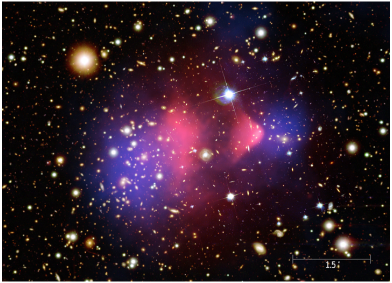
DM models with two mediators.

How to save the WIMP



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Michael Duerr

Dark Interactions 2016

Brookhaven, 6 October 2016

based on:
arXiv:1304.0576, arXiv:1309.3970, arXiv:1409.8165, arXiv:1508.01425, and arXiv:1606.07609

in collaboration with:
P. Fileviez Pérez, F. Kahlhoefer, K. Schmidt-Hoberg, Th. Schwetz, J. Smirnov, S. Vogl, M. B. Wise

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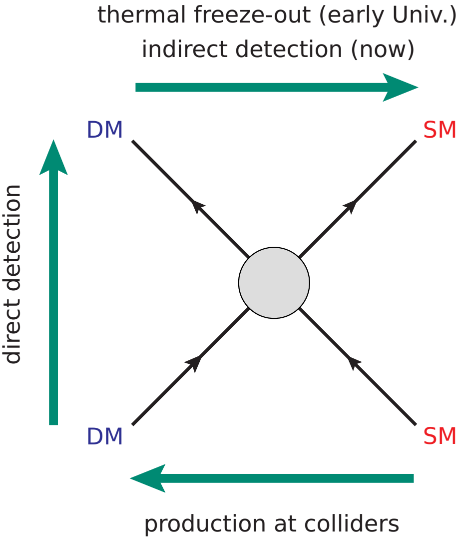
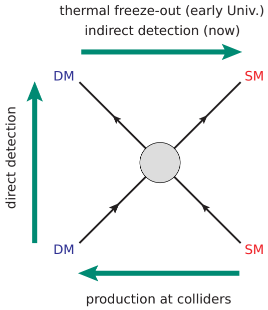
DM–SM interaction.



Connecting different DM experiments.



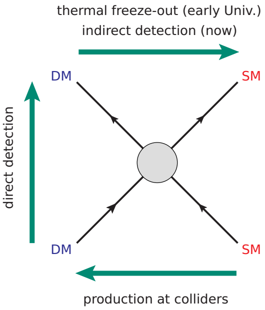
- Effective theories for DM: keep DM, integrate out the rest
  - good description of DM direct detection
  - potentially problematic for DM searches at the LHC
- Simplified dark matter models: keep DM and one mediator (the lightest)
  - example: fermionic DM χ interacts with SM fermions f via a Z'

$$\mathcal{L} \supset -Z'_\mu \bar{\chi}\left(g^V_{\mathrm{DM}}\gamma^\mu + g^A_{\mathrm{DM}}\gamma^\mu\gamma_5\right)\chi - \sum_f Z'_\mu \bar{f}\left(g^V_f\gamma^\mu + g^A_f\gamma^\mu\gamma_5\right)f$$

  - potential problems with perturbative unitarity and gauge invariance

[Kahlhoefer *et al.*, arXiv:1510.02110]

Connecting different DM experiments.



Questions

- Origin of the model?
- Relations betweeen couplings?
- SM gauge invariance?

- Effective theories for DM: keep DM, integrate out the rest
  - good description of DM direct detection
  - potentially problematic for DM searches at the LHC
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$$\mathcal{L} \supset -Z'_\mu \bar{\chi} \left(g^V_{\mathrm{DM}} \gamma^\mu + g^A_{\mathrm{DM}} \gamma^\mu \gamma_5 \right) \chi - \sum_f Z'_\mu \bar{f} \left(g^V_f \gamma^\mu + g^A_f \gamma^\mu \gamma_5 \right) f$$

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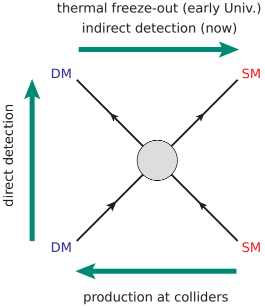

Perturbative unitarity

- Consider $\chi\chi \rightarrow Z'_L Z'_L$ for axial couplings
- Matrix element grows with energy
- New physics, e.g., new Higgs, to restore perturbative unitarity

- Effective theories for DM: keep DM, integrate out the rest
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  - potential problems with perturbative unitarity and gauge invariance

[Kahlhoefer *et al.*, arXiv:1510.02110]

Part I:

A consistent simplified DM model

[MD, Kahlhoefer, Schmidt-Hoberg, Schwetz, Vogl, arXiv:1606.07609]

Dark matter model with two mediators.

- Majorana DM particle χ and two mediators:
  - massive vector boson Z' and real scalar s
- Natural framework: SM gauge group extended by spontaneously broken $U(1)' \rightarrow$ generation of mass for χ and Z'
- Interactions of DM and the SM quarks with the mediators:

$$\mathcal{L}_\chi \supset -\frac{g_\chi}{2}\bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu - \frac{y_\chi}{2\sqrt{2}}\bar{\chi}\chi s$$

$$\mathcal{L}_q \supset -\sum_q \left(g_q \bar{q}\gamma^\mu q Z'_\mu + \sin\theta \frac{m_q}{v}\bar{q}qs \right)$$

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$$\mathcal{L}_q \supset -\sum_q \left(g_q \bar{q}\gamma^\mu q Z'_\mu + \sin\theta \frac{m_q}{v}\bar{q}qs \right)$$

- couplings are connected:

$$\frac{y_\chi}{m_\chi} = 2\sqrt{2}\,\frac{g_\chi}{m_{Z'}}$$

- 6 independent parameters:

particle masses		coupling constants	
DM mass	m_χ	dark-sector coupling	g_χ or y_χ
Z' mass	$m_{Z'}$	quark–Z' coupling	g_q
dark Higgs mass	m_s	Higgs mixing angle	θ

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$$\mathcal{L}_\chi \supset -\frac{g_\chi}{2}\bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu - \frac{y_\chi}{2\sqrt{}}$$

$$\mathcal{L}_q \supset -\sum_q \left(g_q \bar{q}\gamma^\mu q Z'_\mu + \mathrm{si}\right.$$

flavor-universal vector couplings to quarks = baryon number

→ see model building later

- couplings are connected:

$$\frac{y_\chi}{m_\chi} = 2\sqrt{2}\,\frac{g_\chi}{m_{Z'}}$$

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The connection to simplified models.

