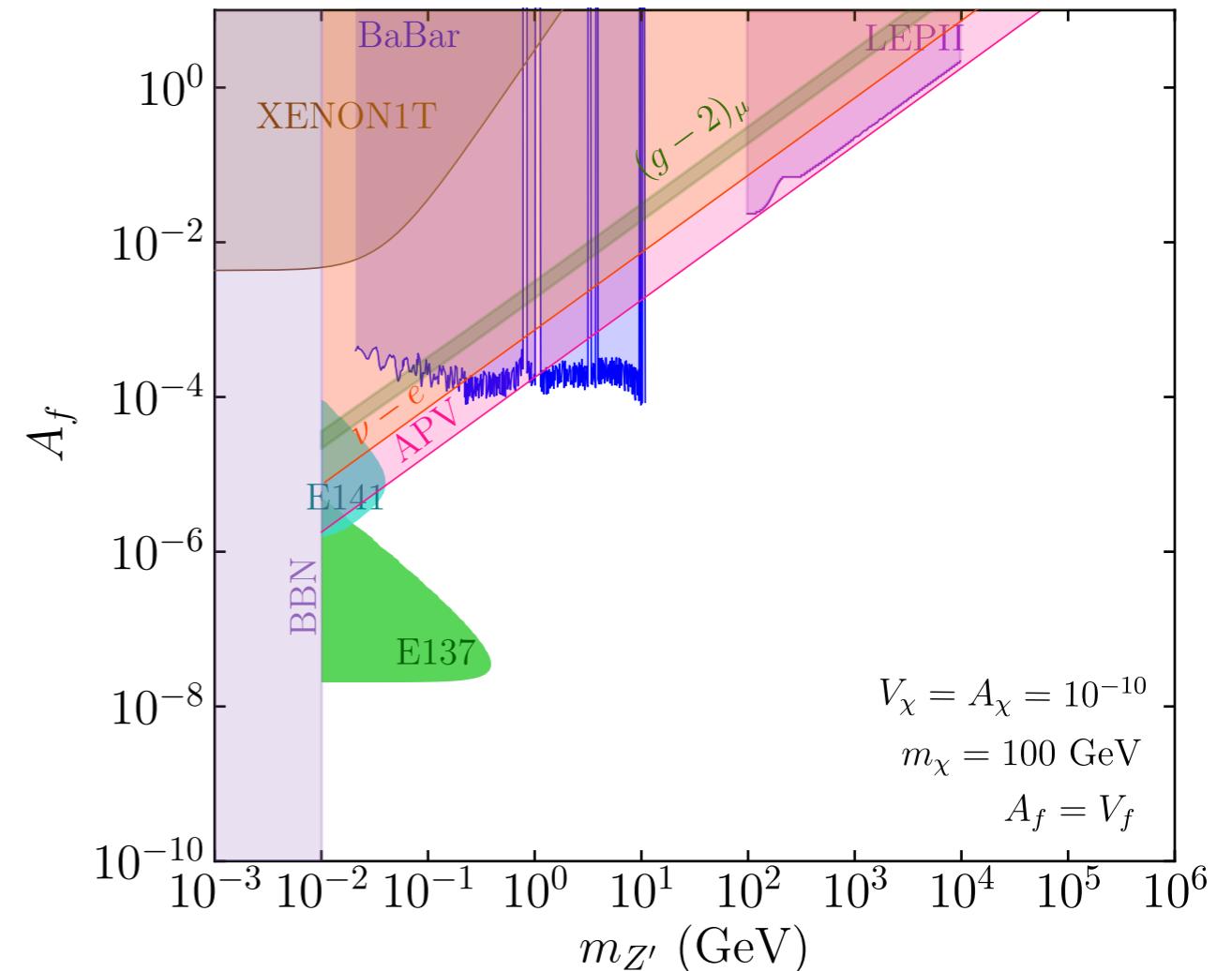
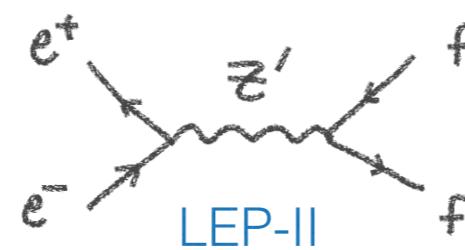
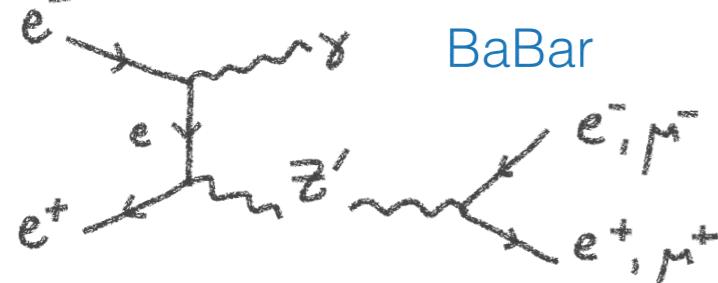
## Colliders&Accelerators

