Z' Mediated Dark Matter Interactions

Andrey Katz

1706.***** with Ahmed Ismail and Davide Racco

CERN-CKC workshop "What is going on at the Electroweak scale?"
June 5th, 2017

UNIVERSITÉ DE GENÈVE

CERN

Outline

- Setup description
- Anomalous Z’s: how can they emerge, what is the correct EFT, what are the interactions with the SM gauge bosons?
- Phenomenological consequences: DM thermal relic abundance, Ice Cube, signals from DSph Galaxies
- Conclusions

What To Expect from the Z'?

Z' should be a gage boson of a consistent gauge theory, whose gauge invariance is spontaneously broken at some scale $\gtrsim m_{Z'}$

Without introducing spectator fermions, the SM field content constraints the new U(1) group to be a linear combination of B-L and Y-sequential. The generator is:

$$\cos\theta\ t_Y + \sin\theta\ t_{B-L}$$

Non Anomalous Z'

If the DM is a scalar or a Dirac fermion — the calculation of annihilation channels is straightforward and most of the interesting results can be obtained at the tree level

Majorana fermions:

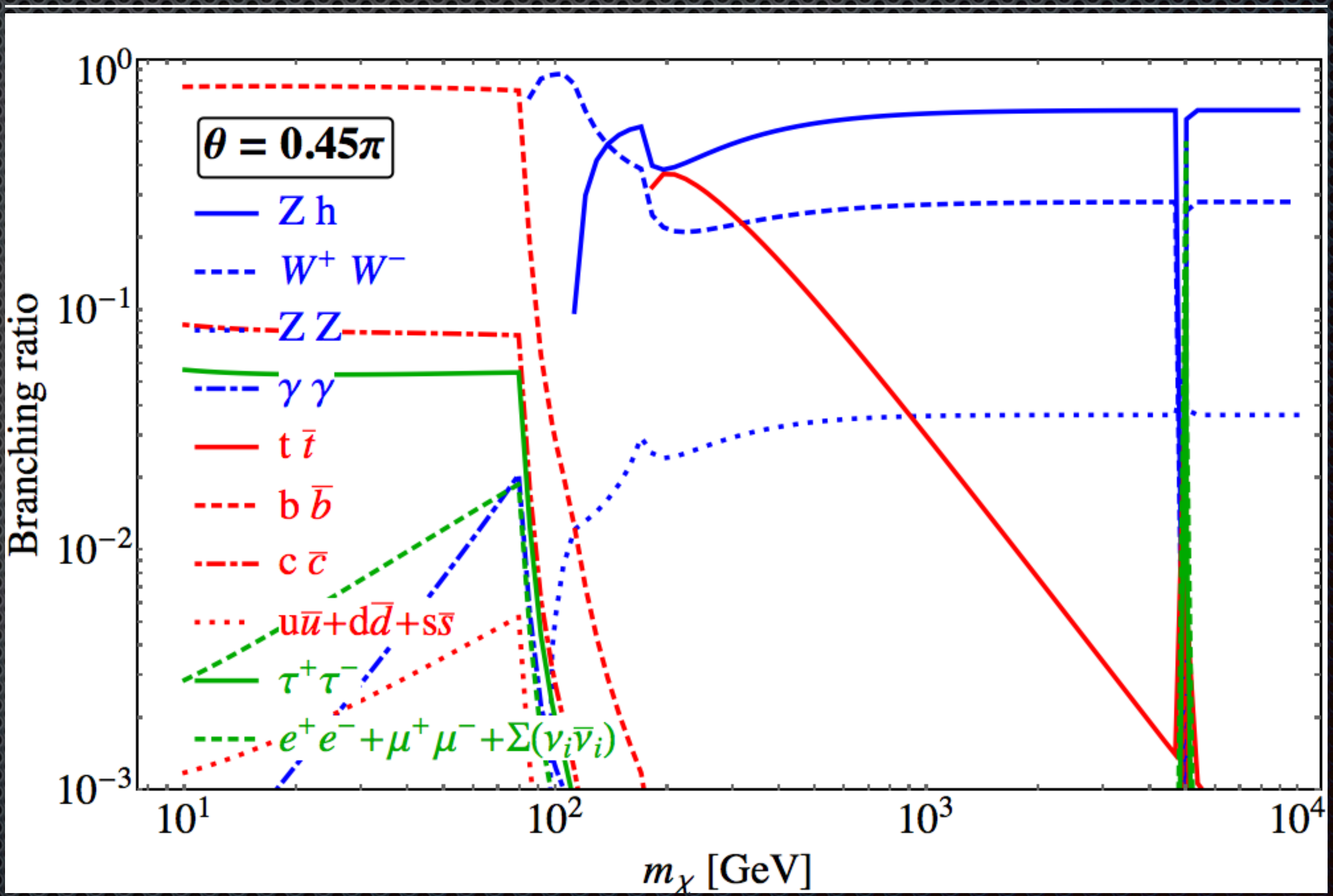
1. Annihilations into the SM fermions are helicity suppressed, $\sim(m_f/m_\chi)^2$
2. Direct detection is SD ☛ weaker bounds

Loop induced, chirality non-suppressed annihilations can exceed the tree level effects