> A combination of different simplified models:

	$g_q \gg \sin\theta$	$g_q \sim \sin\theta$	$\sin\theta \gg g_q$
$m_s \gg m_{Z'}$	Spin-1 mediator simplified model		Spin-0 mediator with spin-1 terminator
$m_{Z'} \sim m_s$		Two-mediator model	
$m_{Z'} \gg m_s$	Spin-1 mediator with spin-0 terminator		Spin-0 mediator simplified model

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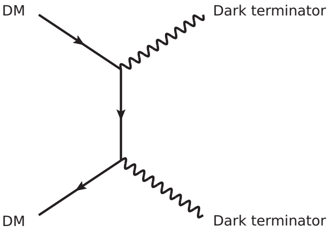

Dark terminator

new final state for DM annihilation

The connection to simplified models.

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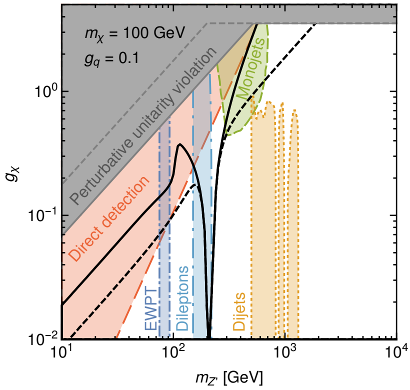
	$g_q \gg \sin\theta$	$g_q \sim \sin\theta$	$\sin\theta \gg g_q$
$m_s \gg m_{Z'}$	Spin-1 mediator simplified model		Spin-0 mediator with spin-1 terminator
$m_{Z'} \sim m_s$		Two-mediator model	
$m_{Z'} \gg m_s$	Spin-1 mediator with spin-0 terminator		Spin-0 mediator simplified model

> Additional effects not present in usual simplified models:

- The two mediators can interact with each other
- Mixing between the dark Higgs and the SM Higgs
- DM stability is a consequence of the gauge symmetry
- Kinetic mixing at loop level from SM quarks

Spin-1 mediation ($\theta \approx 0$).



> Relic density curve
  > solid: $m_s = 3 m_\chi$
  > dashed: $m_s = 0.1 m_\chi$

Partial wave perturbative unitarity:

> conditions on couplings and masses
  > from $\chi\chi \to \chi\chi$:

$$g_\chi < \sqrt{4\pi}\,, \qquad y_\chi < \sqrt{8\pi}$$

  > equations can be rewritten in terms of the couplings, e.g.,

$$g_\chi m_\chi / m_{Z'} < \sqrt{\pi}$$

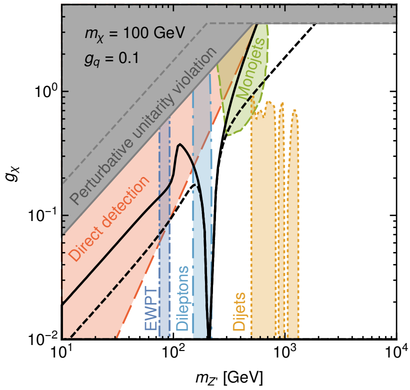
  > from $ss \to ss$ and $hh \to hh$:

$$3(\lambda_h + \lambda_s) \pm \sqrt{9(\lambda_h - \lambda_s)^2 + \lambda_{hs}^2} < 16\pi$$

  > for $\lambda_{hs} = 0$ (no Higgs mixing):

$$m_s < \sqrt{4\pi/3}\, m_{Z'}/g_\chi$$

Spin-1 mediation ($\theta \approx 0$).



- Relic density curve
  - solid: $m_s = 3m_\chi$
  - dashed: $m_s = 0.1m_\chi$

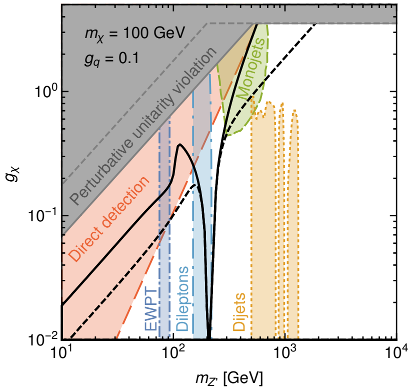
Direct detection:

- DM–nucleus scattering is suppressed by the DM velocity $\vec{v}$ and the momentum transfer $\vec{q}$:

$$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q$$
$$\rightarrow 2\vec{v}^\perp\cdot\vec{S}_\chi + 2i\vec{S}_\chi\cdot\left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$

- coherent enhancement leads nevertheless to relevant constraints
- recoil spectrum substantially different from standard spin-(in)dependent interactions
- we translate the LUX 2015 results into bound on this interaction

Spin-1 mediation ($\theta \approx 0$).