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SLAC E137  
SLAC E141



### Electron-positron collisions



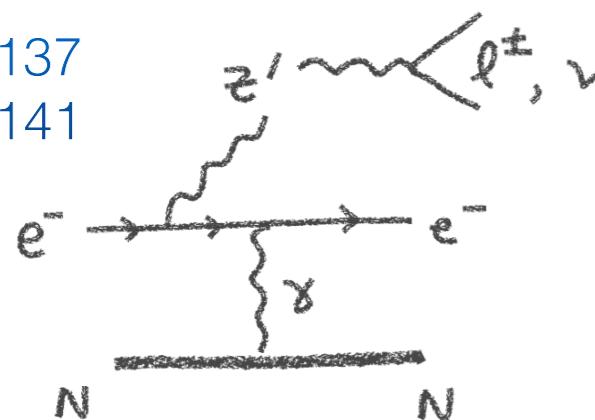
Catarina Cosme, MD, Steve Godfrey, and Taylor Gray  
arXiv:2104.13937

# Espaço de parâmetros viável: vínculos

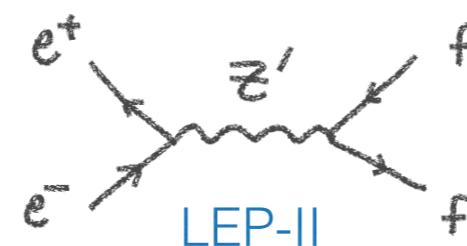
