

# INVISIBLES23

*August 28 – September 01, Göttingen, Germany*

Reconciliation of Secluded Dark Sector and Muon  
( $g - 2$ ) in the Light of Fast Expanding Universe

Ananya Tapadar

*Based on: Sougata Ganguly, Sourov Roy, Ananya Tapadar,  
JCAP 02 (2023) 044 (arxiv:2208.13608)*

Indian Association for the Cultivation of Science – Kolkata, India

# Motivation

## I. Dark Matter

## II. Muon anomalous magnetic moment

### Model

→ Gauge theory of Model

$$SM \otimes U(1)_X \otimes U(1)_{L_\mu - L_\tau}$$


→ The Lagrangian of our model :

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{SM} - \frac{1}{4} \hat{X}_{\rho\sigma} \hat{X}^{\rho\sigma} - \frac{1}{4} \hat{F}_{\mu\tau\rho\sigma} \hat{F}^{\rho\sigma} + \frac{\sin \delta}{2} \hat{X}_{\rho\sigma} \hat{F}_{\mu\tau}^{\rho\sigma} + \bar{\chi} (p_\mu \gamma^\mu - m_\chi) \chi \\ & - g_X \bar{\chi} \gamma^\rho \chi \hat{Z}'_\rho - g_{\mu\tau} (\bar{\mu} \gamma_\rho \mu + \bar{\nu}_\mu \gamma_\rho P_L \nu_\mu - \bar{\tau} \gamma_\rho \tau + \bar{\nu}_\tau \gamma_\rho P_L \nu_\tau) \hat{Z}_{\mu\tau}^\rho \\ & + \frac{1}{2} \hat{m}_{\mu\tau}^2 \hat{Z}_{\mu\tau}^\rho \hat{Z}_{\mu\tau\rho} + \frac{1}{2} \hat{m}'^2 \hat{Z}'^\rho \hat{Z}'_\rho. \end{aligned}$$

kinetic mixing parameter

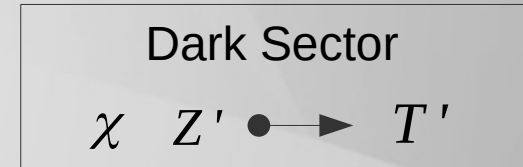
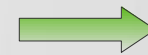
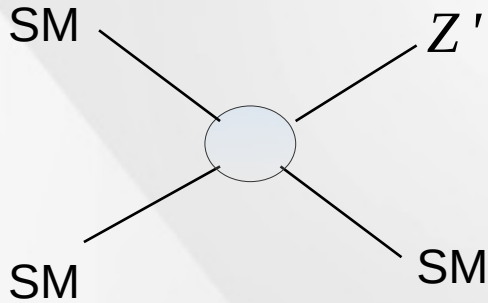
- After diagonalizing and rewriting the Lagrangian in mass basis,

$$\mathcal{L} \supset -g_X \bar{\chi} \gamma^0 \chi Z'_\rho - \epsilon (\bar{\mu} \gamma_\rho \mu + \bar{\nu}_\mu \gamma_\rho P_L \nu_\mu - \bar{\tau} \gamma_\rho \tau + \bar{\nu}_\tau \gamma_\rho P_L \nu_\tau) Z'_\rho$$