> Relic density curve
  > solid: $m_s = 3m_\chi$
  > dashed: $m_s = 0.1m_\chi$

EWPT and Dileptons

> SM quarks are charged under both $U(1)_Y$ and $U(1)'$ and will induce kinetic mixing at loop level:

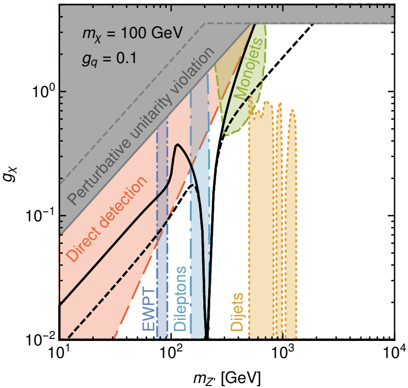
$$\mathcal{L} = -1/2 \sin\epsilon \, F'^{\mu\nu} B_{\mu\nu}$$

$$\epsilon(\mu) = \frac{e\, g_q}{2\pi^2 \cos\theta_W} \log\frac{\Lambda}{\mu} \simeq 0.02\, g_q \log\frac{\Lambda}{\mu}$$

> kinetic mixing leads to couplings of the Z' to leptons, constrained by dilepton searches

> kinetic mixing also modifies the S and T parameters, which are constrained by EWPT

Spin-1 mediation ($\theta \approx 0$).



> Relic density curve
  > solid: $m_s = 3m_\chi$
  > dashed: $m_s = 0.1m_\chi$

Monojets

> 8 TeV CMS results

Dijets

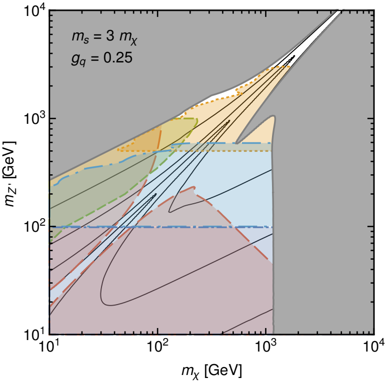
> model-independent bounds on the Z' coupling as a function of its mass and width

> combination of ATLAS and CMS results at 8 and 13 TeV, for $\Gamma_{Z'}/m_{Z'} \leq 0.3$

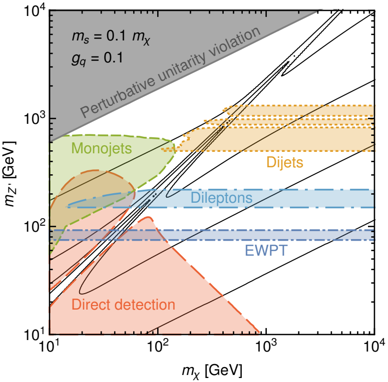
[Fairbairn *et al.*, `arXiv:1605.07940`]

Spin-1 mediation: results.

> Dark Higgs decoupled



> Dark Higgs terminator

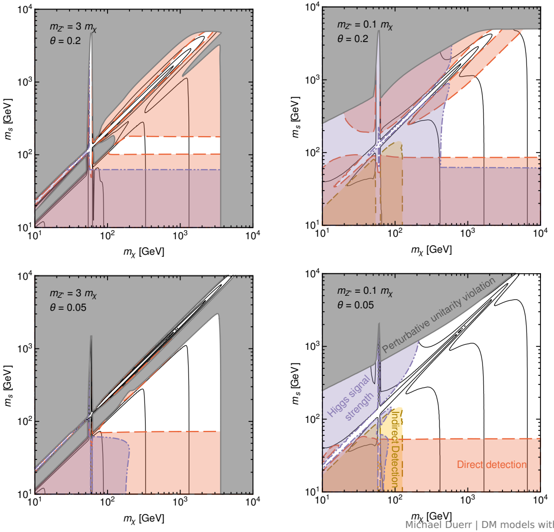


> Dark sector coupling fixed to reproduce observed relic density

Spin-0 mediation ($g_q \ll 1$).

> Z' decoupled

> Z' terminator



Higgs signal strength

> Reduction of SM Higgs signal strength:

> Mixing reduces SM Higgs production cross section
> for $m_\chi < m_h/2$: invisible decays
> for $m_s < m_h/2$ or $m_{Z'} < m_h/2$: decays into dark Higgs or Z'

> $\mu = \dfrac{\cos^2\theta\,\Gamma_{\mathrm{SM}}}{\Gamma_{\mathrm{SM}} + \Gamma_{ss} + \Gamma_{Z'Z'} + \Gamma_{\mathrm{inv}}}$

> Current bound:

$$\mu > 0.89$$

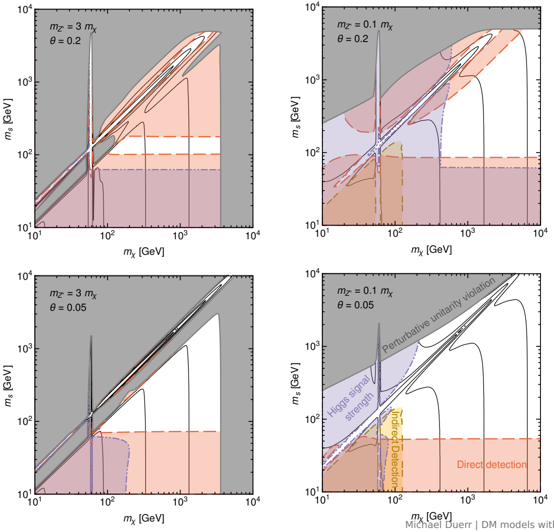
> for $\Gamma_{ss} = \Gamma_{Z'Z'} = \Gamma_{\mathrm{inv}} = 0$:

$$\theta < 0.34$$

Spin-0 mediation ($g_q \ll 1$).

