

Ameen Ismail
Pheno 2023 symposium
8 May 2023



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(Z -portal continuum dark matter models)

arXiv:2210.16326

with C. Csáki and S. J. Lee
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Why continuum DM?

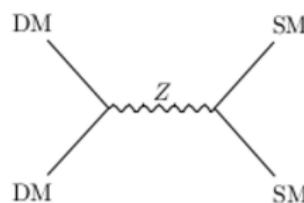
Simple WIMP-like portal
models viable for continuum
DM

[2105.07035](#), [2105.14023](#)

(Csáki, Hong, Kurup, Lee, Perelstein, Xue)

Kinematic suppression of DD
cross sections

Our work: **fermion, vector**
continuum models



The Continuum Dark Matter Zoo

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

Continuum crash course

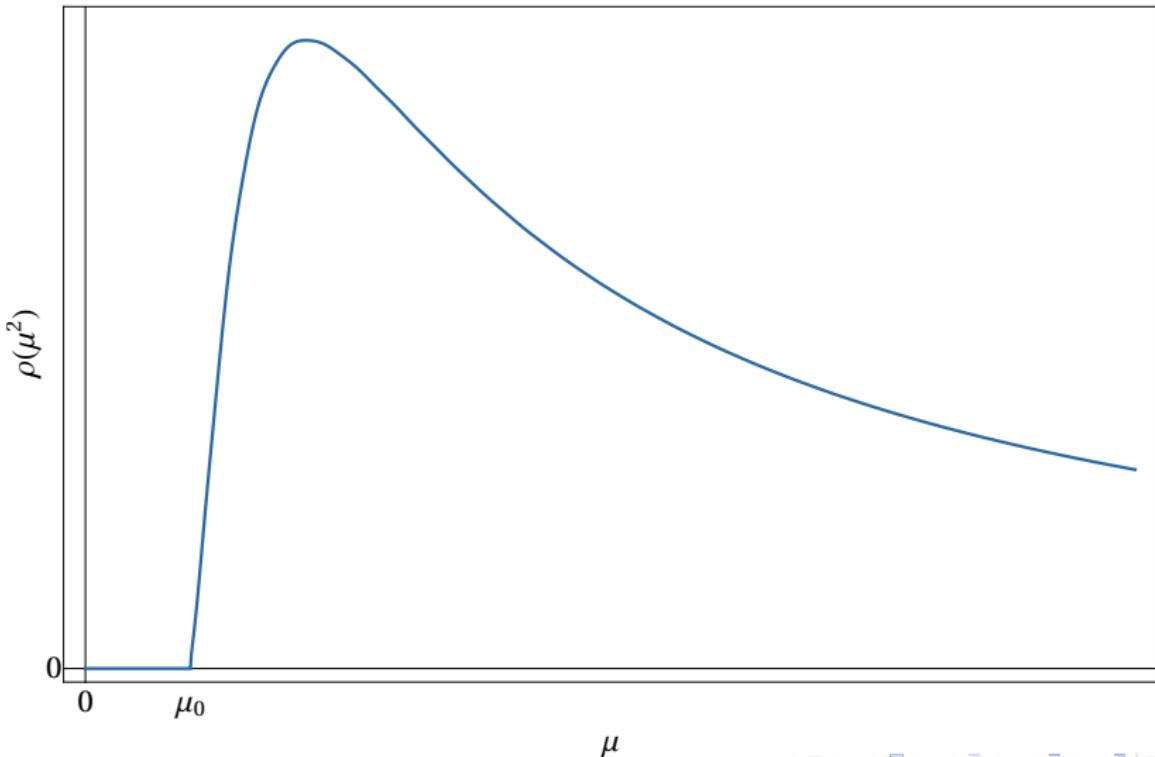
Scalar example: $S = \int \frac{d^4 p}{(2\pi)^4} \phi^\dagger(p) \Sigma(p^2) \phi(p)$

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

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

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 :

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

Interactions

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

Continuum effects are captured by the phase space integral:

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

(Integrate over mass, weighted by spectral density)

Effective Z -portal model

Singlet continuum fermion ψ_L with gap scale μ_0 ($\mathcal{O}(100)$ GeV)

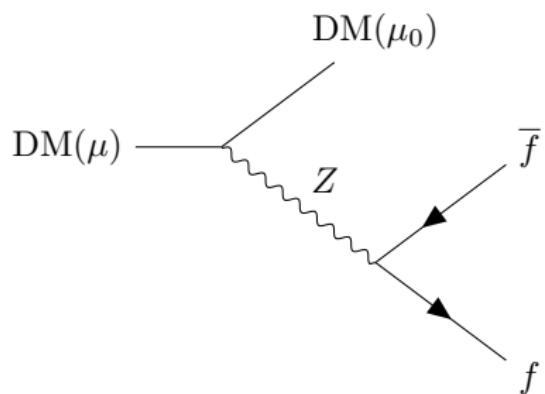
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_\psi - \frac{g_Z \sin^2 \alpha}{2} \overline{\psi_L} \not{Z} \psi_L$$