Assumption:  $\frac{m_{Z'}}{m_{\mu\tau}}, \delta \ll 1$

$$g_{\mu\tau} \frac{m_{Z'}^2}{m_{\mu\tau}^2} \tan(\delta)$$

## Dark sector formation,

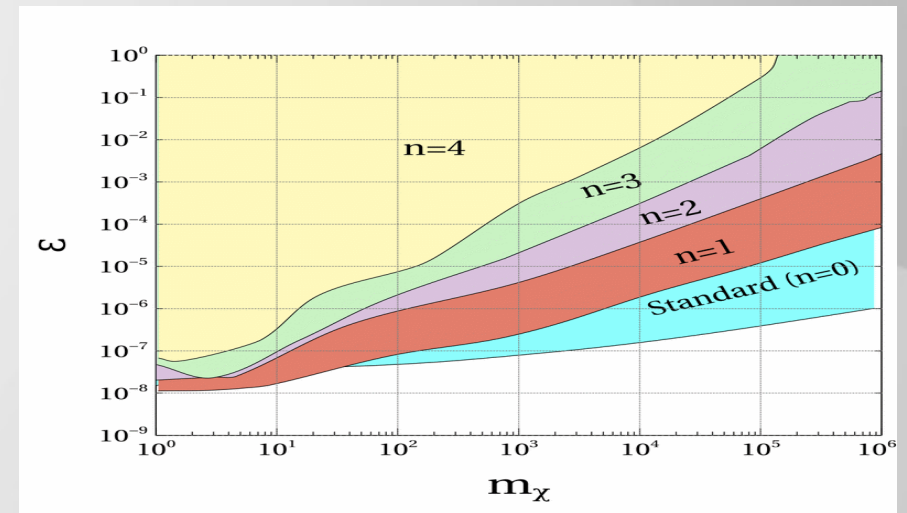
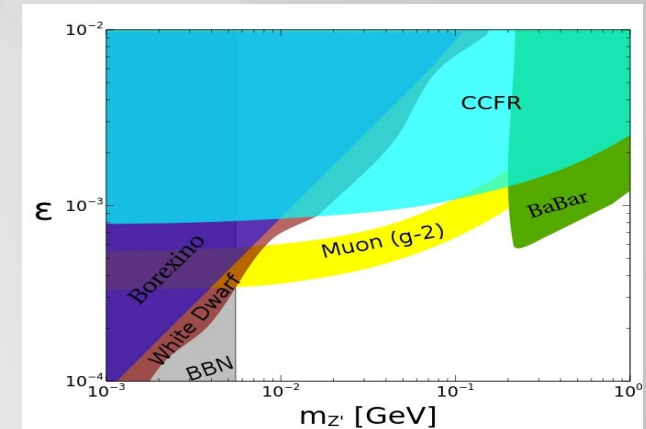


# Muon anomalous magnetic moment

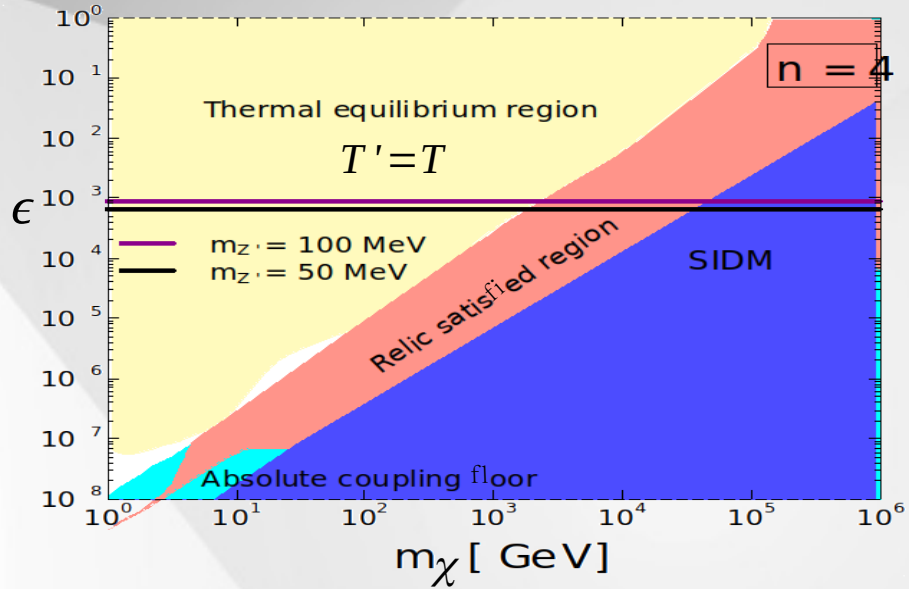
- In presence of light gauge boson ( $Z'$ ), yellow region represents allowed parameter space for muon ( $g-2$ ).

## Single framework

- A new species  $\phi$  and energy density of  $\phi$  redshifts as  $\rho_\phi \propto a^{-(n+4)}$ ,  $n \geq 0$  where  $a$  is scale factor and  $n$  is expansion parameter.
- Shaded region represents thermal equilibrium region where DS and VS share same temperature.



# Results



- Thermal equilibrium region

Dark sector temperature = Visible sector temperature

- Absolute coupling floor

Correct relic abundance of DM by dark sector freeze-out not possible.

- Relic satisfied region

1) Late time annihilation

2) Freeze-in

- Self interaction of DM

$$\chi\chi(\bar{\chi}) \rightarrow \chi\chi(\bar{\chi}), \bar{\chi}\bar{\chi} \rightarrow \bar{\chi}\bar{\chi}$$

Galactic properties produced in N -body simulations.