> Z' decoupled

> Z' terminator



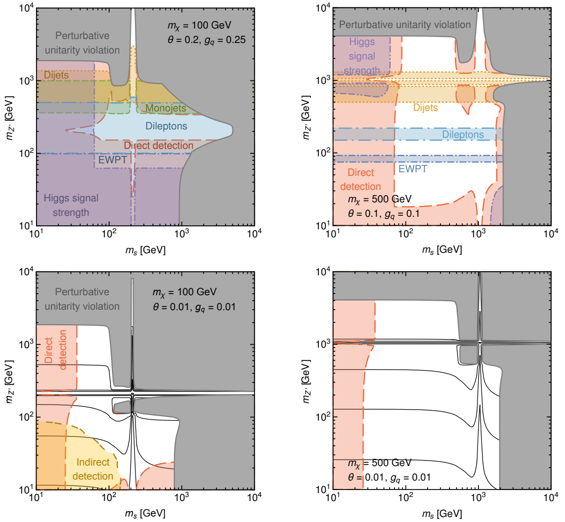
Direct detection

- the scalar mediators induce unsuppressed spin-indep. DM–nucleus interactions

Indirect detection

- $\chi\chi \to sZ'$ is dominantly s-wave, and dominates thermal freeze-out when kinematically allowed
- Then, observable indirect detection signals may be obtained from cascade annihilations
- Relevant constraints can be set using FermiLAT observations of MW dwarf spheroidals for $m_{Z'}, m_s < m_\chi \lesssim 100\,\mathrm{GeV}$

Two mediators: results.



> **sizeable g_q and $\sin\theta$:**

- for $m_\chi = 100\,\mathrm{GeV}$, only small regions close to the resonances remain viable
- for $m_\chi = 500\,\mathrm{GeV}$, larger regions are allowed because s or Z' can be terminators without being strongly constrained

> **secluded from the SM:**

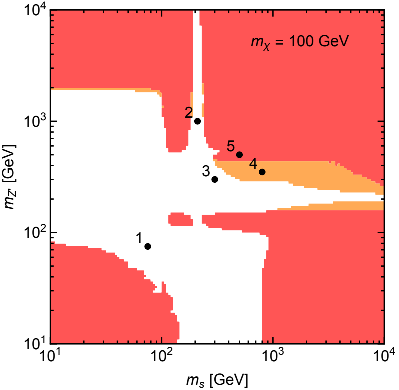
- region with $m_{Z'}, m_s > m_\chi$ is tightly constrained because annihilations into SM final states cannot reproduce the relic abundance with perturbative couplings
- for $m_{Z'}, m_s < m_\chi$, annihilation into dark terminators typically dominates
- experimental constraints can be suppressed since g_q and θ can be small → difficult to probe
- for small masses, set-up can still be probed by indirect detection

Global scan of couplings: set-up.

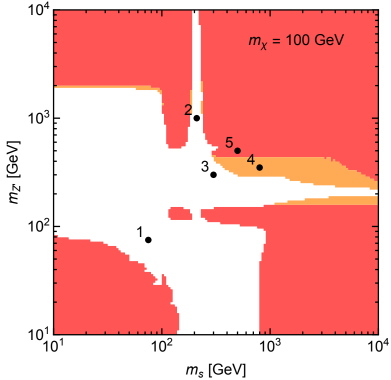
- Scan over g_q and θ for fixed masses, dark sector coupling determined by the relic abundance

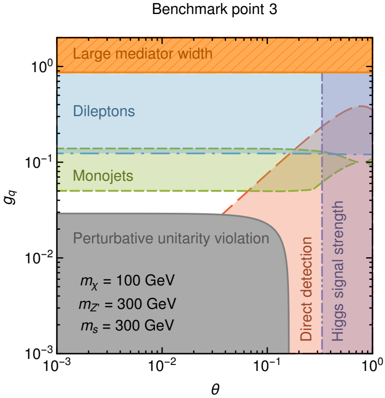
- Three categories of mass combinations:

  - Red: all combinations of g_q and θ are excluded by at least one constraint
  - White: at least one combination of g_q and θ is consistent with all constraints
  - Orange: for at least one combination of g_q and θ current constraints do not apply (broad mediator width, $\Gamma_{Z'}/m_{Z'} > 0.3$)



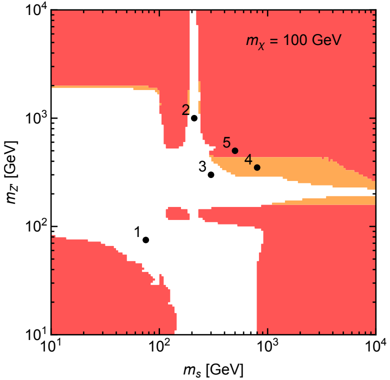
Global scan of couplings: benchmark 3.

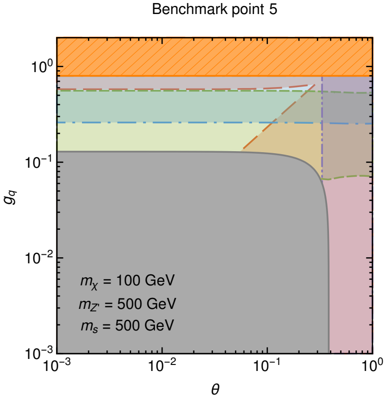




> Parameter point allowed for $g_q \approx 0.04$ and small θ

Global scan of couplings: benchmark 5.

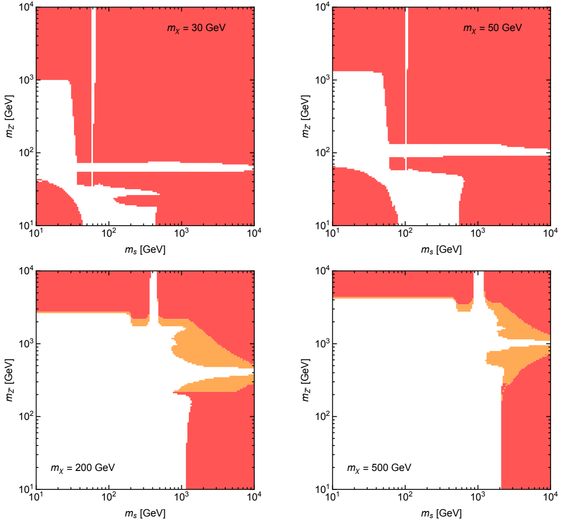




> A combination of all constraints rules out this parameter point

Global scan of couplings: results.