Non Anomalous Z' and Majorana DM Annihilations

T. Jacques, AK, E. Morgante, D. Racco, M. Rameez, A. Riotto

As expected, WW and ZZ vastly exceed the light fermions BRs. Tops and bottoms contribute only near thresholds



Other (Anomalous) Z's

Brief overview of Z's previously considered in the DM literature

Field	$U(1)_{\text{universal}}$	$U(1)_{B-xL}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$
Q_L	x	$\frac{1}{3}$	$\frac{1}{3}$	0
u_R	x	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{x}{3}$
d_R	x	$\frac{1}{3}$	$-\frac{x}{3}$	$\frac{1}{3}$
l_L	x	$-x$	$\frac{x}{3}$	$\frac{-1+x}{3}$
e_R	x	$-x$	$-\frac{1}{3}$	$\frac{x}{3}$

Alves, Berlin, Profumo, Queiroz; 2015

Atlas + CMS DM benchmark models (used for reporting results); 2015

$$\mathcal{L}_{\text{vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

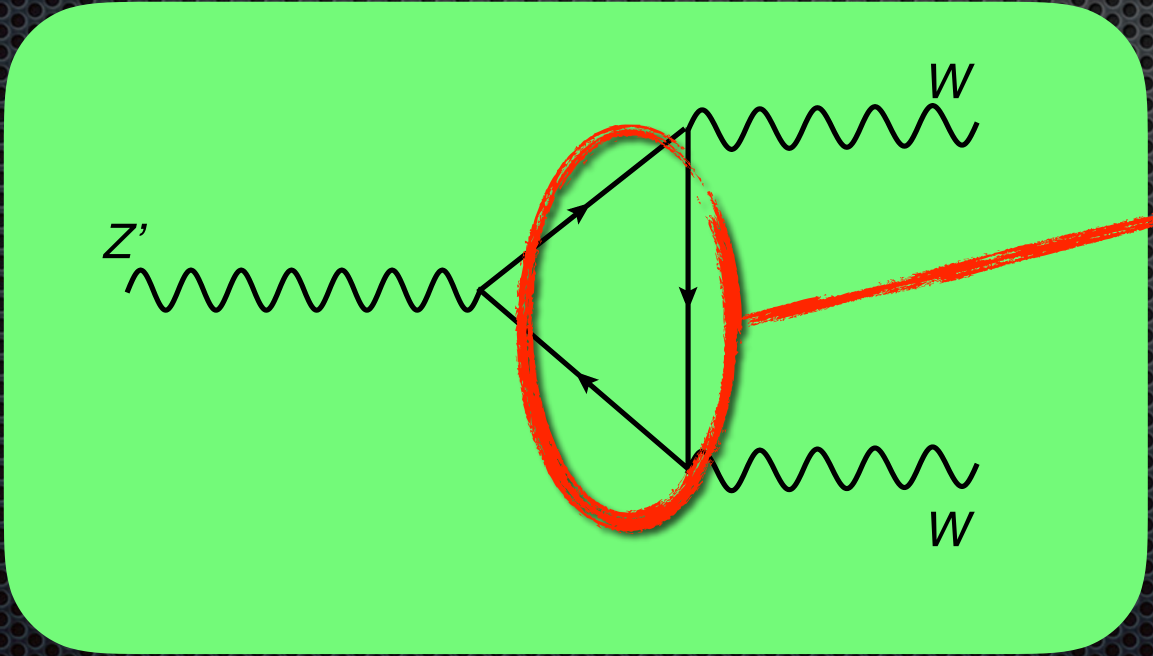
$$\mathcal{L}_{\text{axial-vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi.$$

In fact, (almost) all these models are anomalous. What are we missing with this approach?

Troubles with Anomalous Z's

In an anomalous theory gauge invariance is broken at the quantum level — a priori not a consistent gauge invariant theory.

Practical question:



In an anomalous theory this loop is divergent, signalling non-renormalizability of the EFT

Is EFT Formulation Possible? — The SM w/o the Top Quark

D'Hoker & Farhi; 1983

The SM w/o the top is an anomalous effective field theory. One can systematically integrate out tops and get an EFT with the terms that preserve gauge invariance. The gauge-boson interactions are calculable (up to mass thresholds)

Restores U(1) gauge invariance and cancels the mixed anomaly

$$-y_N \frac{g_1 g_2}{24\pi^2} \int \mathrm{d}^4x\, \varepsilon^{\mu\alpha\beta\gamma}\, \mathrm{Tr}\, [\varepsilon_L(x)\partial_\mu \{2A_\alpha \partial_\beta B_\gamma + \tfrac{1}{2} i g_2 B_\alpha A_\beta A_\gamma\}] .$$

$$-y_N \frac{g_2^2}{24\pi^2} \int \mathrm{d}^4x\, \theta(x) \varepsilon^{\mu\alpha\beta\gamma} \partial_\mu\, \mathrm{Tr}\, [A_\alpha \partial_\beta A_\gamma + \tfrac{1}{2} i g_2 A_\alpha A_\beta A_\gamma]$$

$$+ y_N \frac{g_1^2}{32\pi^2} \int \mathrm{d}^4x\, \theta(x) F_{1\mu\nu} F_1^{\mu\nu} .$$

Restores SU(2) gauge invariance

Warm Up: Anomalous U(1)'

