A Global Fit of Non-Relativistic Effective Dark Matter Operators Including Solar Neutrinos

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Work with Aaron Vincent, Pat Scott, and help from the GAMBIT collaboration

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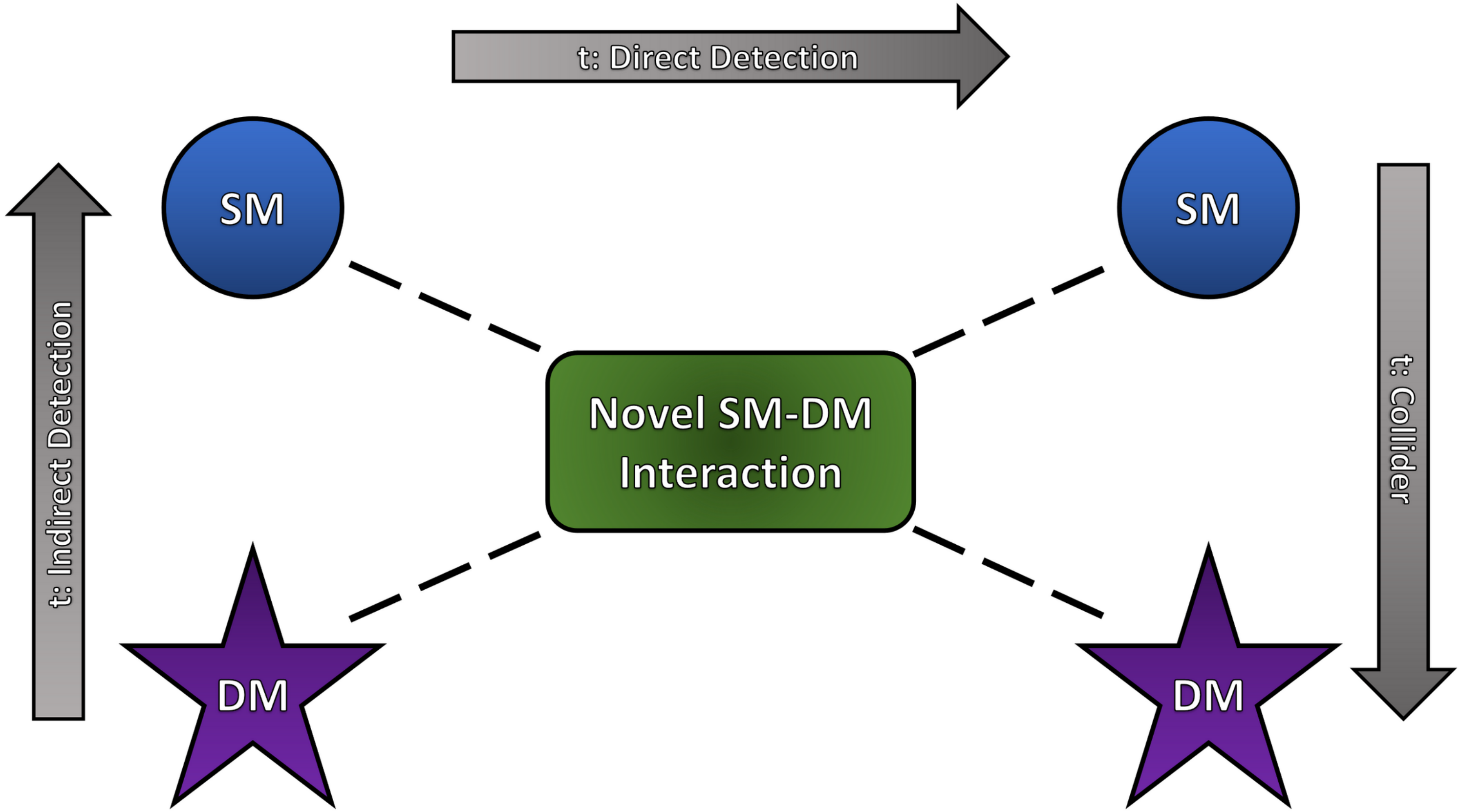
Introduction to Non-Relativistic Effective Operators

(NREOs)

Search Types

- Indirect detection, direct detection, collider searches
- Each are independent detection methods
- Solar neutrinos act as a compliment to direct detection

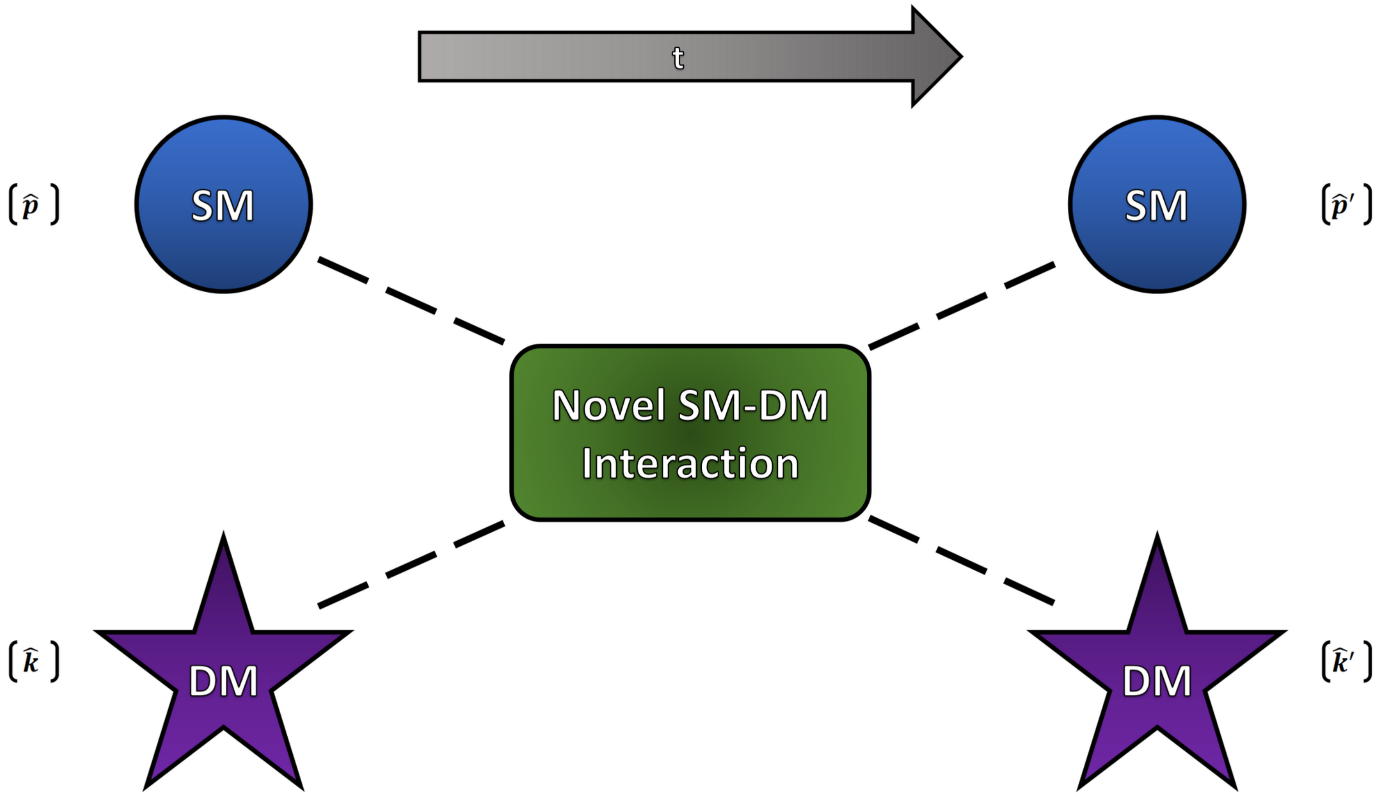


Hermitian Operators

- The general case of a dark matter scattering interaction is considered
- The Hermitian operators that govern the interaction are

$$\mathbb{1}_{\chi N} \quad , \quad i\hat{\mathbf{q}} \quad , \quad \hat{\mathbf{v}}^{\perp} \quad , \quad \hat{\mathbf{S}}_{\chi} \quad , \quad \hat{\mathbf{S}}_{N}$$

$$\hat{\mathbf{v}}^{\perp} = \hat{\mathbf{v}} + \hat{\mathbf{q}}/(2\mu_N)$$



Non-Relativistic Effective Operators

- Spin-independent: $\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$
- Spin-dependent: $\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$
- Novel interactions, such as

$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

- Acts as leading contributor to higher-energy theories [3]:

$$\mathcal{L} \supset \lambda_1 \phi \bar{\chi}\chi - i h_2 \phi \bar{q} \gamma^5 q \rightarrow \hat{\mathcal{H}} \supset \left(c_{10}^0 t^0 + c_{10}^1 t^1\right) \hat{\mathcal{O}}_{10}$$

$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$	$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_2 = \hat{\mathbf{v}}^\perp \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$	$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$	$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$
$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$	

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Non-Relativistic Effective Operators

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$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$
$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$	

Cross Section

- Cross section becomes a large sum over response functions

$$\frac{d\sigma_i}{dE}(w^2, q^2) = \frac{m_T}{2\pi w^2} P_{\text{tot}}(w^2, q^2)$$

$$\begin{aligned} P_{\text{tot}}(w^2,q^2) = \frac{4\pi}{2J+1} \sum_{\tau=0,1} \sum_{\tau'=0,1} \Bigg\{ \Bigg[& R_M^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_M^{\tau\tau'}(y) \\ & + R_{\Sigma''}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_{\Sigma''}^{\tau\tau'}(y) + R_{\Sigma'}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_{\Sigma'}^{\tau\tau'}(y) \Bigg] \\ & + \frac{q^2}{m_N^2} \Bigg[R_{\Phi''}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_{\Phi''}^{\tau\tau'}(y) + R_{\Phi'' M}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_{\Phi'' M}^{\tau\tau'}(y) \\ & + R_{\tilde{\Phi}'}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_{\tilde{\Phi}'}^{\tau\tau'}(y) + R_{\Delta}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_{\Delta}^{\tau\tau'}(y) \\ & + R_{\Delta\Sigma'}^{\tau\tau'}\left(v_T^{\perp 2}, \frac{q^2}{m_N^2}\right) W_{\Delta\Sigma'}^{\tau\tau'}(y) \Bigg] \Bigg\} \end{aligned}$$