Two free parameters: μ_0 , mixing angle $\sin^2 \alpha$

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

Continuum decays

$\psi(\mu) \rightarrow \psi(\mu') f\bar{f}$: important continuum effect!



$$\Gamma \sim \frac{g_Z^4 \sin^4 \alpha \mu_0^5}{m_Z^4} \times \left(\frac{\Delta \mu}{\mu_0} \right)^{13/2}$$

$$(w/ \Delta \mu = \mu - \mu_0)$$

Affects cosmology (hydrogen reionization) and phenomenology
(DD suppression)

Continuum decays and the CMB

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

Decays could reionize hydrogen after recombination

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

DD suppression

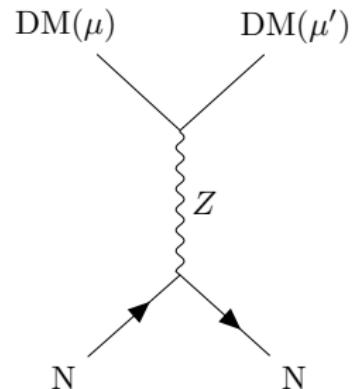
DM-nucleon scattering:

Cross section

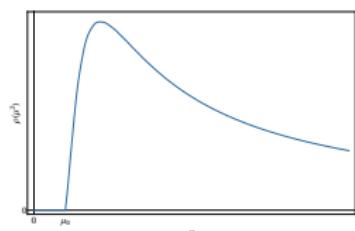
$$\int \frac{d\mu'^2}{2\pi} \rho(\mu'^2) \frac{3g_Z^4 \sin^4 \alpha \mu_{\psi N}^2 f_N^2}{4\pi m_Z^4}$$

Continuum kinematics

Same as particle DM



Small kinematically accessible range for μ'



DD suppression

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

Matching $\Gamma = H_0$:

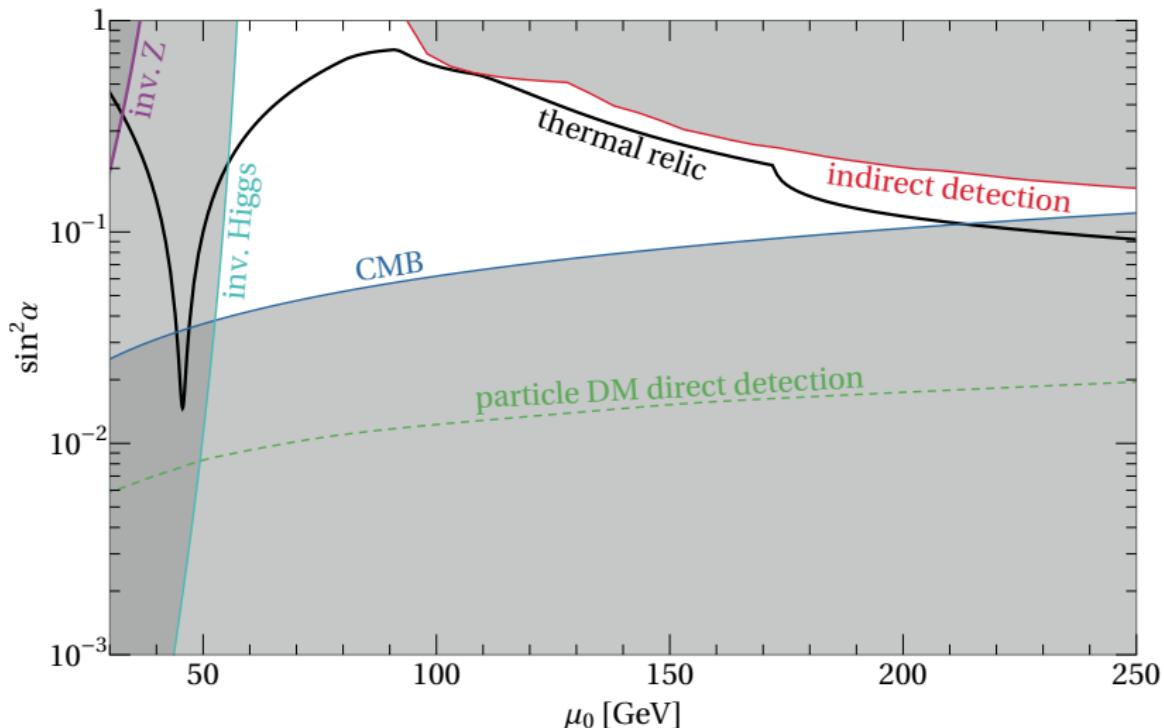
$$\mu - \mu_0 \approx 0.4 \text{ MeV} \frac{(\mu_0/100 \text{ GeV})^{3/13}}{(\sin^2 \alpha/0.01)^{4/13}}$$

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 !

