Ameen Ismail
CoSy HEP
12 November 2022

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(Z-portal continuum dark matter models)

arXiv:2210.16326
with C. Csáki and S. J. Lee
CoSy HEP

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Dark matter and WIMPs

WIMP DM typically motivated from Higgs naturalness, "WIMP miracle"

Minimal models under pressure from DD experiments

Ways out: abandon WIMP paradigm, or more sophisticated WIMPs

The Waning of the WIMP?
A Review of Models, Searches, and Constraints (2017)

Giorgio Arcadi[a,*] Maíra Dutra[b,†] Pradipta Ghosh[b,c,‡] Manfred Lindner [a,§] Yann Mambrini[b,¶] Mathias Pierre[b,**] Stefano Profumo[d,e,††] and Farinaldo S. Queiroz[a,‡‡]

(2016) **Toward (Finally!) Ruling Out Z and Higgs Mediated Dark Matter Models**

Miguel Escudero,[a,b] Asher Berlin,[c] Dan Hooper[b,d,e] and Meng-Xiang Lin[d]

First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment (2022)

The LUX-ZEPLIN (LZ) experiment is a dark matter detector centered on a dual-phase xenon time projection chamber operating at the Sanford Underground Research Facility in Lead, South Dakota, USA. This Letter reports results from LZ's first search for Weakly Interacting Massive Particles (WIMPs) with an exposure of 60 live days using a fiducial mass of 5.5 t. A profile-likelihood ratio analysis shows the data to be consistent with a background-only hypothesis, setting new limits on spin-independent WIMP-nucleon, spin-dependent WIMP-neutron, and spin-dependent WIMP-proton cross-sections for WIMP masses above $9\,\mathrm{GeV}/c^2$. The most stringent limit is set for spin-independent scattering at $30\,\mathrm{GeV}/c^2$, excluding cross sections above $6.5 \times 10^{-48}\,\mathrm{cm}^2$ at the 90 % confidence level.

Continuum dark matter to the rescue

Scalar Z-portal continuum DM introduced last year (2105.07035, 2105.14023)

Continuum Dark Matter

Csaba Csáki,[a] Sungwoo Hong,[a,b,c] Gowri Kurup,[a,d] Seung J. Lee,[e] Maxim Perelstein,[a] and Wei Xue[f]

Z-portal Continuum Dark Matter

Csaba Csáki,[1] Sungwoo Hong,[1,2,3] Gowri Kurup,[1,4] Seung J. Lee,[5] Maxim Perelstein,[1] and Wei Xue[6]
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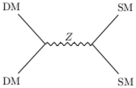

Kinematic suppression of DD cross sections, continuum decays

Today's goal: generalize to fermion, vector continuum DM

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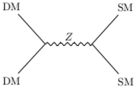


The Continuum Dark Matter Zoo

Csaba Csáki,[a] Ameen Ismail,[a] and Seung J. Lee[b]

Gapped continuum crash course

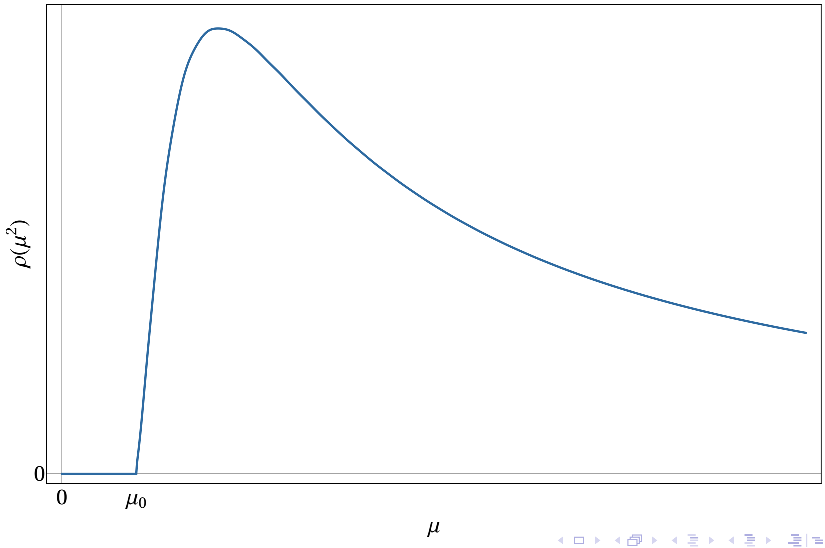
Scalar example: $S = \int \frac{d^4 p}{(2\pi)^4} \phi^\dagger(p)\Sigma(p^2)\phi(p)$

