Relic density in simplified models of dark matter - the axial vector case

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Overview

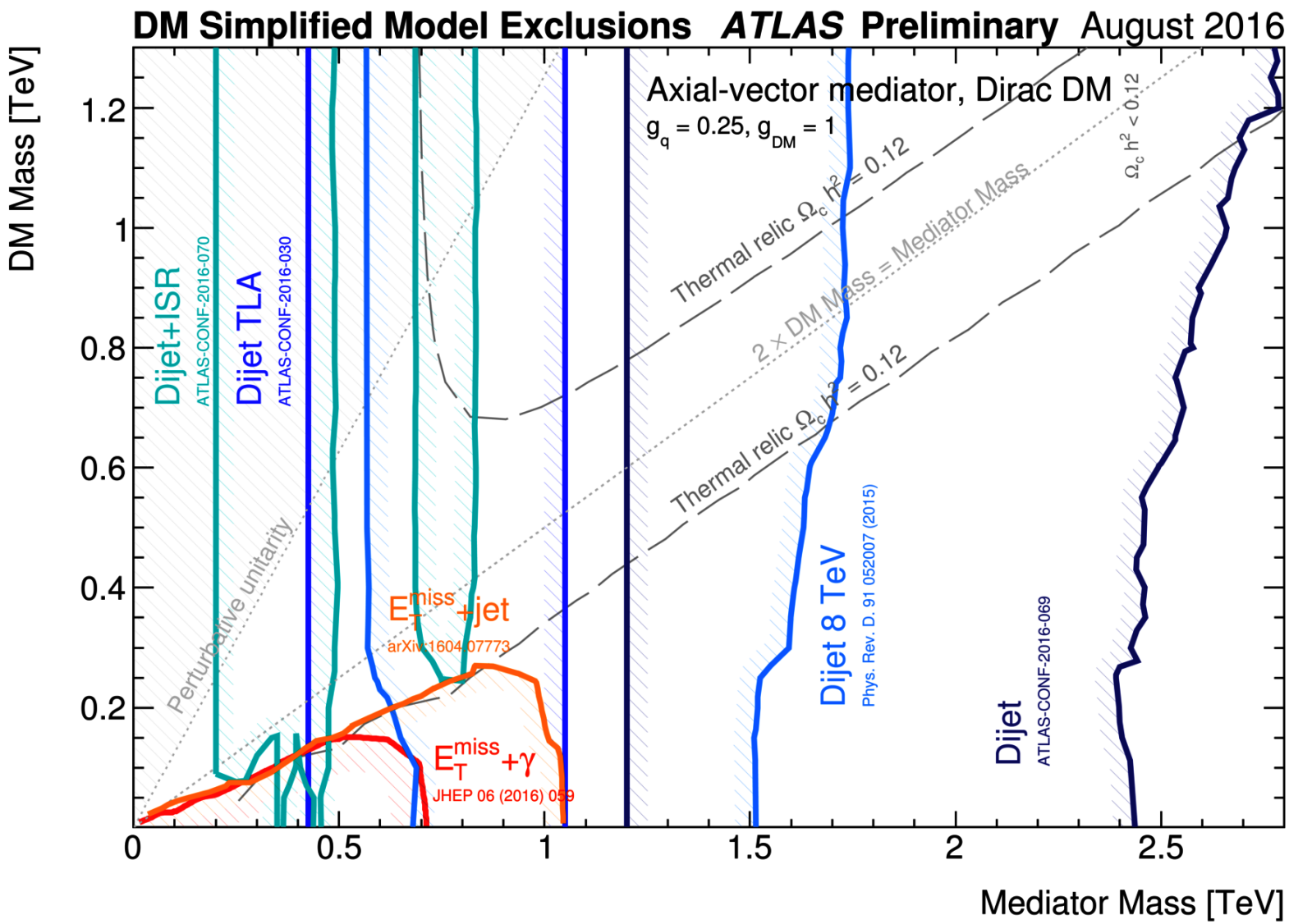
- The model:

$$\mathcal{L}_{\text{kin}} = i\bar{\chi}\gamma^{\mu}\partial_{\mu}\chi - m_{DM}\bar{\chi}\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{Z'}Z'_{\mu}Z'^{\mu} \,,$$

$$\mathcal{L}_{\text{int}} = -g_{DM}Z'_{\mu}\bar{\chi}\gamma^{\mu}\gamma^5\chi - g_q Z'_{\mu}\sum_q \bar{q}\gamma^{\mu}\gamma^5 q \,.$$