Relic abundance



Outlook

We can easily construct viable WIMP-like continuum DM models

Uniquely continuum effects: DD suppression, cascade decays, etc.

Detection prospects:

- ▶ indirect detection (identical to ordinary particles)
- ▶ collider signatures (see Steven Ferrante's talk)

Many opportunities for further continuum model building!

Thank you!



more info:

arxiv.org/abs/2210.16326

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Fermion model UV completion

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

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

$$\mathcal{L}_\psi = i\bar{\psi}_L \Sigma(p^2) \bar{\sigma}^\mu p_\mu \psi_L$$

$$\mathcal{L}_\chi = i\bar{\chi}_L \bar{\sigma}^\mu D_\mu \chi_L + i\bar{\chi}_R \sigma^\mu D_\mu \chi_R - M(\bar{\chi}_L \chi_R + \bar{\chi}_R \chi_L)$$

$$\mathcal{L}_{\text{int}} = -\kappa \bar{\chi}_R \psi_L H$$

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

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

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

Derivation of fermion model EFT

Classical EOM for χ^0 :

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

Substitute back into action, leads to effective coupling

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

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

Vector model

Abelian gauge field V_μ , continuum w/ gap scale μ_0

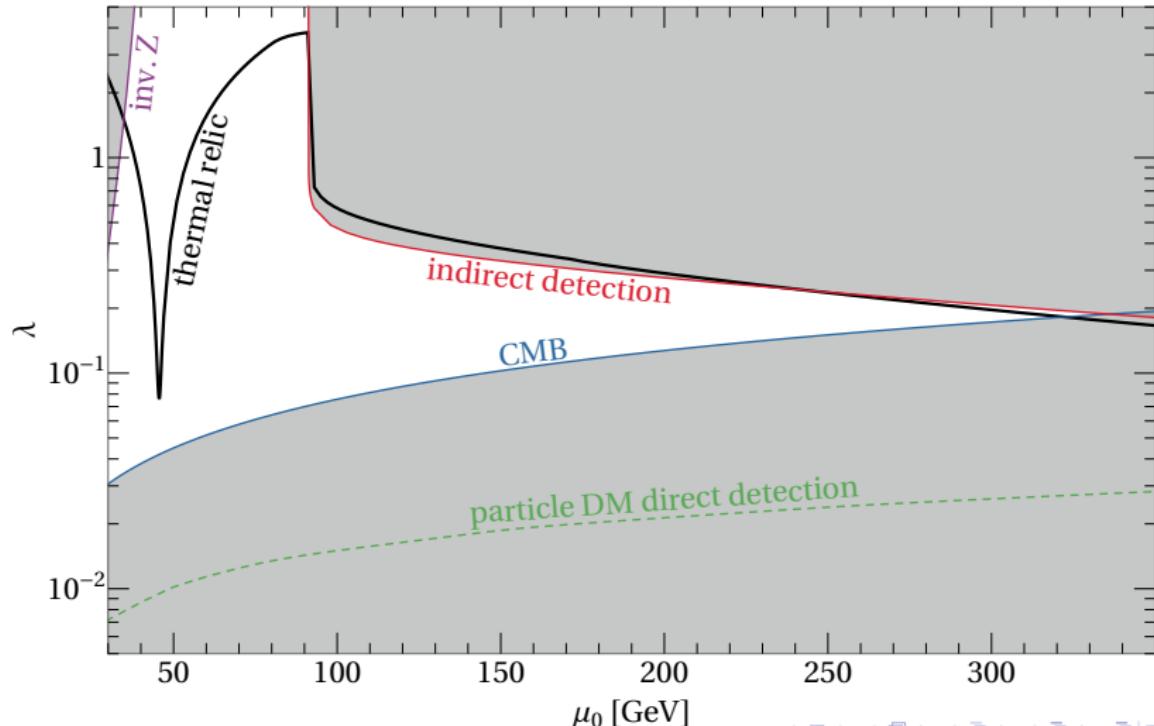
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_V + \mathcal{L}_{\text{int}},$$

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

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

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

Relic abundance



Embedding vector model in consistent EFT

Introduce four Weyl fermions with $(U(1)_D, U(1)_Y)$ 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 $U(1)_D^2 U(1)_Y$

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

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

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 $\psi(\mu)N \rightarrow \psi(\mu')N$:

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

(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 $\mathcal{O}(\text{keV})$

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