# Dijets and Dark Matter (arXiv:1605.07940)

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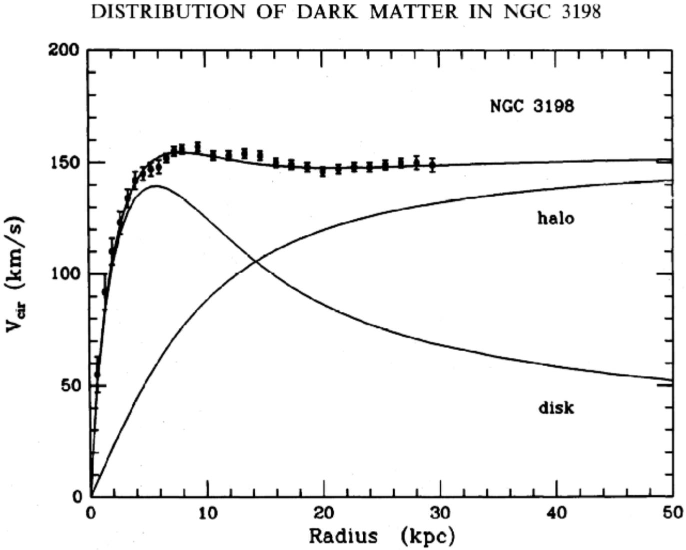
King's College London

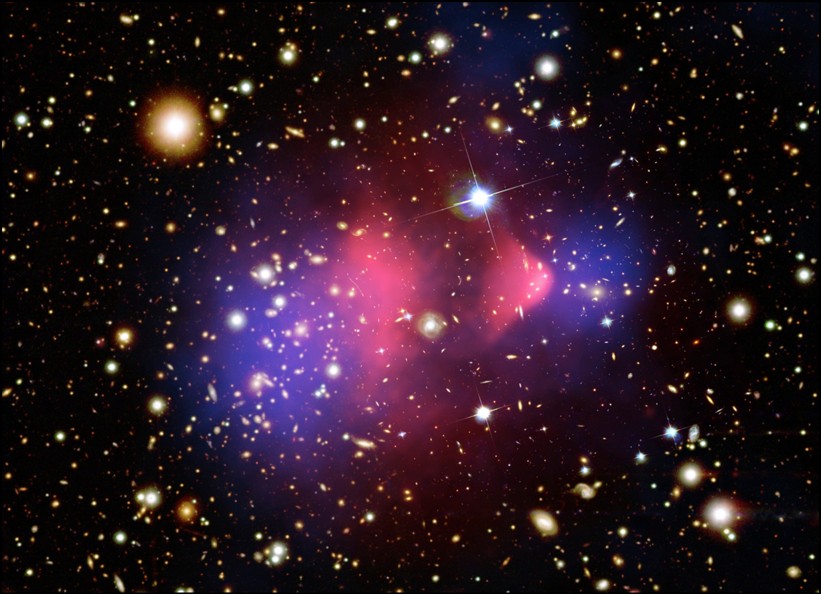
# Introduction

- Dark Matter (DM) evidence
- Simplified Models of DM
- An experimental constraint: dijets at the LHC
- An experimental observation: relic abundance
- Final bounds on DM mass

# Galaxy Rotation Curves



# Bullet Cluster



# DM-Standard Model (SM) interactions

- Taking a bottom up approach one could start building an effective field theory (DM is $\chi$)

$$\frac{c_1}{\Lambda^2}\bar{\chi}\chi\bar{q}q + \frac{c_2}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q + \ldots \tag{1}$$

- But when we look for DM at the LHC we can't guarantee $\Lambda$ is bigger than the energy scale of collisions
- EFT breaks down[1]
- Solution: include dynamical mediator that will link the dark and visible sectors.

