Calculating the relic density for a light vector mediator with MadDM and MicrOMEGAs

Thanks to Geneviève Bélanger, Bryan Zaldivar, Andreas Goudelis, Antonio Boveia and Caterina Doglioni

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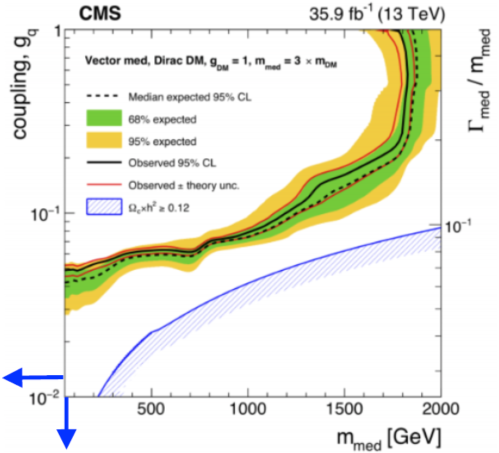
General information

Aim:

- investigation of relic density for a vector mediator Z' for light particle masses and small SM couplings

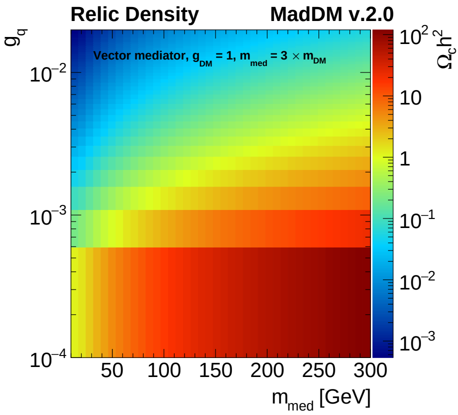
General settings:

- vector mediator
- Dirac DM
- $g_{DM} = 1$
- $m_{med} = 3 \cdot m_{DM}$
- couplings to SM from 0.0001 to 0.1
- mediator mass from 10 GeV to 300 GeV in steps of 1 GeV
- freeze-out scenario

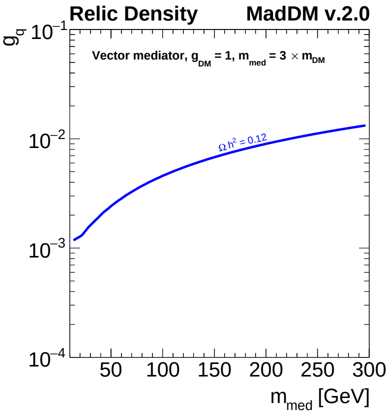


Relic density and contour line

Standard Model couplings only to quarks (g_q):



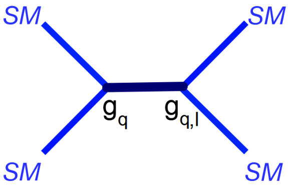
Relic density

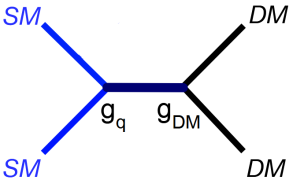


Contour for $\Omega h^2 = 0.12$

$\Rightarrow$ agrees with CMS plot

Couplings to DM, and quarks and leptons





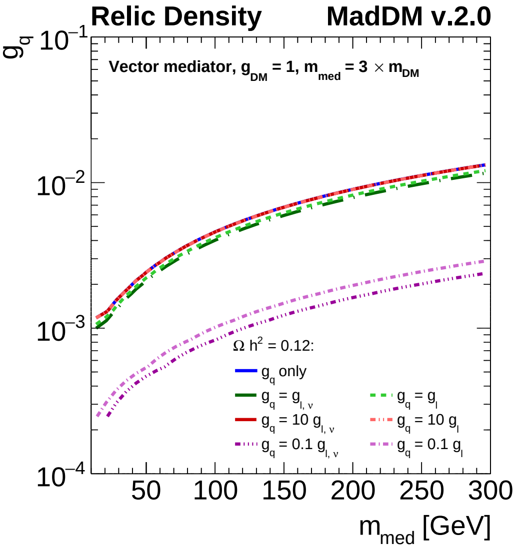
3 scenarios for lepton couplings (g_{l}):