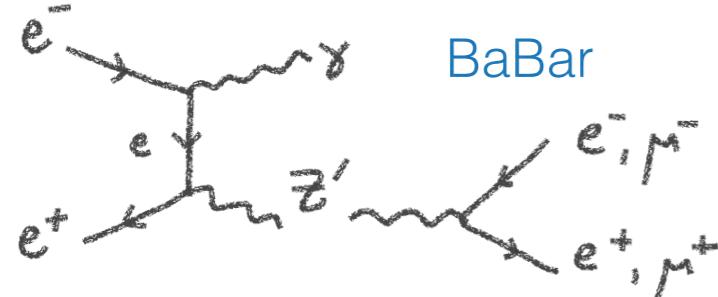
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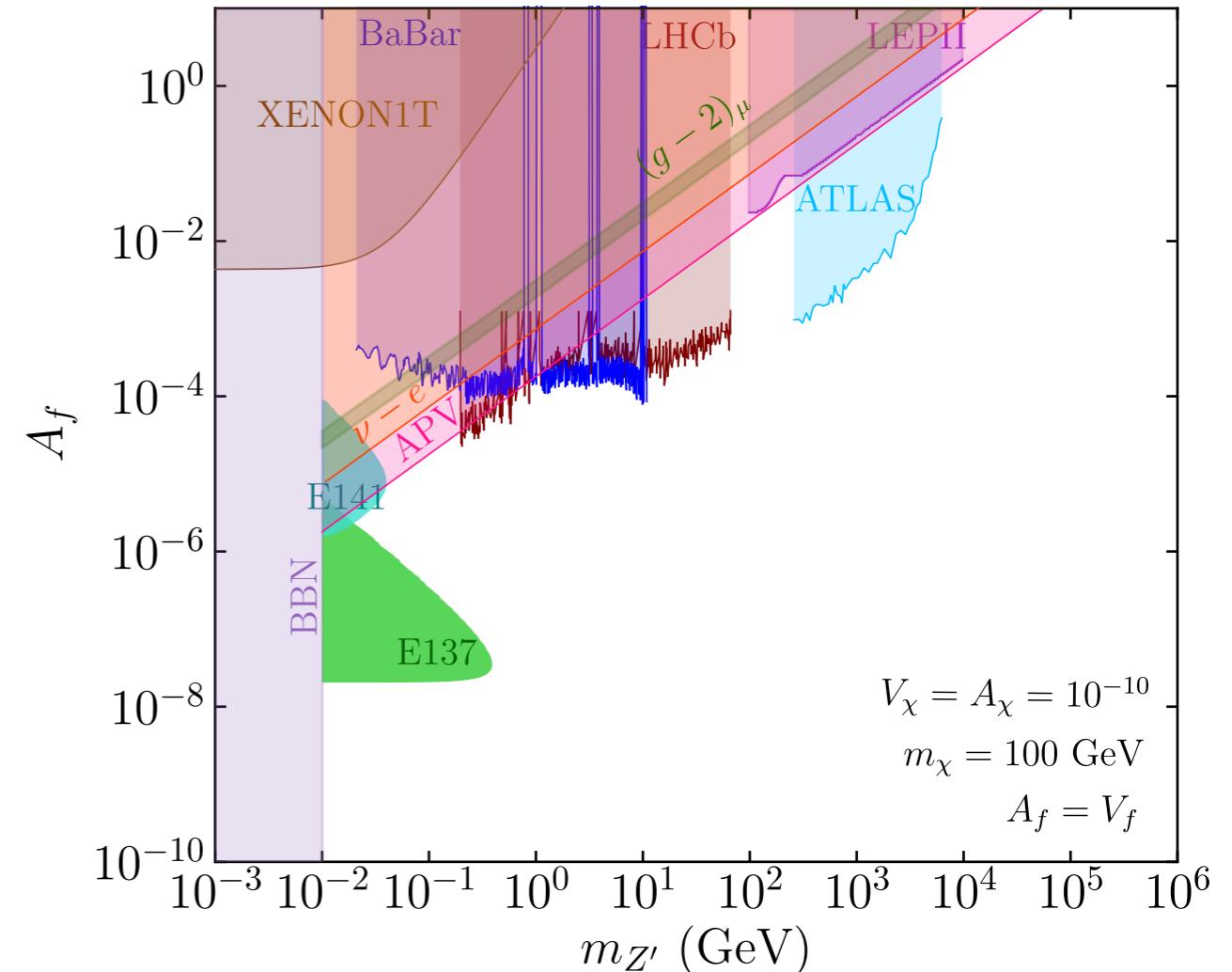
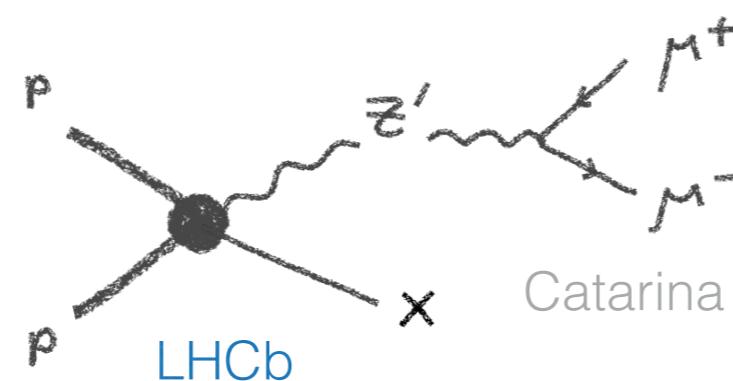
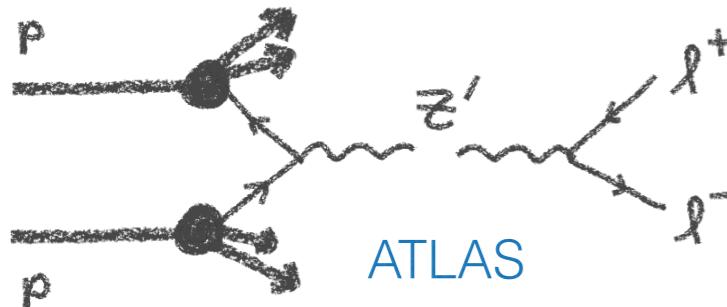
SLAC E137  
SLAC E141