- Scan for different values of m_χ:



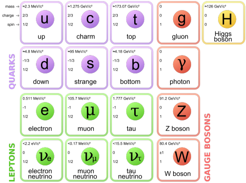
- Small DM masses are tightly constrained: only allowed on a resonance or with at least one dark terminator.

- For large DM masses, the inconclusive regions become more important, but heavy mediators still tightly constrained. No constraints from indirect detection.

Part II:

Model building aspects

The Standard Model of particle physics.



[Figure: Wikipedia]

> $U(1)'$ gauge extension of the SM:

$$G' = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)'$$

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Q_L	**3**	**2**	1/6	1/3	0
u_R	**3**	**1**	2/3	1/3	0
d_R	**3**	**1**	−1/3	1/3	0
ℓ_L	**1**	**2**	−1/2	0	1
e_R	**1**	**1**	−1	0	1
H	**1**	**2**	1/2	0	0

Baryonic and leptonic anomalies.

> New gauge group:

$$SU(3) \otimes SU(2) \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$$

> Purely baryonic anomalies:

$$\mathcal{A}_1\left(SU(3)^2 \otimes U(1)_B\right),\ \mathcal{A}_2\left(SU(2)^2 \otimes U(1)_B\right),\ \mathcal{A}_3\left(U(1)_Y^2 \otimes U(1)_B\right),$$
$$\mathcal{A}_4\left(U(1)_Y \otimes U(1)_B^2\right),\ \mathcal{A}_5\left(U(1)_B\right),\ \mathcal{A}_6\left(U(1)_B^3\right).$$

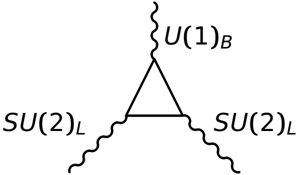
> Purely leptonic anomalies:

$$\mathcal{A}_7\left(SU(3)^2 \otimes U(1)_L\right),\ \mathcal{A}_8\left(SU(2)^2 \otimes U(1)_L\right),\ \mathcal{A}_9\left(U(1)_Y^2 \otimes U(1)_L\right),$$
$$\mathcal{A}_{10}\left(U(1)_Y \otimes U(1)_L^2\right),\ \mathcal{A}_{11}\left(U(1)_L\right),\ \mathcal{A}_{12}\left(U(1)_L^3\right).$$

> Mixed anomalies:

$$\mathcal{A}_{13}\left(U(1)_B^2 \otimes U(1)_L\right),\ \mathcal{A}_{14}\left(U(1)_L^2 \otimes U(1)_B\right),$$
$$\mathcal{A}_{15}\left(U(1)_Y \otimes U(1)_L \otimes U(1)_B\right).$$

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Q_L	**3**	**2**	$\frac{1}{6}$	$\frac{1}{3}$	0
u_R	**3**	**1**	$\frac{2}{3}$	$\frac{1}{3}$	0
d_R	**3**	**1**	$-\frac{1}{3}$	$\frac{1}{3}$	0
ℓ_L	**1**	**2**	$-\frac{1}{2}$	0	1
ν_R	**1**	**1**	0	0	1
e_R	**1**	**1**	-1	0	1
H	**1**	**2**	$\frac{1}{2}$	0	0



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$$\mathcal{A}_4\left(U(1)_Y \otimes U(1)_B^2\right),\ \mathcal{A}_5\left(U(1)_B\right),\ \mathcal{A}_6\left(U(1)_B^3\right).$$

> Purely leptonic anomalies:

$$\mathcal{A}_7\left(SU(3)^2 \otimes U(1)_L\right),\ \mathcal{A}_8\left(SU(2)^2 \otimes U(1)_L\right),\ \mathcal{A}_9\left(U(1)_Y^2 \otimes U(1)_L\right),$$
$$\mathcal{A}_{10}\left(U(1)_Y \otimes U(1)_L^2\right),\ \mathcal{A}_{11}\left(U(1)_L\right),\ \mathcal{A}_{12}\left(U(1)_L^3\right).$$

> Mixed anomalies:

$$\mathcal{A}_{13}\left(U(1)_B^2 \otimes U(1)_L\right),\ \mathcal{A}_{14}\left(U(1)_L^2 \otimes U(1)_B\right),$$
$$\mathcal{A}_{15}\left(U(1)_Y \otimes U(1)_L \otimes U(1)_B\right).$$

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Q_L	**3**	**2**	$\frac{1}{6}$	$\frac{1}{3}$	0
u_R	**3**	**1**	$\frac{2}{3}$	$\frac{1}{3}$	0
d_R	**3**	**1**	$-\frac{1}{3}$	$\frac{1}{3}$	0
ℓ_L	**1**	**2**	$-\frac{1}{2}$	0	1
ν_R	**1**	**1**	0	0	1
e_R	**1**	**1**	-1	0	1
H	**1**	**2**	$\frac{1}{2}$	0	0

SM + right-handed ν's

$$\mathcal{A}_2 = -\mathcal{A}_3 = \frac{3}{2},$$
$$\mathcal{A}_8 = -\mathcal{A}_9 = \frac{3}{2}$$

Baryonic and leptonic anomalies.