Define spectral density $\rho(\mu^2)$:

$$\rho(\mu^2) = -2\,\mathrm{Im}\,\frac{1}{\Sigma(\mu^2)} \quad \Leftrightarrow \quad \frac{1}{\Sigma(p^2)} = \int \frac{d\mu^2}{2\pi}\frac{\rho(\mu^2)}{p^2 - \mu^2 + i\epsilon}.$$

Ordinary particle: $\rho(\mu^2) = 2\pi\delta(\mu^2 - m^2)$

Gapped continuum spectral density



Gapped continuum spectral density

Gapped continuum: $\rho(\mu^2) = 0$ for $\mu < \mu_0$ ("gap scale")

Can arise from 4D eff. theory in 5D warped construction, but not our focus today

see: 2105.07035;
Cabrer, von Gersdorff, Quirós 0907.5361;
Megías, Quirós 1905.07364

I *do* care that ρ takes a universal form near μ_0:

$$\rho(\mu^2) = \frac{\rho_0}{\mu_0^2}\sqrt{\frac{\mu^2}{\mu_0^2} - 1}$$

Fermions and vectors

Everything carries over from scalars:

$$S_{\text{fermion}} = -i \int \frac{d^4 p}{(2\pi)^4} \overline{\psi}(p) \Sigma(p^2) \frac{\overline{\sigma}^\mu p_\mu}{p^2} \psi(p)$$

$$S_{\text{vector}} = \frac{1}{2} \int \frac{d^4 p}{(2\pi)^4} A_\mu(p) \Sigma(p^2) \left[\eta^{\mu\nu} - (1 - \frac{1}{\xi}) \right] A_\nu(p)$$

$$\rho(\mu^2) = -2 \,\mathrm{Im}\, \frac{1}{\Sigma(\mu^2)} \quad \Leftrightarrow \quad \frac{1}{\Sigma(p^2)} = \int \frac{d\mu^2}{2\pi} \frac{\rho(\mu^2)}{p^2 - \mu^2 + i\epsilon}$$

near gap scale: $\rho(\mu^2) \sim \frac{\rho_0}{\mu_0^2} \sqrt{\frac{\mu^2}{\mu_0^2} - 1}$

Interactions

We can couple continuum fields to other fields just like ordinary particles, e.g. $\overline{\psi}\not{Z}\psi$

All continuum effects are captured by the phase space integral:

$$\int \frac{d\mu^2}{2\pi}\rho(\mu^2) \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{1}{2\sqrt{\mu^2 + |\vec{p}|^2}}$$

Boltzmann eq., etc. all unchanged w.r.t ordinary particles

Fermion model

Continuum singlet ψ_L (gap scale μ_0), Dirac fermion $\chi(2)_{1/2}$

$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_\psi + \mathcal{L}_\chi + \mathcal{L}_{\rm int}\,,$

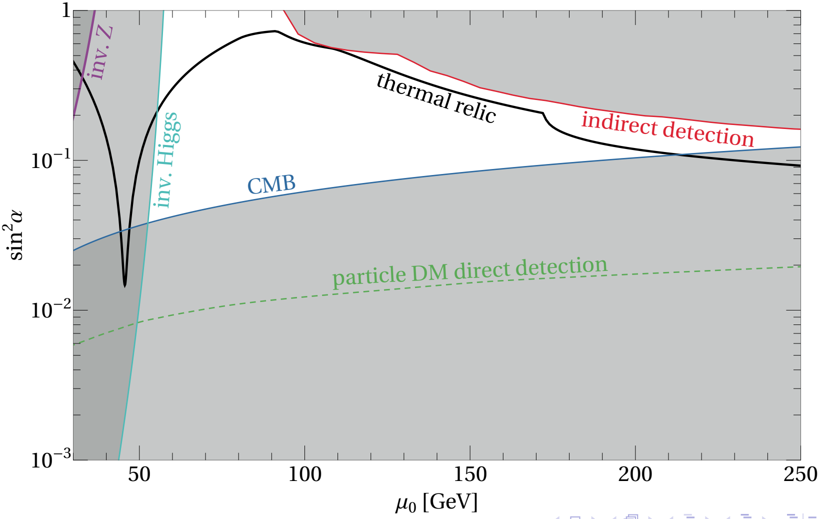
$$
\begin{aligned}
\mathcal{L}_\psi &= i\overline{\psi}_L \Sigma(p^2)\overline{\sigma}^\mu p_\mu \psi_L \\
\mathcal{L}_\chi &= i\overline{\chi}_L \overline{\sigma}^\mu D_\mu \chi_L + i\overline{\chi}_R \sigma^\mu D_\mu \chi_R - M(\overline{\chi}_L \chi_R + \overline{\chi}_R \chi_L) \\
\mathcal{L}_{\rm int} &= -\kappa \overline{\chi}_R \psi_L H
\end{aligned}
$$