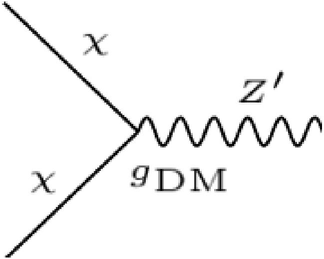
[1] O. Buchmueller, M. J. Dolan and C. McCabe in arXiv:1308.6799 and others

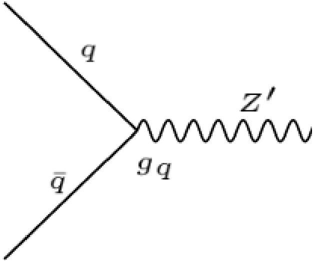
# The Theory

A simplified model of Majorana DM $\chi$ with a spin-one mediator $Z'$

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

$$\mathcal{L}_{\text{int}} = -\frac{1}{2}g_{DM}Z'_{\mu}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi - g_{q}Z'_{\mu}\sum_{q}\bar{q}\gamma^{\mu}q\ . \quad (3)$$



# The width

The theory has 4 free parameters: $\{m_{DM}, m_{Z'}, g_q, g_{DM}\}$. The width of the Z' particle is determined from these as

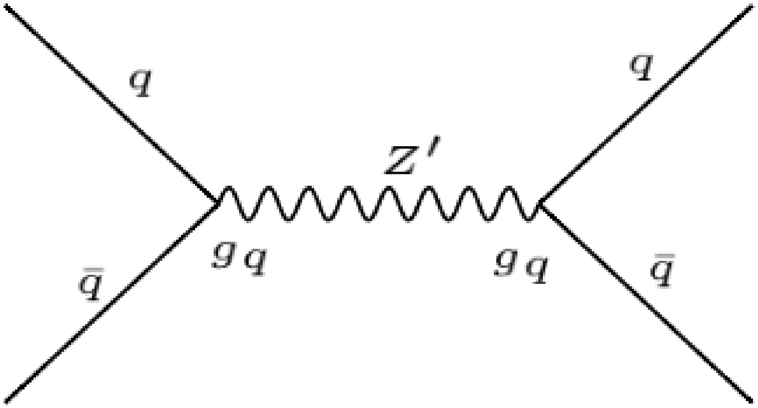
$$\Gamma(Z' \to q\bar{q}) = \frac{m_{Z'}\, g_q^2}{4\pi} \sqrt{1 - \frac{4m_q^2}{m_{Z'}^2}} \left(1 + 2\frac{m_q^2}{m_{Z'}^2}\right) , \qquad (4)$$

$$\Gamma(Z' \to \chi\chi) = \frac{m_{Z'}}{24\pi} (g_{\mathrm{DM}})^2 \left(1 - \frac{4m_{\mathrm{DM}}^2}{m_{Z'}^2}\right)^{3/2} , \qquad (5)$$

$$\Gamma = \sum_i \Theta(m_{Z'} - 2m_i)\Gamma(Z' \to ii) . \qquad (6)$$

Can take $\Gamma$ as a free parameter for now and apply these equations later.

# LHC dijet searches

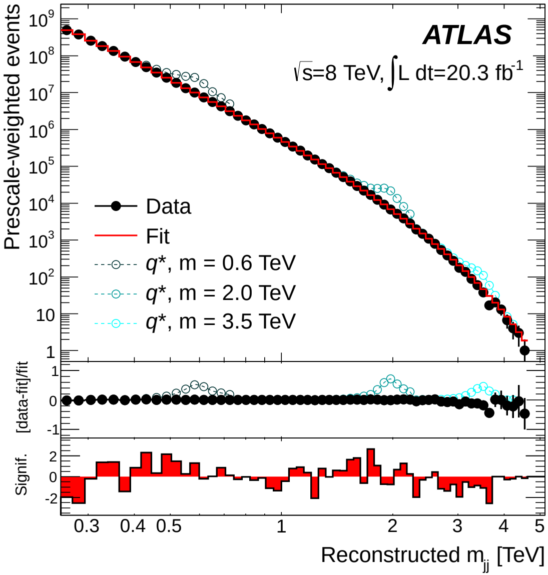



$m_{Z'}$, $\Gamma$ and $g_q$ are the only (unknown) parameters this process depends upon.