- Annihilation processes
  - $\chi\bar{\chi} \to q\bar{q}$
  - $\chi\bar{\chi} \to Z'Z'$
- Methods to calculate the relic density
  - Velocity expansion of the DM annihilation cross-section.
  - `micrOMEGAs`
  - `MadDM v 2.0.6` versus `MadDM v 2.0.5`

Working Group plot



Approximate relic density calculation

- Expand the DM annihilation cross section in powers of relative DM velocity $\sigma v = a + bv^2 + \ldots$
- Need to do this in the lab frame (C.O.M. frame gives wrong answer, see P. Gondolo and G. Gelmini, Nucl. Phys. B **360** (1991) 145).
- With a little approximation, you can solve the Boltzmann equation analytically to get

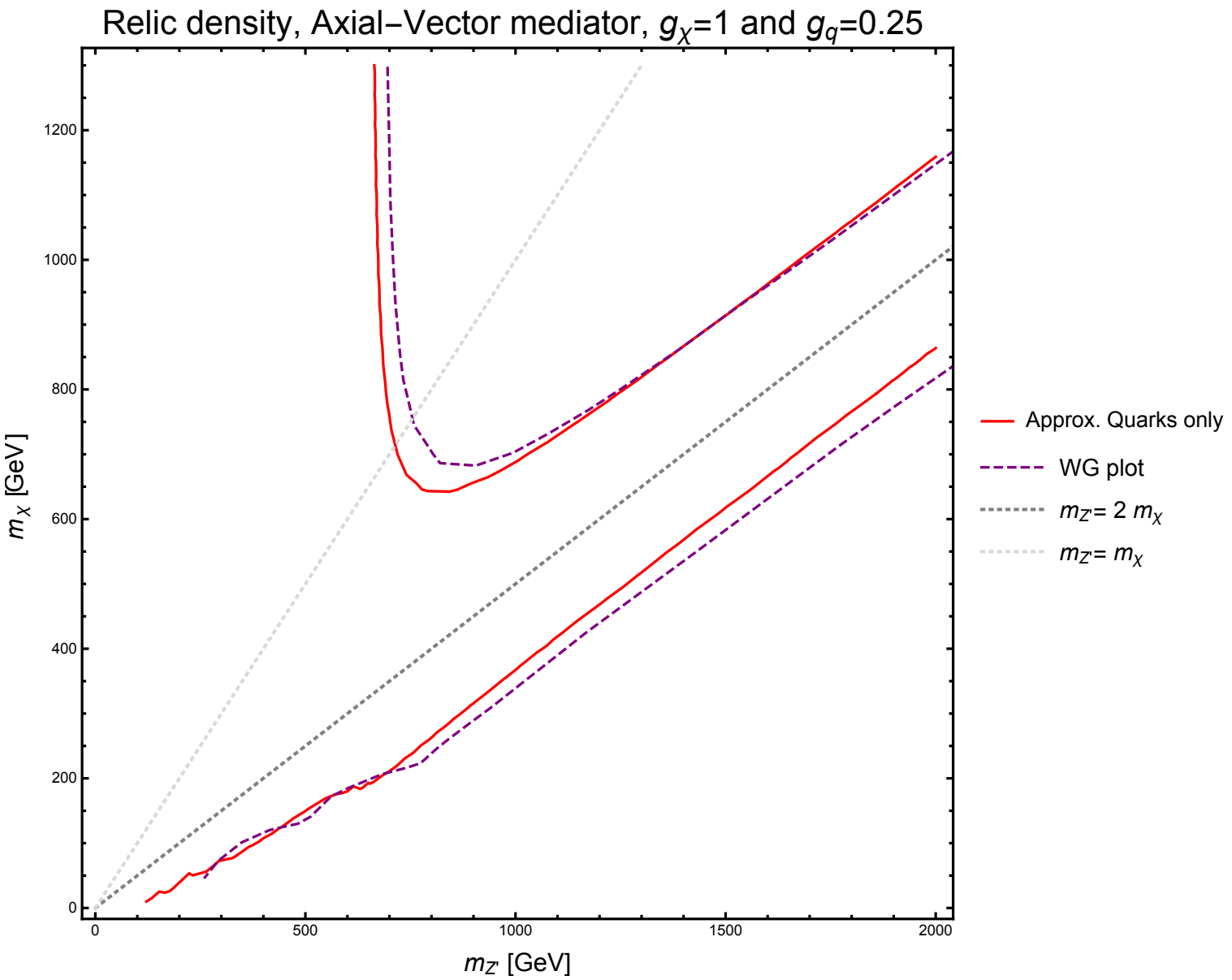
$$\Omega h^2 = 2 \times \frac{1.07 \times 10^9 GeV^{-1}}{M_{Pl}} \frac{X_f}{\sqrt{g_\star}} \frac{1}{a + 3b/X_f} \ .$$

- a and b depend on model parameters, $X_f = m_{DM}/T$ at freeze-out, $g_\star$ is relativistic degrees of freedom at freeze-out.
- Can get away with estimating $X_f \approx 28$ and $\sqrt{g_\star} \approx 9$ across this parameter space.