### Electron-positron collisions



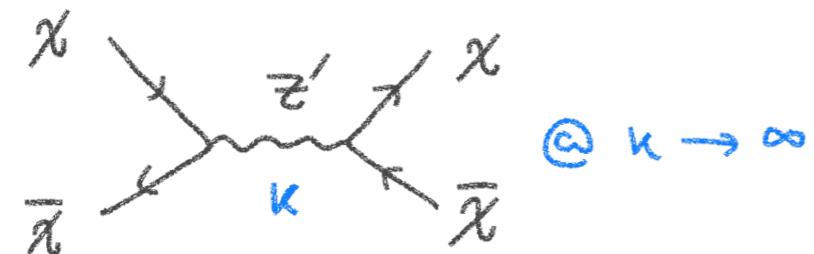
### Proton-proton collisions



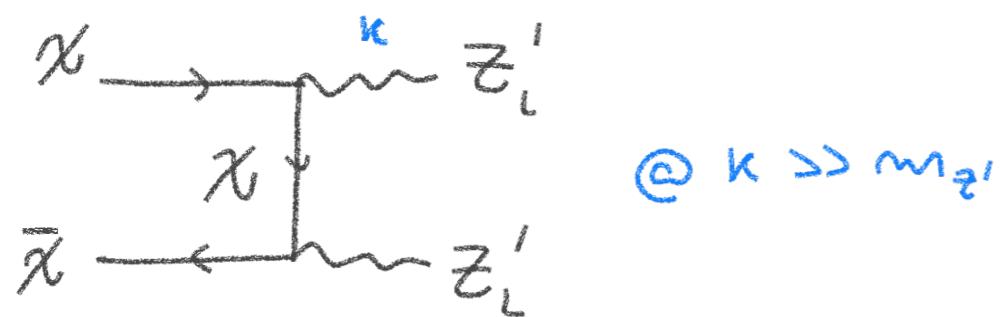
Catarina Cosme, MD, Steve Godfrey, and Taylor Gray  
arXiv:2104.13937

# Espaço de parâmetros viável: vínculos

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



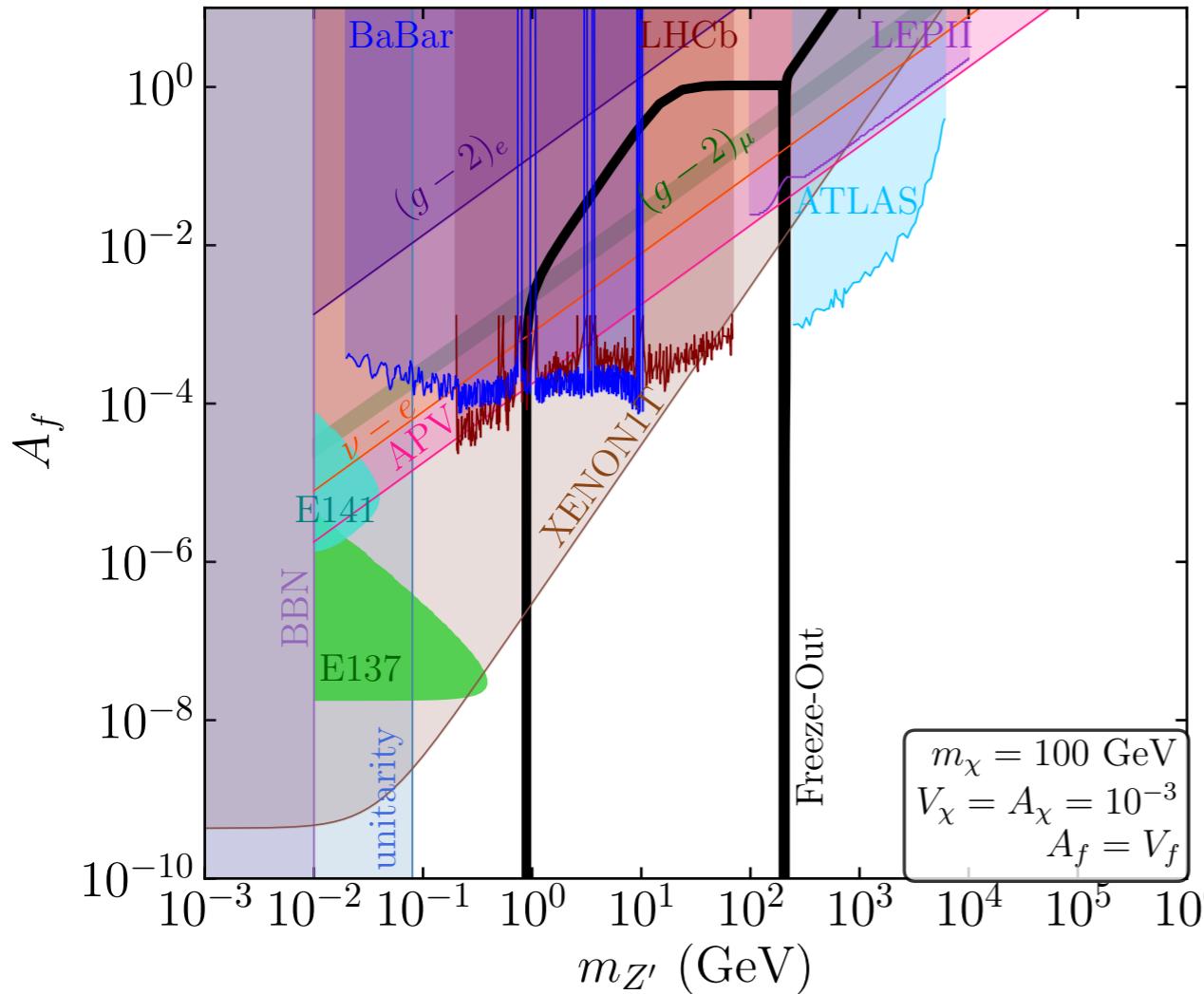
$$M_X < \frac{\pi}{A_\chi^2} \frac{m_{Z'}^2}{m_\chi}$$

