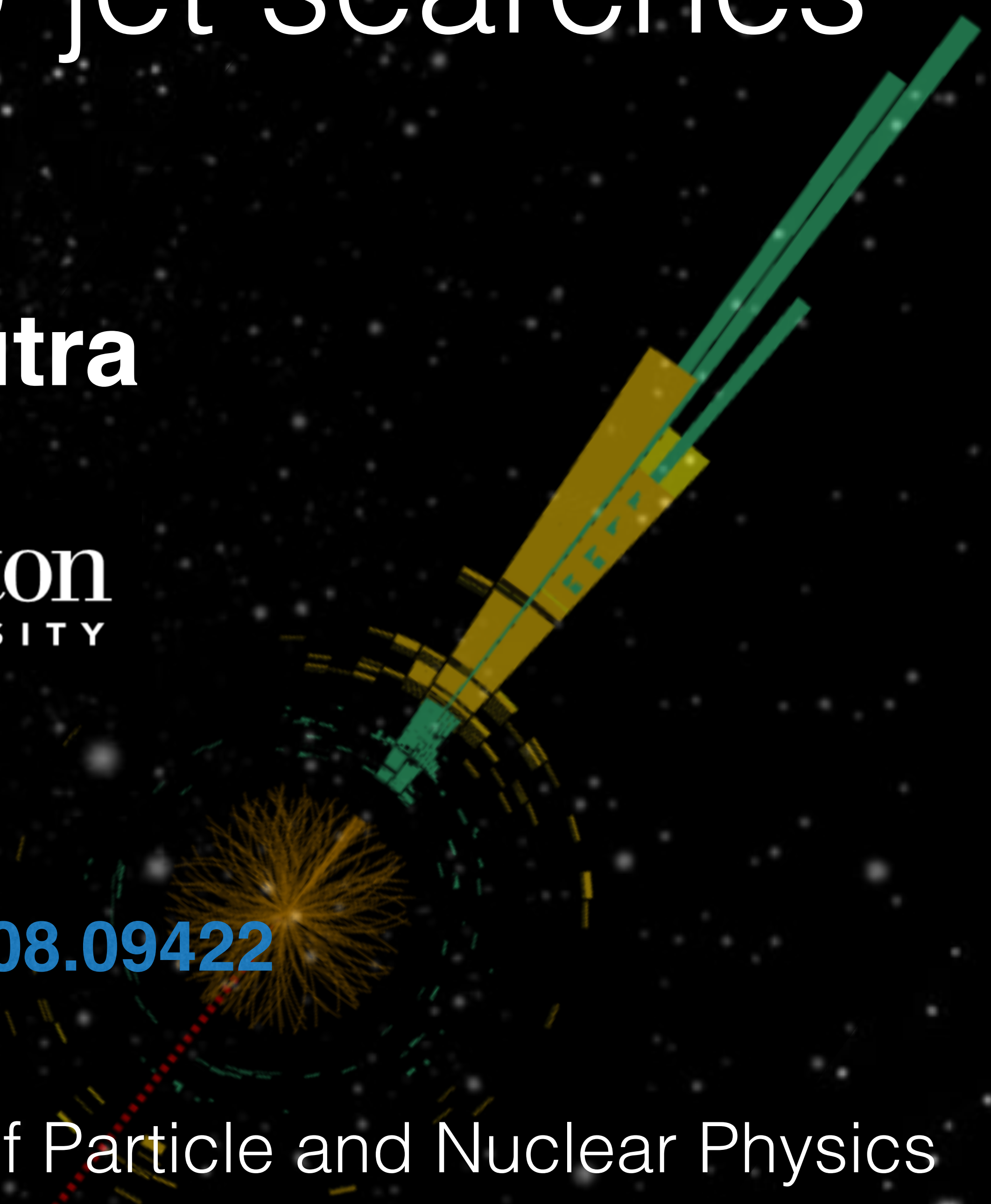
Probing feebly interacting dark matter with mono-jet searches

Maíra Dutra

Carleton University



Talk based on
J. Claude, M. Dutra, S. Godfrey **arXiv:2208.09422**

14th Conference on the Intersections of Particle and Nuclear Physics
Lake Buena Vista, Florida

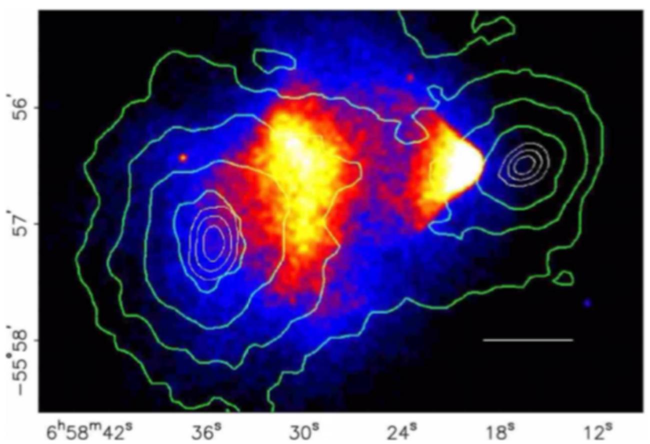
September 3, 2022

Outline

1. Introduction
2. The gluophilic Z' portal
3. Conclusions

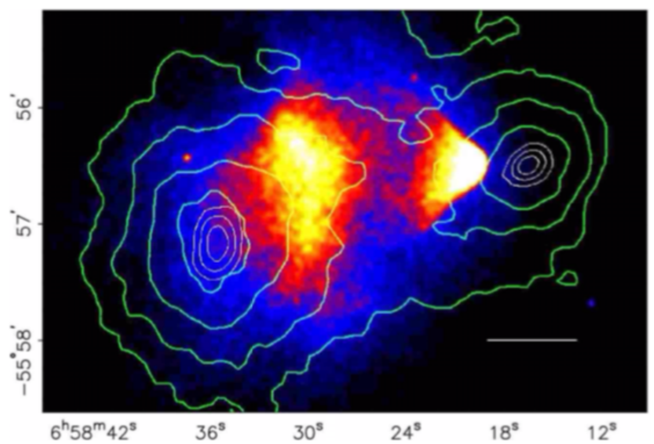
Outline

1. Introduction
2. The gluophilic Z' portal
3. Conclusions



astro-ph/0608407

85% of the **matter** in the universe
(@ Galaxies, @ Galaxy clusters, @ cosmological scales)
is effectively neutral



astro-ph/0608407

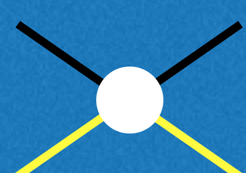
85% of the **matter** in the universe
(@ Galaxies, @ Galaxy clusters, @ cosmological scales)
is effectively neutral

Searches for dark matter particles: non-gravitational interactions

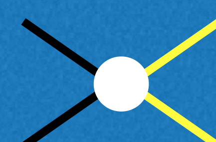
@ Underground detectors (Direct Detection)

DM

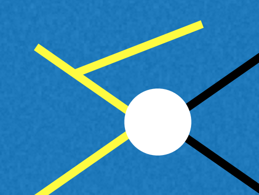
SM



@ Telescopes (Indirect Detection)

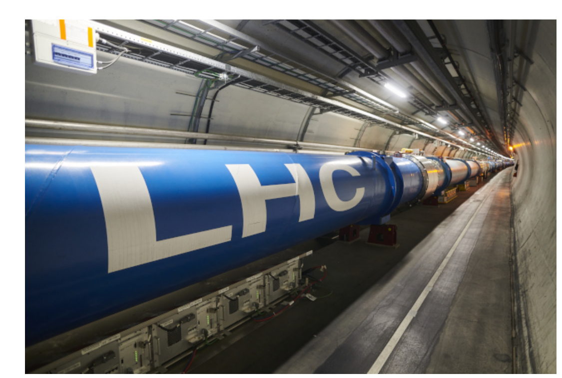


@ Particle accelerators



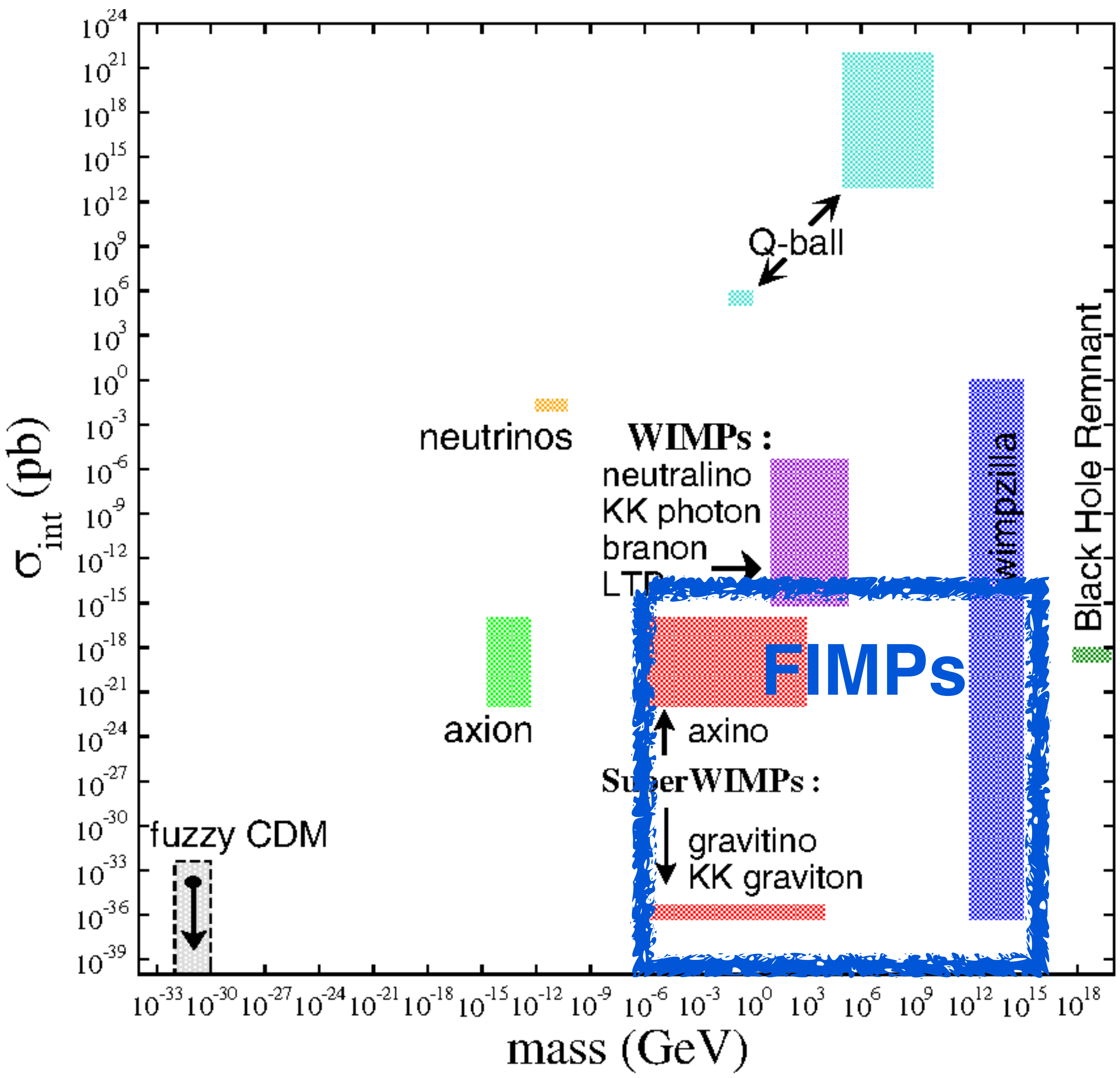
XENON1T experiment

Fermi-LAT satellite



Large Hadron Collider

Introduction: dark matter nature & origin



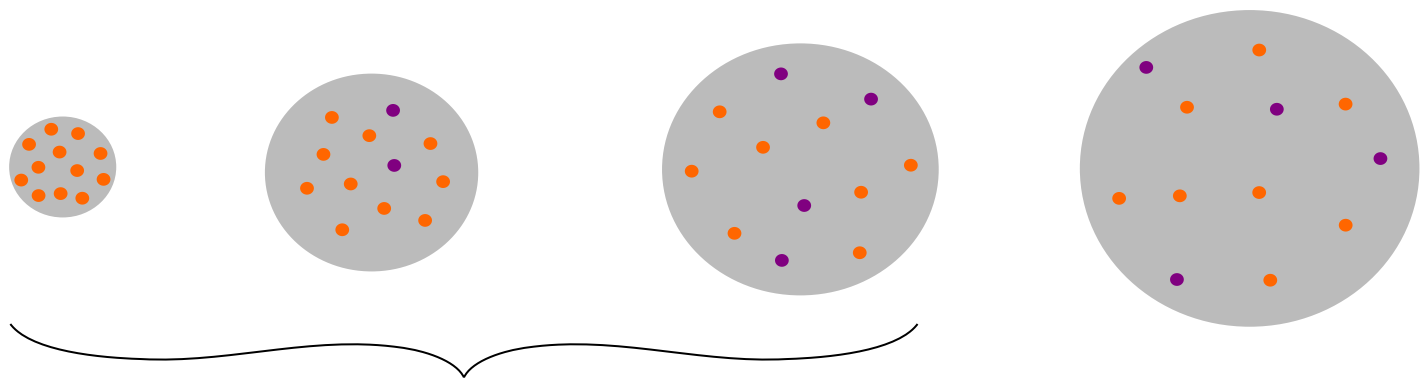
The Dark Matter Scientific Assessment Group 2007

A joint sub-panel of HEPAO and AAAC

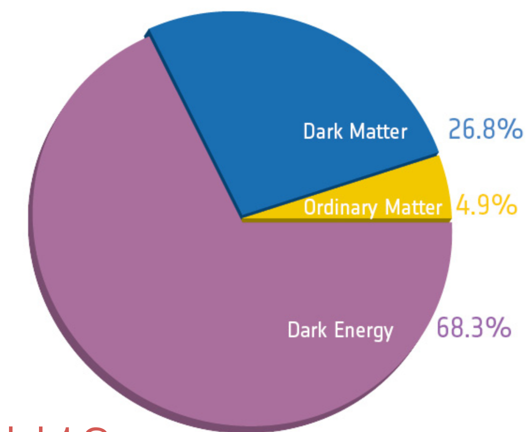
The mass and couplings of viable DM candidates depend on how they are produced in the early universe