- Effective Cross section

$$\sigma_p = \frac{(c_i^\tau \mu_n)^2}{\pi}$$

Solar Capture

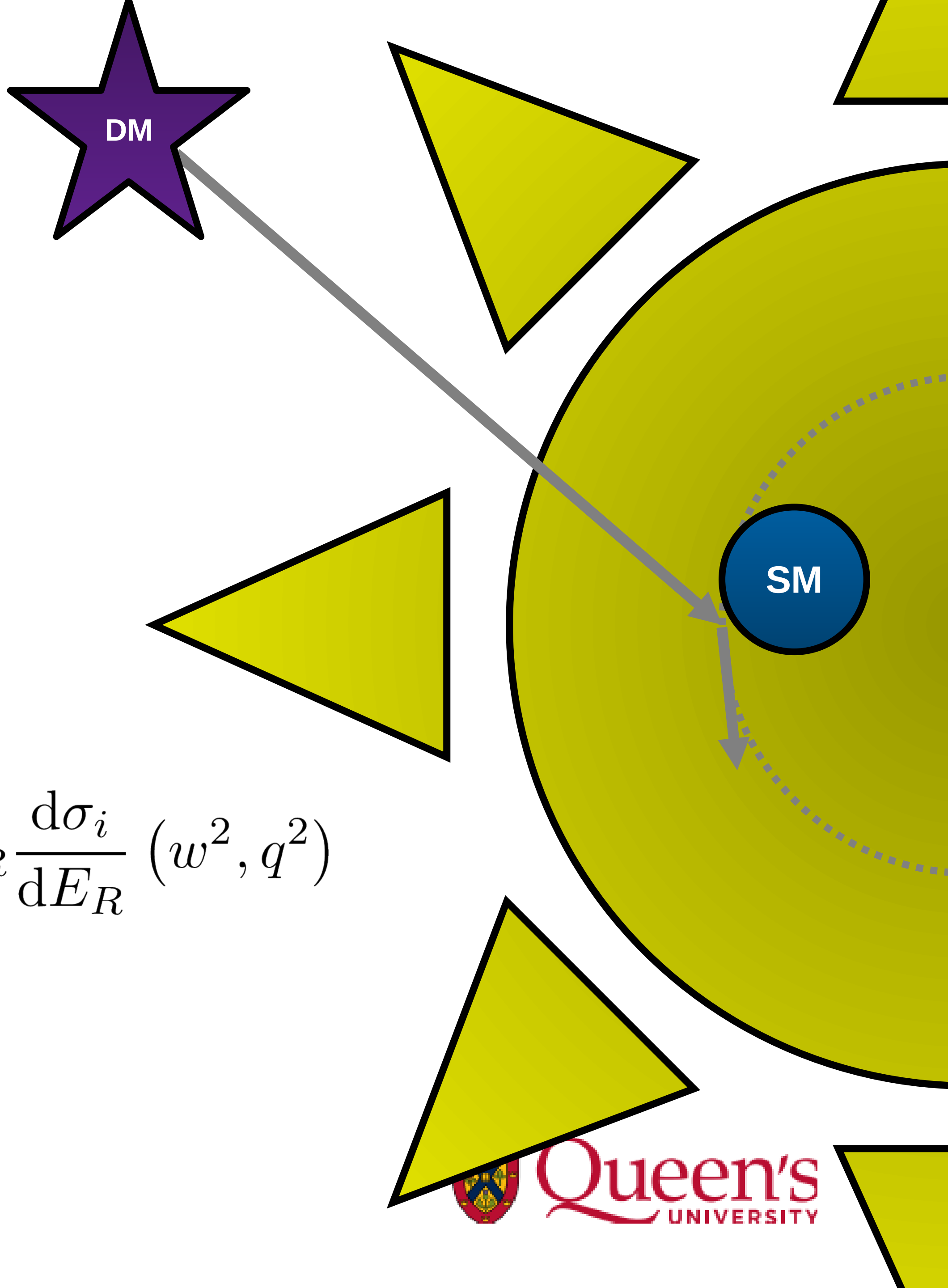
Capt’n General

Capture Process

- Dark matter is captured when it scatters to below the local escape velocity in the Sun

$$C = 4\pi \int_0^{R_\odot} \mathrm{d}R R^2 \int_0^\infty \mathrm{d}u \frac{f(u)}{u} w \Omega_v^-(w)$$

$$\Omega_v^-(w) = \sum_i n_i w \Theta\left(\frac{\mu_i}{\mu_{+,i}^2} - \frac{u^2}{w^2}\right) \int_{E_k u^2/w^2}^{E_k \mu_i/\mu_{+,i}^2} \mathrm{d}E_R \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R}(w^2, q^2)$$



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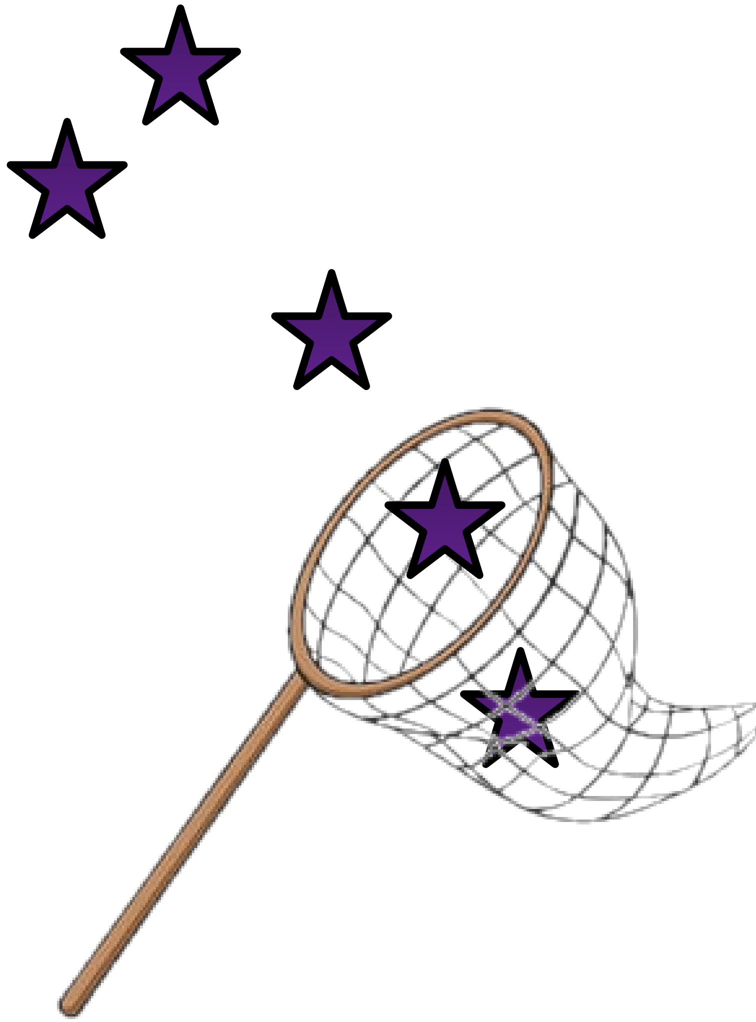
Geometric Limit

- The Sun has a hard limit of dark matter capture

$$C_{\max}(t) = \pi R_\odot^2(t) \int_0^\infty \frac{f_\odot(u)}{u} w^2(u, R_\odot) \mathrm{d}u$$

$$C_{\max}(t) = \frac{1}{3}\pi \frac{\rho_\chi}{m_\chi} R_\odot^2(t) \left(e^{-\frac{3}{2}\frac{u_\odot^2}{u_0^2}} \sqrt{\frac{6}{\pi}} u_0 + \frac{6G_\mathrm{N} M_\odot + R_\odot(u_0^2 + 3u_\odot^2)}{R_\odot u_\odot} \mathrm{Erf}\left[\sqrt{\frac{3}{2}} \frac{u_\odot}{u_0}\right] \right)$$

- We take minimum of the limit and capture rate



Annihilation in the Sun

- The number density of dark matter is given by

$$\frac{\mathrm{d}N_\chi(t)}{\mathrm{d}t} = C(t) - A(t) - E(t) = 0$$

- At steady state, the annihilation rate only depends on the capture:

$$\Gamma_A = (C/2)\tanh^2(t/\tau)$$

- The final neutrino flux is found from branching ratios

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{\Gamma_A}{4\pi D^2}\sum_f B_\chi^f \frac{\mathrm{d}N_\nu^f}{\mathrm{d}E_\nu}$$

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Other Applications

- The same calculation in other stars can be performed
  - Working on integration with GARSTEC to facilitate stellar evolution

- Can look at other phenomena like
  - Energy transport [4,5]
  - Modified main sequence lifetimes [6]
  - Triggering thermonuclear explosions in stellar remnants [7-9]