> New gauge group:

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Q_L	**3**	**2**	$\frac{1}{6}$	$\frac{1}{3}$	0
					0
					0
					1
					1
					1
					0

$SU(3) \otimes SU(2) \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$

Some history

- Early attempts to gauge B and L
  - A. Pais, PRD **8**, 1844 (1973)
  - S. Rajpoot, Int. J. Theor. Phys. **27**, 689 (1988)
  - R. Foot, G. C. Joshi, H. Lew, PRD **40**, 2487 (1989)
  - C. D. Carone, H. Murayama, PRD **52**, 484 (1995)
  - H. Georgi, S. L. Glashow, PLB **387**, 341 (1996)
- First realistic models **(ruled out!)**
  - P. Fileviez Pérez, M. B. Wise, PRD **82**, 011901 (2010), JHEP **08** (2011) 068

$$\mathcal{A}_{13}\left(U(1)_B^2 \otimes U(1)_L\right), \ \mathcal{A}_{14}\left(U(1)_L^2 \otimes U(1)_B\right),$$
$$\mathcal{A}_{15}\left(U(1)_Y \otimes U(1)_L \otimes U(1)_B\right).$$

$$\mathcal{A}_8 = -\mathcal{A}_9 = \frac{3}{2}$$

Simplest scenario.

Consider only uncolored fields:

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Ψ_L	$\mathbf{1}$	$\mathbf{2}$	$\pm\frac{1}{2}$	B_1	L_1
Ψ_R	$\mathbf{1}$	$\mathbf{2}$	$\pm\frac{1}{2}$	B_2	L_2
η_R	$\mathbf{1}$	$\mathbf{1}$	± 1	B_1	L_1
η_L	$\mathbf{1}$	$\mathbf{1}$	± 1	B_2	L_2
χ_R	$\mathbf{1}$	$\mathbf{1}$	0	B_1	L_1
χ_L	$\mathbf{1}$	$\mathbf{1}$	0	B_2	L_2

Anomaly cancellation demands: $B_1 - B_2 = -3$, $L_1 - L_2 = -3$

[MD, Fileviez Pérez, Wise, arXiv:1304.0576]

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χ_R	$\mathbf{1}$	$\mathbf{1}$	0	B_1
χ_L	$\mathbf{1}$	$\mathbf{1}$	0	B_2

Anomaly cancellation demands: $B_1 - B_2 = -3$,

[MD, Fileviez Pérez, Wise, arXiv:1304.0576]

[MD, Fileviez Pérez, arXiv:1309.3970]

Spontaneous symmetry breaking.

- Relevant interactions of the new fields (for $B_1 \neq -B_2$):

$$-\mathcal{L} \supset h_1 \overline{\Psi}_L H \eta_R + h_2 \overline{\Psi}_L \tilde{H} \chi_R + h_3 \overline{\Psi}_R H \eta_L + h_4 \overline{\Psi}_R \tilde{H} \chi_L$$
$$+ \lambda_1 \overline{\Psi}_L \Psi_R S_B + \lambda_2 \overline{\eta}_R \eta_L S_B + \lambda_3 \overline{\chi}_R \chi_L S_B + \text{h.c.}$$

$$S_B \sim (\mathbf{1}, \mathbf{1}, 0, B_1 - B_2)$$

- $\langle S_B \rangle \neq 0$ generates vector-like masses:

$$-\mathcal{L} \supset M_\Psi \overline{\Psi}_L \Psi_R + M_\eta \overline{\eta}_R \eta_L + M_\chi \overline{\chi}_R \chi_L + \text{h.c.}$$

$$S_B \sim (\mathbf{1}, \mathbf{1}, 0, -3) \Rightarrow \Delta B = 3 \Rightarrow \text{no proton decay}$$

- Remnant $\mathcal{Z}_2$ stabilizes lightest new fermion.

Baryonic dark matter.

Condition from anomaly cancellation: $B_1 - B_2 = -3$
$\Rightarrow$ two options:

$B_1 \neq -B_2$

- Dirac DM, SM singlet-like:

$$\chi = \chi_R + \chi_L$$

- Coupling to the Z_B:

$$-\mathcal{L} \supset g_B \overline{\chi} \gamma_\mu Z_B^\mu (B_2 P_L + B_1 P_R) \chi$$

[MD, Fileviez Pérez, arXiv:1309.3970, arXiv:1409.8165]

$B_1 = -B_2 = -3/2$:

- Majorana DM with axial coupling to the Z_B:

$$-\mathcal{L} \supset \frac{3}{2} g_B \bar{\chi} \gamma_\mu \gamma^5 \chi Z_B^\mu$$

- Completion of the consistent simplified model considered in Part I

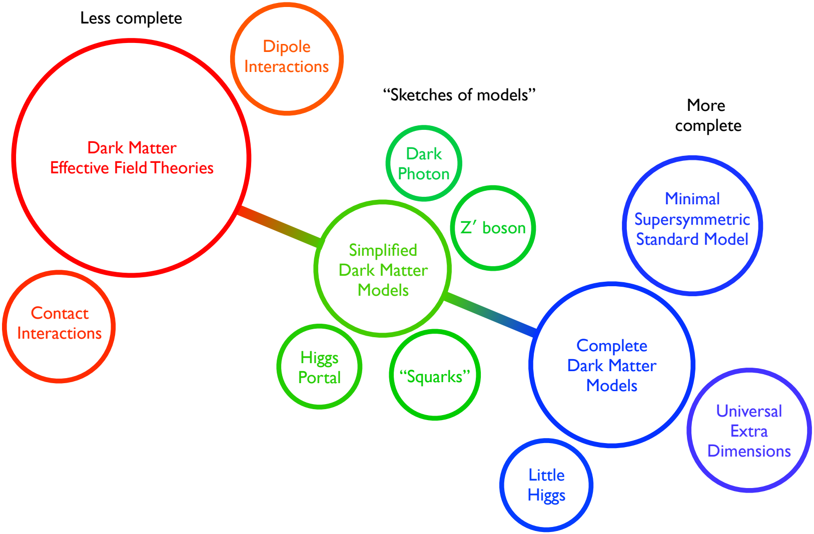
[MD, Fileviez Pérez, Smirnov, arXiv:1508.01425]

Summary.