Introduction: DM genesis - freeze-in

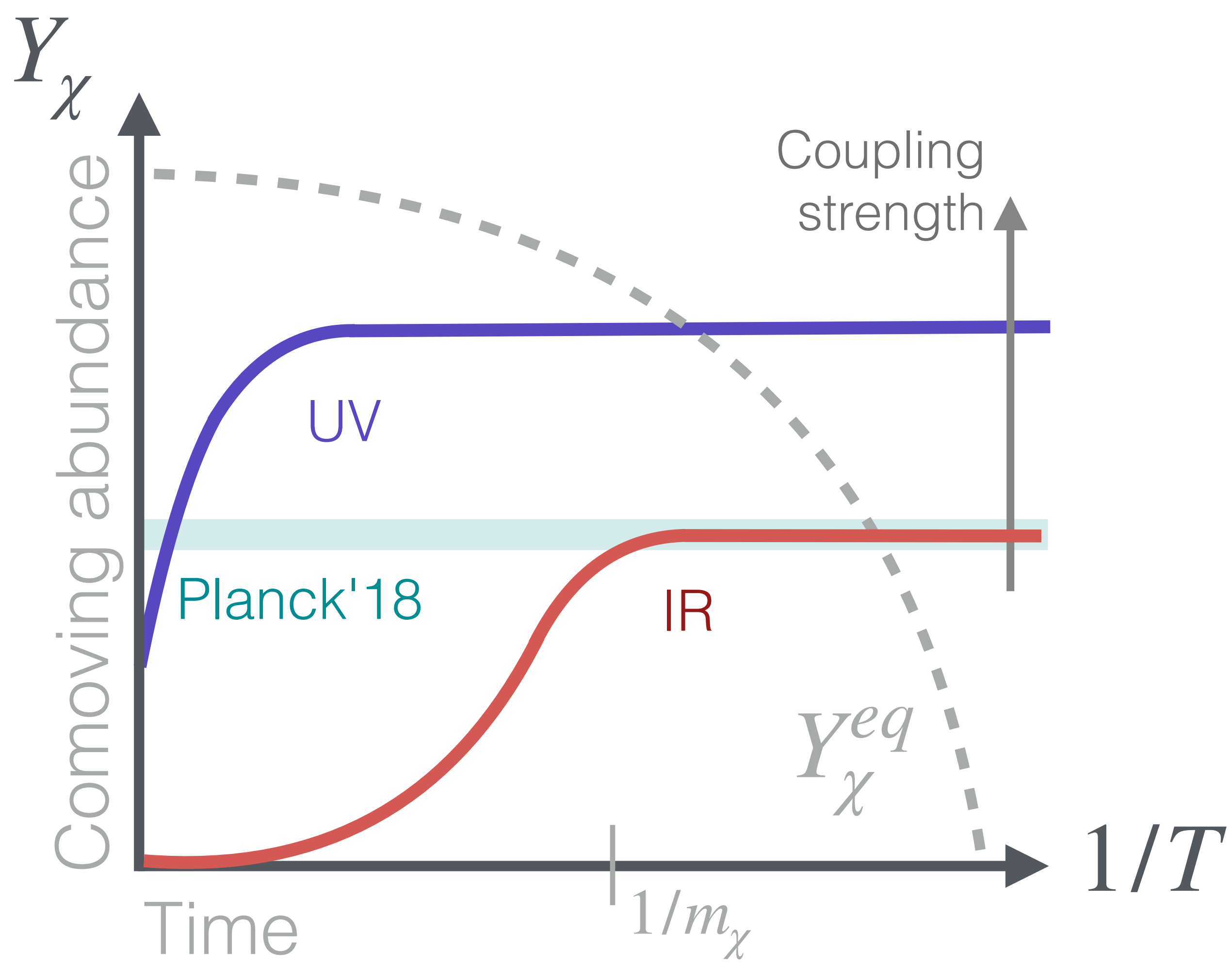
Evolution of feebly interacting massive particles (**FIMPs**) in the early universe:

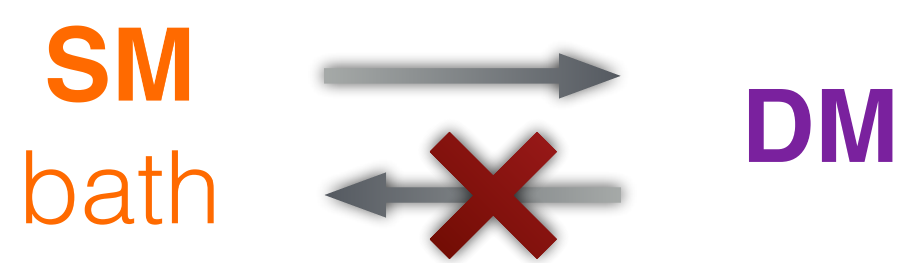


(out-of-equilibrium) **freeze-in**



Planck'18



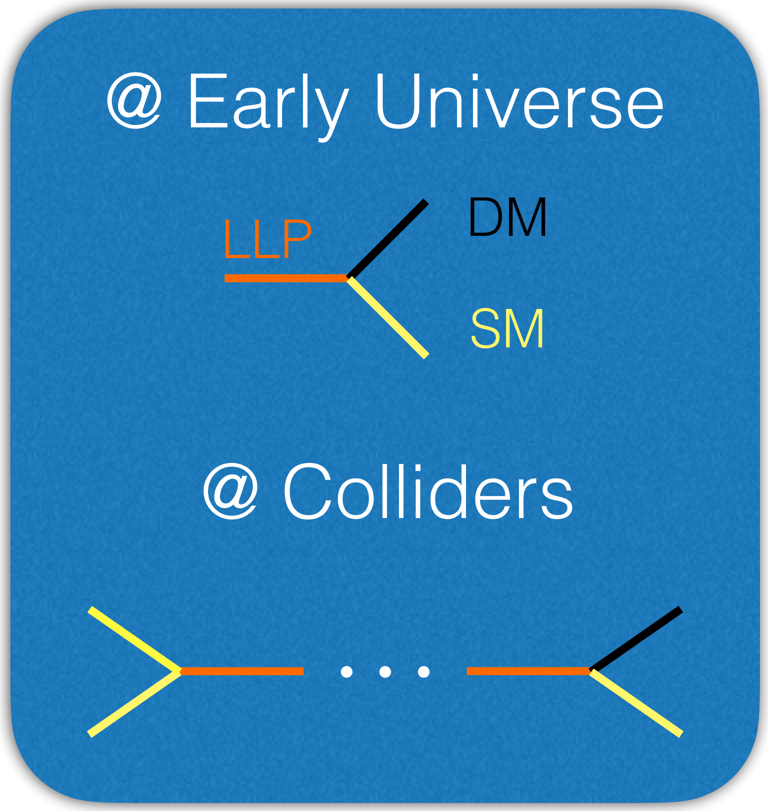


too small couplings

Masses: 10s keV - 10^{16} GeV
Couplings: $\sim 10^{-12}$

Introduction: Testing freeze-in

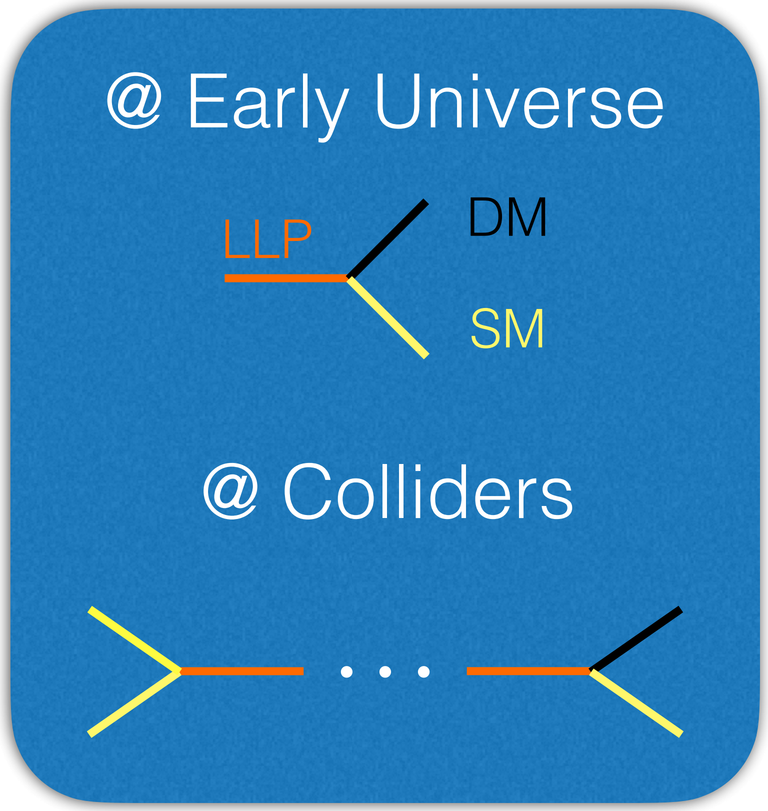
Colliders&Accelerators



Models with long-lived particles

1506.07532
1611.09540
1805.04423
1811.05478
1908.11387

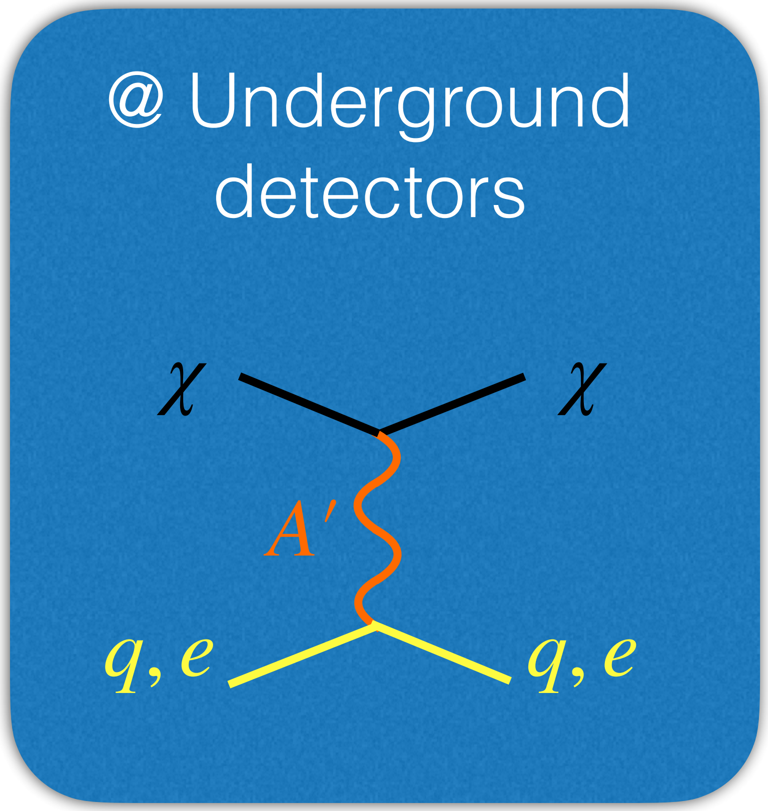
Colliders&Accelerators



Models with long-lived particles

1506.07532 1611.09540 1805.04423 1811.05478 1908.11387

Direct detection

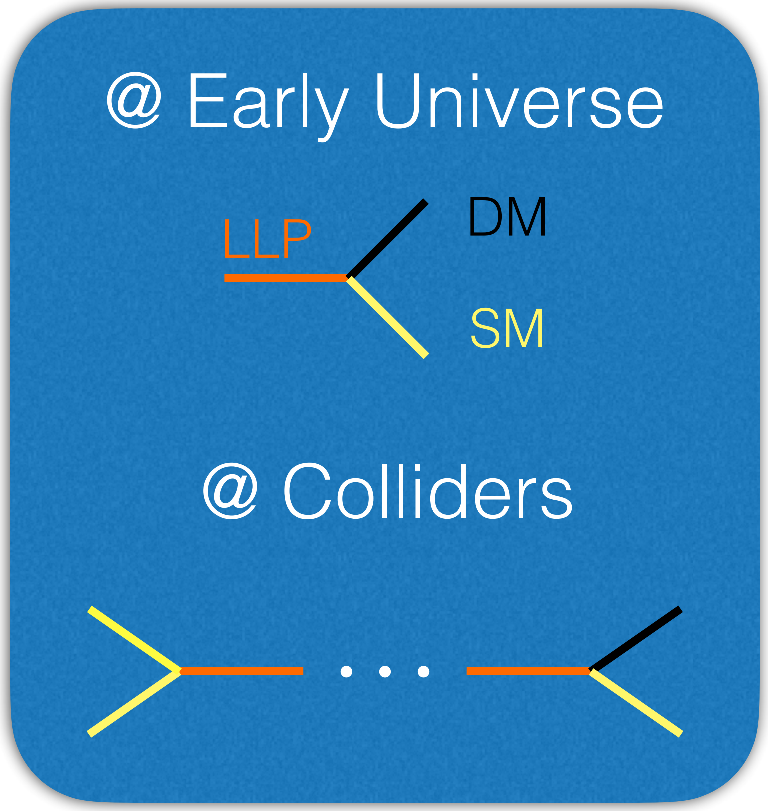


Models with light mediators

1707.04591 1807.05022 1908.09834 2006.15672 2104.13937 2112.12798

Introduction: Testing freeze-in

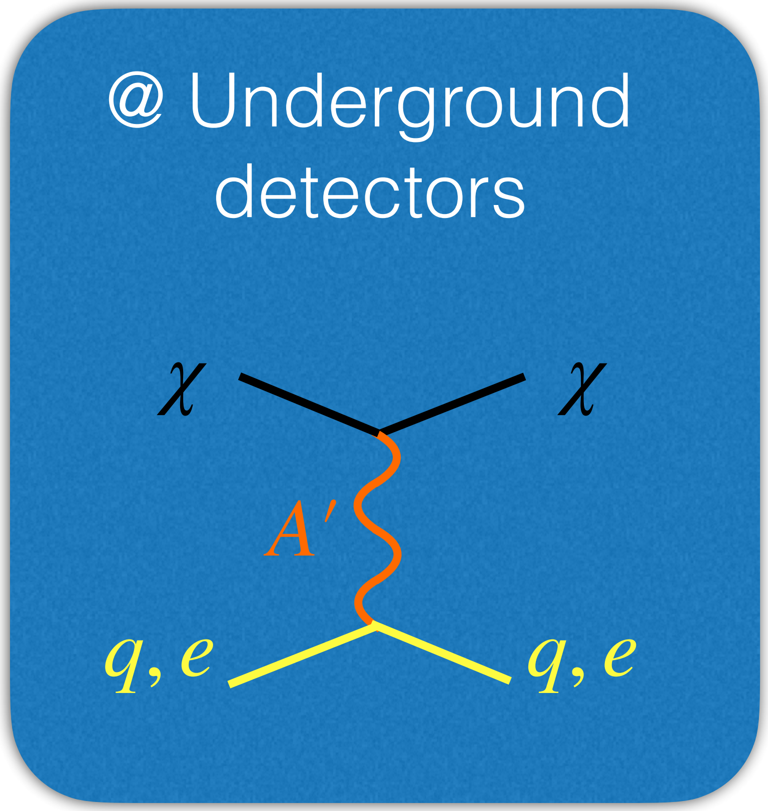
Colliders&Accelerators



Models with long-lived particles

1506.07532 1811.05478
1611.09540 1908.11387
1805.04423

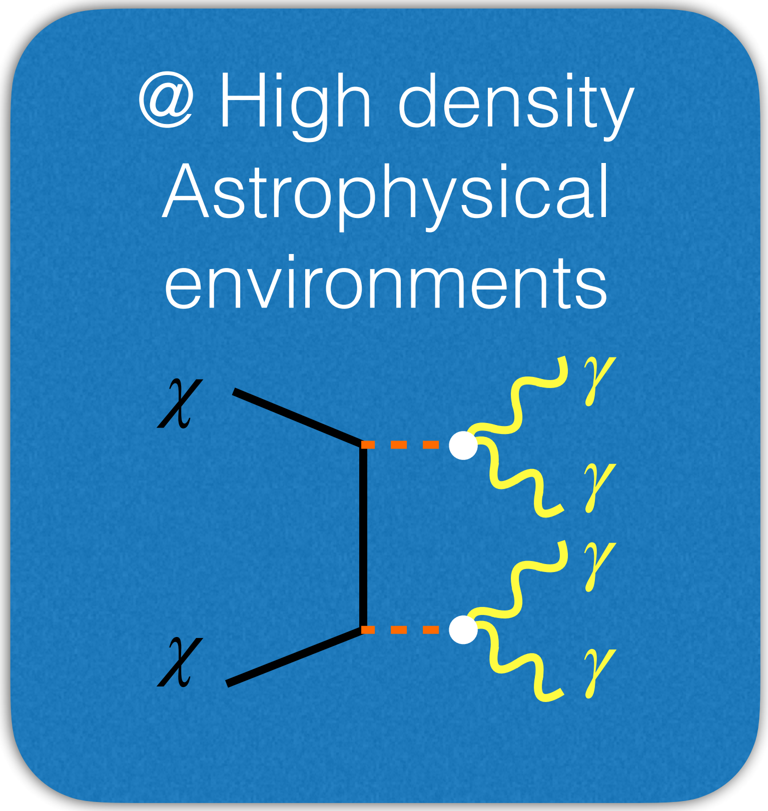
Direct detection



Models with light mediators

1707.04591 2006.15672
1807.05022 2104.13937
1908.09834 2112.12798

Indirect detection



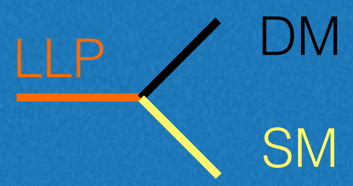
Models with mediators effectively coupled to photons

1710.02146
1907.07973

Introduction: Testing freeze-in

Colliders&Accelerators

@ Early Universe



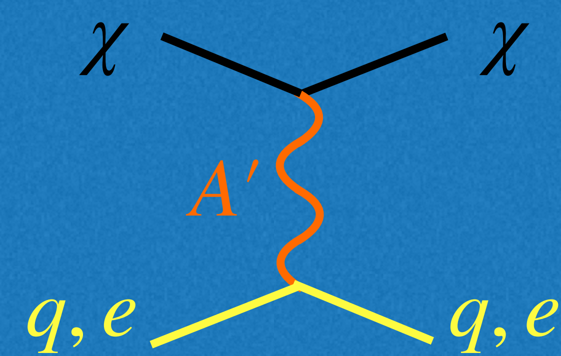
@ Colliders

Models with long-lived particles

1506.07532 1811.05478
1611.09540 1908.11387
1805.04423

Direct detection

@ Underground detectors

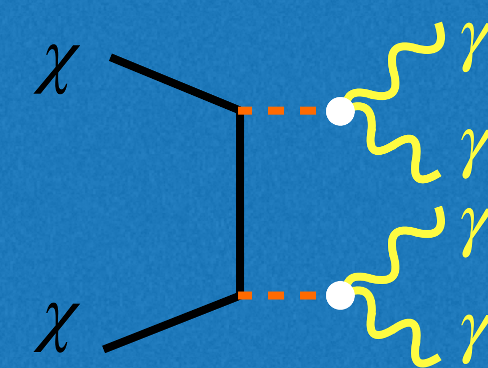


Models with light mediators

1707.04591 2006.15672
1807.05022 2104.13937
1908.09834 2112.12798

Indirect detection

@ High density Astrophysical environments



Models with mediators effectively coupled to photons

1710.02146
1907.07973

Early matter-dominated era → Larger couplings for FIMPs

Any particle physics model!

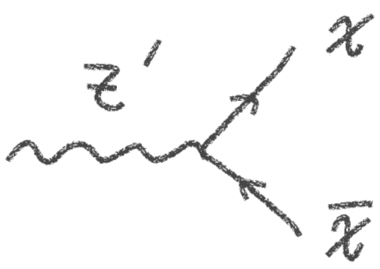
1506.07532 2111.15665
2003.01723 2203.13269

Outline

1. Introduction
2. The gluophilic Z' portal
3. Conclusions

Model: $U(1)'$ extensions

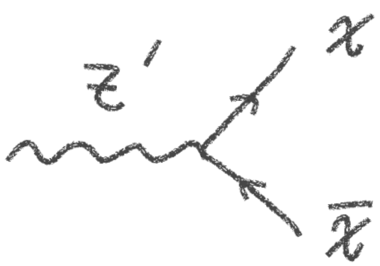
- Extra $U(1)$ symmetries are present in many BSM scenarios



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

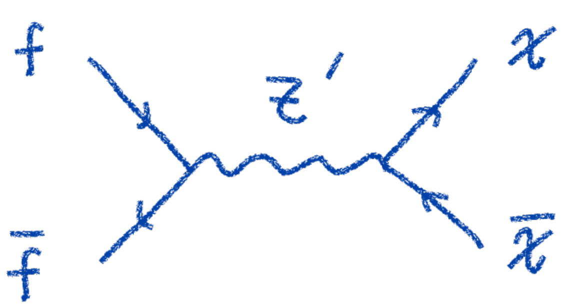
Model: $U(1)'$ extensions

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

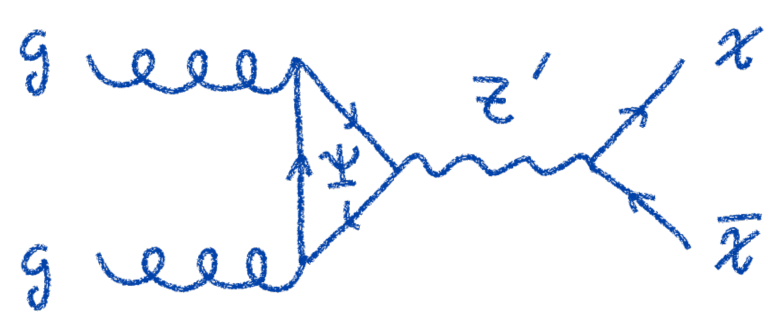


$$\mathscr{L} \supset \bar{\chi}_R \gamma^\mu D_\mu \chi_R + \bar{\chi}_L \gamma^\mu D_\mu \chi_L \supset \bar{\chi}\gamma^\mu \left(\underbrace{g_{Z'} \frac{q_{\chi_L} + q_{\chi_R}}{2}}_{V_\chi} - \underbrace{g_{Z'} \frac{q_{\chi_L} - q_{\chi_R}}{2}}_{A_\chi} \gamma_5 \right) \chi Z'_\mu$$

SM fermions **charged** under $U(1)'$

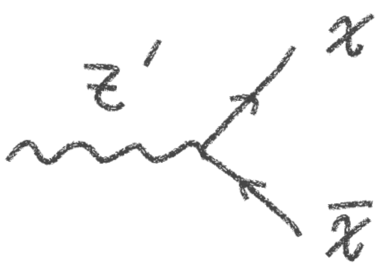


SM fermions **neutral** under $U(1)'$



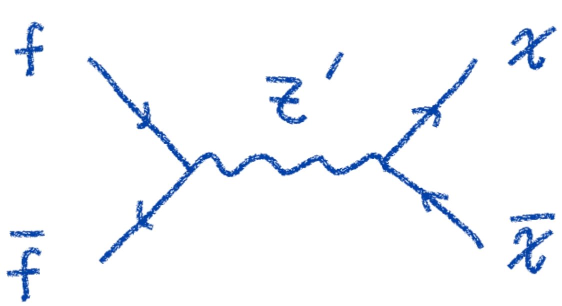
Model: $U(1)'$ extensions

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

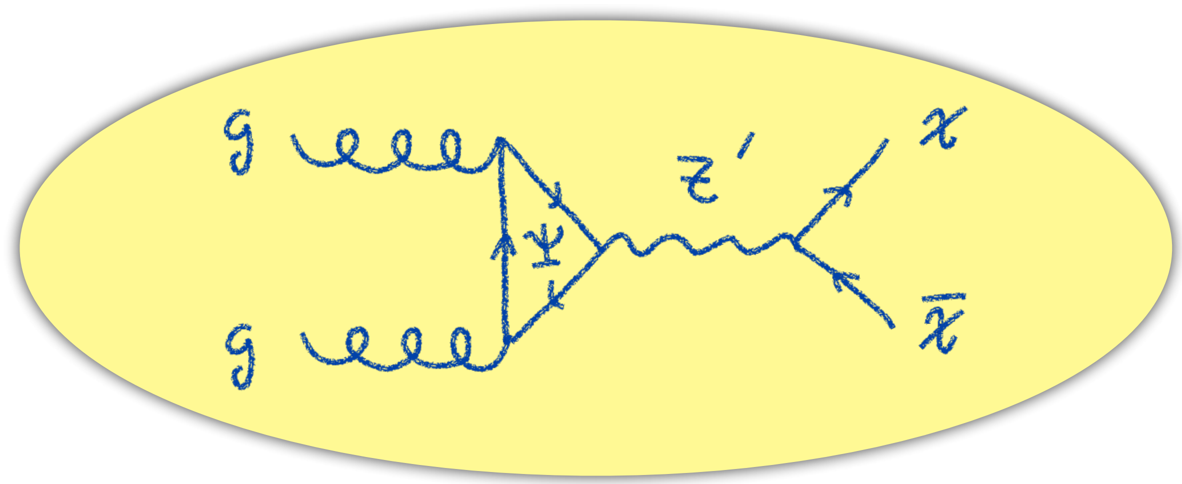


$$\mathscr{L} \supset \bar{\chi}_R \gamma^\mu D_\mu \chi_R + \bar{\chi}_L \gamma^\mu D_\mu \chi_L \supset \bar{\chi}\gamma^\mu \left(\underbrace{g_{Z'} \frac{q_{\chi_L} + q_{\chi_R}}{2}}_{V_\chi} - \underbrace{g_{Z'} \frac{q_{\chi_L} - q_{\chi_R}}{2}}_{A_\chi} \gamma_5 \right) \chi Z'_\mu$$

SM fermions **charged** under $U(1)'$



SM fermions **neutral** under $U(1)'$



Model: The gluophilic Z' portal

Probing feebly interacting dark matter with mono-jet searches
Jérôme Claude, MD, Steve Godfrey
arXiv: 2208.09422