Capt’n General

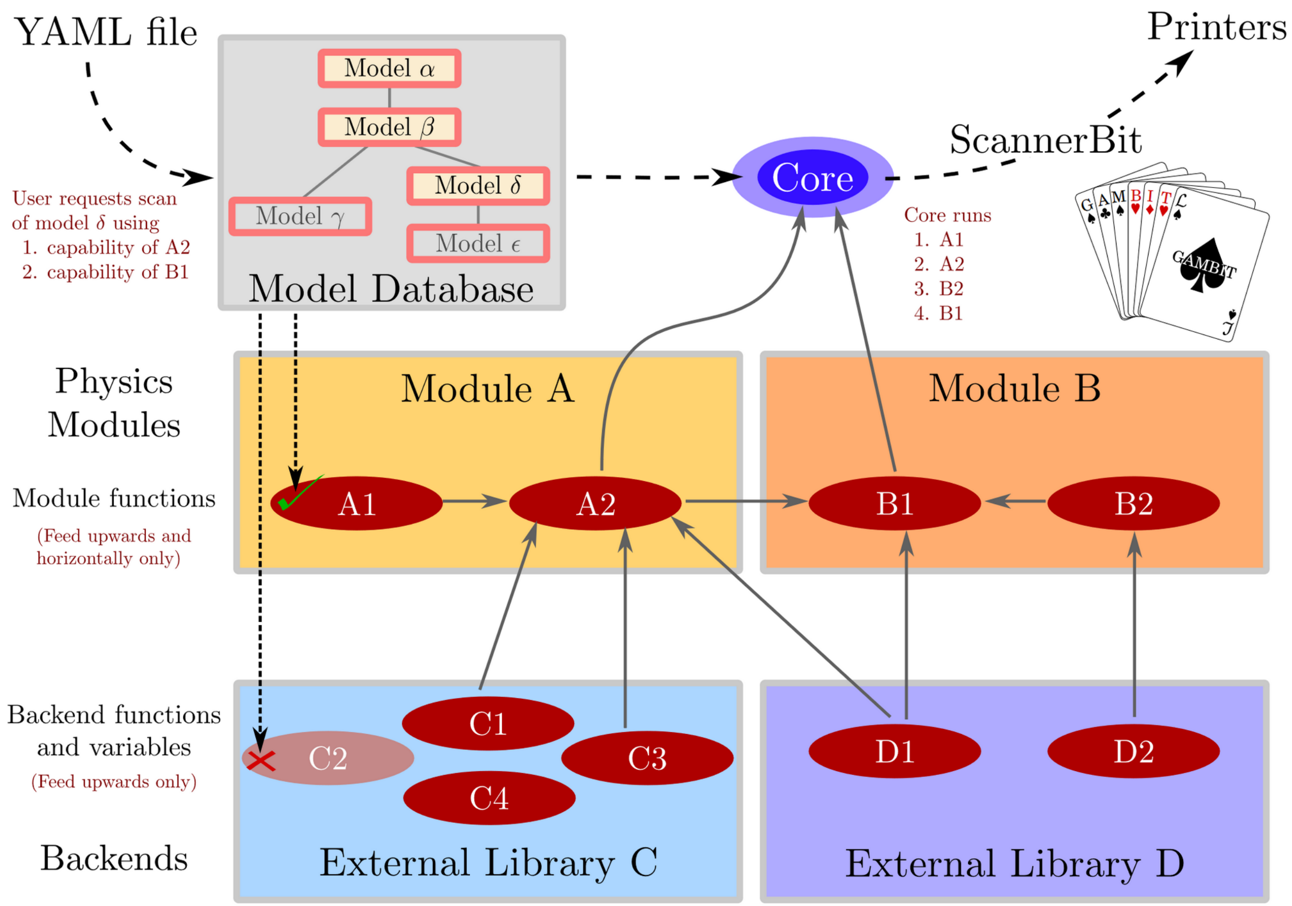
- Capt’n [10] was designed for capture rate calculations
  - As standalone
  - GAMBIT backend
  - DarkMESA companion
  - GARSTEC integration
- Capt’n uses several parameters to calculate the DM capture rate in s^{-1}
  - Solar model including isotopic abundances
  - Dark matter halo parameters
  - Interaction model

Global and Modular BSM Inference Tool

(GAMBIT)

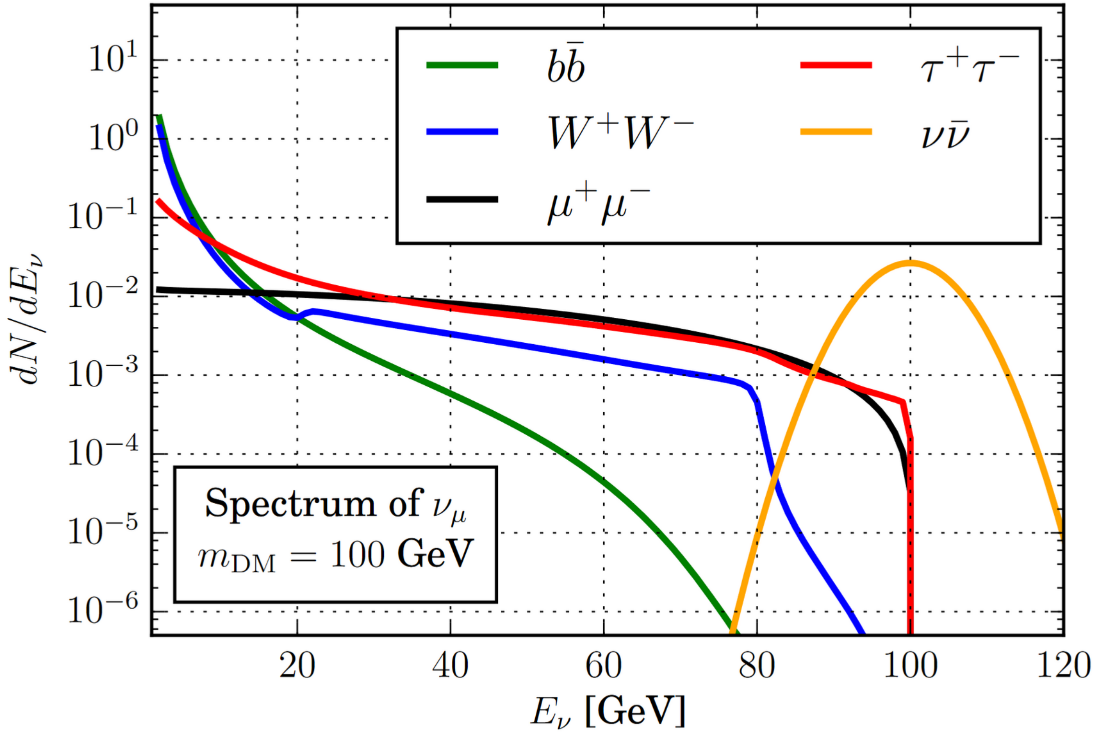
GAMBIT

- GAMBIT [11] combines many separate branches of physics to perform global scans of novel physics using existing experimental data
- Modular design to promote contributions
- Global scans can pick out signals of new physics before single experiments



IceCube Neutrino Observatory

- For the 79-string run, IceCube's [12] digital optical modules were arranged as:
  - 73 strings with 125 m horizontal spacing and 17 m vertical spacing
  - 6 strings with less than 75 m horizontal spacing and 7 m vertical spacing in the DeepCore [13]
- The data is broken into three independent streams, of two varieties:
  - Low energy: exterior strings act as muon veto for the central array (Summer Low and Winter Low)
  - Higher energy: no restrictions (Winter High)
- IceCube performs better at higher-energy neutrino detection



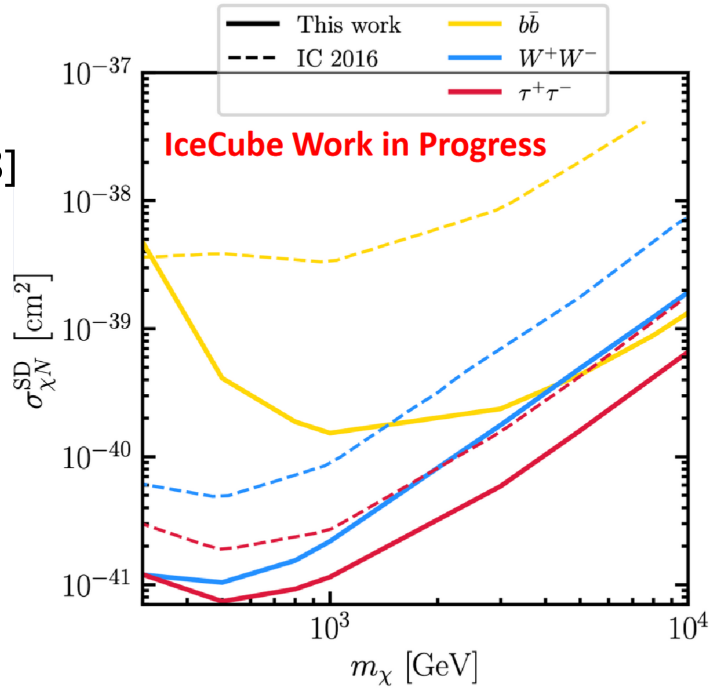
[14]

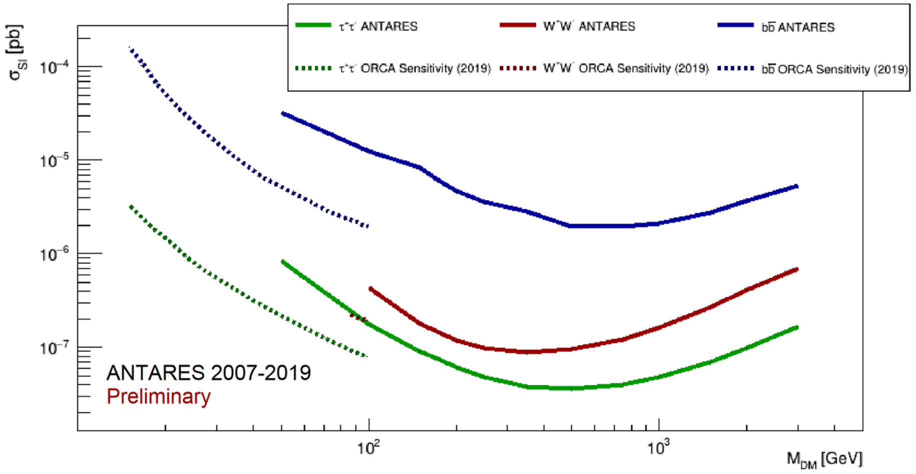
Direct Detection Experiments

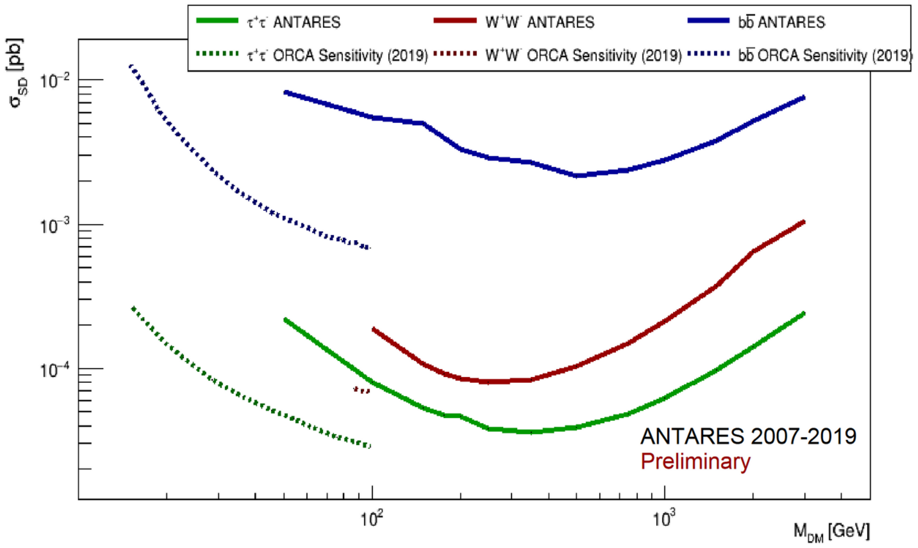
- Fourteen direct detection experiments were included:
  - LUX 2016 [15]
  - XENON1T 2018 [16]
  - PandaX-II 2016 [17] and 2017 [18]
  - PICO-60 2017 [19]
  - CRESST-II [20]
  - CDMSlite [21]
  - DarkSide-50 [22]
  - CRESST-III [29]
  - LZ [30]
  - PandaX-4T [31]
  - SIMPLE [32]
  - SuperCDMS [33]
  - XENON100 [34]
- Additionally, projections are included from:
  - DARWIN [35]
  - PICO-500 [36]