- equal couplings: $g_{\mathrm{q}} = g_{\mathrm{l}}$
- lepton couplings smaller than quark couplings: $g_{\mathrm{q}} = 10 g_{\mathrm{l}}$
- quark couplings smaller than lepton couplings: $g_{\mathrm{q}} = 0.1 g_{\mathrm{l}}$

inspired from:

- *Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels*, Albert et al. arXiv:1703.05703 (V1, V2 benchmarks)
- email conversation with M. Williams (LHCb)

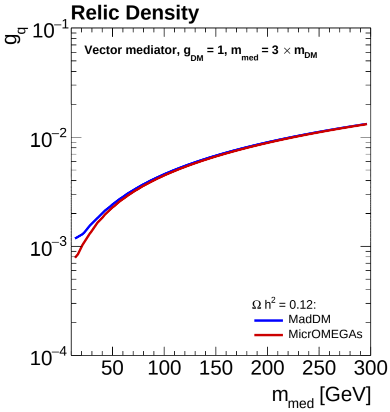
Relic density with couplings to DM and quarks and leptons, with and without neutrinos



- significant change between small and large lepton couplings (relative to quark couplings)
- impact of neutrinos visible but small

Comparison of MadDM and MicrOMEGAs

- same input as with MadDM
- generation of one set of data takes ≈ 15 minutes (several hours in MadDM)



Comparison for case with only quark couplings:

- similar results for MadDM and MicrOMEGAs
- some divergence at low mediator masses (< 20 GeV)

m_{med}	MadDM	MicrOMEGAs
300 GeV	5.657281e-02	5.58489682e-02
200 GeV	2.643482e-02	2.56617172e-02
100 GeV	7.322865e-03	6.94493222e-03
50 GeV	2.160695e-03	1.93027573e-03
10 GeV	4.517275e-04	1.97988878e-04

Relic density for $g_q = 1.99 \cdot 10^{-2}$

Investigating smaller couplings

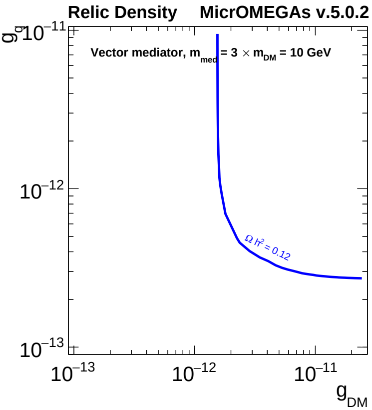
- MicrOMEGAs offers freeze-in option
- freeze-in for this mass range requires very small couplings, otherwise relic density too large due to not enough DM annihilation because of small annihilation cross section

Different scan approach:

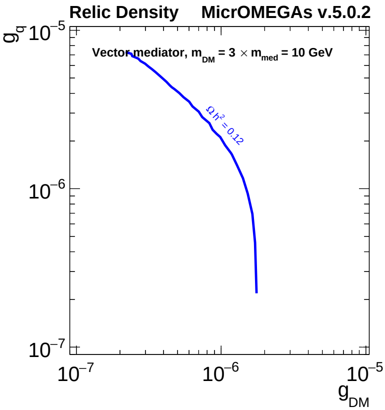
- fix mediator mass and DM mass to scan over SM and DM couplings to find the combination giving the relic density $\Omega h^2 = 0.12$:

  1. on-shell:
     - $m_{\text{med}} = 10$ GeV, $m_{\text{DM}} = 3.3$ GeV
  2. off-shell:
     - $m_{\text{med}} = 3.3$ GeV, $m_{\text{DM}} = 10$ GeV