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

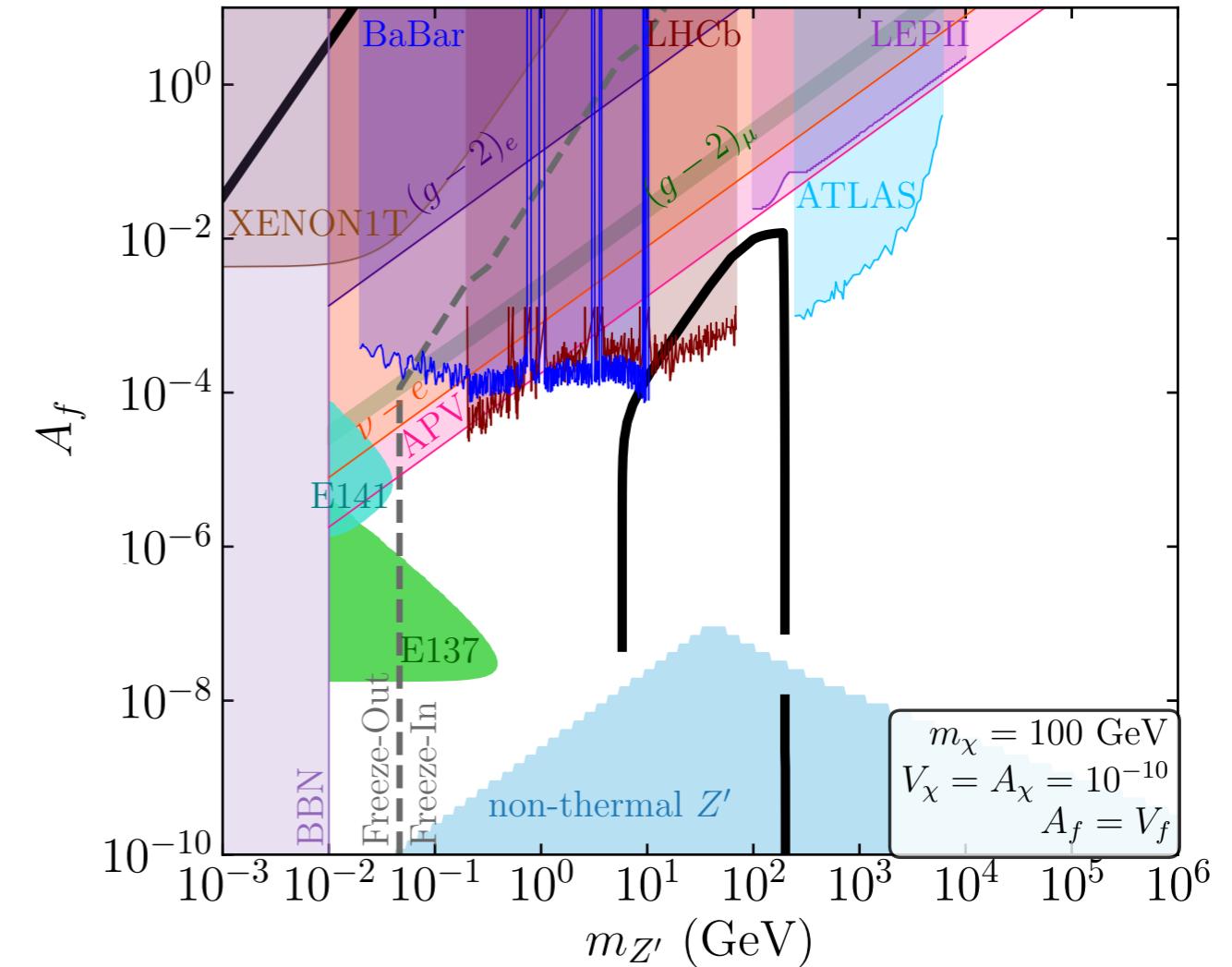
Simplified  $Z'$  portals are more natural in the freeze-in regime