Added Experiments

- Four extra experiments were included in a post processing run:
  - ANTARES from Dark Ghosts 2022 presented by Chiara Poirè [23]
  - IceCube Update from Dark Ghosts 2022 presented by Stephan Meighen-Berger [24]
  - SuperK analysis from 2015 [27]
  - DeepCore analysis from 2022 [28]







Results and Scans

GAMBIT Scan Parameters

- The common parameters are shared between all GAMBIT scans

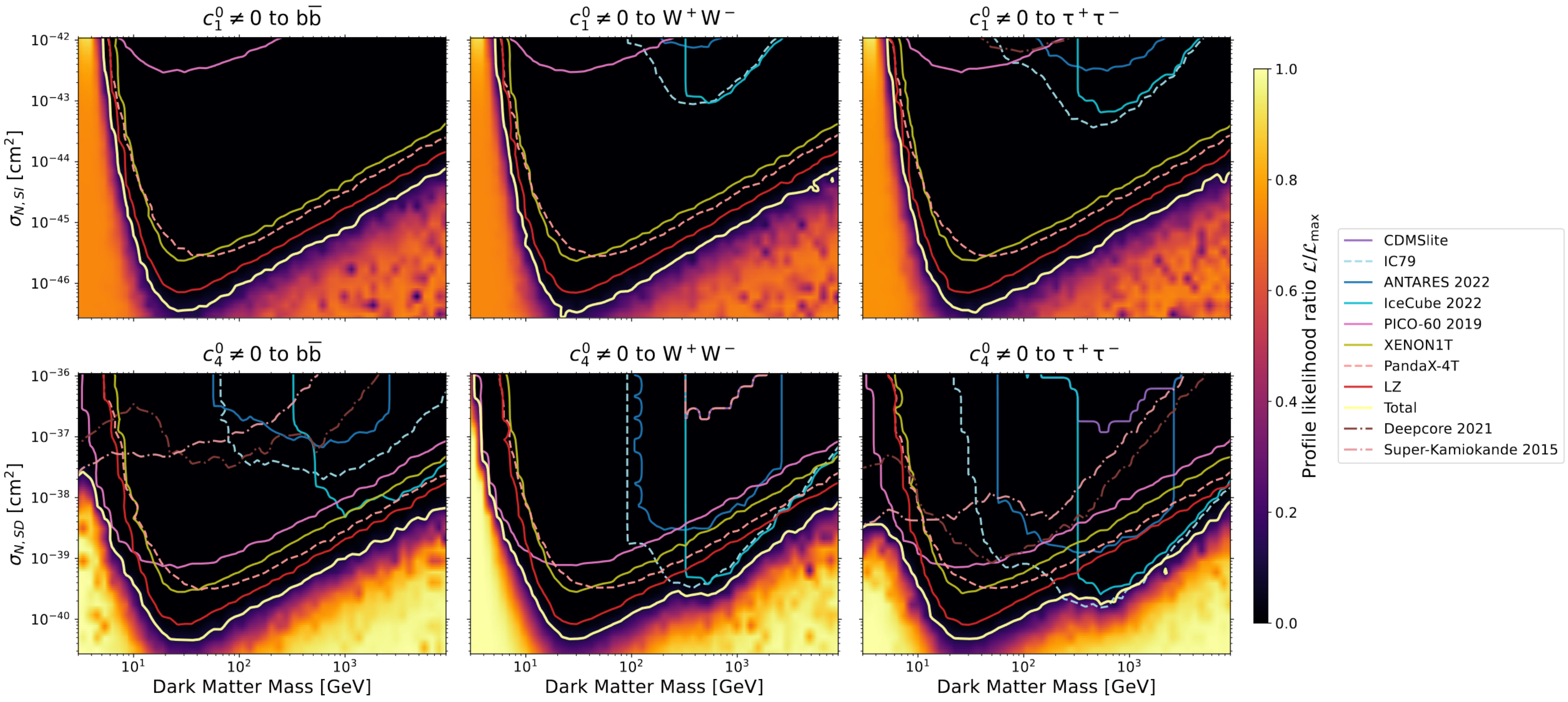
Common model parameters	
$\log_{10}(m_{\rm dm})$ (GeV)	(0, 4)
ρ_0 (GeV cm^{-3})	0.5
v_0 (km sec^{-1})	(216, 264)
v_{rot} (km sec^{-1})	(216, 264)
v_{esc} (km sec^{-1})	(453, 603)

- These scans are presented as profiled likelihoods with 90% C.L.
- All scans have 3 decay channel versions: bottom quark, W boson, and tau

Coupling parameters (GeV^{-2})	
$\log_{10}(c_1^0)$	(−10, −6)
$\log_{10}(c_3^0)$	(−6, −3)
$\log_{10}(c_4^0)$	(−8, −3)
$\log_{10}(c_5^0)$	(−5, −2)
$\log_{10}(c_6^0)$	(−5, −1)
$\log_{10}(c_7^0)$	(−4, −1)
$\log_{10}(c_8^0)$	(−6, −4)
$\log_{10}(c_9^0)$	(−6, −1)
$\log_{10}(c_{10}^0)$	(−6, −2)
$\log_{10}(c_{11}^0)$	(−9, −5)
$\log_{10}(c_{12}^0)$	(−8, −4)
$\log_{10}(c_{13}^0)$	(−5, −1)
$\log_{10}(c_{14}^0)$	(−3, 1)
$\log_{10}(c_{15}^0)$	(−5, −2)

Spin-Independent and Spin-Dependent Channel

- The three annihilation channels for c_1 (top) and c_4 (bottom)



$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$

$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$

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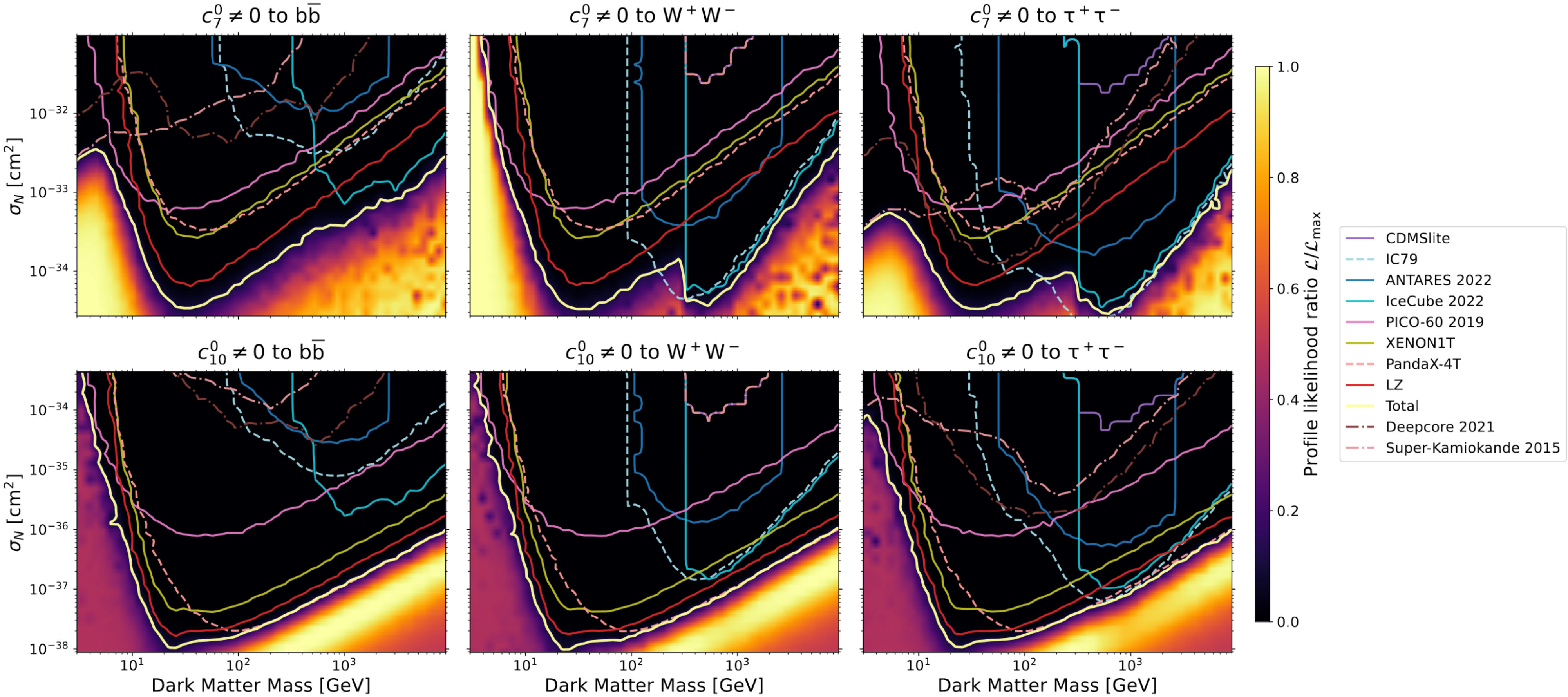
C_7 and C_{10} Coupling Experiment Breakdown

- The three annihilation channels for c_7 (top) and c_{10} (bottom)

$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_{\mathrm{N}} \cdot \hat{\mathbf{v}}^{\perp}$$

$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$



$$\mathcal{L} \supset -\lambda_3 \bar{\chi}\gamma^{\mu}\chi G_{\mu} - h_4 \bar{q}\gamma_{\mu}\gamma^5 q G^{\mu} \to \hat{\mathcal{H}} \supset \left(c_7^0 t^0 + c_7^1 t^1\right) \hat{\mathcal{O}}_7$$

$$\mathcal{L} \supset -\lambda_1 \phi \bar{\chi}\chi - i h_2 \phi \bar{q}\gamma^5 q \to \hat{\mathcal{H}} \supset \left(c_{10}^0 t^0 + c_{10}^1 t^1\right) \hat{\mathcal{O}}_{10}$$