- Two-mediator DM as a framework to realize simplified DM models in a theoretically consistent way
- WIMP hypothesis under severe pressure, heavy mediators strongly constrained. Two viable options:
  - DM and mediator masses are tuned close to an *s*-channel resonance
  - One or both mediators are lighter than the DM and open additional parameter space as a dark terminator
- Dark terminators are hard to test:
  - Constraints from indirect detection of DM cascade annihilations if $\chi\chi \to Z's$ or $\chi\chi \to Z'h$ kinematically allowed
  - Outlook: search for dark Higgs terminator in $pp \to Z'^{(*)} \to \chi\chi s$
- Extensions of the SM with gauged B provide a simple and complete scenario for the DM of the Universe:
  - No proton decay even though B can be broken at the low scale
  - DM stability as an automatic consequence of the gauge symmetry
  - Complete and fully consistent model: gauge invariance, perturbative unitarity, anomaly cancellation

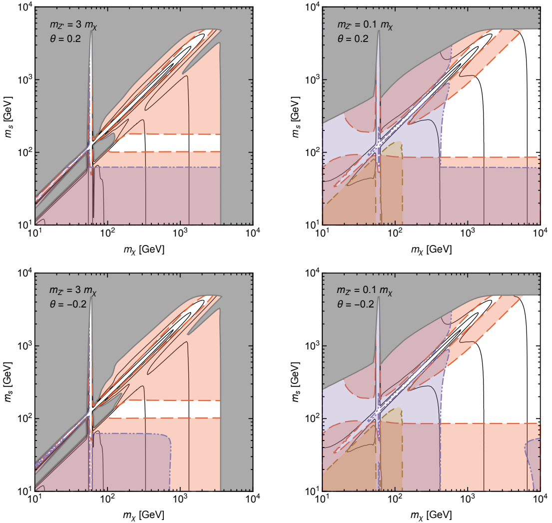
Backup slides.

Dark matter theory space.



[Worm *et al.*, arXiv:1506.03116]

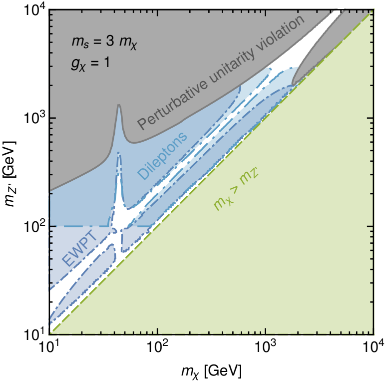
Spin-0 mediation: negative mixing angle.



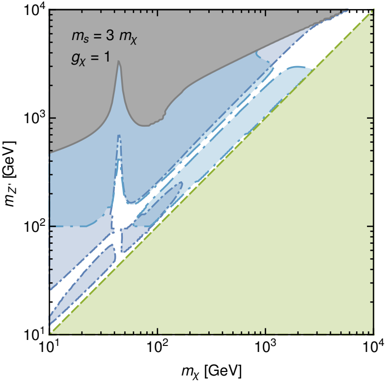
- Sign of θ relevant for trilinear vertices between the SM Higgs and the dark Higgs.
- Considering $\theta < 0$ modifies the prediction for $h \to ss$, hence the bound from the Higgs signal strength is significantly relaxed for $m_s < m_h/2$
- However, this parameter region is independently excluded by direct detection experiments (not sensitive to the sign of θ).
- Relic density calculation not significantly affected by the sign of θ
- Effect is smaller for smaller values of $|\theta|$

Tree-level kinetic and mass mixing.

> Kinetic mixing ϵ



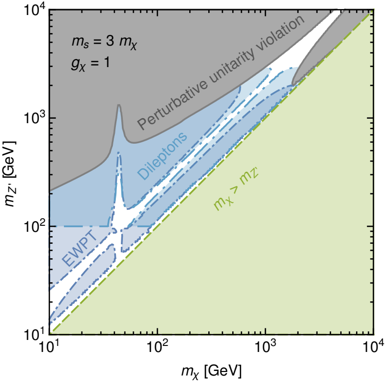
> Axial couplings



- Mass mixing can be realized if the SM Higgs is charged under the $U(1)'$. This leads to axial couplings of the Z' to SM fermions.
- ϵ (left) and g_q^A (right) are varied for the correct relic abundance.

Tree-level kinetic and mass mixing.

> Kinetic mixing ϵ



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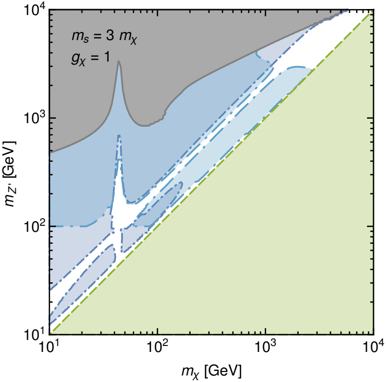


> Only possible for resonant enhancement from the Z or the Z'.

Baryon and lepton numbers.

B and L are accidental global symmetries in the SM

> Violation of B:
  > Baryon asymmetry of the Universe:

$$(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$$

  > Proton decay ($\Delta B = 1$, $\Delta L = \text{odd}$):

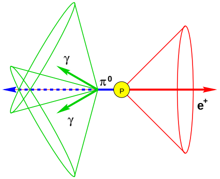
$$\tau_p \geq 10^{32-34}\,\text{years}$$

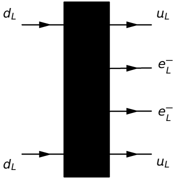
> Violation of L:
  > ν oscillation experiments:

$$\Delta L_e \neq 0,\ \Delta L_\mu \neq 0,\ \Delta L_\tau \neq 0$$

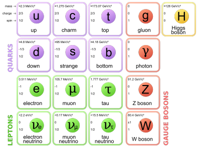
  > $\Delta L = 2$: Majorana neutrino masses

[Figure: Viren, arXiv:hep-ex/9903029]





The Great Desert.