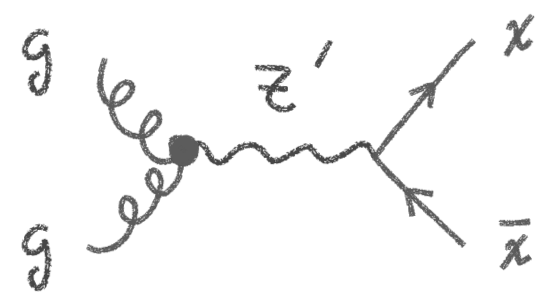
Visible sector

Gluons

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

Dark sector

Dark matter: χ

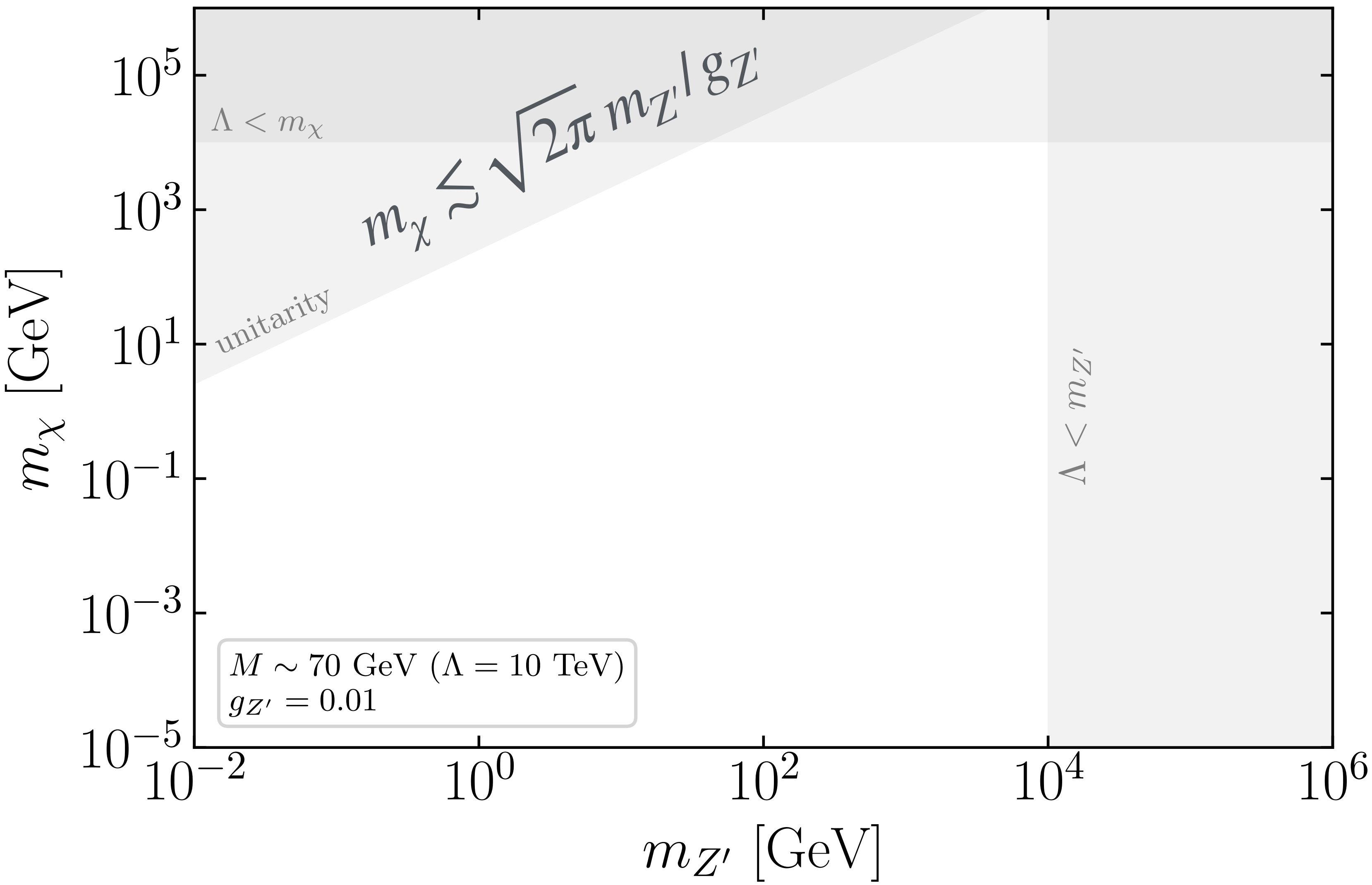


$$\mathscr{L}_{\text{eff}} = -\frac{\epsilon^{\mu\nu\rho\sigma}}{\Lambda^2}\left[\partial^\alpha Z'_\alpha \text{Tr}(G_{\mu\nu}G_{\rho\sigma}) - 2Z'_\mu \text{Tr}(G_{\nu\lambda}\partial^\lambda G_{\rho\sigma})\right] + \frac{g_{Z'}}{2}\bar{\chi}\gamma^\mu(1-\gamma_5)\chi Z'$$

$$\Lambda \approx \sqrt{\frac{24\pi}{N_\Psi \alpha_s g_{Z'}}}M$$

Free parameters: m_χ, $m_{Z'}$, $g_{Z'}$, M,
$q_{\chi_L} = 1$, $N_\Psi = 3$

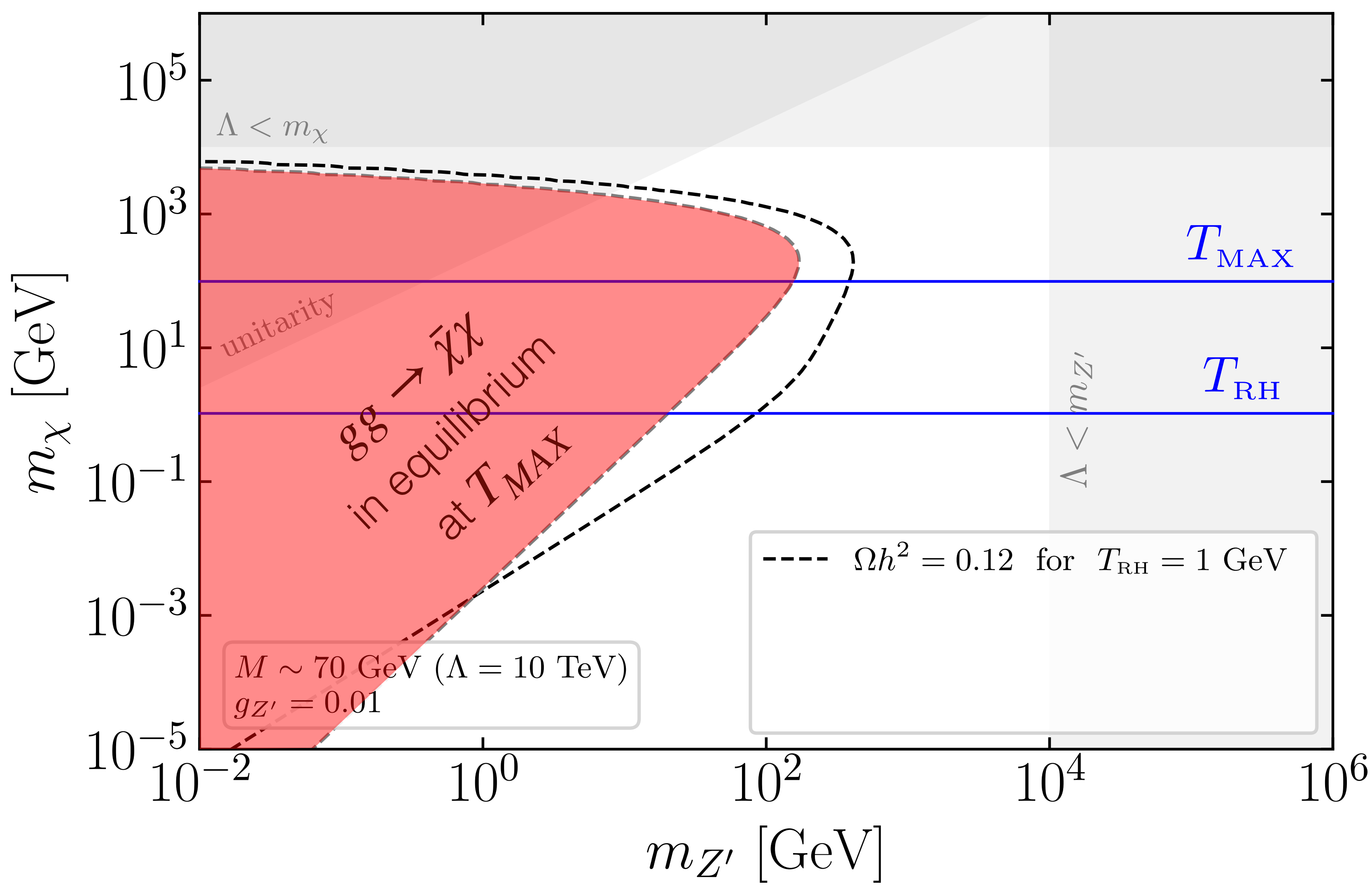
Model: The viable parameter space



$$\Lambda \approx \sqrt{\frac{24\pi}{N_\Psi \alpha_s g_{Z'}}} M$$

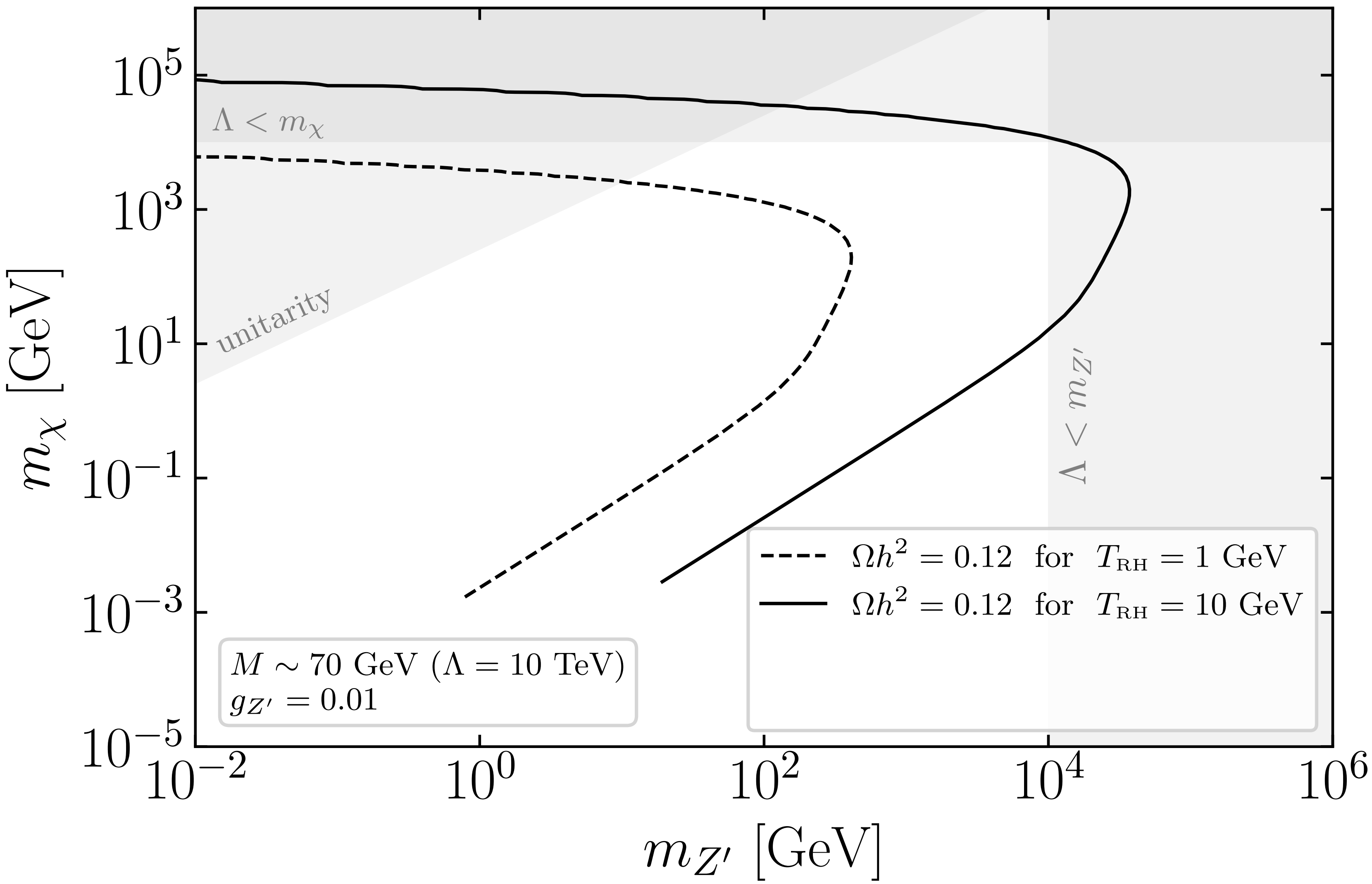
- The freeze-in process ($gg \to \bar{\chi}\chi$) vanishes if the axial coupling ($A_\chi = g_{Z'}/2$) is zero ➡ The process $\bar{\chi}\chi \to \bar{\chi}\chi$ violates unitarity at high energies

Model: The viable parameter space



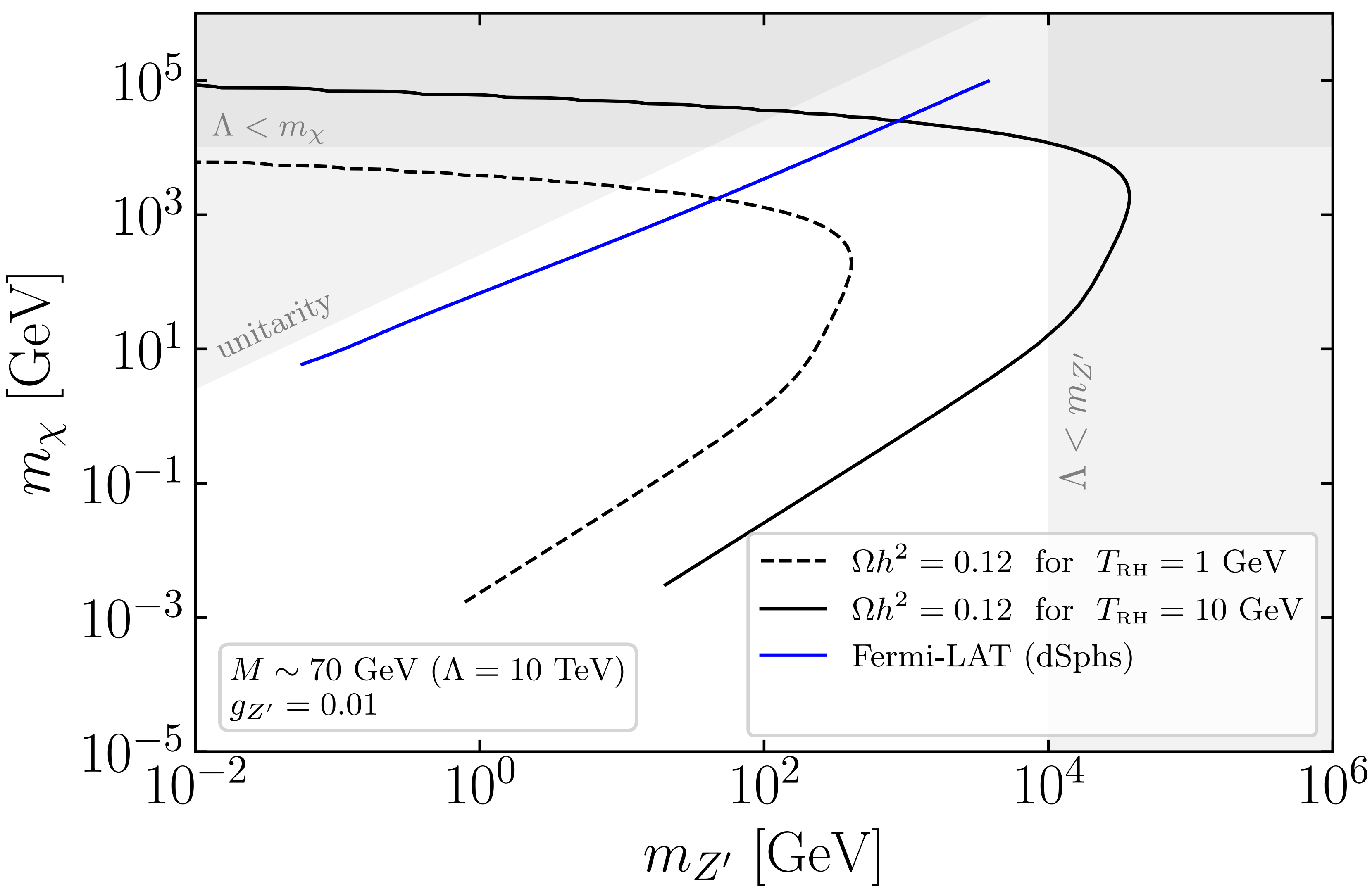
- High temperature dependence from $Z'gg$ vertex → The freeze-in process ($gg \to \bar{\chi}\chi$) happens during reheating
- The freeze-in condition imposes a lower bound on m_χ