Preskill; 1990

Under a gauge transformation the effective action is not invariant:

$$\delta\Gamma = \sum_i Q_i^3 \frac{g^2}{48\pi^2}\int d^4x\,\epsilon F_{\mu\nu}\tilde{F}^{\mu\nu}$$

add to cancel the anomaly

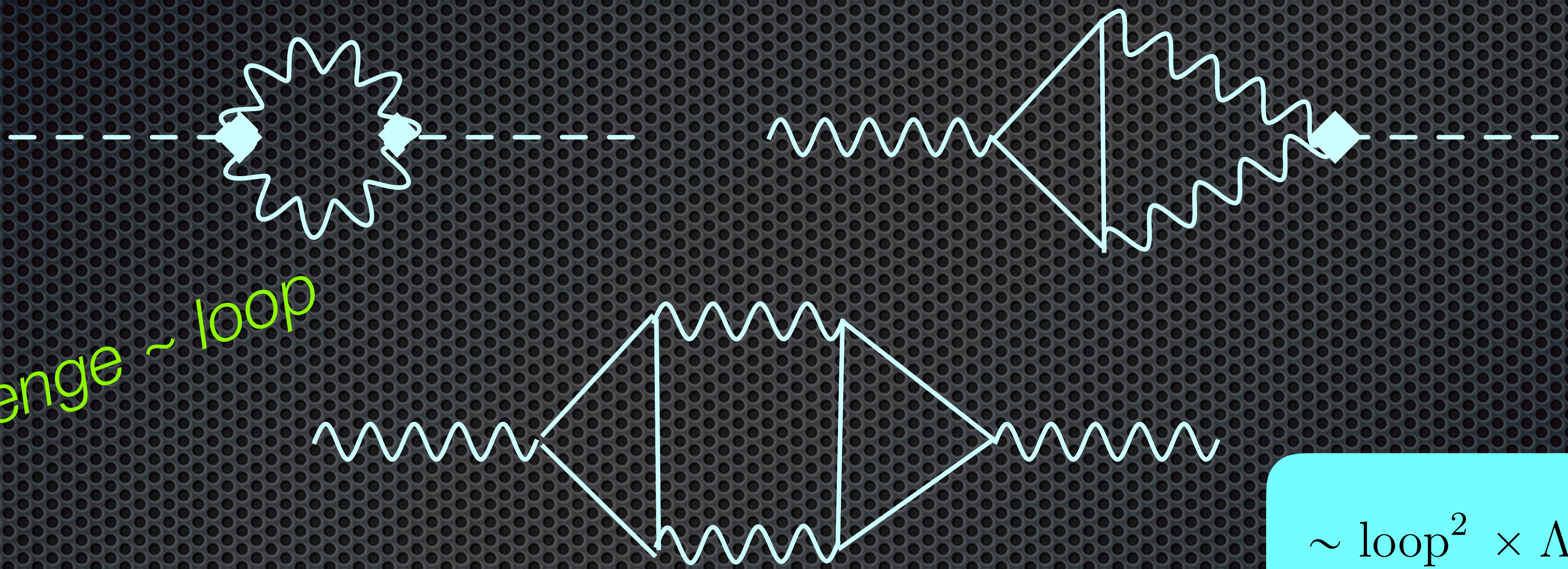
$$\delta\mathcal{L} = \sum_i Q_i^3 \frac{g^2}{48\pi^2}\theta(x) F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad \theta(x) \to \theta(x) + \epsilon(x)$$

Secretly the action depends only on the derivates of θ. How can we see this? Perform fermions chiral rotation to get rid of this term. The contribution to the effective action is:

$$\delta\mathcal{L} = \sum_i Q_i^3 \partial_\mu\theta\bar{\psi}\gamma^\mu\psi$$

Warm Up: Anomalous U(1)’

Even if we start without a kinetic term for θ, it is induced by



each lozenge ~ loop

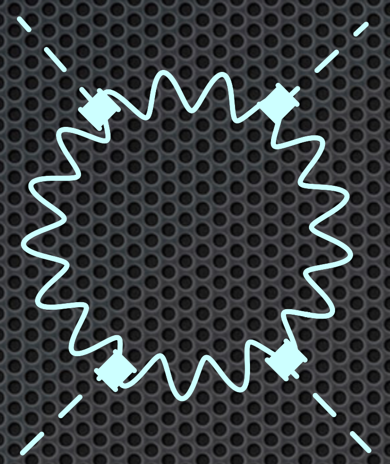
$$\sim \mathrm{loop}^2 \times \Lambda^2 \left(\partial_\mu \theta - g Z'_\mu\right)^2$$

This becomes a Stückelberg U(1) coupled to the fermions. We can switch to unitary gauge and get rid of the “fake” scalar.

The theory will still be EFT, non renormalizable

Where is the cutoff?