## Conclusion

- 1) If Universe expands at a faster rate than radiation then even after considering astrophysical ,cosmological and laboratory constraints DM phenomenology and muon (g-2) can be explained in a single framework.
- 2) The region of interest for  $n=4$  , is  $1\text{ TeV} \lesssim m_\chi \lesssim 10\text{ TeV}$  ,  $5.5\text{ MeV} \lesssim m_Z \lesssim 200\text{ MeV}$  and  $2 \times 10^{-4} \lesssim \epsilon \lesssim 10^{-3}$  where DM phenomenology and muon (g-2) can be explained in a single framework.

# Thank you

## Reconciliation of Secluded Dark Sector and Muon (g-2) in the Light of Fast Expanding Universe

Sougata Ganguly, Sourov Roy, Ananya Tapadar  
Indian Association for the Cultivation of Science

Invisible23 Workshop  
August 28 - September 01, 2023, Goettingen, Germany

### Abstract

- In this work we have addressed two issues Dark Matter (DM) and muon (g-2) anomaly in a single beyond Standard Model (SM) framework.
- We have considered  $U(1)_{L-L} \otimes U(1)_{\nu}$  extension of SM in light of fast expanding Universe.
- We studied different phases of cosmological evolution of thermally decoupled dark sector  $\chi$  and produced from SM bath at very early Universe.
- If we consider DM mass to be  $1 - 10$  GeV, partial coupling  $2 \times 10^{-4} - 10^{-3}$  and mediator mass  $5.5 - 20$  MeV then both muon (g-2) anomaly and relic abundance of dark matter can be explained together.

### Model

#### Theoretical part:

- Our model has two sectors - visible sector (VS-SM and  $U(1)_{L-L}$ , gauge boson) and dark sector (DS-fermions, DM and  $U(1)_{\nu}$  gauge boson).
- We have assumed very small tree level kinetic mixing between  $U(1)_{L-L}$  and  $U(1)_{\nu}$  and the Lagrangian of our model is as follows:

$$\mathcal{L} = \mathcal{L}_{SM} + \chi (\not{\partial} - m_\chi) \chi - \frac{1}{2} \xi^{ab} X_{ab} - \frac{1}{2} \xi^{cd} Y_{cd} + \frac{m_{\nu\mu}}{2} \bar{\nu}_\mu \chi + \text{h.c.} + \bar{\nu}_\mu \gamma^\mu \not{\partial} \nu_\mu - \bar{\nu}_\mu \gamma^\mu \not{\partial} \nu_\mu + \frac{m_{\nu\mu}}{2} \bar{\nu}_\mu \chi + \text{h.c.} + \bar{\nu}_\mu \gamma^\mu \not{\partial} \nu_\mu - \bar{\nu}_\mu \gamma^\mu \not{\partial} \nu_\mu + \frac{m_{\nu\mu}}{2} \bar{\nu}_\mu \chi + \text{h.c.}$$

- In physical basis dark vector boson ( $Z'$ ) interacts with DM and SM particles.
- $\mathcal{L} \supset -g_1 \bar{\chi} \gamma^\mu Z'_\mu \chi + \epsilon (\bar{\nu}_\mu \gamma^\mu + \bar{\nu}_\mu \gamma^\mu P_{L,R}) Z'_\mu - \tau \gamma^\mu Z'_\mu \tau + \dots$
- where,  $\epsilon = g_{\nu\mu} \xi^{ab}$  and in the limit  $m_\nu \gg m_\mu$  and  $\delta \ll 1$ .

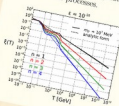
#### Cosmological part:

- Temperature of DS and VS are different and are defined by  $T'$  and  $T$  respectively.
- $n/p$  ratio predicts that Universe was radiation dominated at the time of BBN.
- We have assumed that before BBN, the energy budget of the Universe is dominated by a new species  $\phi$  whose energy redshifts as  $a^{-4}$  with  $n > 0$ . Therefore, modified Hubble parameter is

$$H(T) = \frac{1}{M_{pl}} \sqrt{\frac{\rho(T) + \rho(T')}{3}}$$

### Dark sector Production

- At early Universe HS is populated from SM bath by  $f\bar{f} \rightarrow \gamma(Z, h)Z'$ ,  $f\bar{f}\gamma(Z, h) \rightarrow f\bar{f}Z'$  charged current processes.

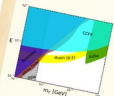


Expression of  $T'$  is derived through analytic calculation, while the prefactor  $W$  is obtained through numerical analysis.

$$T' = \frac{10\sqrt{2}}{(1+\beta)^2} T \left(\frac{m_\nu}{T}\right)^2$$

### Motivation

- $Z'$  can contribute to the anomalous magnetic moment of muon if its coupling strength with muon is  $\sim 10^{-3}$  and  $m_{Z'} \sim 10$  MeV.