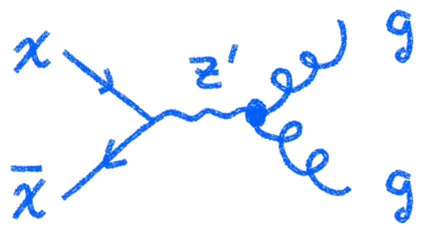
Model: The viable parameter space



- High temperature dependence from $Z'gg$ vertex ➡ for a given m_χ, higher T_{RH} means more DM ➡ heavier mediators needed to avoid overproduction

Model: Indirect detection

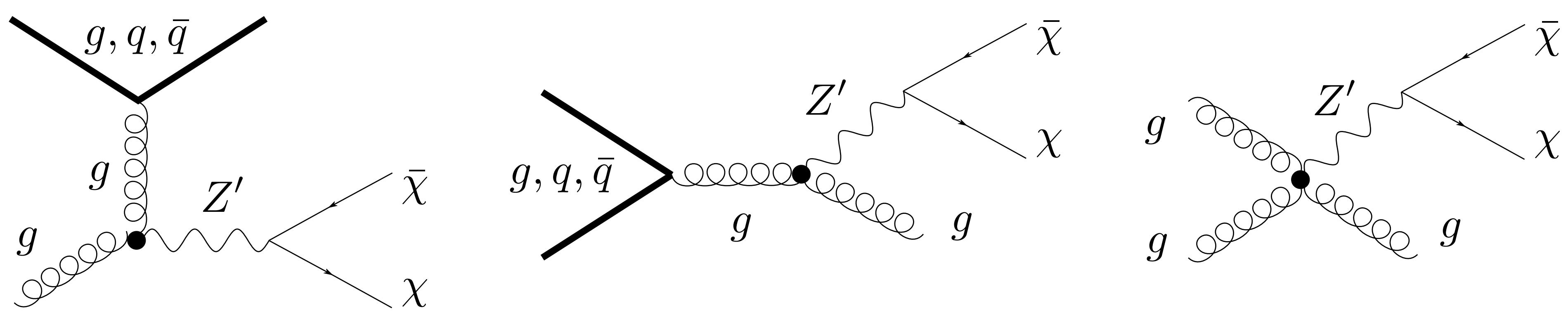




- DM self-annihilation into gluons in dwarf spheroidal galaxies produce a continuum flux of γ-rays ➡ Fermi-LAT limits
- Freeze-in is tested by indirect detection for m_χ from few GeV to few TeV!

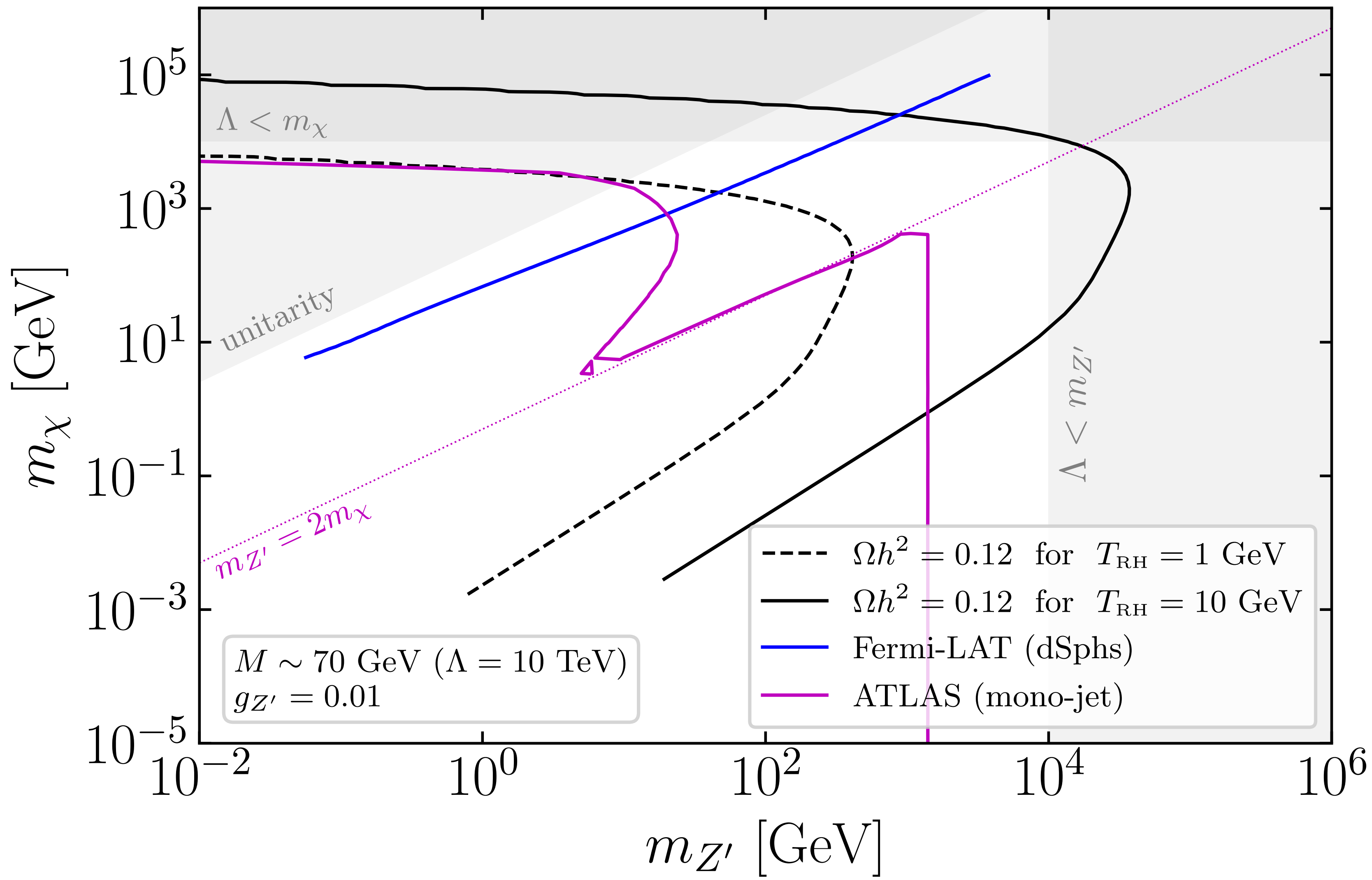
Model: Mono-jet + E_T^{miss}

Our FIMP candidate χ can be produced in pp collisions at the LHC in association with an energetic jet



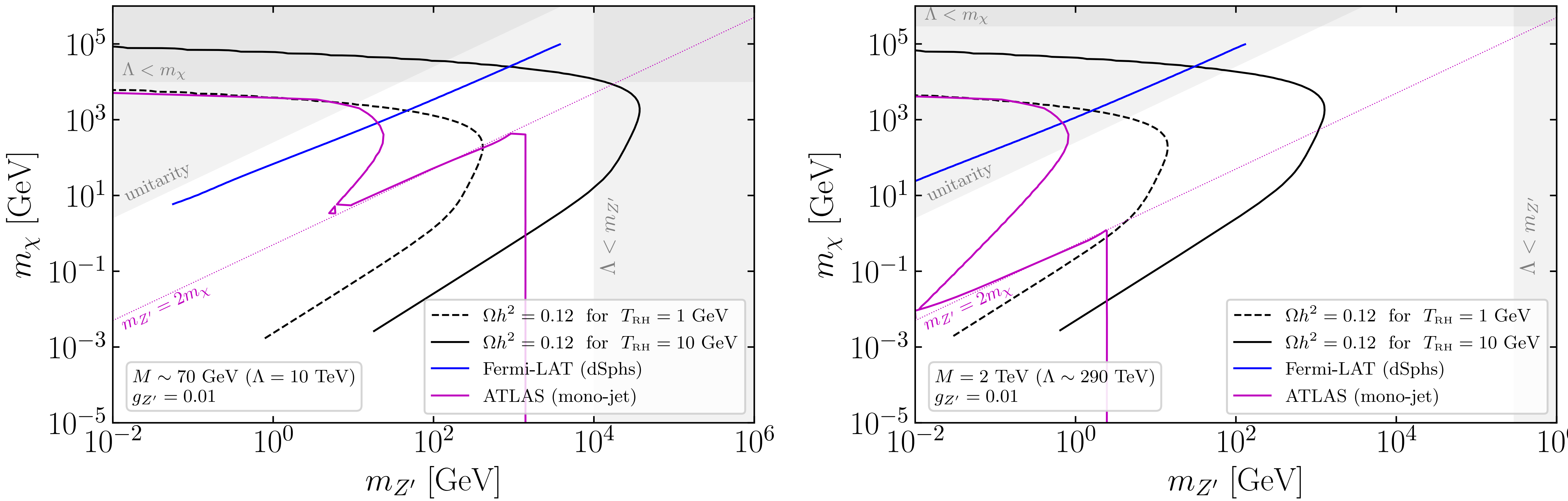
- The ATLAS collaboration provided model-independent limits on the visible cross section (139 fb^{-1} @ $\sqrt{s} = 13$ TeV): $\sigma \times A \times \epsilon > 0.3$fb is excluded at 95% C.L. for $E_T^{miss} > 1200$ GeV [arXiv:2102.10874]
- We generated events featuring a single jet with $p_T > 1200$ GeV and $|\eta| < 2.4$ using MadGraph5_aMCNLO

Model: Mono-jet + E_T^{miss}



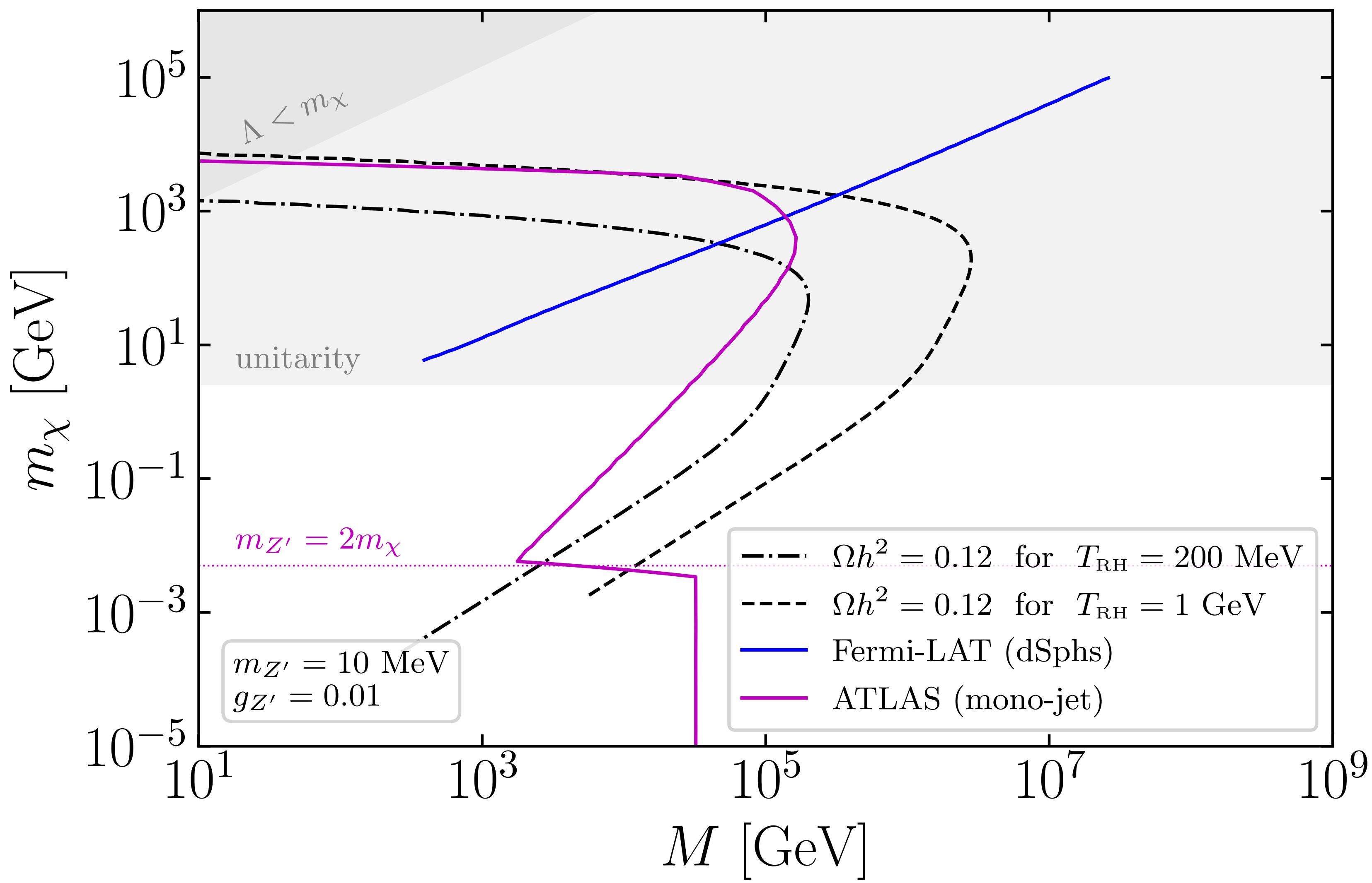
- The freeze-in is tested by mono-jet searches for $m_\chi < \sqrt{s}/2$, even in the off-shell mediator regime!
- FIMPs might be “discovered” in the Run 3 of the LHC

Model: The gluophilic Z' portal



- Higher values of Λ weakens the indirect detection and mono-jet bounds
  - ➡ the unitarity bound rules-out the region probed by indirect detection
  - ➡ the mono-jet limits still probe freeze-in

Model: The gluophilic Z' portal



- Sub-GeV Z' are also of interest in our scenario
- FIMPs can completely evade the mono-jet limits if T_{RH} is too high!