# Espaço de parâmetros viável: resultados

axial and vector (FO)

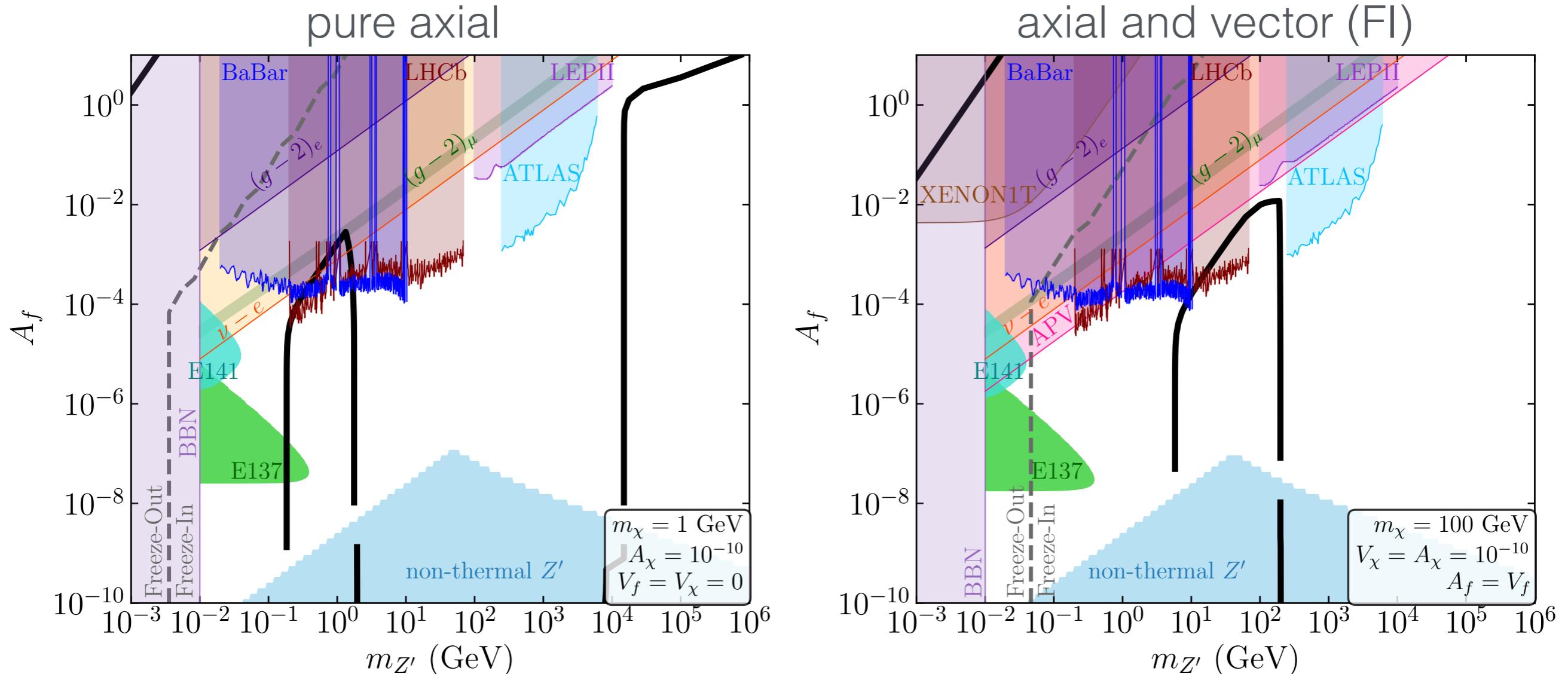


axial and vector (FI)