Annihilation to quarks

- All relevant processes, if kinematically allowed, will contribute to σv.
- Most obvious is $\chi\bar{\chi} \to q\bar{q}$ (s-channel Z').
- a term (s-wave) helicity suppressed by factor $\frac{m_q^2}{m_{Z'}^2}$.
- b term (p-wave) is important, although this is suppressed by v^2.

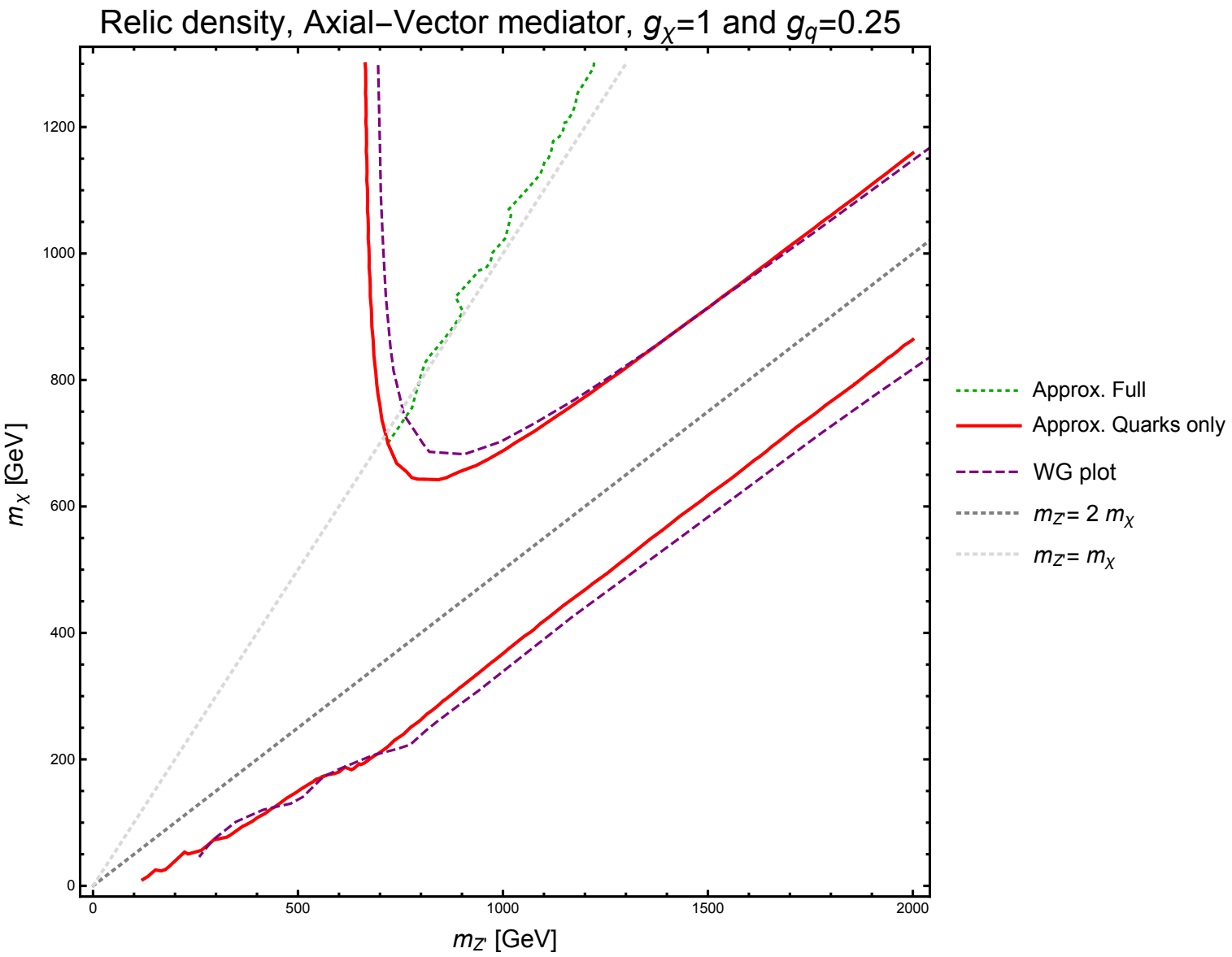
Annihilation to quarks only



Annihilation to mediators

- However there is also the process $\chi\bar{\chi} \to Z'Z'$ (t-channel χ).
- This channel opens up when $m_{DM} > m_{Z'}$.
- Included a and b term although the a term typically dominates.