Outline

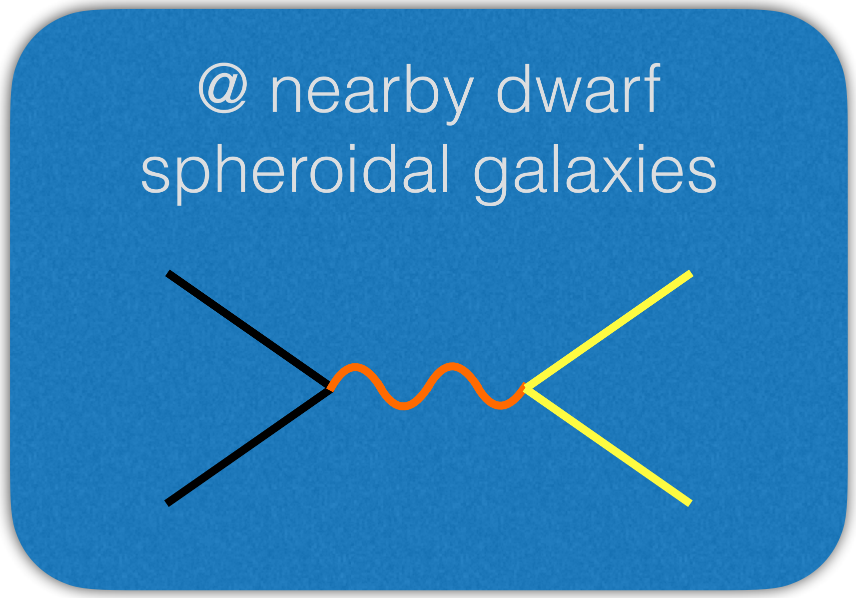
1. Introduction

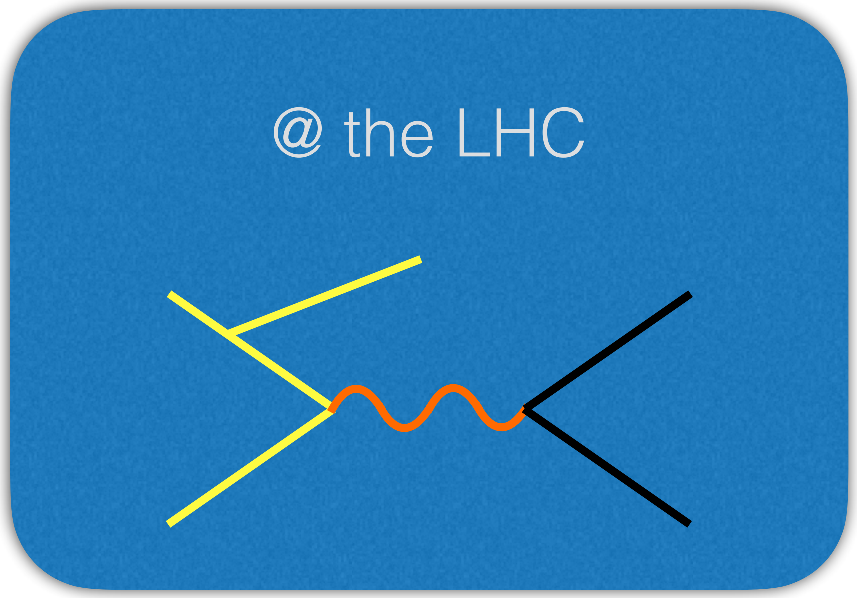
2. The gluophilic Z' portal

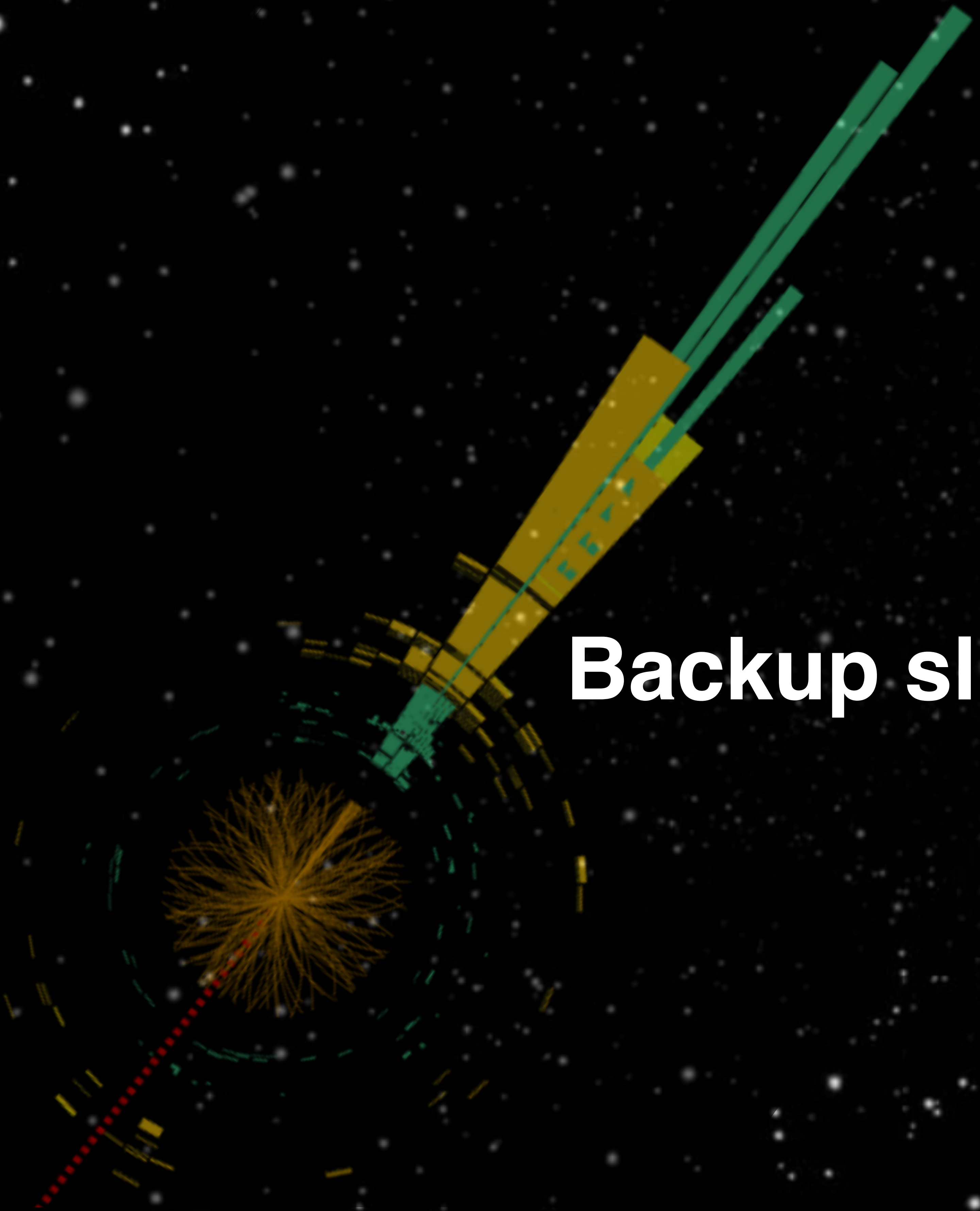
3. Conclusions

Conclusions

- The freeze-in is an appealing mechanism for dark matter genesis, and is testable in some scenarios
- **Gluophilic Z' portal:**
  - FIMP self-annihilation in dSphs can produce detectable γ-rays
  - Proton-proton collisions at the LHC can produce FIMPs in association with mono-jet signals
  - The LHC Run 3 might find hints of FIMPs!