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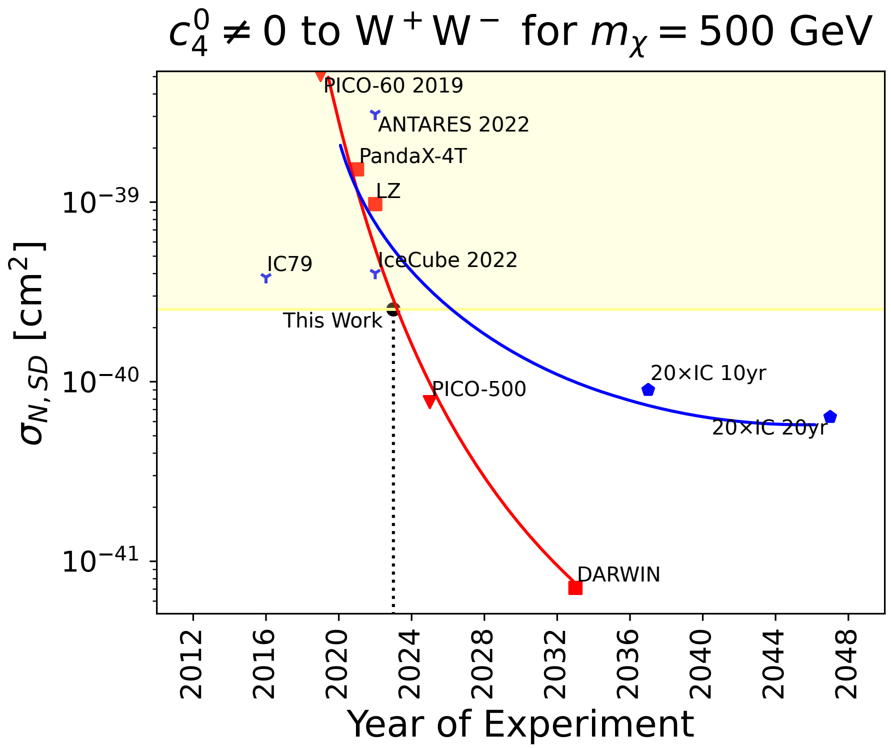
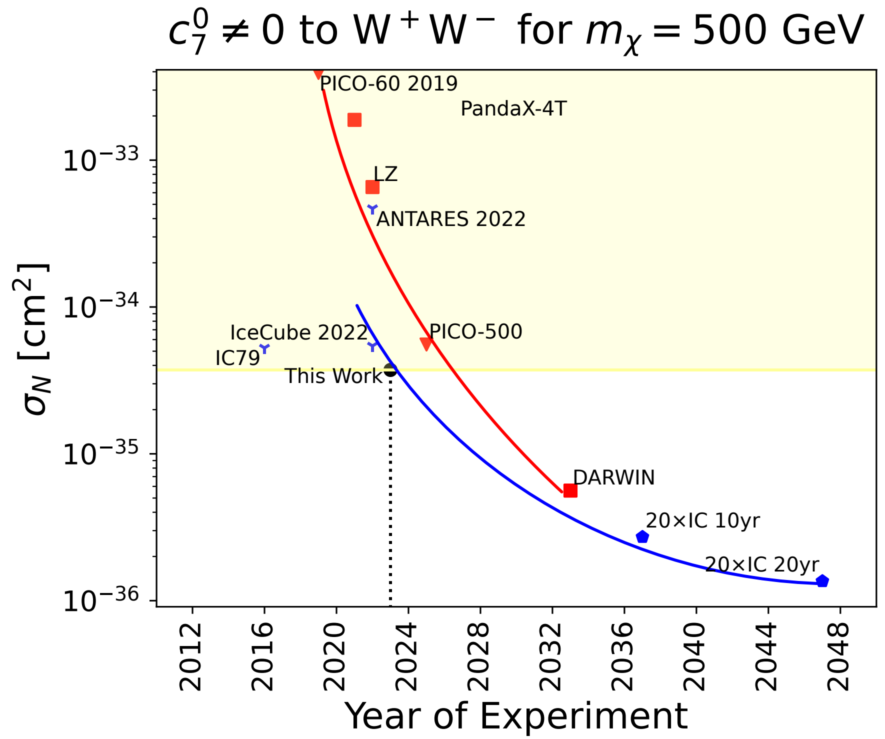
Future Outlook

- Future prospects for neutrino telescopes in comparison with direct detection

$$\text{Projection} = \text{IC2022} \times \left(\frac{V}{V_{\text{IC2022}}} \frac{T}{T_{\text{IC2022}}} \right)^{-\frac{1}{2}}$$





Conclusions

Conclusions

- Capt'n open to public and has already seen use by GAMBIT community (2106.02056)
- This is some of the first set of global constraints on non-relativistic effective operator dark matter from direct detection experiments in addition to solar neutrinos
- IceCube solar neutrinos can assist with spin-dependent direct detection searches
- Whenever new data is added to GAMBIT this work can be re-run with trivial modifications to improve constraints
- This work has been modified for use in a Supernova scattering search lead by Christopher Cappiello
- Current work to use this in stellar evolution and solar calibration

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Thank You

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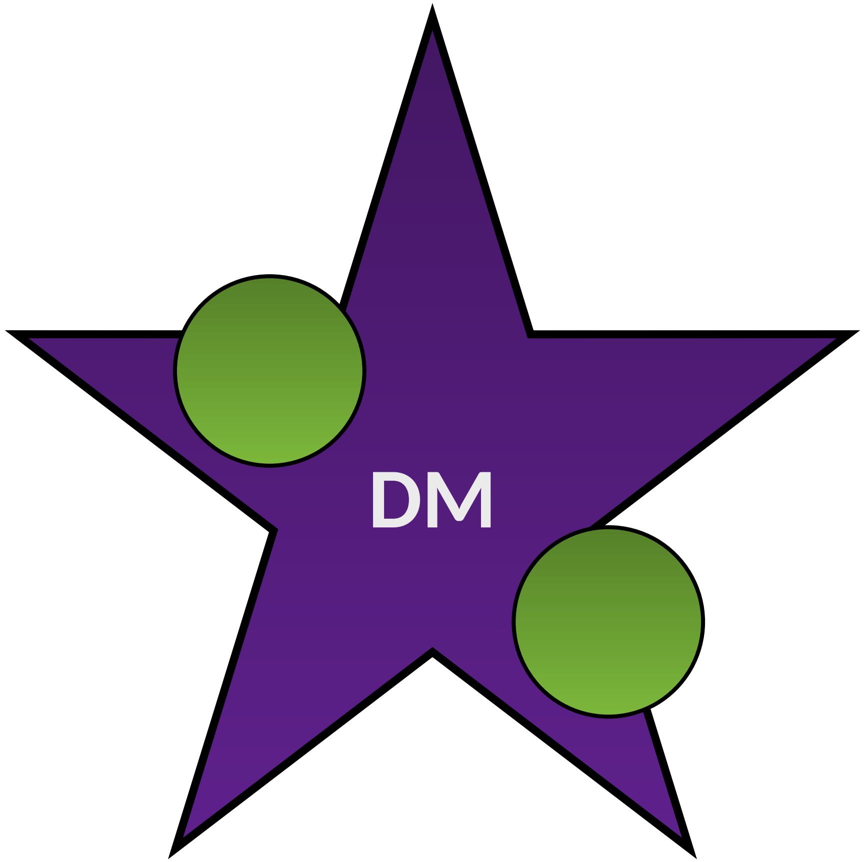
Backup Slides

Advantages of an Effective Field Theory

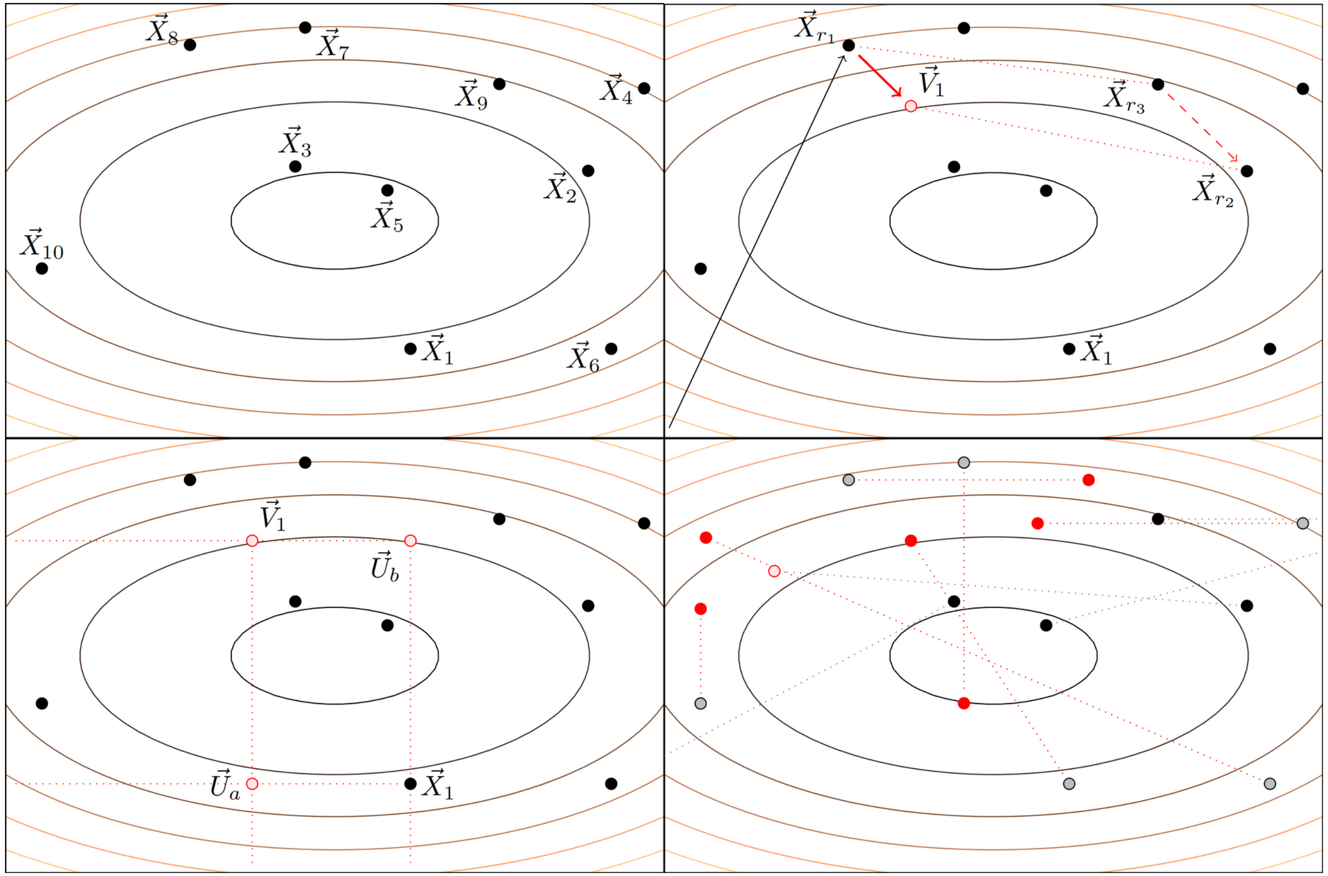
- High-energy theory parameterization
- Fitzpatrick et. al. [2] describe a toy model dark matter effective field theory
- Dark matter substructure can be ignored at galactic halo velocities