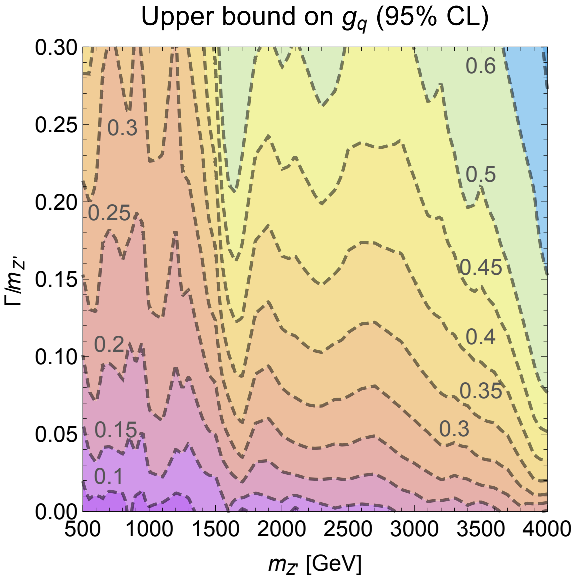
# Limit setting methodology

- Model implementation in `FeynRules`
- BSM matrix elements from `MadGraph`
- Showering and Hadronisation in `Pythia`
- Jet finding with `FastJet` (anti-$k_T$ algorithm)
- Smearing (in $m_{jj}$) to approximate detector effects
- Combined 5 data-sets from ATLAS and CMS at 8 TeV and 13 TeV

# Dijet invariant mass distribution



# $g_q$ exclusion

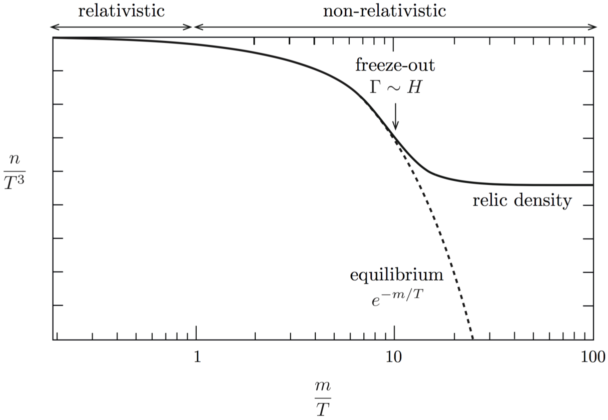


# Link to dark matter

- Dijets constrain the properties of the mediator - the Z'
- Now let us connect to DM
- The relic density is simply the fraction of the universe's energy budget devoted to DM
- Planck's measurements of the CMB (combined with Baryon Acoustic Oscillations, supernova data and $H_0$ measurements) have given:

$$\Omega h^2 = 0.1188 \pm 0.0010 \tag{7}$$

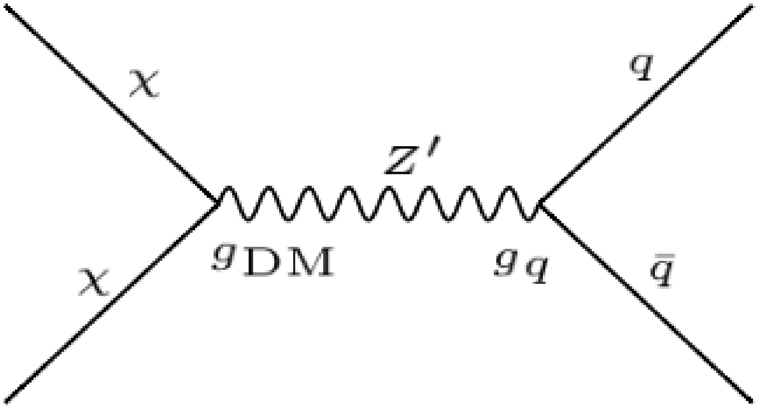
# Freeze-out




Here Γ is characteristic rate of annihilation (not the width).