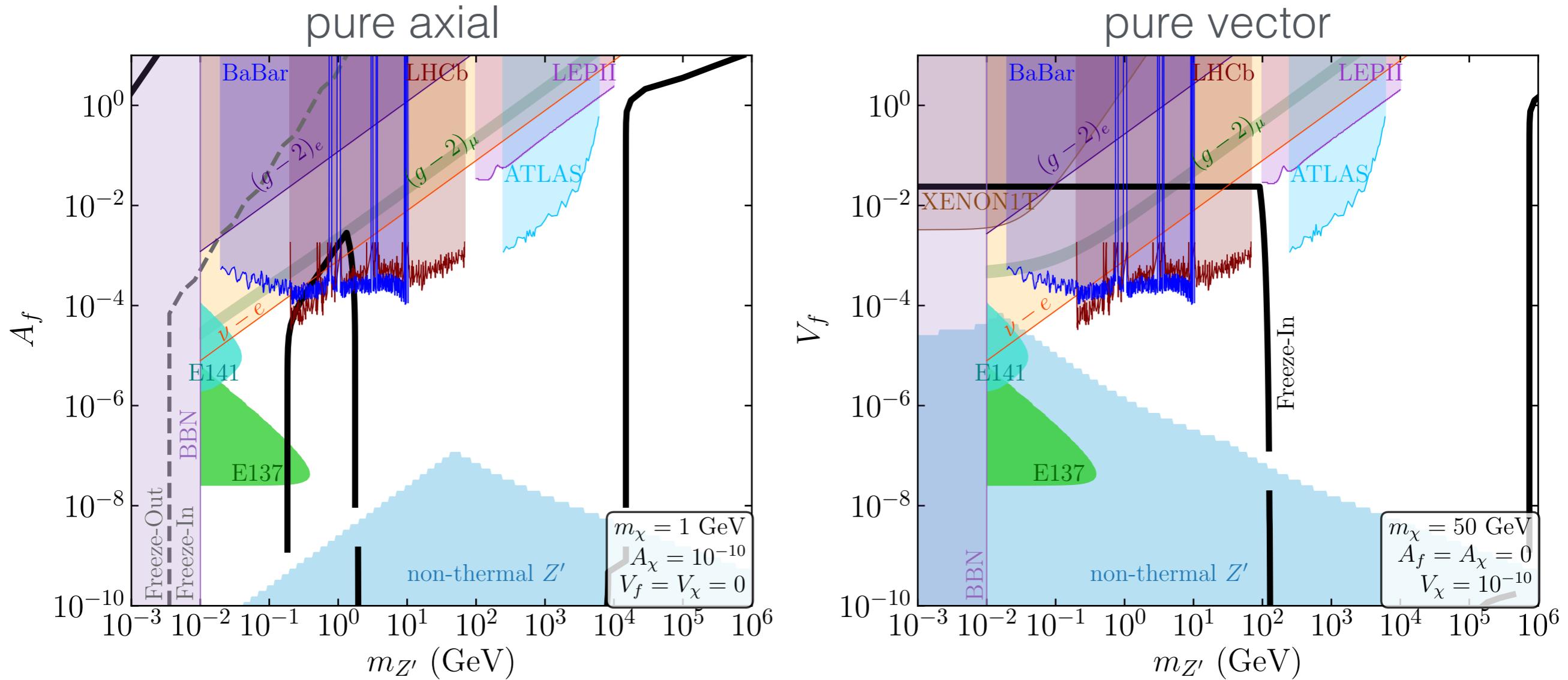
- FO: only  $m_{Z'} \sim 2m_\chi$  and (if  $A_{f/\chi} \neq 0$ )  $m_{Z'} \ll m_\chi$  regions are viable
- Smaller  $V/A_\chi$  requires larger  $V/A_f$
- FI: tested with colliders, APV,  $\nu - e$  scatt., and beam-dump experiments for  $m_\chi$  in the range of  $\sim 100$  MeV - 100 GeV!

# Espaço de parâmetros viável: resultados



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

# Espaço de parâmetros viável: resultados



- 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  $V_\chi$ , FI is also testable at beam dump experiments

# Conclusões

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- Bosons  $Z'$  com acoplamentos tanto vetoriais quanto axiais a fermions do MP podem mediar interações com WIMPs e FIMPs



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- Vínculos complementares vindos de detecção direta, BBN, unitariedade, espalhamento  $\nu - e$ , colisões  $e^+e^-$  e  $pp$ ,  $(g - 2)_{\mu,e}$ , APV, e experimentos de  $e^-$  beam-dump



# Conclusões

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- WIMPs só são viáveis se  $m_\chi \sim m_{Z'}/2$  e (se  $A_{f/\chi} \neq 0$ )  $m_\chi \gg m_{Z'}$



# Conclusões

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- Vínculos complementares vindos de detecção direta, BBN, unitariedade, espalhamento  $\nu - e$ , colisões  $e^+e^-$  e  $pp$ ,  $(g - 2)_{\mu,e}$ , APV, e experimentos de  $e^-$  beam-dump
- WIMPs só são viáveis se  $m_\chi \sim m_{Z'}/2$  e (se  $A_{f/\chi} \neq 0$ )  $m_\chi \gg m_{Z'}$



- A maioria dos experimentos que consideramos já está testando FIMPs, especialmente se  $m_\chi > m_{Z'}/2$

Obrigada!