Freeze-in relic density



Relic density for on-shell mediator



Relic density for off-shell mediator

- very small couplings required to obtain $\Omega h^2 = 0.12$

Summary and conclusion

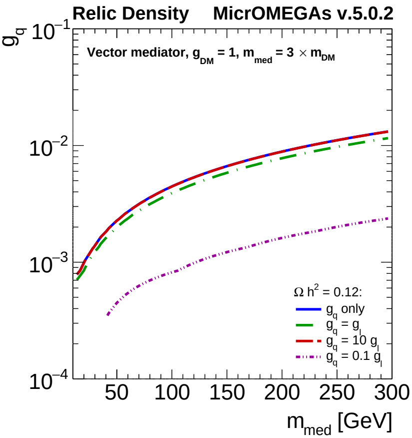
1. calculated relic density for light (< 50 GeV) mediator and small (< 0.01) couplings
   - reproduced CMS curve with MadDM
   - estimated impact of lepton couplings
   - tested MicrOMEGAs vs MadDM obtaining the same results

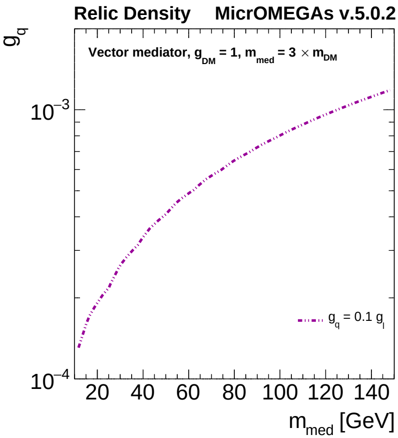
2. calculated freeze-in relic density for same model ($m_{\text{med}} = 10$ GeV)
   - DM and SM couplings have to be very small ($\lesssim 10^{-11}$) to give correct relic density

3. added case for off-shell mediator and calculated relic density
   - DM and SM have to be small ($\approx 10^{-6}$) to give correct relic density

Backup slides

MicrOMEGAs: Relic density and contour plots (freeze-out)





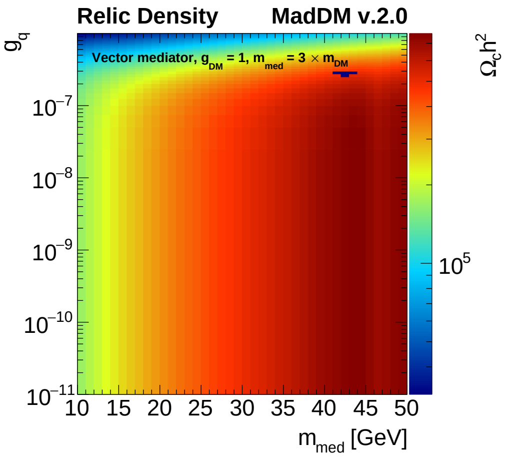
Left: Summary of all contour lines. Right: Focused in on the $g_q = 0.1 g_l$ contour line from left plot (due to ROOT plotting issue).

Investigating smaller couplings

- freeze-out with MadDM and MicrOMEGAs, freeze-in with MicrOMEGAs
- freeze-in possible for $g_{\text{DM}} \cdot g_{\text{SM}} \approx 10^{-11}$
- 3 scenarios:
  1. $g_{\text{DM}} = 1$, varying g_{SM}
  2. $g_{\text{DM}} = g_{\text{SM}}$
  3. $g_{\text{DM}} = 10 g_{\text{SM}}$
- g_{SM} contains both quark and lepton couplings (equal)

Smaller couplings with MadDM I

For scenario (1):



- extends previous plots to much smaller couplings
- breaks for a few values (blue rectangular area)
- relic density very large
- below $g_q = 10^{-7}$: relic density values only change a bit for each mass
- above $g_q = 10^{-8}$: relic density ~ 10