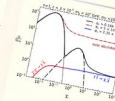


- In the left panel yellow region is the allowed parameter space where muon (g-2) can be satisfied.
- In the right panel shaded yellow region represents thermal equilibrium region where DS and VS have same temperature.

### Boltzmann Equations

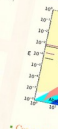
- Number density Boltzmann equation in our scenario,  $\frac{dn_\chi}{dt} + 3Hn_\chi = \frac{1}{2} \langle \sigma v \rangle_{\nu\nu} (n_{\nu\nu}^2 - n_\chi^2) + 2 \sum_{f \neq \chi} \langle \sigma v \rangle_{f\bar{f}} (n_f n_{\bar{f}} - n_\chi^2)$ .
- Energy density Boltzmann equation in our scenario,  $\frac{d\rho_\chi}{dt} + 4H\rho_\chi = CE(T, T')$ , where,  $CE(T, T')$  is the collision term for  $Z'$  production.

### Numerical Analysis

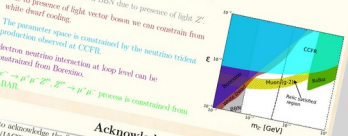


- For very small self-coupling of HS, DM is produced via freeze-in from SM bath.
- After decoupling from thermal bath, DM are produced rapidly from SM bath and attain quasi-static equilibrium (QSE) at later time DM decouples from the QSE and freezes out, known as freeze-in.
- For small coupling DM is produced from SM bath at early era via freeze-in.
- Initially dark matter is overproduced via freeze-in mechanism which at later time annihilates into  $Z'$ . This mechanism we depict as late-time annihilation.

### Results



- DS and VS are in thermal equilibrium for large partial coupling.
- DM relic is satisfied.
- Constraint from Initial cluster observation on self interaction of DM.
- DS is not internally thermalized due to high expansion rate of Universe.
- Two straight lines represents muon (g-2) satisfied a zero two different way.



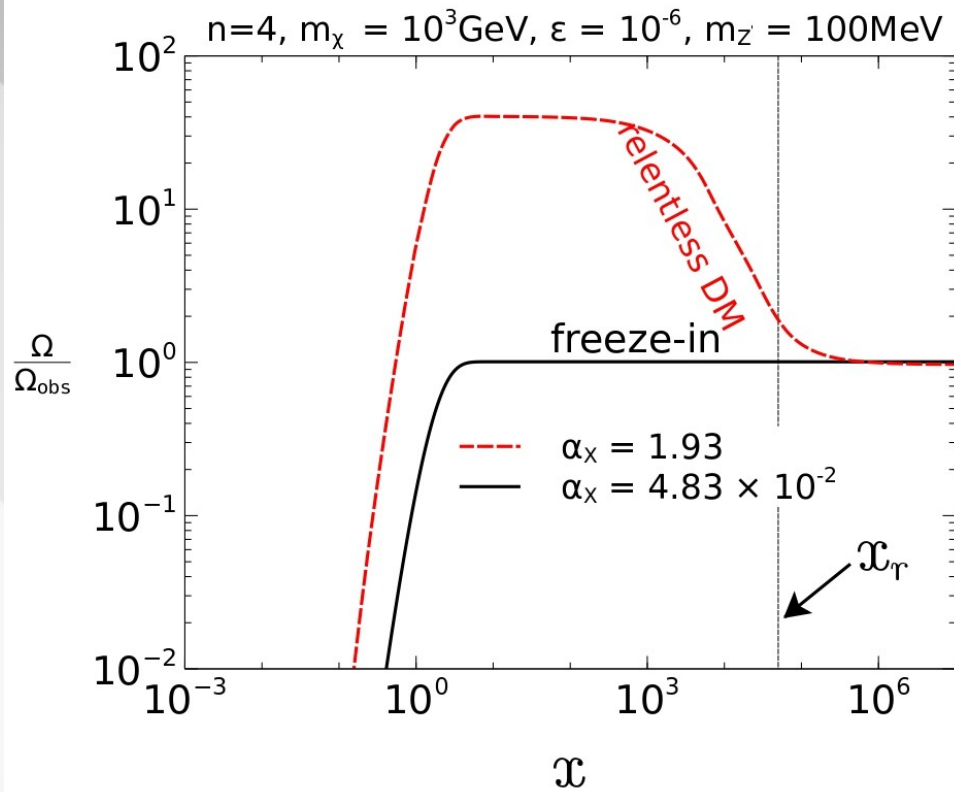
- Model is constrained from recent measurement of FermiLab on muon g-2 anomaly.
- Due to presence of BBN due to presence of light  $Z'$  while dwarf nucleosynthesis.
- The parameter space is constrained by the sensitive tritium production observed at CKPT.
- electron neutrino interaction at keV level can be constrained from Borexino.
- $e \rightarrow e + \mu^+ \mu^-$ ,  $Z' \rightarrow \mu^+ \mu^-$  process is constrained from BABAR.