**BACKUP slides**

# Pra não dizer que não falei das equações

Número total da espécie  $\chi$  num volume comóvel ( $a^3$ ):  $N_\chi(t) \equiv \underbrace{n_\chi(t)a^3}_{\text{densidade de número}} = \frac{g_\chi}{(2\pi)^3} \int d^3 p_\chi f_\chi(E_\chi, t)$

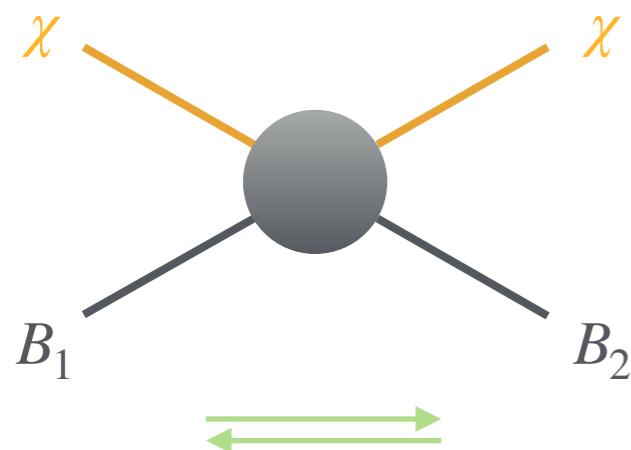
Equação de Boltzmann:

$$E_\chi \frac{\partial f_\chi}{\partial t} - \underbrace{H(t)p_\chi^2 \frac{\partial f_\chi}{\partial E_\chi}}_{\text{operador de colisão (física de partículas)}} = \hat{C}[f_\chi]$$

Taxa de expansão de Hubble:

$$H(t) \equiv \frac{da/dt}{a}$$

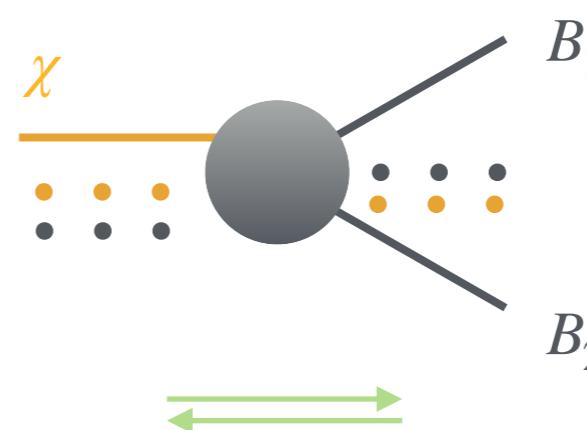
## Equilíbrio cinético



$$T_\chi = T$$

$$f_\chi(E_\chi, t) = \frac{e^{\mu_\chi/T}}{e^{E_\chi/T} \mp e^{\mu_\chi/T}} \propto f_\chi^{eq}(E_\chi, T) \frac{n_\chi(t)}{n_\chi^{eq}(T)}$$

## Equilíbrio químico



$$\sum_{\text{iniciais}} \mu = \sum_{\text{finais}} \mu$$

$$n_\chi(t) = n_\chi^{eq}(T)$$

# Pra não dizer que não falei das equações

---

Quando há equilíbrio químico:

$$\frac{dn_\chi(t)}{dt} + 3 H(t) n_\chi(t) = 0$$

Quando há equilíbrio cinético (freeze-out usual):

$$\frac{dn_\chi(t)}{dt} + 3 H(t) n_\chi(t) = - \sum_{A \rightarrow B} n_\chi^{eq}(T) \Gamma_{A \rightarrow B}(T) \left( \prod_{a \in A} \frac{n_a(t)}{n_a^{eq}(T)} - \prod_{b \in B} \frac{n_b(t)}{n_b^{eq}(T)} \right)$$

$\chi \in A \qquad \qquad \qquad A \rightarrow B \qquad \qquad \qquad B \rightarrow A$

Quando o equilíbrio químico nunca é alcançado (freeze-in):

$$\frac{dn_\chi(t)}{dt} + 3 H(t) n_\chi(t) = \sum_{B \rightarrow A} n_b^{eq}(T) \Gamma_{B \rightarrow A}(t)$$

# Freeze-out & freeze-in

$$\dot{n}_\chi(t) + 3 H(t) n_\chi(t) = s(t) \dot{Y}_\chi + Y_\chi \dot{S}(t)/a^3$$