Integrate out χ ($M \gg \mu_0$), leads to effective Z-portal DM:

$$
\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_\psi - \frac{g_Z \sin^2\alpha}{2}\overline{\psi_L} \not{Z} \psi_L
$$

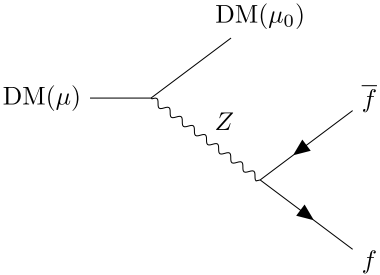
(also dim-5 Higgs coupling $\sim (\sin\alpha/v) H^\dagger H \overline{\psi_L}\psi_L$)

Relic abundance



CMB constraint

Continuum decays can reionize hydrogen:



Decay width $\sim \dfrac{g_Z^4 \sin^4 \alpha \mu_0^5}{m_Z^4} \times \left(\dfrac{\Delta\mu}{\mu_0}\right)^{13/2}$ (w/ $\Delta\mu = \mu - \mu_0$)

CMB constraint

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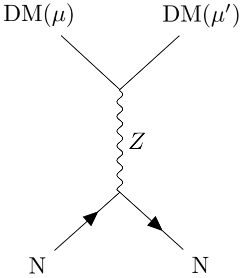
$$\text{Decay width} \sim \frac{g_Z^4 \sin^4 \alpha \mu_0^5}{m_Z^4} \times \left(\frac{\Delta\mu}{\mu_0}\right)^{13/2} \quad (\text{w/ } \Delta\mu = \mu - \mu_0)$$

Estimate $\Delta\mu$ by solving $\Gamma = H(t_{\mathrm{CMB}})$; heavier states would have already decayed

Require $\Delta\mu < 2m_e$ so $\psi \to \psi e^+ e^-$ kinematically forbidden at t_{CMB}

DD suppression

DM-nucleon scattering:



Cross section

$$\int \frac{d\mu'^2}{2\pi}\rho(\mu'^2)\,\frac{3g_Z^4 \sin^4 \alpha \mu_{\psi N}^2 f_N^2}{4\pi\ m_Z^4}$$

Continuum kinematics

Same as particle DM

DD suppression

Accessible mass range $\mu' \in (\mu_0, \mu_0 + \Delta\mu)$, where $\Delta\mu \approx \mu - \mu_0$

Matching $\Gamma = H_0$:

$$\mu - \mu_0 \approx 0.4 \text{ MeV} \frac{(\mu_0/100 \text{ GeV})^{3/13}}{(\sin^2\alpha/0.01)^{4/13}}$$

Spectral density integral (using universal form near μ_0):

$$\int_{\mu_0^2}^{(\mu_0+\Delta\mu)^2} \frac{d\mu^2}{\mu_0^2}\sqrt{\frac{\mu^2}{\mu_0^2} - 1} \approx \frac{2 \times 10^{-8}}{(\sin^2\alpha/0.01)^{6/13}(\mu_0/100 \text{ GeV})^{15/13}}$$

Enormous kinematic suppression of DM-nucleon σ!