### Acknowledgements

I wish to acknowledge the financial support provided by the Indian Association for the Cultivation of Science (IACS), Kolkata. I would also like to thank my collaborators for their collaboration based on ref[1,4].

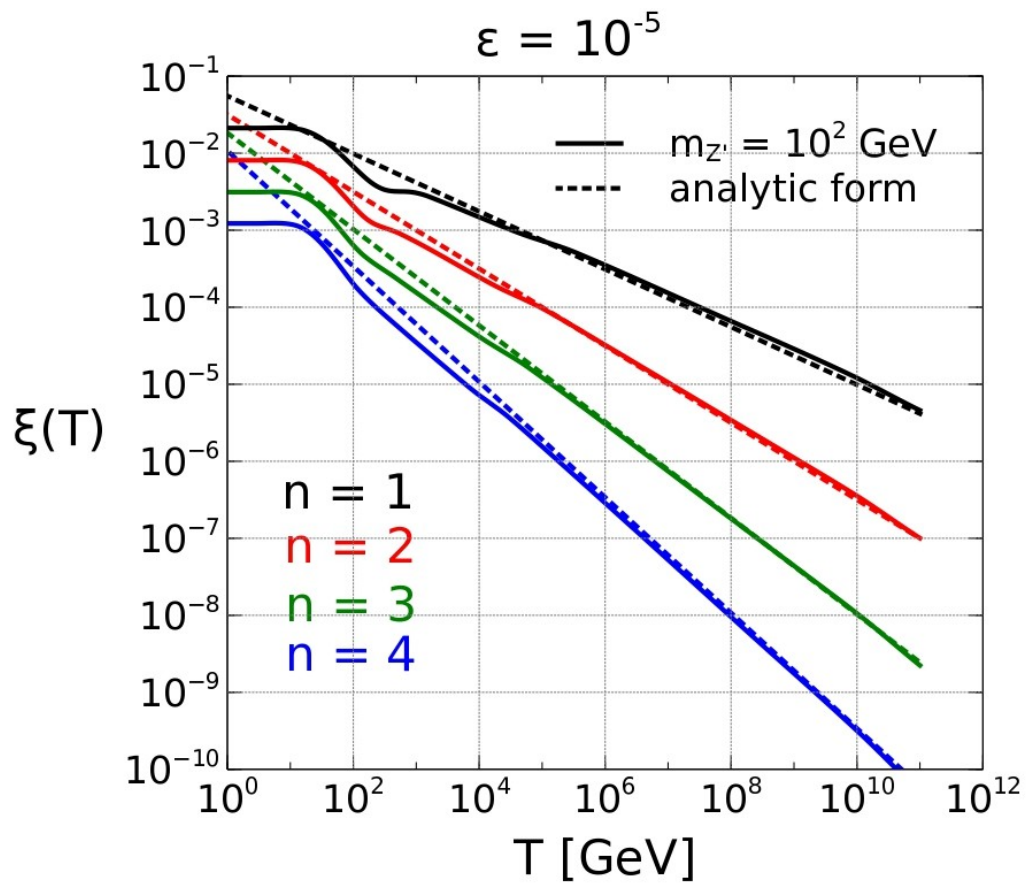
### References

- Sougata Ganguly, Sourov Roy, A Tapadar, Secluded dark sector and muon (g-2) in the light of fast expanding Universe, JCAP 02 (2023) 044.
- David A. Evans, Cristian G. Gudea, Jesús Sánchez-Lapuente, Secluded Dark Matter, JHEP 01 (2020) 052.
- Francesco Ferraro, Nicola Ferraro, Stefano Profumo, When the Universe Expands Too Fast/Too Slow: Reheating Dark Matter, JCAP 05 (2017) 012.
- A Tapadar, Sougata Ganguly, Sourov Roy, Non-adiabatic evolution of dark sector in the presence of  $U(1)_{L-L}$  gauge symmetry, JCAP 02 (2022) 05, 019.



$$\alpha_X = \frac{g_X^2}{4\pi}$$





$$\xi(T) = \frac{T'}{T}$$