The contribution to the n-point function does not stop at n = 2



+ Z' external legs

$$\sim \frac{\mathrm{loop}^4\,\Lambda^4}{m_{Z'}^4}\left(\partial_\mu\theta - gZ'_\mu\right)^4$$

Consistency of loop expansion requires:

$$\Lambda \lesssim \frac{64\pi^3}{g^3\left|\sum_i Q_i^3\right|}m_{Z'}$$

The spectators can be much heavier than the Z', but not arbitrarily heavy

Theories with Mixed Anomalies

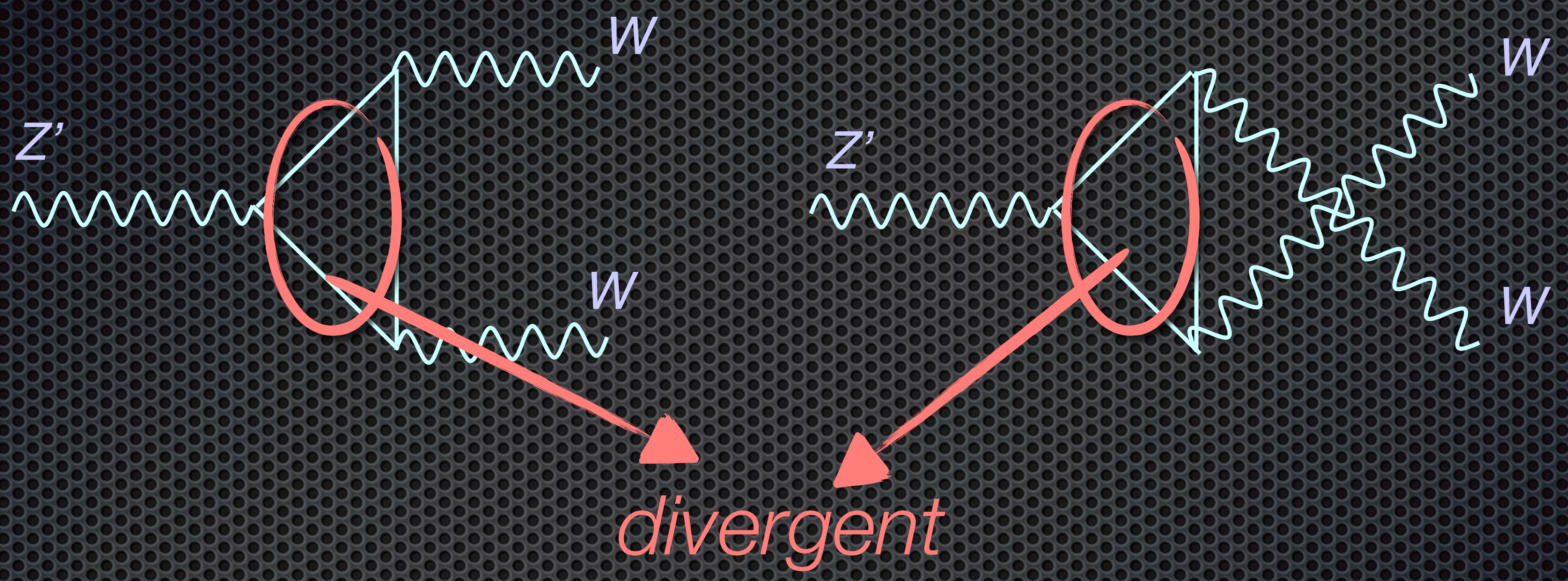
In our case the $U(1)^3$ will not have any interesting consequences beyond that we know the cutoff. But we have mixed anomalies. What should we do with the to calculate Z' → WW, ZZ?

Here we can add a local counterterm:

$$\mathcal{L} = \frac{g_1 g_N^2 \mathcal{A}}{8\pi^2} \epsilon_{\mu\nu\rho\sigma} Z'_\mu \left(A_N^{\nu a} \partial^\rho A_N^{\sigma a} + \frac{1}{3} g_N \epsilon_{abc} A_N^{\nu a} A_N^{\rho b} A_N^{\sigma c} \right)$$

Depending on this counterterm we can change the variation of the action, such that we can always set the gauge variation with respect to the SU(N) to vanish

Gauge Boson Couplings Calculation



In anomaly free theories there can be an arbitrary momentum shift between the loop momenta of the diagrams. In the anomalous EFT the shift is not arbitrary if we demand that the Ward identity of the SM gauge group is satisfied

Calculation Prescription

- Choose the favorite counterterm (often useful to put it to zero)
- Calculate the diagram momentum shift such that the Ward identity for the SM SU(2)XU(1) is not violated
- Use this momentum shift to calculate the coupling
- This gives the non-decoupling effect of the spectators, up to finite mass thresholds

Back to the “Axial” Z’ Mediated DM

Purely axial in its couplings to all the SM fermions is not only anomalous, in fact it prohibits the renormalizable top Yuakawa couplings — we should better discard this option.

The best we can do:

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-L}$	$U(1)'^{\,c_V^t,c_V^b}_{\rm ax}$	$U(1)'^{\,c_V^t}_{\rm ax}$
$\begin{pmatrix}\nu_L^e\\ e_L^i\end{pmatrix}, \begin{pmatrix}\nu_L^\mu\\ \mu_L^i\end{pmatrix}, \begin{pmatrix}\nu_L^\tau\\ \tau_L^i\end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1	-1	-1
$(e_R^i)^{\rm C}$, $(\mu_R^i)^{\rm C}$, $(\tau_R^i)^{\rm C}$	$\mathbf{1}$	$\mathbf{1}$	1	$+1$	-1	-1
$\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \begin{pmatrix}c_L\\ s_L\end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$+\frac{1}{3}$	-1	-1
$(u_R)^{\rm C}$, $(c_R)^{\rm C}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-\frac{1}{3}$	-1	-1
$(d_R)^{\rm C}$, $(s_R)^{\rm C}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$-\frac{1}{3}$	-1	-1
$\begin{pmatrix}t_L\\ b_L\end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$+\frac{1}{3}$	-1	-1
$(t_R)^{\rm C}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-\frac{1}{3}$	$+1$	$+1$
$(b_R)^{\rm C}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$-\frac{1}{3}$	$+1$	-1
Higgs $\begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0	0	0

Both are axial in the first two generations. One of them is vectorial in tops and bottoms, another in tops only.