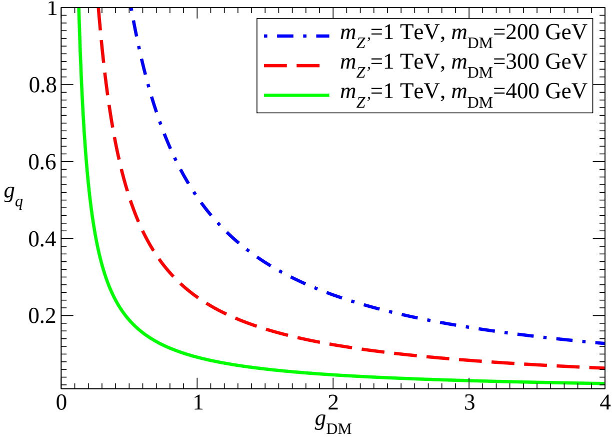
Credit: Daniel Baumann's Cosmology lecture notes

# DM pair annihilation



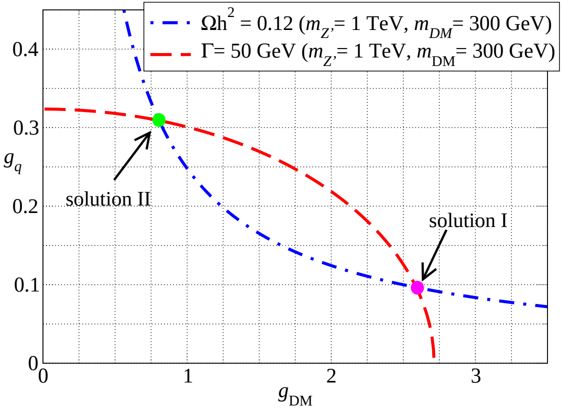

$$\sigma \propto (g_q g_{\mathrm{DM}})^2$$

# Relic Density for different DM masses



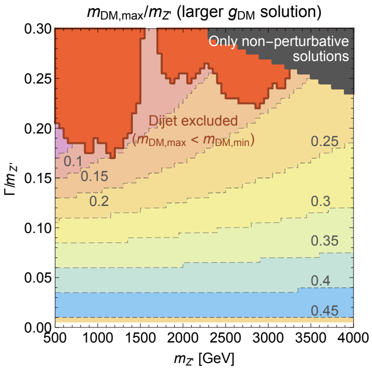

Away from resonance ($m_{DM} \neq \frac{1}{2} m_{Z'}$) $g_{\rm DM} \propto \frac{1}{g_q}$ for fixed masses.
Obtained with `micrOMEGAs`

# Combining constraints



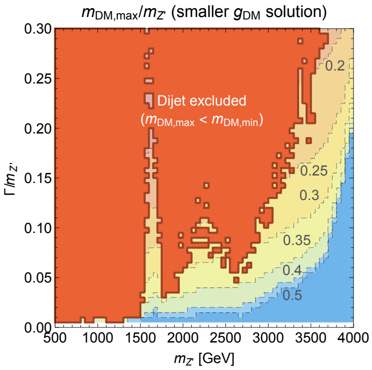

$\Gamma = a g_{\mathrm{DM}}^2 + b g_q^2$ for fixed masses $m_{Z'}$, $m_{DM}$ (where $a$, $b$ const.)

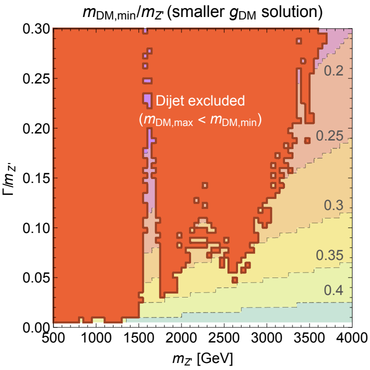
# Bounds on DM mass




Upper (left) and lower (right) bound on DM mass (relative to Z' mass) using Solution I (larger values of $g_{DM}$).

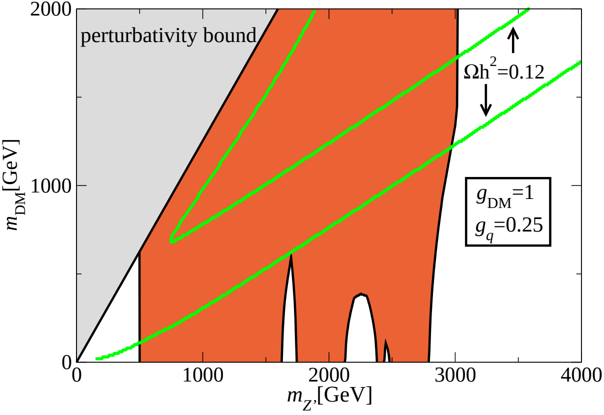
# Bounds on DM mass




Upper (left) and lower (right) bound on the DM mass (relative to Z' mass) using Solution II (smaller values of $g_{DM}$).