$$\hat{\mathbf{q}}_{\mathrm{max}} = 200\ \mathrm{MeV}$$



Scanning with Diver

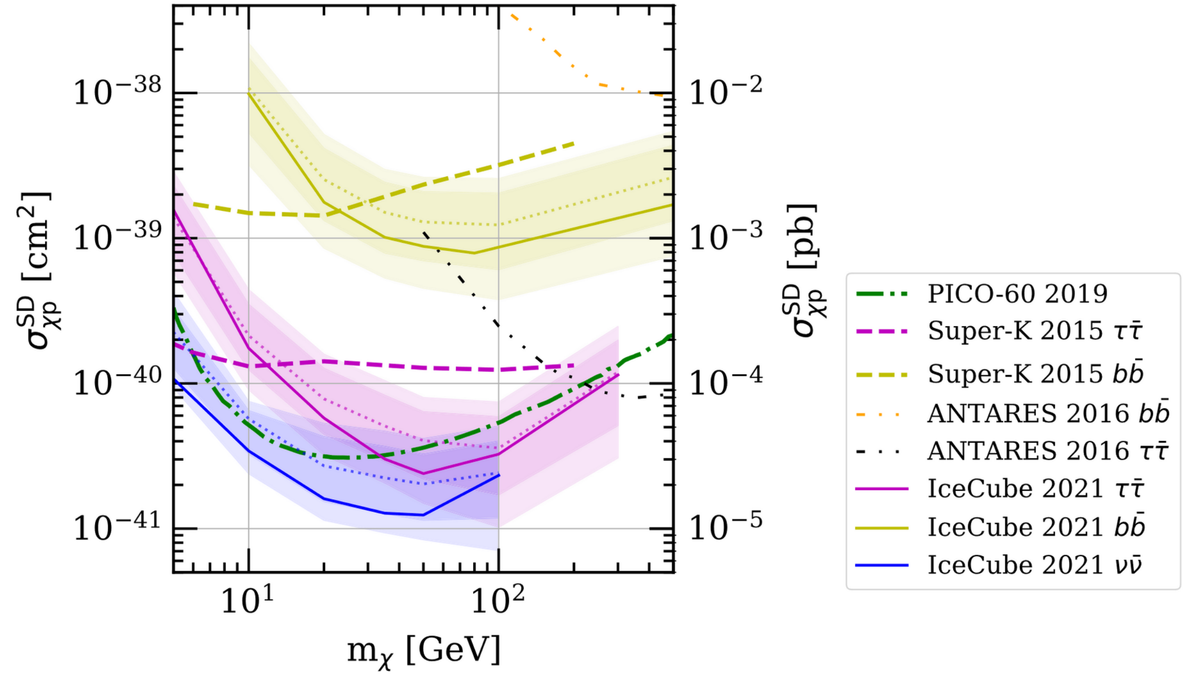
- Diver is a differential evolution scanner in GAMBIT
- It can rapidly map likelihood contours
- But cannot give posteriors
- Differential evolution occurs in three steps
  - Mutation
  - Crossover
  - Selection

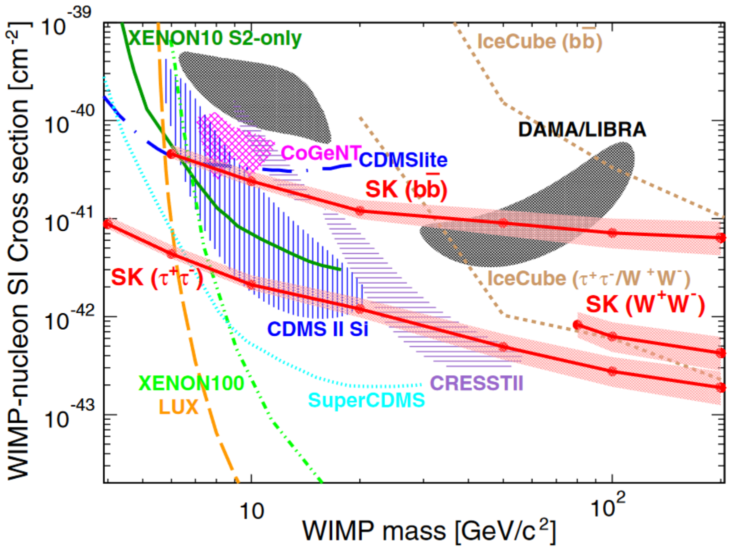


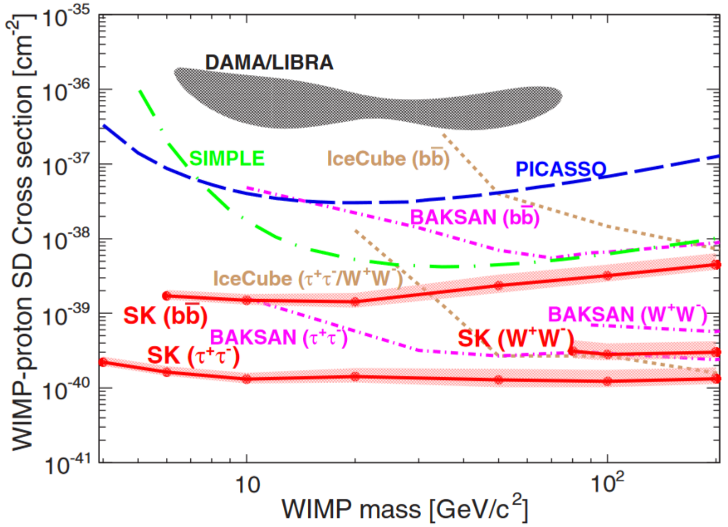
[25]

SuperK and DeepCore

- SuperK analysis from 2015 [27]
- DeepCore analysis from 2022 [28]







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Dent et. al. [3] Tables

- Spin-0 Wimp

TABLE VII. Non-relativistic reduction of operators for a spin-0 WIMP

Scalar Mediator		
$(S^\dagger S)(\bar{q}q)$	$\longrightarrow$	$\left(\frac{h_1^N g_1}{m_\phi^2}\right)\mathcal{O}_1$
$(S^\dagger S)(\bar{q}\gamma^5 q)$	$\longrightarrow$	$\left(\frac{h_2^N g_1}{m_\phi^2}\right)\mathcal{O}_{10}$
Vector Mediator		
$i(S^\dagger\partial_\mu S - \partial_\mu S^\dagger S)(\bar{q}\gamma^\mu q)$	$\longrightarrow$	0
$i(S^\dagger\partial_\mu S - \partial_\mu S^\dagger S)(\bar{q}\gamma^\mu\gamma^5 q)$	$\longrightarrow$	$\left(\frac{2ig_4 h_4^N}{m_G^2}\frac{m_N}{m_S}\right)\mathcal{O}_{10}$
Charged Spinor Mediator		
$(S^\dagger S)(\bar{q}q)$	$\longrightarrow$	$\frac{y_1^\dagger y_1 - y_2^\dagger y_2}{m_Q m_S} f_T^N \mathcal{O}_1$
$(S^\dagger S)(\bar{q}\gamma^5 q)$	$\longrightarrow$	$i\frac{y_2^\dagger y_1 - y_1^\dagger y_2}{m_Q m_S}\tilde{\Delta}^N\mathcal{O}_{10}$

Dent et. al. [3] Tables

- Spin-1/2 WIMP

TABLE VIII. Operators for a spin-$\frac{1}{2}$ WIMP via a neutral mediator

Scalar Mediator		
$\bar{\chi}\chi\bar{q}q$	$\longrightarrow$	$\left(\frac{h_1^N\lambda_1}{m_\phi^2}\right)\mathcal{O}_1$
$\bar{\chi}\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{h_2^N\lambda_1}{m_\phi^2}\right)\mathcal{O}_{10}$
$\bar{\chi}\gamma^5\chi\bar{q}q$	$\longrightarrow$	$\left(-\frac{h_1^N\lambda_2 m_N}{m_\phi^2 m_\chi}\right)\mathcal{O}_{11}$
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{h_2^N\lambda_2 m_N}{m_\phi^2 m_\chi}\right)\mathcal{O}_6$
Vector Mediator		
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\left(-\frac{h_3^N\lambda_3}{m_G^2}\right)\mathcal{O}_1$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\left(-\frac{2h_4^N\lambda_3}{m_G^2}\right)\left(-\mathcal{O}_7+\frac{m_N}{m_\chi}\mathcal{O}_9\right)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\left(-\frac{2h_3^N\lambda_4}{m_G^2}\right)(\mathcal{O}_8+\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\left(\frac{4h_4^N\lambda_4}{m_G^2}\right)\mathcal{O}_4$

TABLE IX. Non-relativistic reduction of operators for a spin-$\frac{1}{2}$ WIMP via a charged mediator (after using Fierz identities)