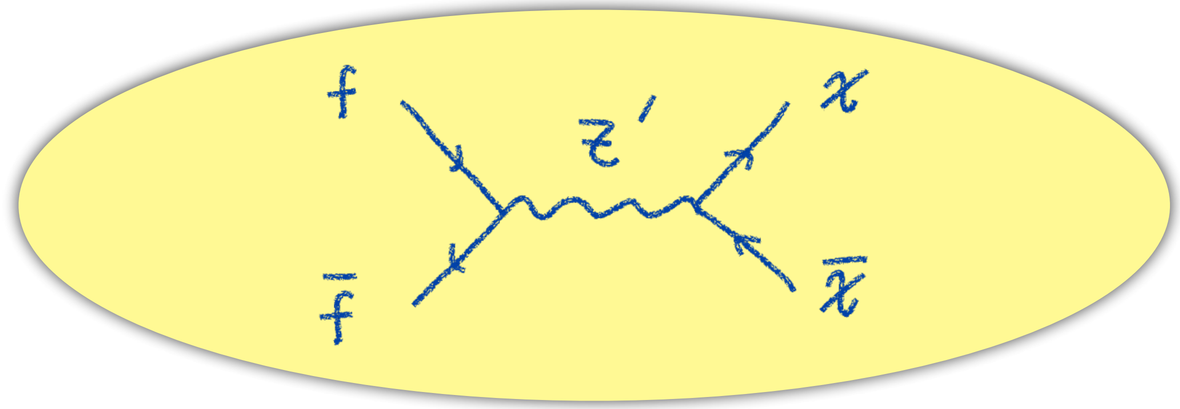


Backup slides

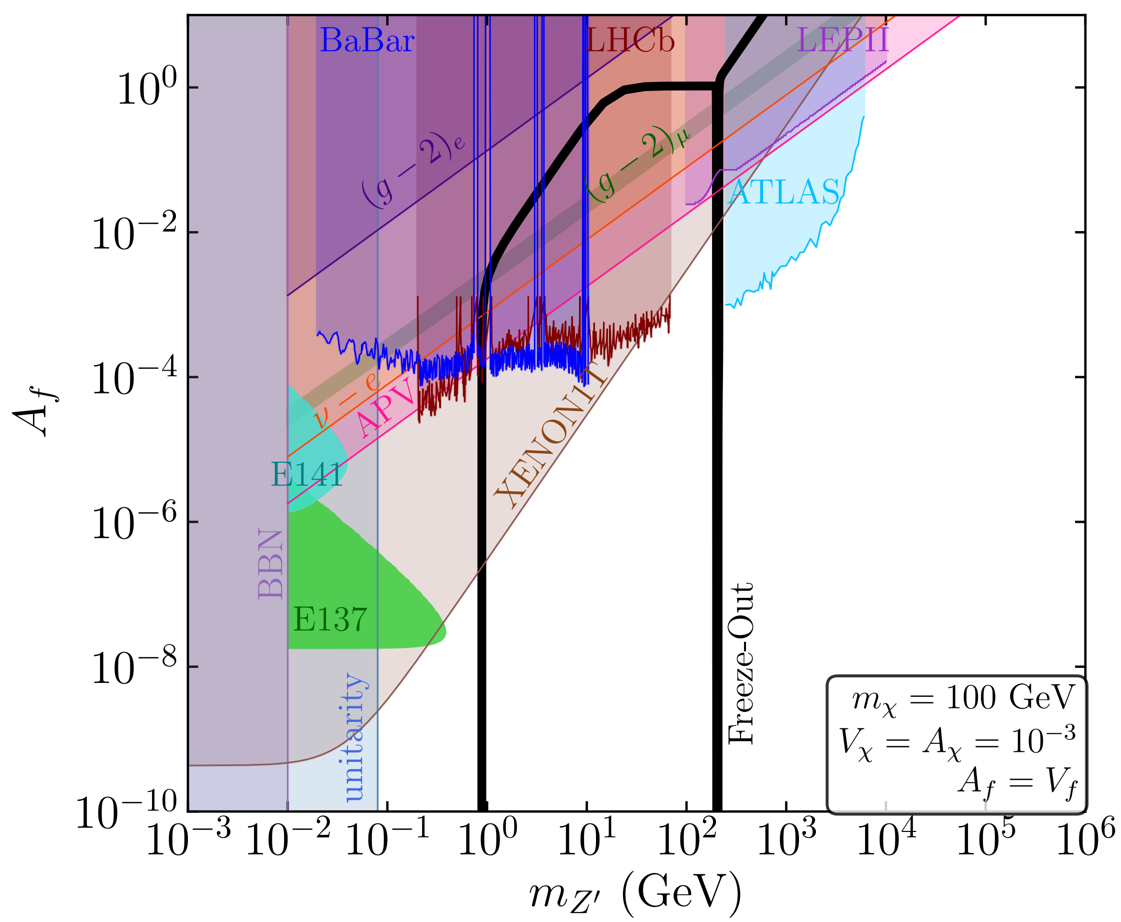
The simplified Z' portal

SM fermions **charged** under $U(1)'$

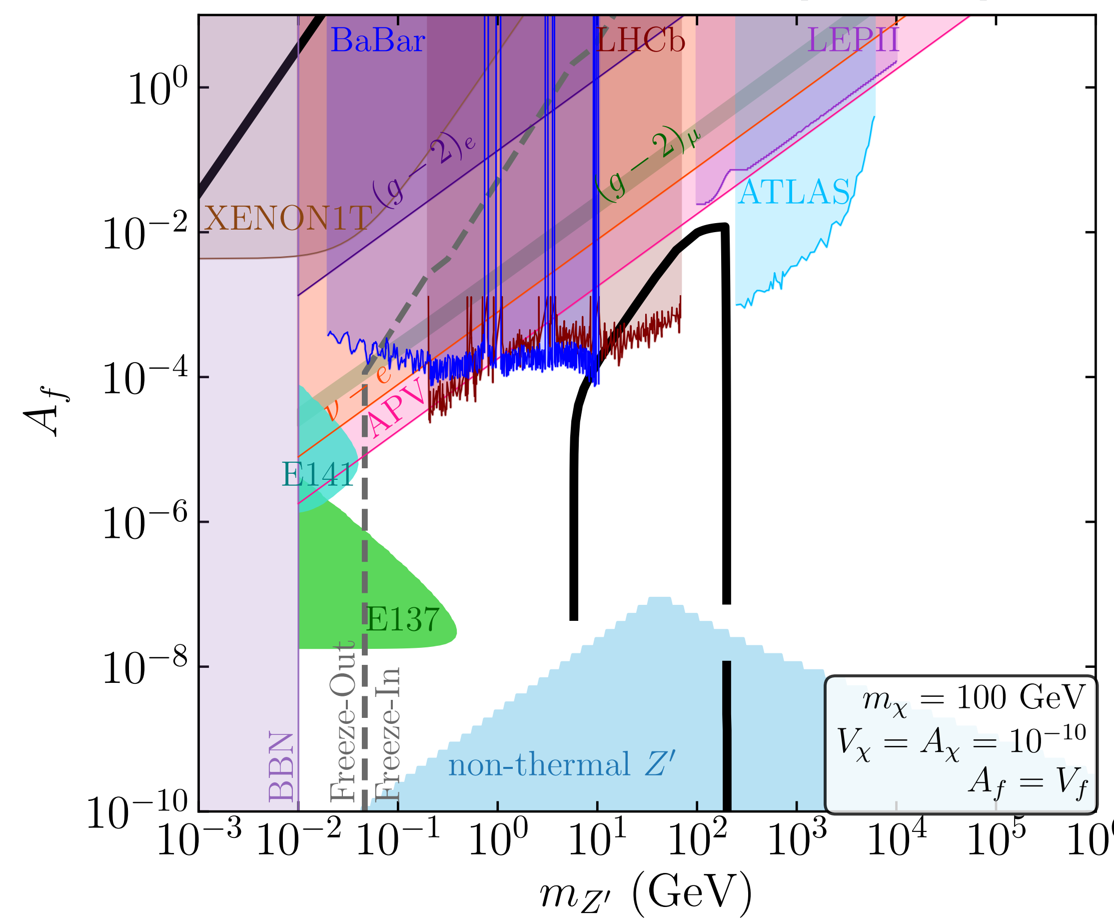
(same V_f and A_f for all SM fermions)



axial and vector (FO)

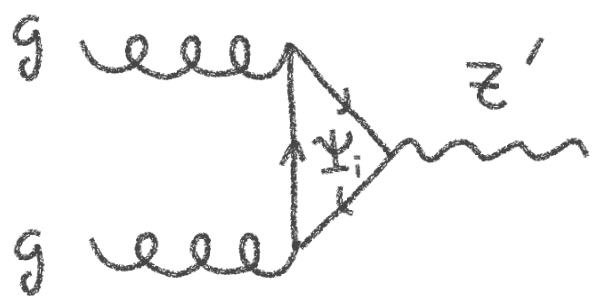


axial and vector (FO/FI)



C. Cosme, MD, S. Godfrey, T. Gray
arXiv:2104.13937

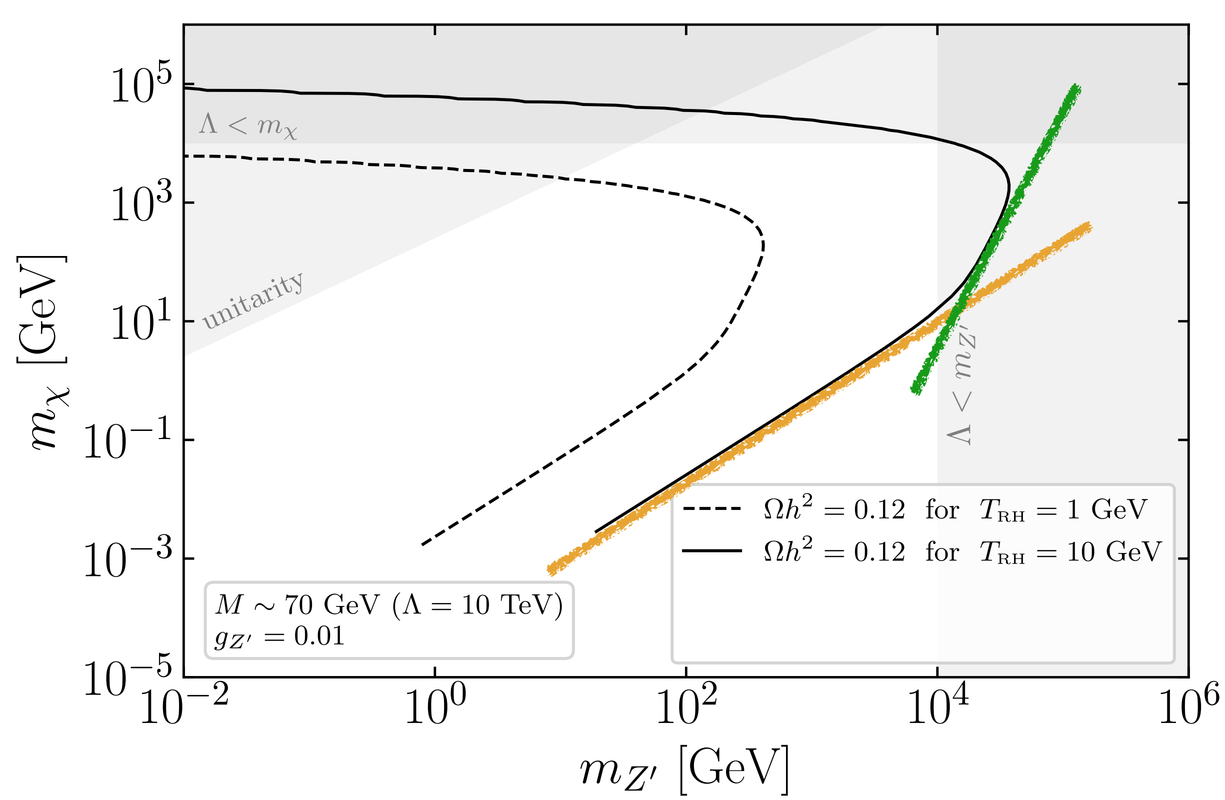
The gluophilic Z' portal



$$\mathcal{O} = \frac{\alpha_s}{6\pi}\sum_i \left(\frac{(q^i_{\Psi_L} - q^i_{\Psi_R})T^aT^a}{M_i^2}\right)[\partial^\mu D_\mu \theta \mathrm{Tr}(G\tilde{G}) - 2D_\mu\theta \mathrm{Tr}(G_{\alpha\nu}D^\nu \tilde{G}^{\mu\alpha})]$$

$$\Lambda \approx \sqrt{\frac{24\pi}{N_\Psi \alpha_s g_{Z'}}}M$$

$$\frac{\Omega h^2}{0.12} \approx \left(\frac{76}{g_{\mathrm{eff}}}\right)^{3/2}\left(\frac{N_\Psi}{3}\right)^2\left(\frac{g_{Z'}}{1}\right)^4\left(\frac{m_\chi}{7.6\mathrm{GeV}}\right)^3\left(\frac{1.4\mathrm{TeV}}{M}\right)^4\left(\frac{1\mathrm{TeV}}{m_{Z'}}\right)^4\left(\frac{T_{\mathrm{RH}}}{1\mathrm{GeV}}\right)^5\left[1 + 8.13\left(\frac{T_{\mathrm{RH}}}{1GeV}\right)^2\left(\frac{7.6\mathrm{GeV}}{m_\chi}\right)^2\right]$$

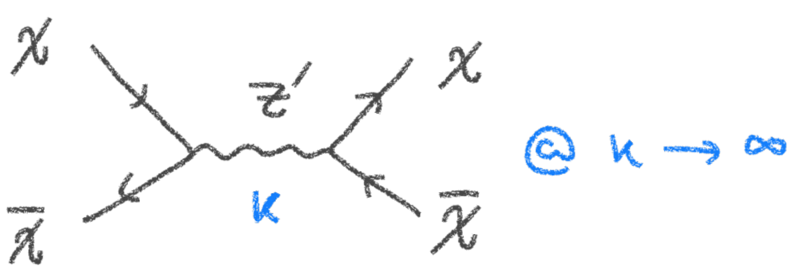


The gluophilic Z' portal

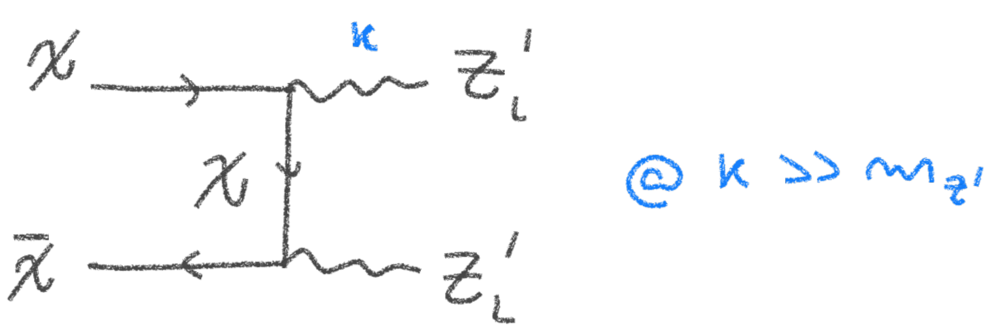
If $A_\chi \neq 0$, perturbative unitarity can be violated @ high energies

F. Kahlhoefer, K. Schimidt-Hoberg, T. Schweitzer, S. Vogl

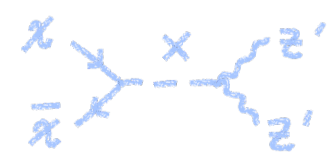
arXiv:1510.02110



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



New particle restoring unitarity

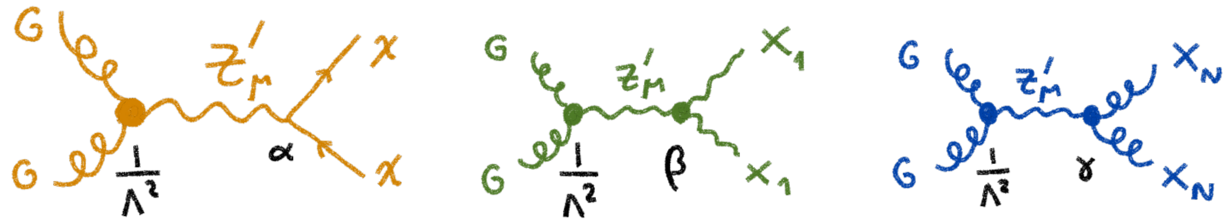


$$M_X < \frac{\pi}{A_\chi^2} \frac{m_{Z'}^2}{m_\chi}$$

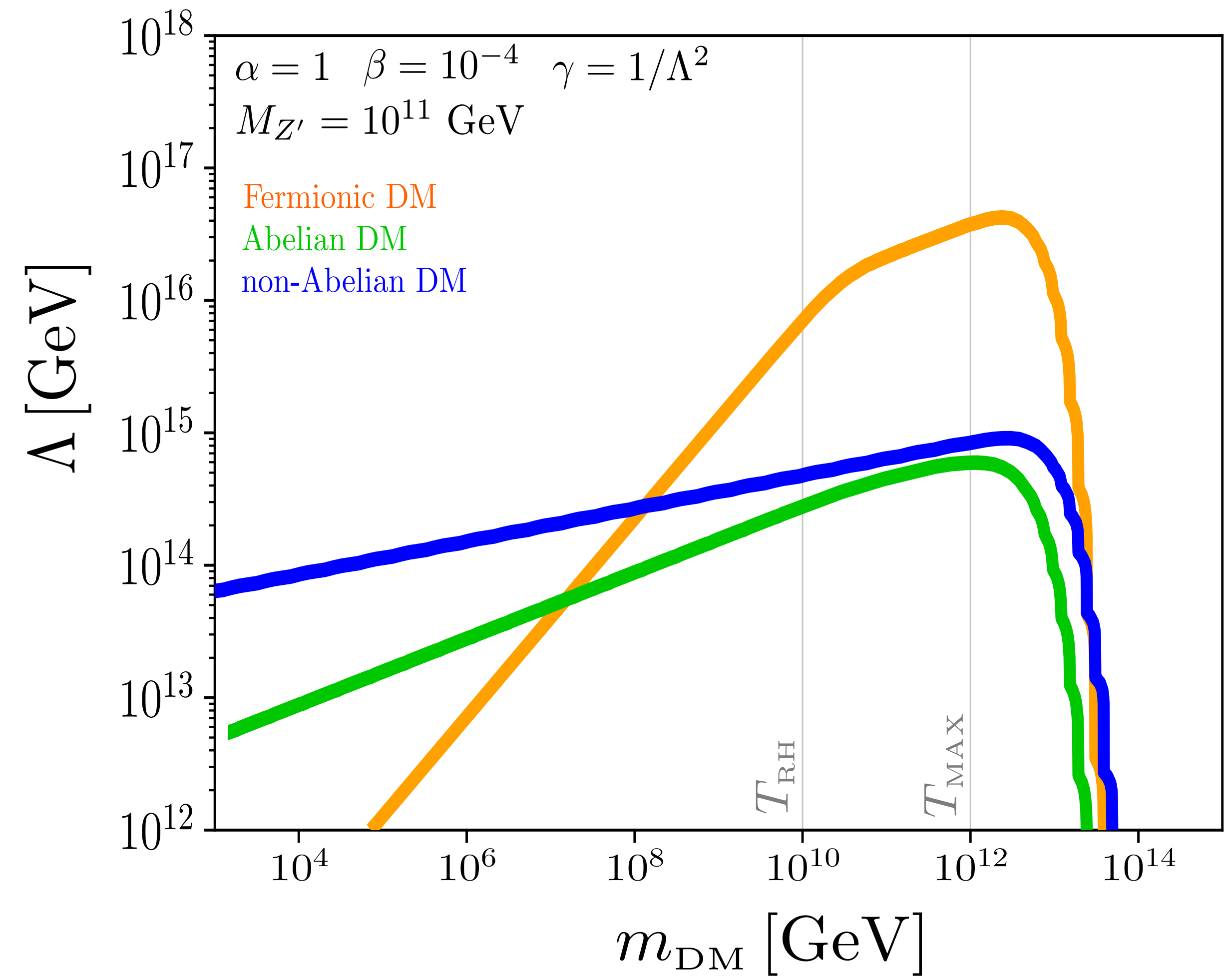
Simplified Z' portals are more natural in the freeze-in regime