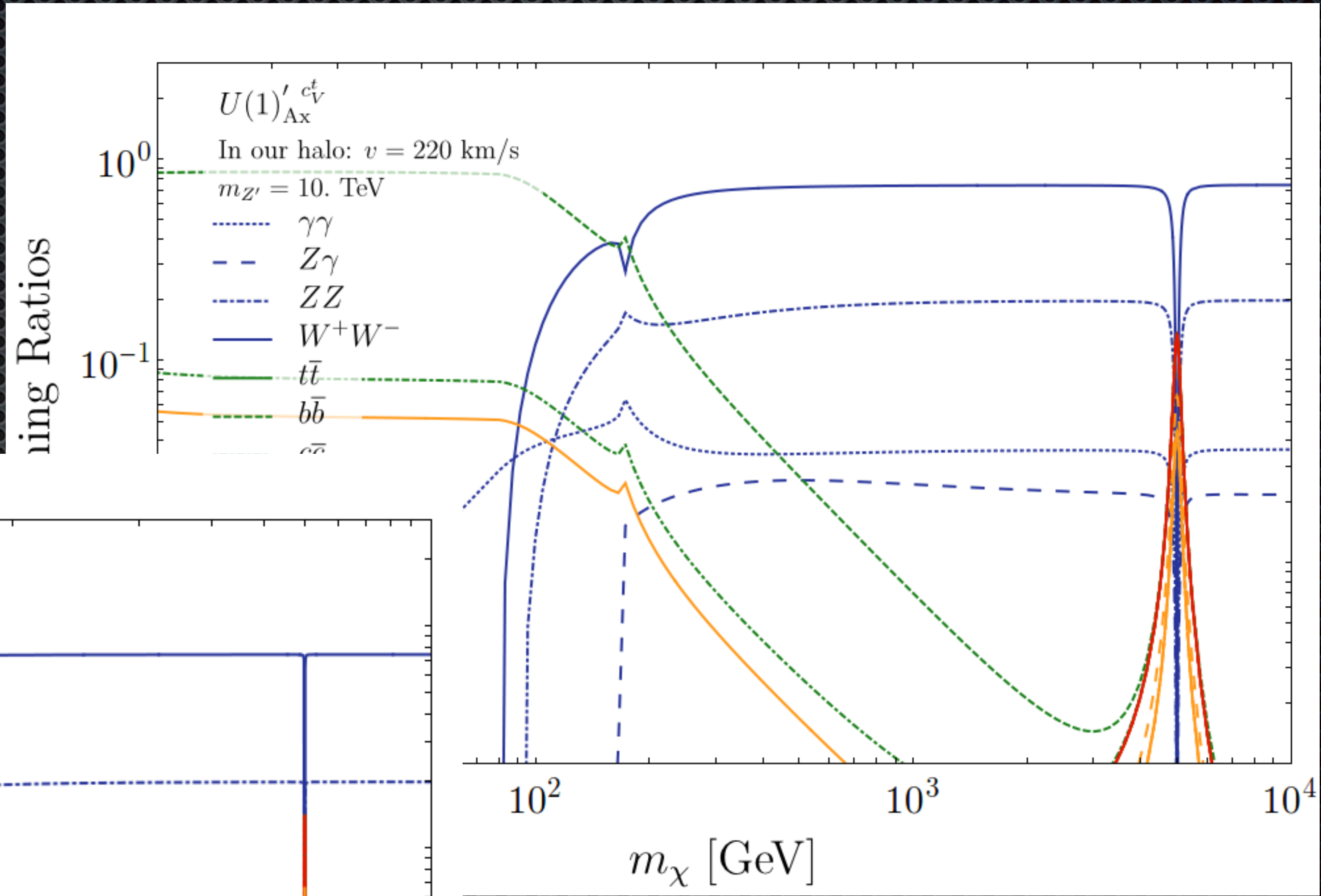
If we want to leave the top Yukawa intact, mixed anomaly with the SU(3) vanishes