Relic density summary table

	MadDM	MicrOMEGAs	
		freeze-out	freeze-in
$g_{DM} = 1,\ g_{SM} = 10^{-4} - 10^{-7}$	$10^0 - 10^5$	$10^0 - 10^6$	breaks
$g_{DM} = 1,\ g_{SM} = 10^{-8} - 10^{-11}$	$10^5 - 10^6$	breaks	$6 \cdot 10^{21}$
$g_{DM} = g_{SM} = 10^{-4} - 10^{-7}$	breaks	$10^3 - 10^6$	$10^8 - 10^{14}$
$g_{DM} = g_{SM} = 10^{-8} - 10^{-11}$	breaks	breaks	—
$g_{DM} = 10 g_{SM},\ g_{SM} = 10^{-4} - 10^{-7}$	breaks	$10^2 - 10^6$	$10^{10} - 10^{16}$
$g_{DM} = 10 g_{SM},\ g_{SM} = 10^{-8} - 10^{-11}$	breaks	breaks	—

Order of magnitude of the relic density (Ωh^2) for the mediator mass range $10 - 50$ GeV.

$\Rightarrow$ DM overproduced everywhere

DM annihilation cross sections

Using equation (3.3) in arXiv:1703.05703 to calculate the DM annihilation cross section:

coupling constants	σv [GeV^{-2}]
$g_{\text{DM}} = 1, g_{\text{SM}} = 10^{-5}$	$5.58569416405 \cdot 10^{-13}$
$g_{\text{DM}} = g_{\text{SM}} = 10^{-5}$	$5.59528938474 \cdot 10^{-23}$
$g_{\text{DM}} = 10 g_{\text{SM}} = 10 \cdot 10^{-5}$	$5.59528938474 \cdot 10^{-21}$

DM annihilation cross sections (s-channel) for $m_{med} = 10$ GeV.

$\Rightarrow$ small DM annihilation cross sections as explanation for large relic density

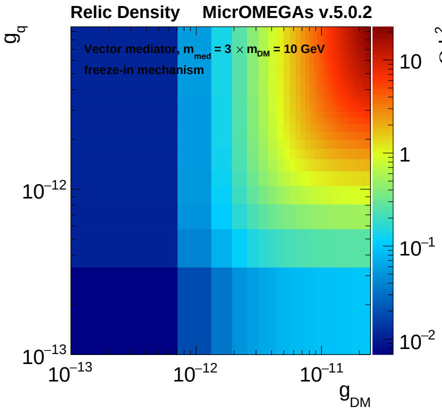
Freeze-in: Scanning over g_{SM} and g_{DM}

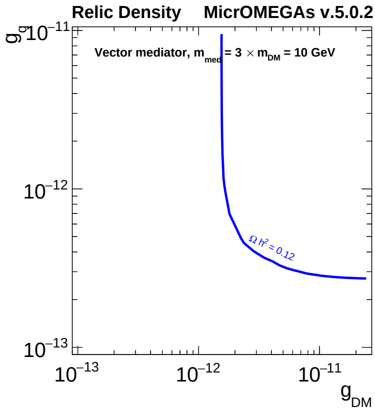
- scan over different values for DM and SM to find the combination giving the relic density $\Omega h^2 = 0.12$

4 scenarios:

- on-shell:
  - $m_{\mathrm{med}} = 10$ GeV, $m_{\mathrm{DM}} = 3.3$ GeV
  - $m_{\mathrm{med}} = 1$ GeV, $m_{\mathrm{DM}} = 0.33$ GeV
- off-shell:
  - $m_{\mathrm{med}} = 3.3$ GeV, $m_{\mathrm{DM}} = 10$ GeV
  - $m_{\mathrm{med}} = 0.33$ GeV, $m_{\mathrm{DM}} = 1$ GeV

