Z_3 Scalar Dark Matter with Strong Positron Fluxes

Bastián Díaz Sáez (USACH), K. Ghorbani (Arak U., Iran)

MPI für Astrophysik, Heidelberg, Deutschland

July 24, 2022

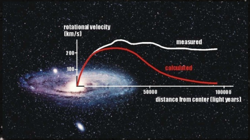
DEPARTAMENTO DE FÍSICA
UNIVERSIDAD DE SANTIAGO DE CHILE

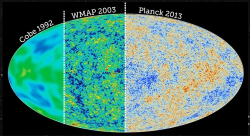
Outline

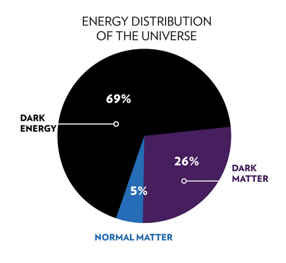
1. Introduction.
2. Z_3 complex scalar DM in a VLL portal.
3. Constraints and results.
4. Conclusions.

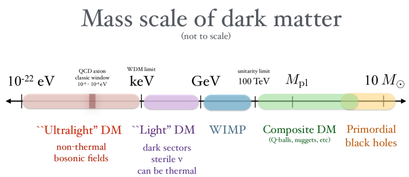
Evidence of DM

Astrophysics: **rotation curves, bullet clusters, CMB, etc...**









Scalar WIMPS: Z_2 based symmetry

1. We focus on thermal DM in a vector-like lepton portal, with coupling to the first family of leptons.
2. This type of models has been studied in the past based on Z_2 symmetries (Ibarra 1405.6917, Giachhino et.al. 1307.6480, Toma 1307.6181, Bai and Berger 1402.6696, Chang et.al. 1402.7358, Bell et.al. 1705.01105, etc...).
3. Real scalar: d-wave annihilation, direct detection (DD) suppressed at two loops, but sensitive indirect detection (ID).
4. Complex scalar: p-wave annihilation, DD at one-loop (sensitive to experiments), no sensitive to ID.

1. **Under collider, DD and ID, both models highly constrained below TeV scale!.**
2. **No positron nor anti-proton strong fluxes.**

Z_2 real scalar DM model: CTA projections

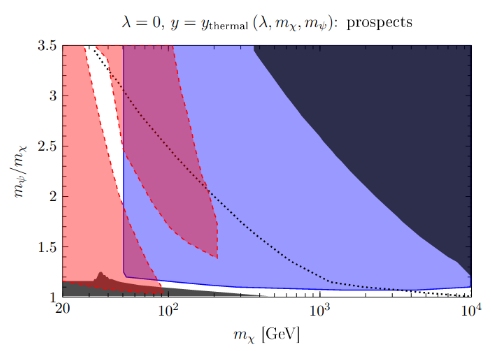


Figure 1: Parameter space constrained by ID (blue regions) and collider (red regions) (Ibarra et. al. 2014).

Z_3 model: The simplest realization

- Lepto-philic new physics consisting of a complex singlet scalar S (no vev) and a VLL ψ with $Y = -1$.
- Under a new global Z_3: $S \to e^{i2\pi/3} S$ and $\psi \to e^{i2\pi/3}\psi$

$$\mathcal{L} = \bar{\psi}(\not{\partial} + m_\psi)\psi + \left(g_\psi S \bar{\psi} e_R + h.c.\right) - V(H, S),$$

where the potential is given by

$$V = \mu_H^2 |H|^2 + \lambda_H |H|^4 + \mu_S^2 |S|^2 + \lambda_S |S|^4 + \lambda_{SH} |S|^2 |H|^2 + \frac{\mu_3}{2}(S^3 + S^{\dagger 3})$$

Parameter space of the model is then

$$(m_S, m_\psi, g_\psi, \lambda_{SH}, \mu_3).$$

Z_3 model: Relic abundance

No Higgs portal!.