Charged Scalar Mediator		
$\bar{\chi}\chi\bar{q}q$	$\longrightarrow$	$\frac{l_2^\dagger l_2-l_1^\dagger l_1}{4m_\Phi^2}f_{Tq}^N\mathcal{O}_1$
$\bar{\chi}\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$i\frac{l_1^\dagger l_2-l_2^\dagger l_1}{4m_\Phi^2}\Delta\tilde{q}^N\mathcal{O}_{10}$
$\bar{\chi}\gamma^5\chi\bar{q}q$	$\longrightarrow$	$i\frac{l_2^\dagger l_1-l_1^\dagger l_2}{4m_\Phi^2}\frac{m_N}{m_\chi}f_{Tq}^N\mathcal{O}_{11}$
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\frac{l_1^\dagger l_1-l_2^\dagger l_2}{4m_\Phi^2}\frac{m_N}{m_\chi}\Delta\tilde{q}^N\mathcal{O}_6$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$-\frac{l_1^\dagger l_1+l_2^\dagger l_2}{4m_\Phi^2}N_q^N\mathcal{O}_1$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\frac{l_1^\dagger l_2+l_2^\dagger l_1}{2m_\Phi^2}N_q^N(\mathcal{O}_8+\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\frac{l_1^\dagger l_2+l_2^\dagger l_1}{2m_\Phi^2}\Delta_q^N(\mathcal{O}_7-\frac{m_N}{m_\chi}\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$-\frac{l_1^\dagger l_1+l_2^\dagger l_2}{m_\Phi^2}\Delta_q^N\mathcal{O}_4$
$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$\longrightarrow$	$\frac{l_2^\dagger l_2-l_1^\dagger l_1}{m_\Phi^2}\delta_q^N\mathcal{O}_4$
$\epsilon_{\mu\nu\alpha\beta}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma^{\alpha\beta}q$	$\longrightarrow$	$\frac{l_2^\dagger l_1-l_1^\dagger l_2}{m_\Phi^2}\delta_q^N(i\mathcal{O}_{10}-i\frac{m_N}{m_\chi}\mathcal{O}_{11}+4\mathcal{O}_{12})$
Charged Vector Mediator		
$\bar{\chi}\chi\bar{q}q$	$\longrightarrow$	$\frac{d_2^\dagger d_2-d_1^\dagger d_1}{4m_V^2}f_{Tq}^N\mathcal{O}_1$
$\bar{\chi}\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$i\frac{d_2^\dagger d_1-d_1^\dagger d_2}{4m_V^2}\Delta\tilde{q}^N\mathcal{O}_{10}$
$\bar{\chi}\gamma^5\chi\bar{q}q$	$\longrightarrow$	$i\frac{d_2^\dagger d_1-d_1^\dagger d_2}{4m_V^2}\frac{m_N}{m_\chi}f_{Tq}^N\mathcal{O}_{11}$
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\frac{d_2^\dagger d_2-d_1^\dagger d_1}{4m_V^2}\frac{m_N}{m_\chi}\Delta\tilde{q}^N\mathcal{O}_6$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\frac{d_2^\dagger d_2+d_1^\dagger d_1}{8m_V^2}N_q^N\mathcal{O}_1$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$-\frac{d_2^\dagger d_1+d_1^\dagger d_2}{4m_V^2}N_q^N(\mathcal{O}_8+\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\frac{d_2^\dagger d_1+d_1^\dagger d_2}{4m_V^2}\Delta_q^N(\mathcal{O}_7-\frac{m_N}{m_\chi}\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$-\frac{d_2^\dagger d_2+d_1^\dagger d_1}{2m_V^2}\Delta_q^N\mathcal{O}_4$

Dent et. al. [3] Tables

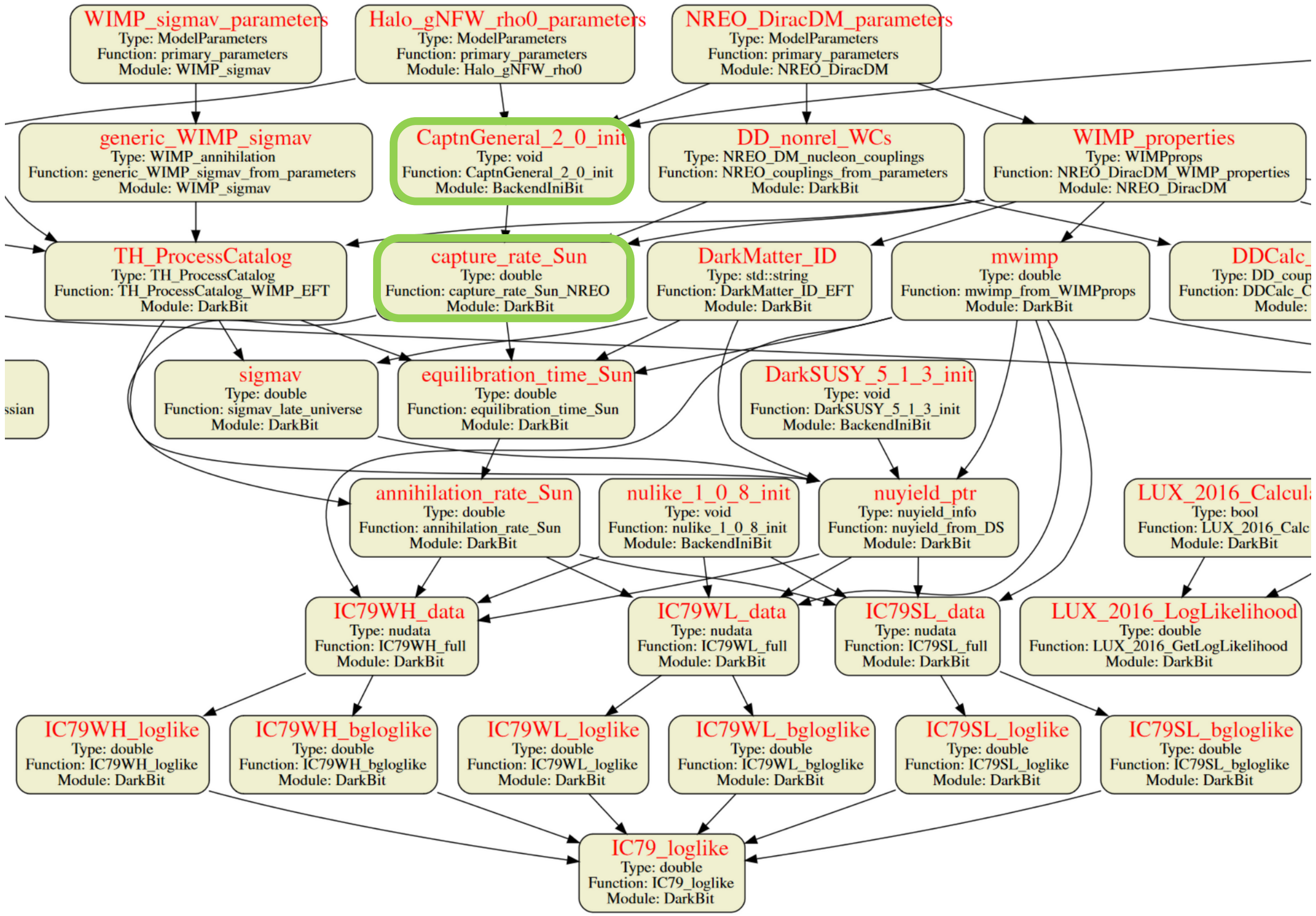
- Spin-1 WIMP

TABLE X. Non-relativistic reduction of operators for a spin-1 WIMP

Operator		Non-relativistic reduction
Scalar Mediator		
$X_\mu^\dagger X^\mu \bar{q} q$	$\longrightarrow$	$\left(\frac{b_1 h_1^N}{m_\phi^2}\right)\mathcal{O}_1$
$X_\mu^\dagger X^\mu \bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{b_1 h_2^N}{m_\phi^2}\right)\mathcal{O}_{10}$
Vector Mediator		
$(X_\nu^\dagger \partial_\mu X^\nu - \partial_\mu X_\nu^\dagger X^\nu)(\bar{q}\gamma^\mu q)$	$\longrightarrow$	0
$(X_\nu^\dagger \partial_\mu X^\nu - \partial_\mu X_\nu^\dagger X^\nu)(\bar{q}\gamma^\mu\gamma^5 q)$	$\longrightarrow$	$\left(\frac{-3b_5 h_4^N}{m_G^2}\frac{m_N}{m_X}\right)\mathcal{O}_{10}$
$\partial_\nu(X^{\nu\dagger}X_\mu + X_\mu^\dagger X^\nu)(\bar{q}\gamma^\mu q)$	$\longrightarrow$	$\left(\frac{\mathrm{Re}(b_6)h_3^N}{m_G^2}\frac{m_N}{m_X}\right)(\mathcal{O}_5 + \mathcal{O}_6 - \frac{q^2}{m_N^2}\mathcal{O}_4)$
$\partial_\nu(X^{\nu\dagger}X_\mu + X_\mu^\dagger X^\nu)(\bar{q}\gamma^\mu\gamma^5 q)$	$\longrightarrow$	$\left(-\frac{2\mathrm{Re}(b_6)h_4^N}{m_G^2}\frac{m_N}{m_X}\right)\mathcal{O}_9$
$\partial_\nu(X^{\nu\dagger}X_\mu - X_\mu^\dagger X^\nu)(\bar{q}\gamma^\mu q)$	$\longrightarrow$	$\left(-\frac{4\mathrm{Im}(b_6)h_3^N}{m_G^2}\frac{m_N}{m_X}\right)\mathcal{O}_{17}$
$\partial_\nu(X^{\nu\dagger}X_\mu - X_\mu^\dagger X^\nu)(\bar{q}\gamma^\mu\gamma^5 q)$	$\longrightarrow$	$\left(\frac{4\mathrm{Im}(b_6)h_4^N}{m_G^2}\frac{m_N}{m_X}\right)\mathcal{O}_{18}$
$\epsilon_{\mu\nu\rho\sigma}\left(X^{\nu\dagger}\partial^\rho X^\sigma + X^\nu\partial^\rho X^{\sigma\dagger}\right)(\bar{q}\gamma^\mu q)$	$\longrightarrow$	$\left(\frac{\mathrm{Re}(b_7)h_3^N}{m_G^2}\frac{m_N}{m_X}\right)\mathcal{O}_{11}$
$\epsilon_{\mu\nu\rho\sigma}\left(X^{\nu\dagger}\partial^\rho X^\sigma + X^\nu\partial^\rho X^{\sigma\dagger}\right)(\bar{q}\gamma^\mu\gamma^5 q)$	$\longrightarrow$	$\left(\frac{\mathrm{Re}(b_7)h_4^N}{m_G^2}\frac{m_N}{m_X}\right)(i\frac{q^2}{m_X m_N}\mathcal{O}_4 - i\frac{m_N}{m_X}\mathcal{O}_6 - 2\mathcal{O}_{14})$
$\epsilon_{\mu\nu\rho\sigma}\left(X^{\nu\dagger}\partial^\rho X^\sigma - X^\nu\partial^\rho X^{\sigma\dagger}\right)(\bar{q}\gamma^\mu q)$	$\longrightarrow$	$\left(\frac{2\mathrm{Im}(b_7)h_3^N}{m_G^2}\right)(\mathcal{O}_8 + \mathcal{O}_9)$
$\epsilon_{\mu\nu\rho\sigma}\left(X^{\nu\dagger}\partial^\rho X^\sigma - X^\nu\partial^\rho X^{\sigma\dagger}\right)(\bar{q}\gamma^\mu\gamma^5 q)$	$\longrightarrow$	$\left(\frac{4\mathrm{Im}(b_7)h_4^N}{m_G^2}\right)\mathcal{O}_4$
Charged Spinor Mediator		
$(X_\mu^\dagger X_\nu)(\bar{q}\gamma^\mu\gamma^\nu q)$	$\longrightarrow$	$\left(\frac{y_3^\dagger y_3 - y_4^\dagger y_4}{m_Q m_X}\right)\left(f_{Tq}^N\mathcal{O}_1 + 2\delta_q^N\mathcal{O}_4\right)$
$(X_\mu^\dagger X_\nu)(\bar{q}\gamma^\mu\gamma^\nu\gamma^5 q)$	$\longrightarrow$	$\left(\frac{y_4^\dagger y_3 - y_3^\dagger y_4}{m_Q m_X}\right)(i\Delta_{\bar{q}}^N\mathcal{O}_{10} + i\delta_q^N\mathcal{O}_{11} - 2i\delta_q^N\mathcal{O}_{12} - 2i\delta_q^N\mathcal{O}_{18})$