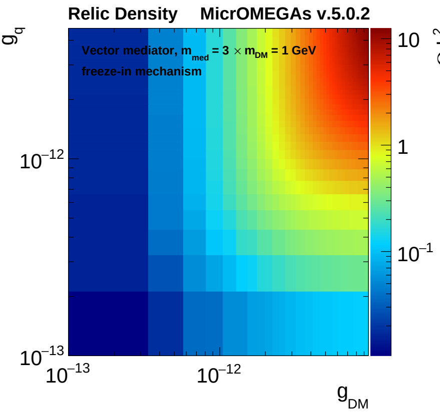
On-shell: $m_{\text{med}} = 10$ GeV, $m_{\text{DM}} = 3.3$ GeV

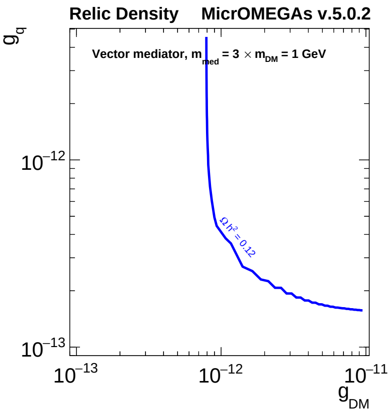




- very small couplings required to obtain $\Omega h^2 = 0.12$

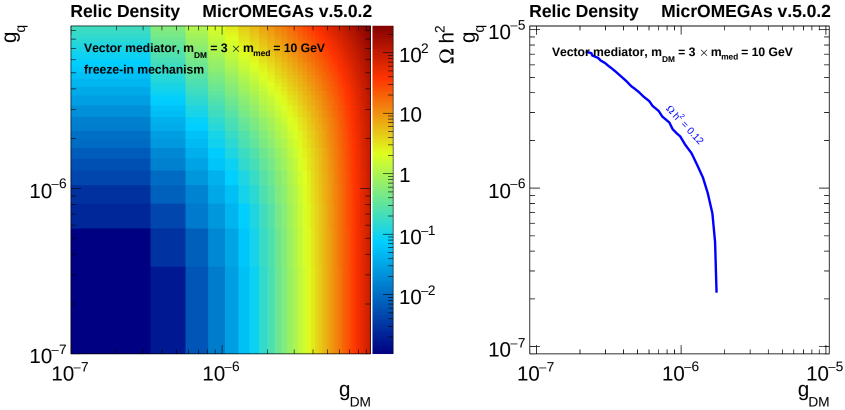
On-shell: $m_{\text{med}} = 1$ GeV, $m_{\text{DM}} = 0.33$ GeV





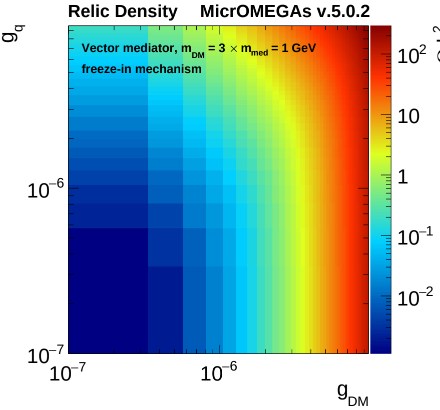
- similar to the 10 GeV case
- g_{SM} a bit smaller and g_{DM} a bit larger for $\Omega h^2 = 0.12$

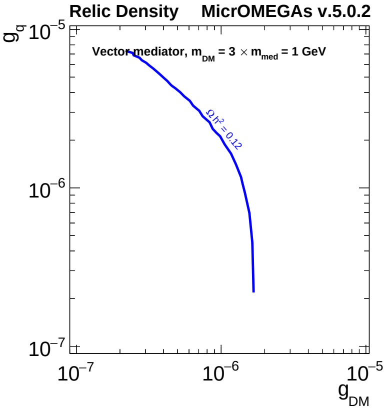
Off-shell: $m_{\text{med}} = 3.3$ GeV, $m_{\text{DM}} = 10$ GeV



- couplings larger compared to on-shell case

Off-shell: $m_{\text{med}} = 0.33$ GeV, $m_{\text{DM}} = 1$ GeV





- almost identical with 10 GeV case