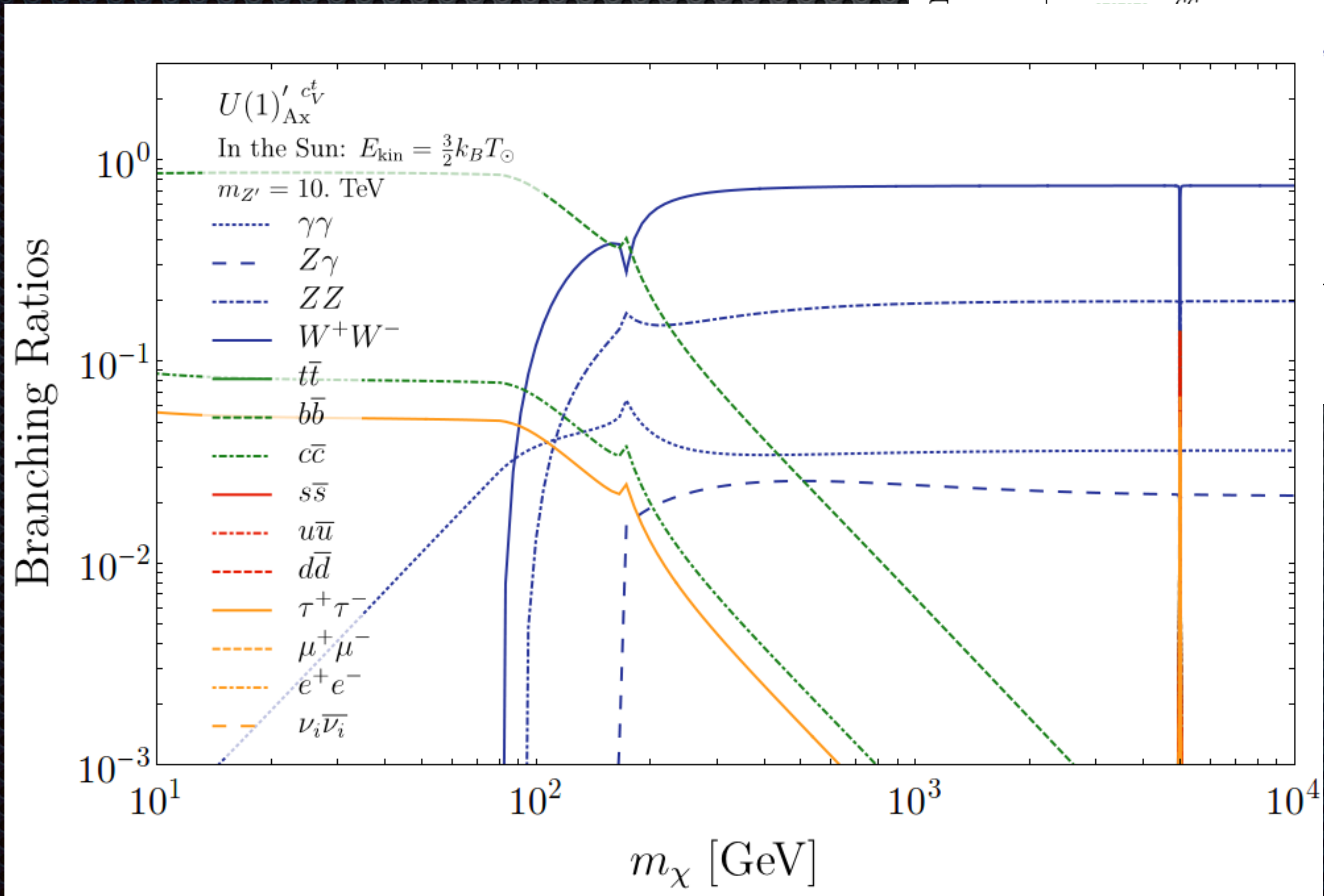
Half Slide on the Flavor

No issue with the “original” axial model. The charges of our “almost axial” models are not proportional to the unity in the flavor space

- The second model is super-safe. It deviates from the unity matrix only in the RH sector — we do not know the angles there! And only the 3rd generation
- The first version is less safe, but the U(2) symmetry is preserved. Some alignment might be needed.