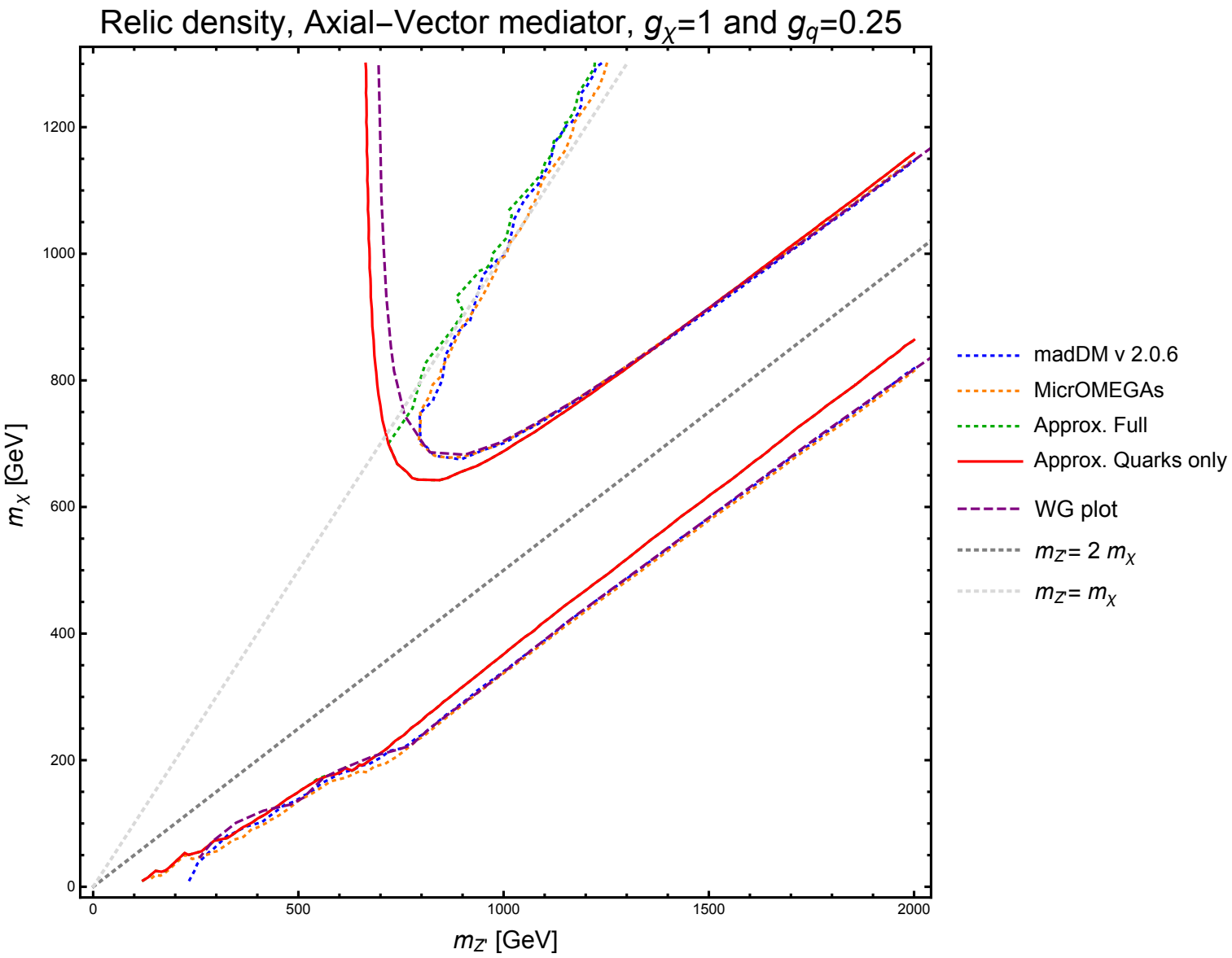
Annihilation to mediators included



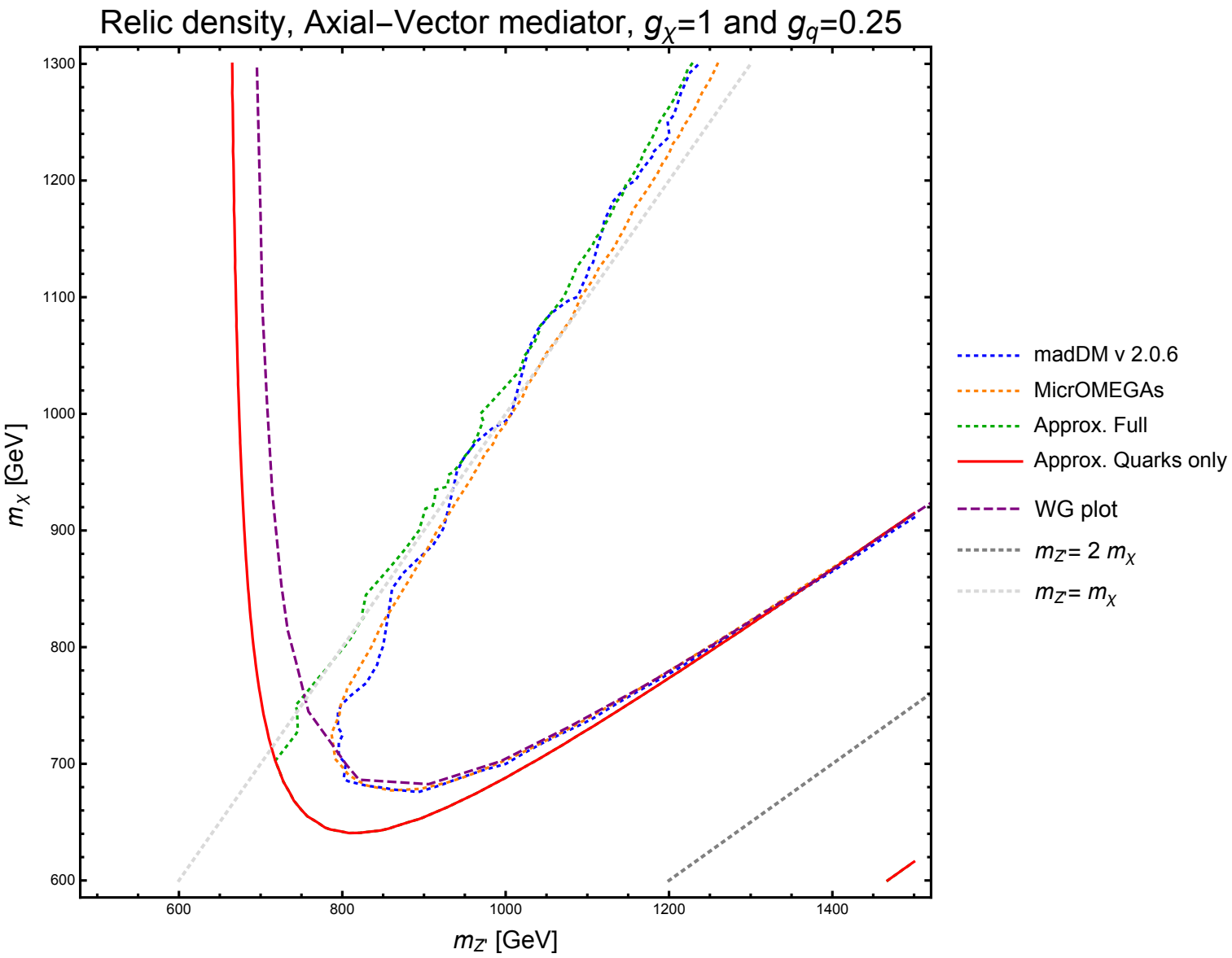
Numerical Options

- Velocity expansion can break down on resonance and near opening of annihilation channels – need numerical tools.
- At least two on the market: `MadDM` and `micrOMEGAs`.
- The working group have been using version 2.0.5, I will show you 2.0.6.

Numerical Options



Numerical Options



Bug in MadDM

- The old version (2.0.5) of MadDM checks the parameter card and will only generate processes that are kinematically allowed.
- If m_{DM} happens to be smaller than $m_{Z'}$ then $\chi\bar{\chi} \to Z'Z'$ will not be generated.
- Even if you raise the value of m_{DM} later via a parameter scan, the code still misses $\chi\bar{\chi} \to Z'Z'$ as it was not generated initially.
- Workaround (Mihailo Backovic) make sure $m_{DM} > m_{Z'}$ **before** running MadDM.
- Fix - upgrade to v 2.0.6!

Conclusion

- Bug is fixed in the newest version of `MadDM` so use v 2.0.6 onwards.
- To avoid future bugs, cross checks can be made using `micrOMEGAs` and analytical approximations.
- We would be happy to help out with any cross-checks in the future.