The gluophilic Z' portal

G. Bhattacharyya, MD, Y. Mambrini, M. Pierre
arXiv:1806.00016



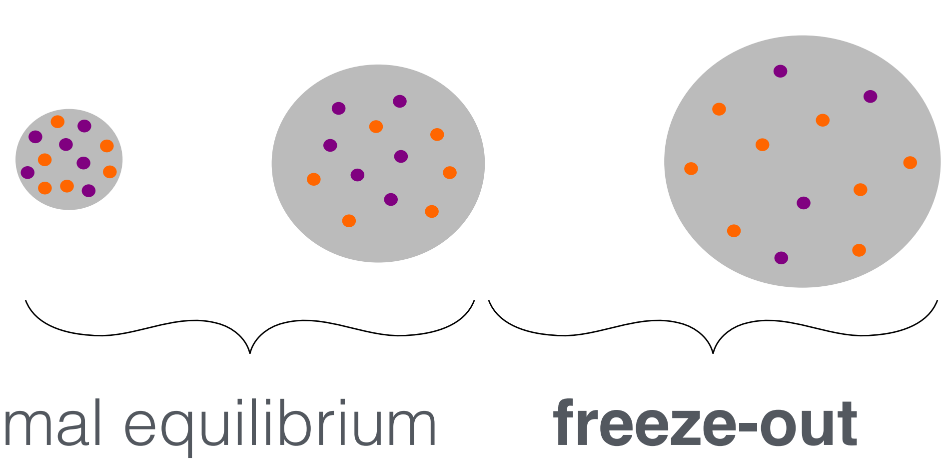
$$\mathcal{L} \supset \begin{cases} \alpha\, \bar{\chi} \gamma^\mu \gamma_5 \chi Z'_\mu \\ \beta\, \epsilon_{\mu\nu\rho\sigma} Z'^\mu X_1^\nu X_1^{\rho\sigma} \\ \gamma\, \partial^\alpha Z'_\alpha\, \epsilon_{\mu\nu\rho\sigma} \mathrm{Tr}[X_N^{\mu\nu} X_N^{\rho\sigma}] \end{cases}$$

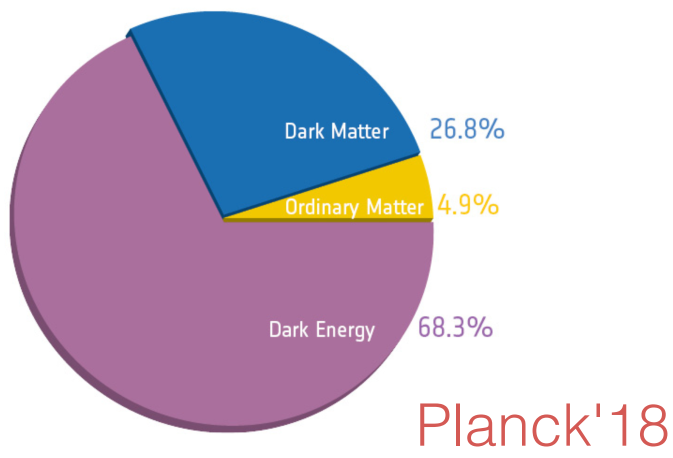


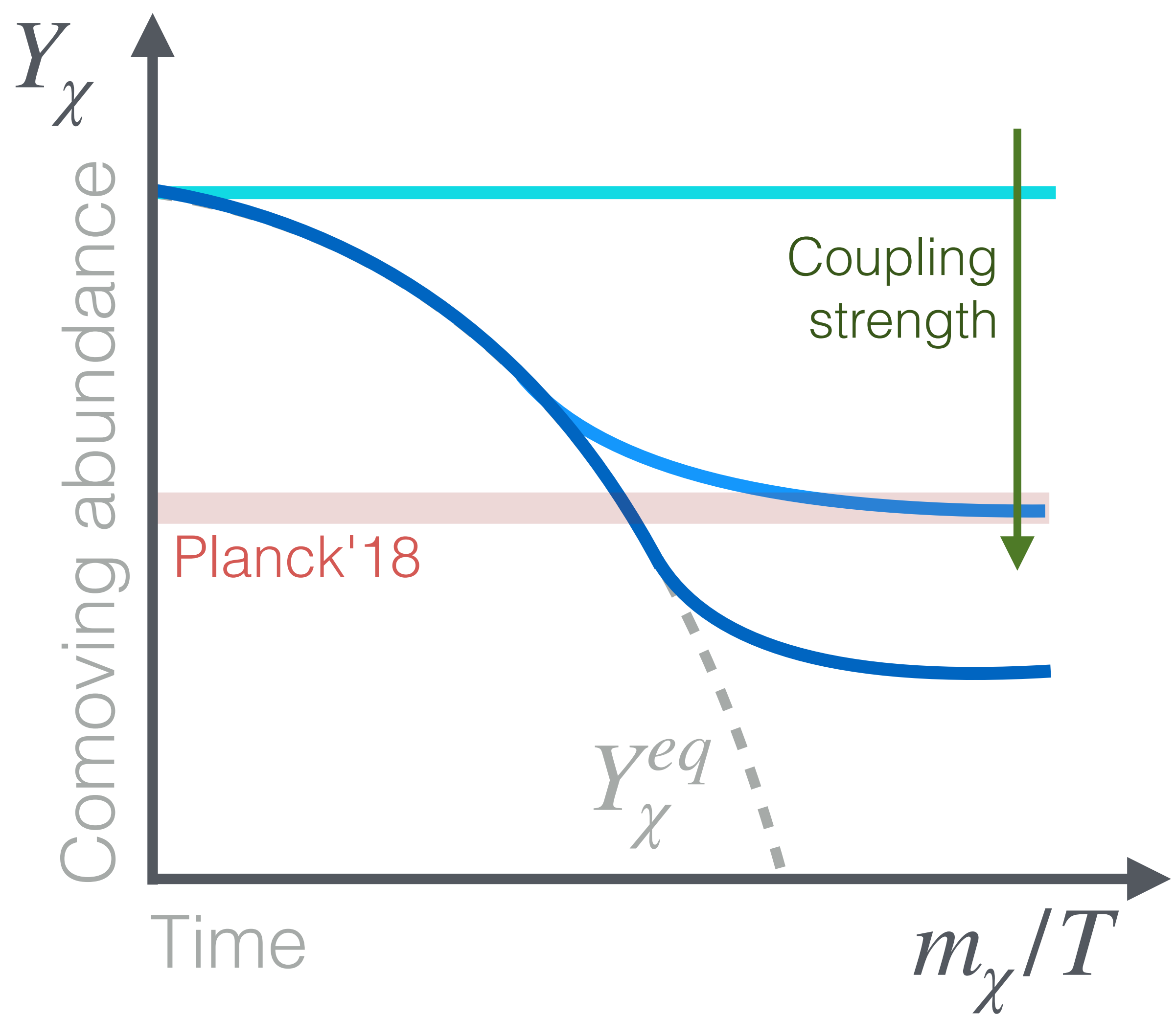
Correct relic density via freeze-in for a wide range of m_{DM}
with $M_{Z'}$ and Λ at intermediate GUT scales

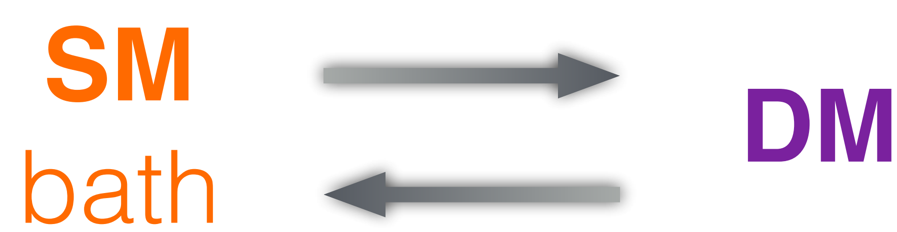
DM genesis - freeze-out

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



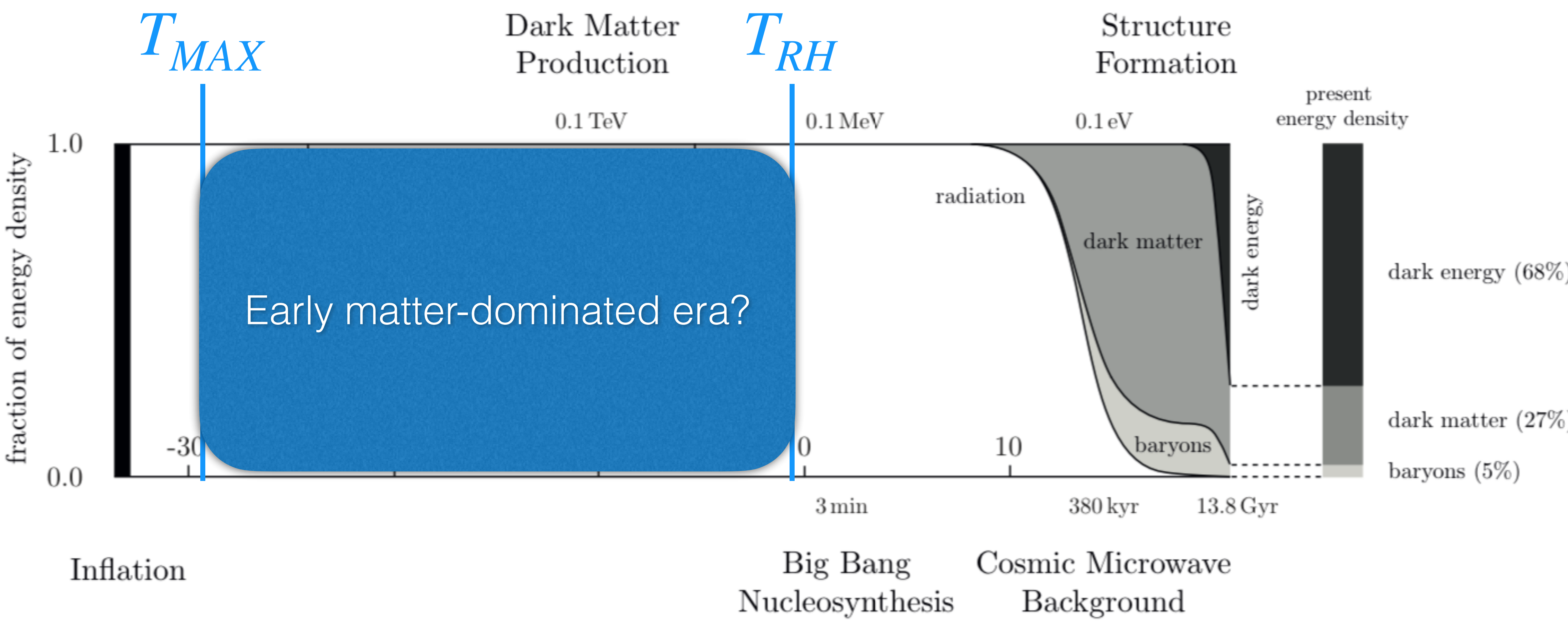




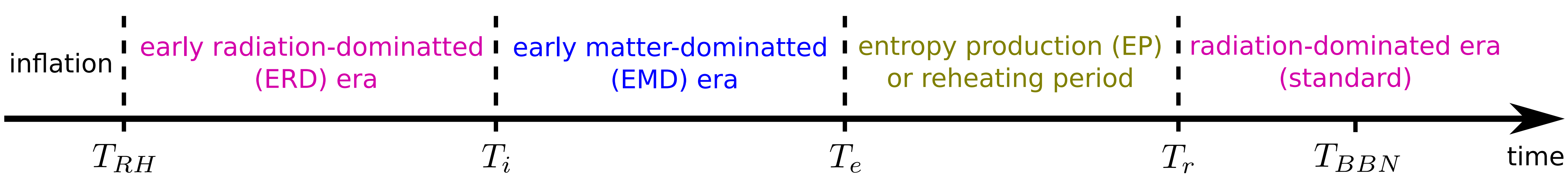


Masses: 10s MeV - 100s TeV
Couplings: $10^{-3} - 10^{-1}$

Early matter era



Daniel Baumann, Cosmology Part III



Early matter era

$$Y_\chi \equiv \frac{N_\chi}{S}$$

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

With EMD

Without EMD