# FINAL PLOT: bounds for fixed couplings

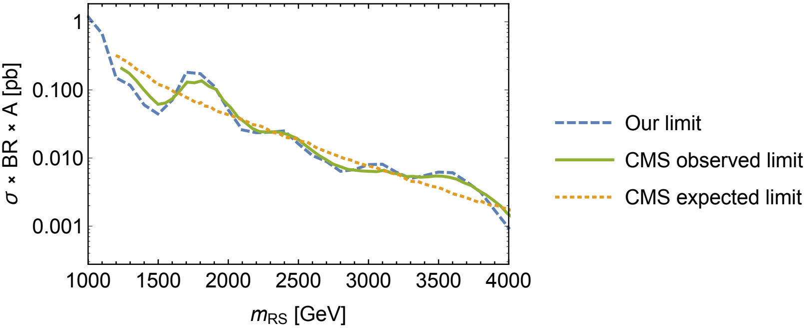



A good old fashioned exclusion plot. Red region is killed by dijets, green line gives you good relic density.

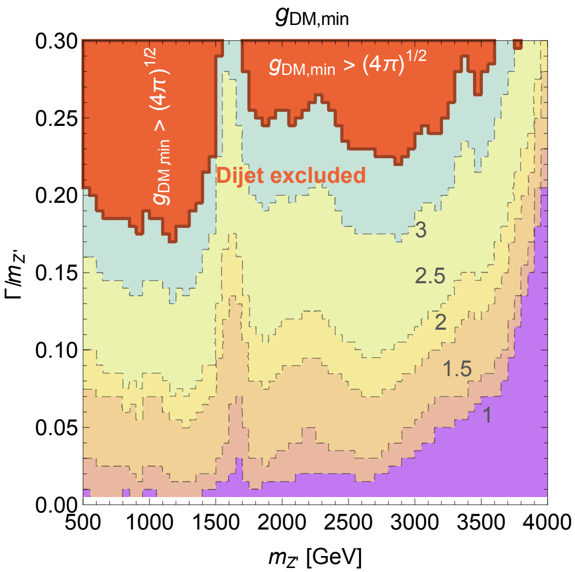
# Conclusions

- We have considered a simplified model of Majorana DM.
- We obtained dijet constraints from the LHC using ATLAS & CMS data from 8 TeV & 13 TeV.
- We combined this with the cosmological constraint of the relic density to give a final bound on the DM mass.
- Future LHC data and the next generation of DM experiments will put additional pressure on thermal relic DM.
- Future things to think about: are these simplified models theoretically consistent? Do they capture all relevant phenomenology?

# BACKUP - Validation of limit setting

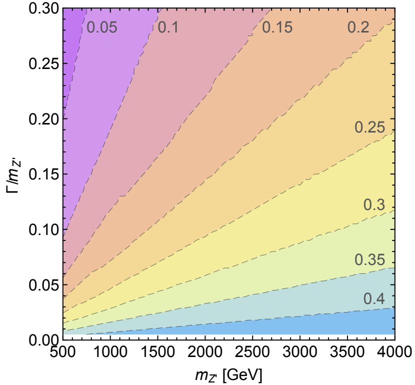


# BACKUP - Lower Bound on $g_{DM}$



# BACKUP - $\frac{m_{DM,\mathbf{min}}}{m_{Z'}}$ before dijet bounds applied

- The requirement to have a relic-width intersect gives a lower bound on the dark matter mass $m_{DM}$ (right).
- This is when the curves just touch, giving only one solution.
- Increasing $m_{DM}$ we get two possibilities, one for each solution.




$\frac{m_{DM,\min}}{m_{Z'}}$ from intersect requirement alone.