Vector model

Abelian gauge field V_μ, continuum w/ gap scale μ_0

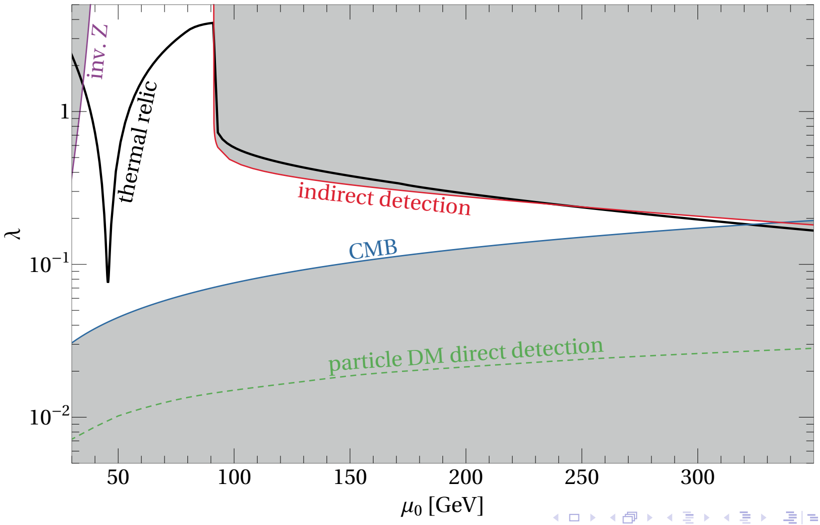
$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_V + \mathcal{L}_{\rm int}$,

$$\mathcal{L}_V = \frac{1}{2} V_\mu \Sigma(p^2) \left[\eta^{\mu\nu} - (1 - \frac{1}{\xi}) \right] V_\nu$$

$$\mathcal{L}_{\rm int} = \frac{g_Z \lambda}{4} \epsilon^{\mu\nu\rho\sigma} V_\mu Z_\nu V_{\rho\sigma}$$

"Generalized Chern-Simons" interaction would arise from integrating out heavy fermions

Relic abundance



Outlook

Z-portal continuum DM models are experimentally viable

- Fermion case: $\mu_0 \in (60, 200)$ GeV
- Vector case: $\mu_0 \in (35, 90)$ GeV

Detection prospects:

- $\mu_0 > m_Z$: indirect detection
- $\mu_0 < m_Z$: maybe collider signatures?

Many opportunities for further continuum model building!

Thank you!

more info:

arxiv.org/abs/2210.16326

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Derivation of fermion model EFT

Classical EOM for χ^0:

$$\chi_L^0 = -\frac{\kappa v M}{\sqrt{2}(\partial^2 + M^2)}\psi_L, \quad \chi_R^0 = -i\frac{\kappa v}{\sqrt{2}(\partial^2 + M^2)}\overline{\sigma}^\mu \partial_\mu \psi_L$$

Substitute back into action, leads to effective coupling

$$-\frac{g_Z}{2}\left[\frac{\kappa v M}{\sqrt{2}(M^2 - \mu^2)}\right]^2 \overline{\psi}_L \not{Z} \psi_L$$

Take limit $M \gg \mu_0$, write in terms of eff. mixing angle

$$\sin\alpha = \frac{\kappa v}{\sqrt{2}M}$$

Higgs coupling from t-channel exchange of χ_R^0

Embedding vector model in consistent EFT

Introduce four Weyl fermions with ($\mathrm{U}(1)_D$, $\mathrm{U}(1)_Y$) charges

$$\psi_1(1,1), \quad \psi_2(-1,1), \quad \psi_3(0,-1), \quad \psi_4(0,-1)$$

All gauge anomalies cancel except $\mathrm{U}(1)_D^2\ \mathrm{U}(1)_Y$

Restore with GCS term: $\dfrac{g_Z \lambda}{4} \epsilon^{\mu\nu\rho\sigma} V_\mu Z_\nu V_{\rho\sigma}$, with

$$\lambda = \frac{2 g_D^2}{3\pi^2}$$

Give ψ's masses with coupling to scalar with unit dark charge (could be abelian Higgs needed to lift DM would-be zero mode)

DD kinematic suppression details

Max accessible mass for outgoing DM in $\psi(\mu)N \to \psi(\mu')N$:

$$\Delta\mu = (\mu - \mu_0) + qv - \frac{q^2}{2\mu_{\psi N}}$$

(q = momentum transfer, $\mu_{\psi N} \sim 1$ GeV = reduced mass)

Last two terms bounded from above by $\mu_{\psi_N} v^2/2$, $v \sim 10^{-3}$ so this is $\mathcal{O}(\mathrm{keV})$

Dominated by $\mu - \mu_0$ which is $\mathcal{O}(\mathrm{MeV})$