DM Annihilation Branching Ratios

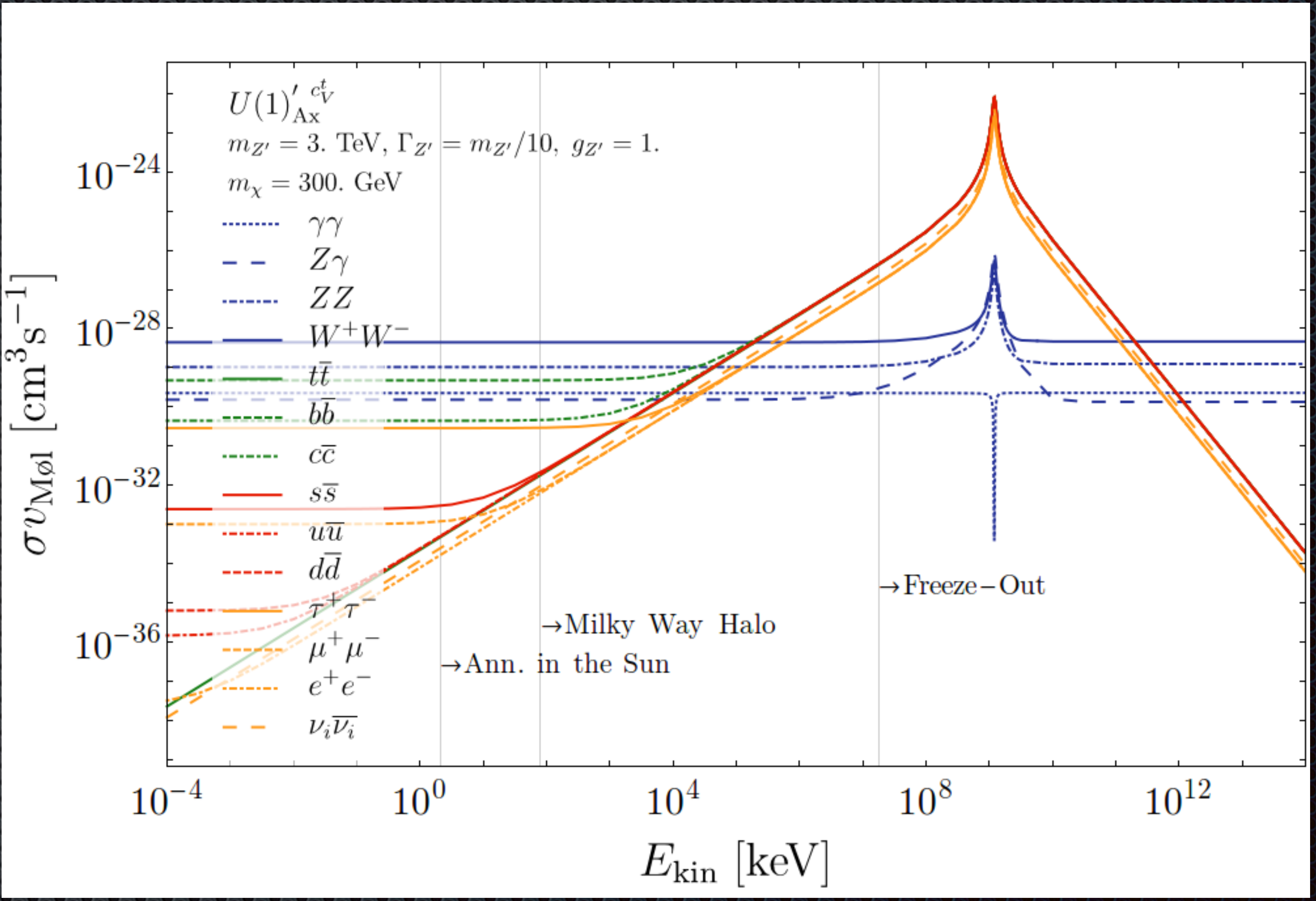




As expected, at low v heavy gauge bosons dominate all possible fermionic channels