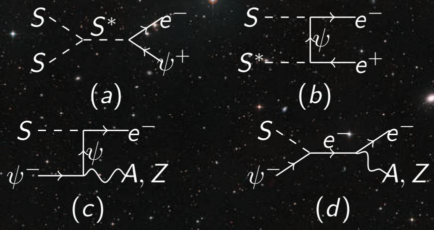


Figure 2: *Leading processes at freeze-out.*

- We use **MicrOMEGAS code** for calculation of observables.
- Diagram (a) proceeds in a s-wave, dominates provided

$$2m_S \gtrsim m_\psi$$

.

Z_3 model: Relic abundance

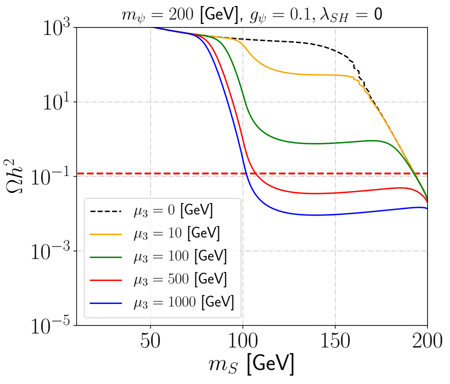


Figure 3: *Predictions for the relic density abundance of $S(S^*)$. The red dashed horizontal line is $\Omega_c h^2 = 0.12$.*

The overall effect is a decreasing of g_ψ!!.

Experiments

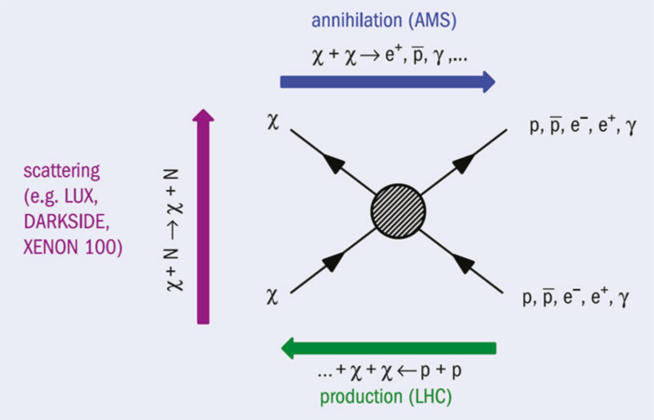


Figure 4: Ways to test the particle DM hypothesis.

Direct detection at one-loop

DM-nucleon interactions via the VLL portal start at one-loop through the dimension-six operator

$$\mathcal{L} = 2C\partial_\mu S^* \partial_\nu S F^{\mu\nu}$$

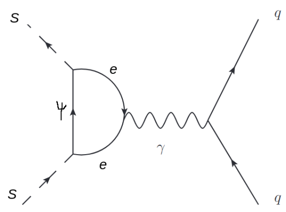


Figure 5: *One-loop process for DD.*

The total cross section for the DM-nucleon system is given by (Bai and Berger, 2014)

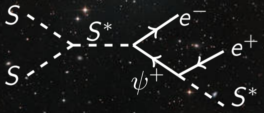
$$\sigma_{SN} = \frac{Z^2 e^2 C^2(m_e, m_\psi)\mu_{SN}^2}{8\pi A^2},$$

with $Z(A)$ the atomic(mass) number, e the electric charge, μ_{SN} the reduced mass of DM-nucleon system, $m_N = 0.94$ GeV, and $C(m_e, m_\psi)$ given by

$$C(m_e, m_\psi) \approx -\frac{g_\psi^2 e}{16\pi^2 m_\psi^2}\left[1 + \frac{2}{3}\log\left(\frac{m_e^2}{m_\psi^2}\right)\right].$$

High positron fluxes

Main process (and its CP-conjugated) contributing to e^+ flux:



1. Box-shaped spectra.

We consider model-independent bounds on positron fluxes based on AMS-02 (Ibarra et.al., 2013).