[Figure: Wikipedia]

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$$\frac{c_6}{\Lambda_B^2} QQQL$$

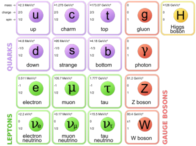
[Weinberg, PRL **43** (1979) 1566]

Low scale
Electroweak scale
($\Lambda_{EW} \sim 10^2$ GeV)

High scale
e.g. GUT scale
($\Lambda_{GUT} \sim 10^{15}$ GeV)

Energy

The Great Desert.



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$$\frac{c_5}{\Lambda_L} LLHH$$

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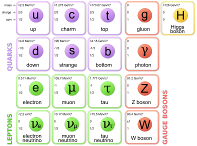
[Weinberg, PRL **43** (1979) 1566]



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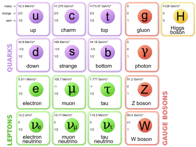

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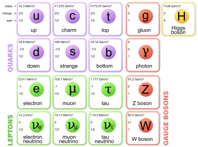

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Energy

First realistic models are ruled out.

- Sequential/Mirror family: [Fileviez Pérez, Wise, arXiv:1002.1754]

  Ruled out: new quarks change gluon fusion Higgs production.

- Vector-like quarks: [Fileviez Pérez, Wise, arXiv:1106.0343]

  Ruled out: new charged leptons reduce BR of $H \to \gamma\gamma$ by a factor of 3.

- One family of leptoquarks: [Dong, Long, arXiv:1010.3818]

  $$F_L \sim (3, 2, 0, -1, -1),\ j_R \sim (3, 1, \frac{1}{2}, -1, -1),\ k_R \sim (3, 1, -\frac{1}{2}, -1, -1).$$

  Ruled out: stable charged fields.

General Solution: gauging B and L.

All anomalies can be cancelled with the following setup:

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
Ψ_L	$\boldsymbol{N}$	$\mathbf{2}$	Y_1	B_1	L_1
Ψ_R	$\boldsymbol{N}$	$\mathbf{2}$	Y_1	B_2	L_2
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η_L	$\boldsymbol{N}$	$\mathbf{1}$	Y_2	B_2	L_2
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χ_L	$\boldsymbol{N}$	$\mathbf{1}$	Y_3	B_2	L_2

Anomaly cancellation demands: $B_1 - B_2 = -3/N$, $L_1 - L_2 = -3/N$
$Y_2 = Y_1 \mp 1/2$ and $Y_3 = Y_1 \pm 1/2$

[MD, Fileviez Pérez, Wise, arXiv:1304.0576]

Possible scenarios.

Guidelines:

- new fields should have direct coupling to SM fields, or
- the lightest new particle is neutral and stable.

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  If the lightest field is neutral → DM.

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  If the lightest field is neutral $\rightarrow$ DM.

- $N = 3$: Use $Y_1 = \pm 1/6$, $Y_2 = \pm 2/3$, $Y_3 = \pm 1/3$.

  Scalar $S_{BL} \sim (1, 1, 0, -1, -1)$ leads to dimension-7 proton decay operator.

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  Scalar $S_{BL} \sim (1, 1, 0, -1, -1)$ leads to dimension-7 proton decay operator.

- $N = 8$: Extra colored fields, e.g., color octet scalars, to couple the new fermions to the SM fermions.

Other solution for anomaly cancellation.

$$\Psi_L \sim \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2}\right), \qquad \Psi_R \sim \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}, -\frac{3}{2}, -\frac{3}{2}\right)$$

$$\Sigma_L \sim \left(\mathbf{1}, \mathbf{3}, 0, -\frac{3}{2}, -\frac{3}{2}\right), \qquad \chi_L \sim \left(\mathbf{1}, \mathbf{1}, 0, -\frac{3}{2}, -\frac{3}{2}\right)$$

[Fileviez Pérez, Ohmer, Patel, arXiv:1403.8029]

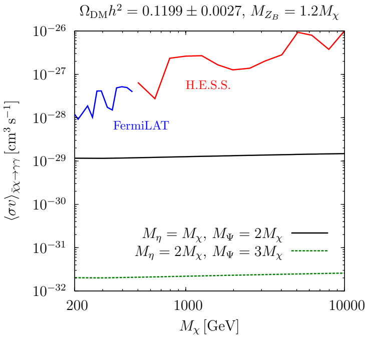
[Ohmer, Patel, arXiv:1506.00954]

> Less representations
> Same degrees of freedom after symmetry breaking
> Majorana dark matter

What about the additional fermions?.

> Majorana DM ($B_1 = -B_2$):

loop-mediated DM annihilation to photons



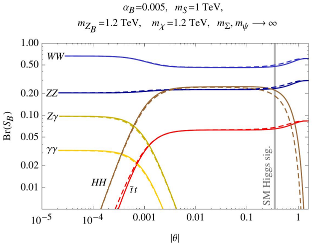
[MD, Fileviez Pérez, Smirnov, arXiv:1508.01425]

> Decays of S_B:

> For $\theta \to 0$, the branching fractions of the fermion-loop-mediated decays of S_B may provide clues about the fermion content of the model at the LHC

> Model with $SU(2)$ triplet:

$$\Gamma_{WW} : \Gamma_{ZZ} : \Gamma_{Z\gamma} : \Gamma_{\gamma\gamma} = 20 : 7 : 3 : 1$$



[Ohmer, Patel, arXiv:1506.00954]

> Vector-like model:

$$\Gamma_{WW} : \Gamma_{ZZ} : \Gamma_{Z\gamma} : \Gamma_{\gamma\gamma} = 2 : 1 : 10^{-3} : 1$$