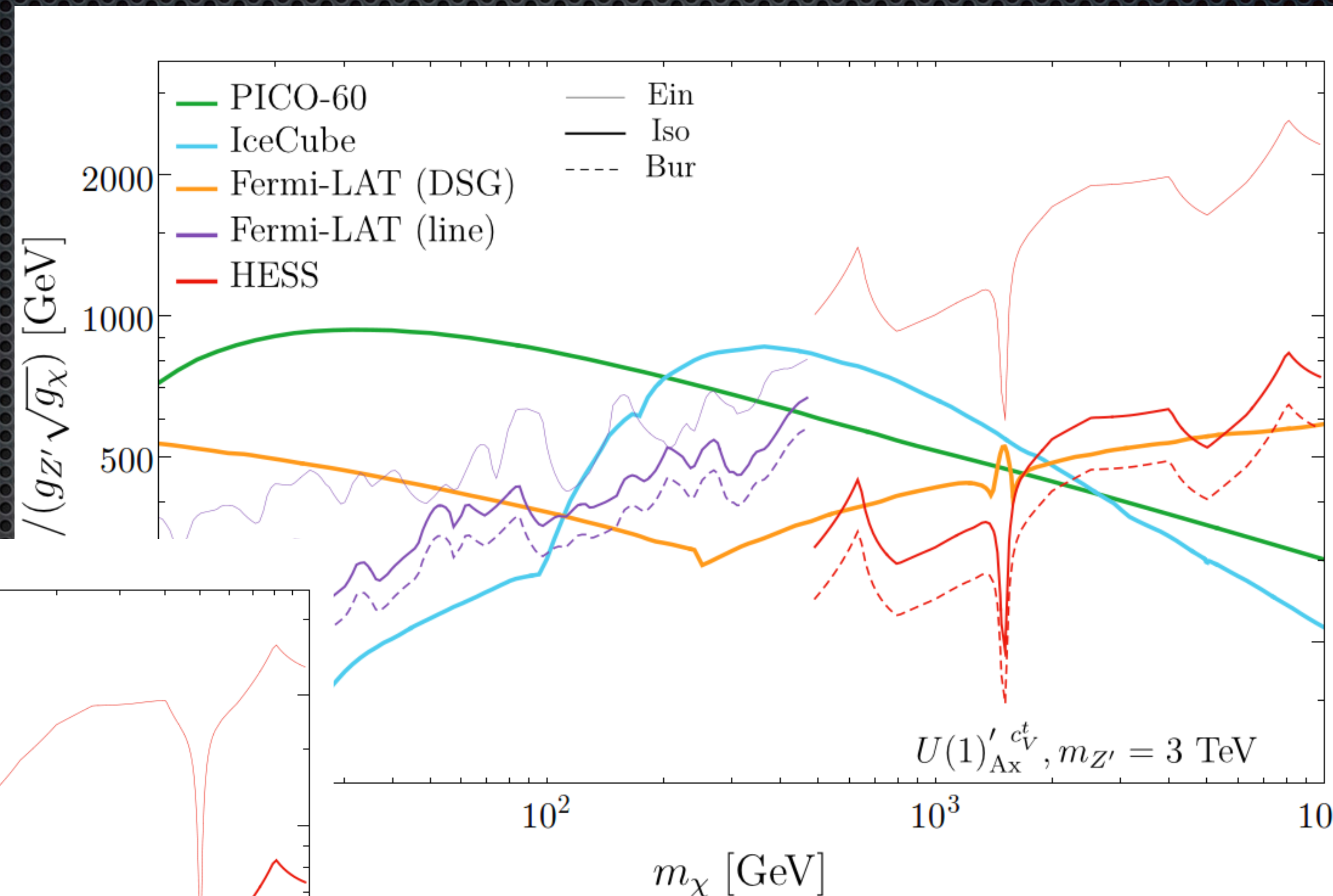
On the “Lost” Unitarity

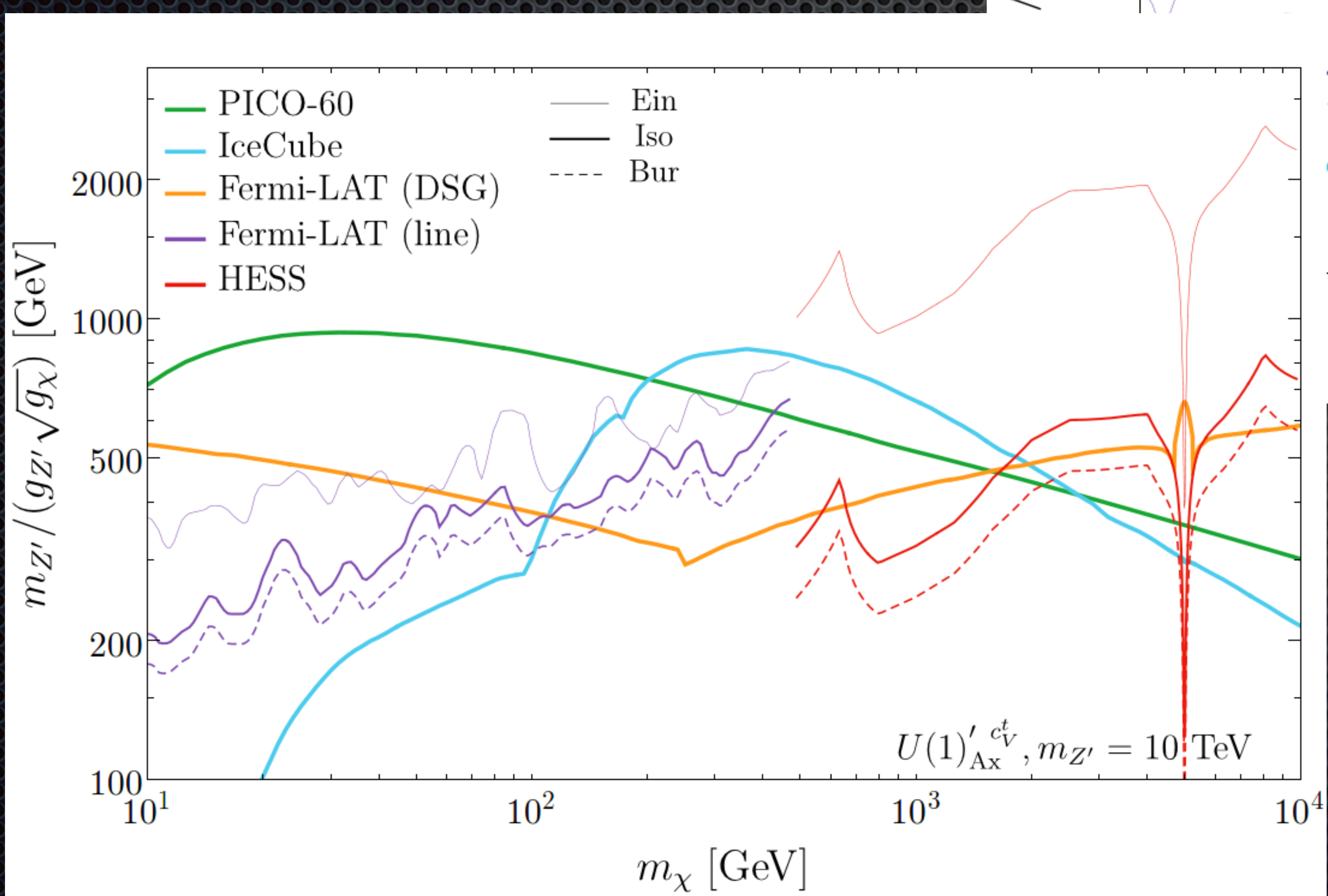
In the unitary gauge there are no explicit high dim. terms, but the annihilations into the gauge bosons do not die with s. Unitarity bounds set the precise bounds on the cutoff.



Preliminary Bounds

Bounds are dominated by the PICO and the LHC (low mass) and Ice Cube





Above ~ 200 GeV the bounds are dominated by IC and DSph

Conclusions

- The only way to make sense of anomalous Z' mediated DM models is to formulate them as consistent EFTs, along the lines of the "SM without tops"
- Anomalous Z' mediated DM models have calculable couplings to the SM gauge bosons within the EFT
- These couplings are experimentally important, especially if the annihilations into the SM fermions suffer from p-wave suppressions
- Ice Cube, Fermi are HESS bounds due to these couplings are non-trivial and sometimes supersede the collider bounds even in low mass range