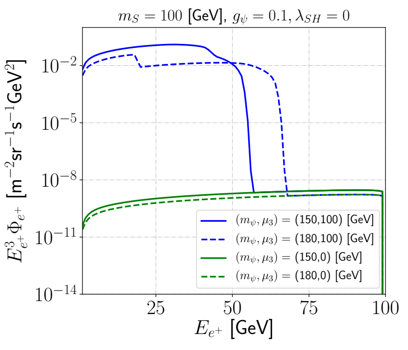


Figure 6: *Positron flux as a function of the positron energy.*

Z_3 model: Results

Left: +perturbativity +relic abundance. **middle**: +ID. **right**: + DD

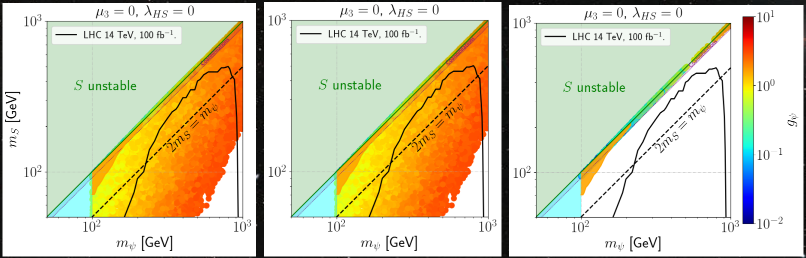


Figure 7: *Color maps for g_ψ for $\mu_3 = 0$. The cyan region corresponds to collider constraints for VLL, and the orange region is the exclusion from compressed spectra for LHC at 13 TeV, and blow the solid black line excluded by simulation. The dashed line is a reference in which above it the $SS(S^*S^*)$ annihilations start to become efficients.*

Z_3 model: Results

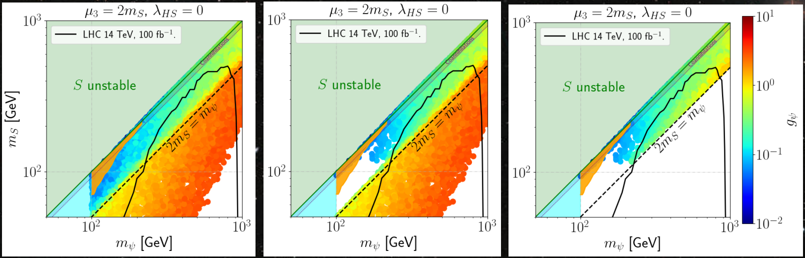


Figure 8: *Same caption than before.*

Conclusions

1. In its simplest form, we have explored a novel model containing two new fields (S, ψ), both transforming under a Z_3 symmetry.
2. The model is able to account for the DM from hundred GeV up to several TeV of mass evading strong constraints, in contrast to previous studies on real and complex scalar DM in a VLL portal based on Z_2 symmetries.
3. Significant positron fluxes, although gamma-ray fluxes stay below CTA sensitivity.
4. More possibilities: Higgs portal, hadro-philic DM, higher representations of the new fields, etc... :)

Backup: Z_3 model stability

There are four stationary points that can be classified by their symmetries:

1. (EW, Z_3)
2. ($\not{\text{EW}}$, Z_3)
3. (EW, $\not{Z}_3$)
4. ($\not{\text{EW}}$, $\not{Z}_3$)

Consider that:

- We demand that ($\not{\text{EW}}$, Z_3) be the global minimum.
- As μ_3 grows too much, the potential energy of the Z_3-breaking extrema rapidly descend below the value of the SM minimum.

Backup: Z_3 model Theory constraints (Belanger et.al. 2012)

- The scalar potential is bounded below if the quartic interactions satisfy the vacuum stability conditions

$$\lambda_H > 0, \quad \lambda_S > 0, \quad \lambda_{SH} > -\sqrt{\frac{2}{3}\lambda_H \lambda_S}. \tag{1}$$

- μ_3 can not be too big because the Z_3-symmetric SM vacuum could not be the global minimum. We demand that

$$\max(\mu_3) \approx 2\sqrt{2}\sqrt{\frac{\lambda_S}{\delta}}\, m_S, \tag{2}$$

with δ a parameter which regulates whether the SM vacuum is or not a global minimum.

- We have (Belanger et.al., 1211.1014)

$$\max(\mu_3) \approx 2 m_S.$$

Z_3 model: Relic abundance

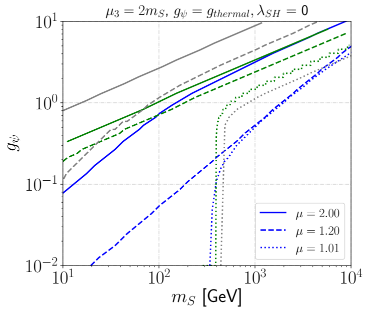


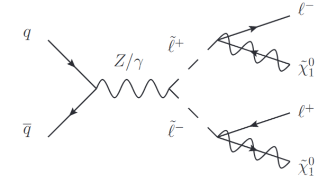
Figure 9: *Yukawa coupling g_ψ leading to the observed DM relic density in the Z_3 model (blue), Z_2 complex DM and in the Z_2 real scalar (gray). Here $\mu \equiv m_\psi/m_S$.*

The overall effect is a decreasing of g_ψ!!.

Backup: Z_3 model: Collider constraints

At hadron colliders, pair production of ψ via **Drell-Yan** is the main production mechanism. **SUSY** searches relevant. We use:

- $m_\psi > 100$ GeV (ALEPH 2002, DELPHI 2003).
- We use projection limits where *pp* events were simulated at 14 TeV at 100 fb^{-1} (Y. Bai and J. Berger 2014).
- Compressed spectra, i.e. $m_\psi \approx m_S$ (P. Athron et.al 2021).



Z_3 model: Indirect detection

Figure 10: *(above) Bremsstrahlung. (below) New Z_3 diagrams.*

Z_3 model: Gamma-rays

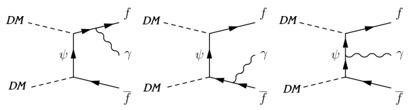


Figure 11: Bremsstrahlung and Final-state radiation.

Gamma-rays below sensitivity of CTA projections! (like Majorana DM)

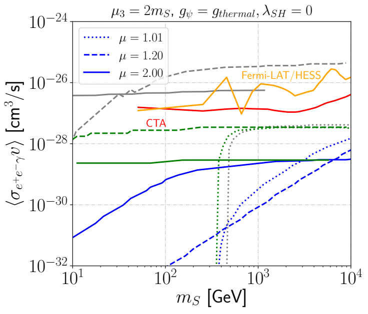


Figure 12: *Cross section as a function of m_S for Z_2 model (grey ones), Z_2 complex (green), Z_3 model (blue curves).*

Z_3 model: High mass range

- Above the TeV scale there is still enough parameter space which evades strong projections of DD and ID.

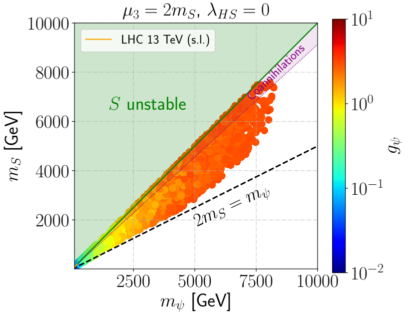


Figure 13: *High mass regime considering fulfilling perturbativity and correct relic abundance, and XENONnT and CTA bound projections.*

Z_3 model: Results

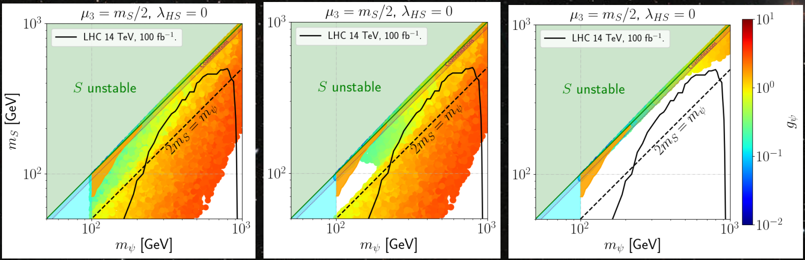


Figure 14: *Same caption than above.*