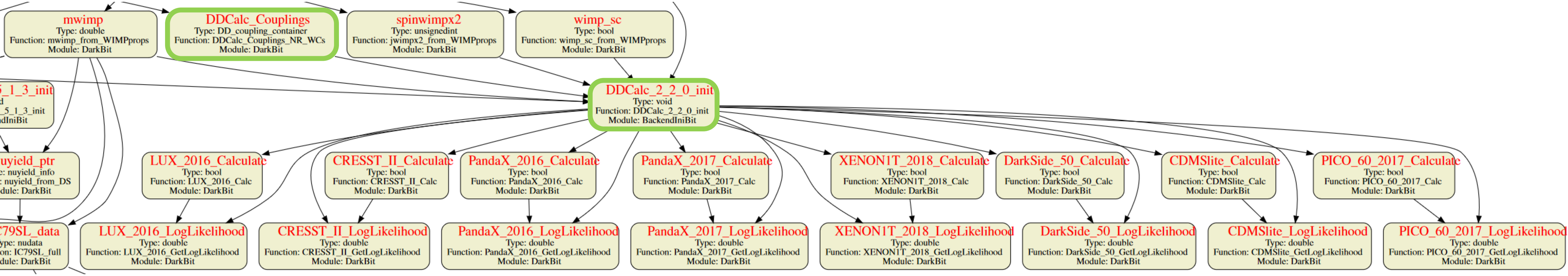
GAMBIT-Capt’n Dependency

- Capt’n acts as a backend of DarkBit
- It is used to calculate the capture rate for GAMBIT

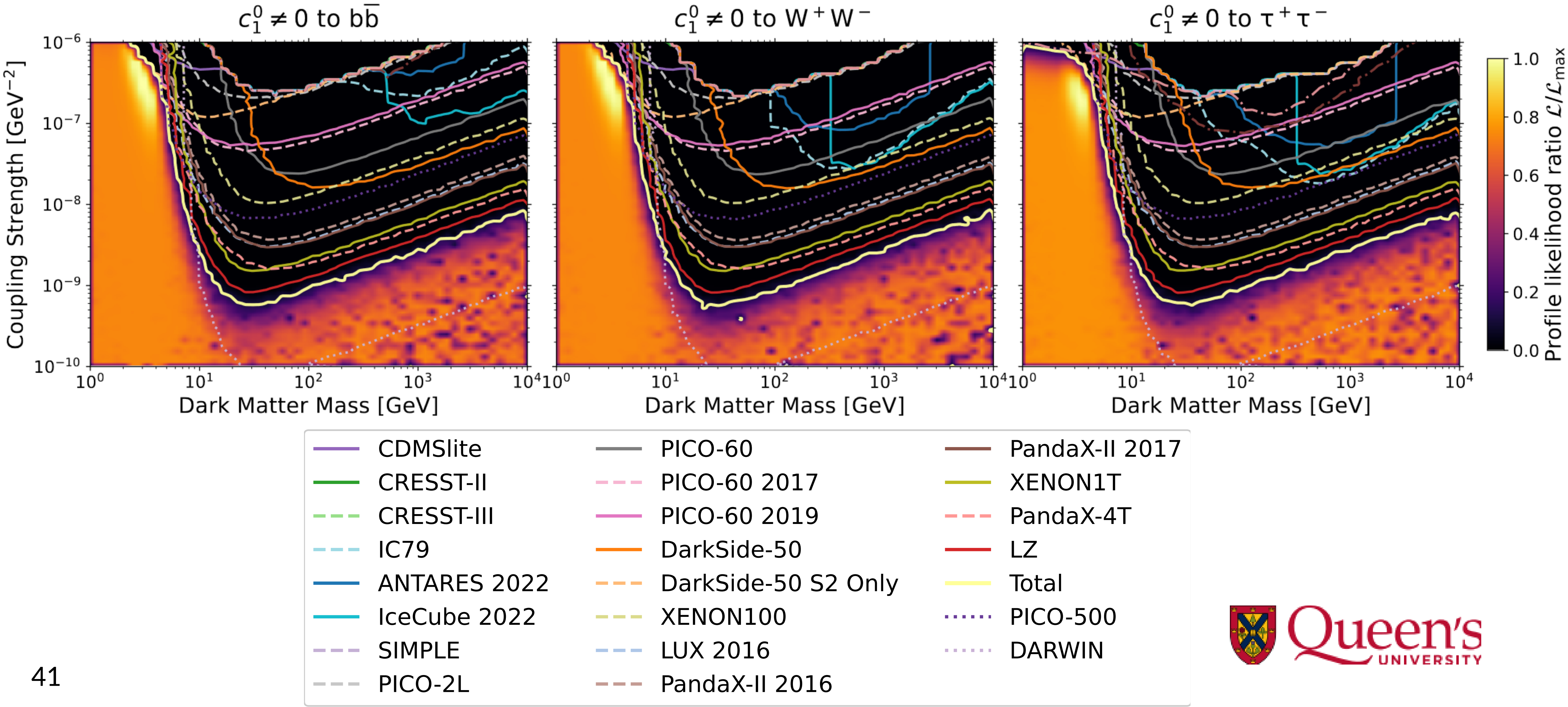


GAMBIT Direct Detection

- DDCalc acts to translate the couplings to cross sections for the DD experiments



c_1 Channels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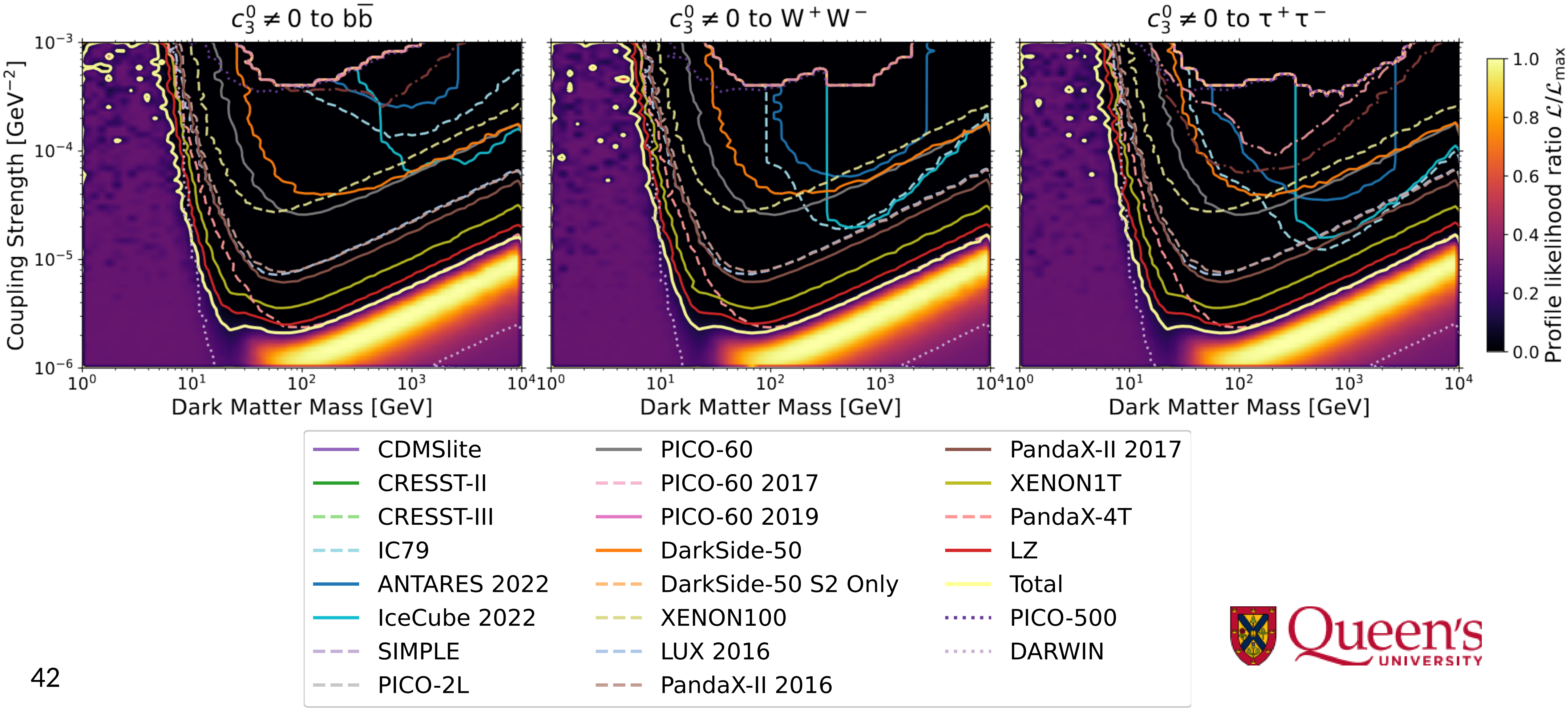
$c_1^0 \neq 0$ to W^+W^-
$c_1^0 \neq 0$ to $\tau^+\tau^-$
Coupling Strength [GeV^{-2}]
Dark Matter Mass [GeV]
Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{max}$
CDMSlite
CRESST-II
CRESST-III
IC79
ANTARES 2022
IceCube 2022
SIMPLE
PICO-2L
PICO-60
PICO-60 2017
PICO-60 2019
DarkSide-50
DarkSide-50 S2 Only
XENON100
LUX 2016
PandaX-II 2016
PandaX-II 2017
XENON1T
PandaX-4T
LZ
Total
PICO-500
DARWIN

c_3 Channels



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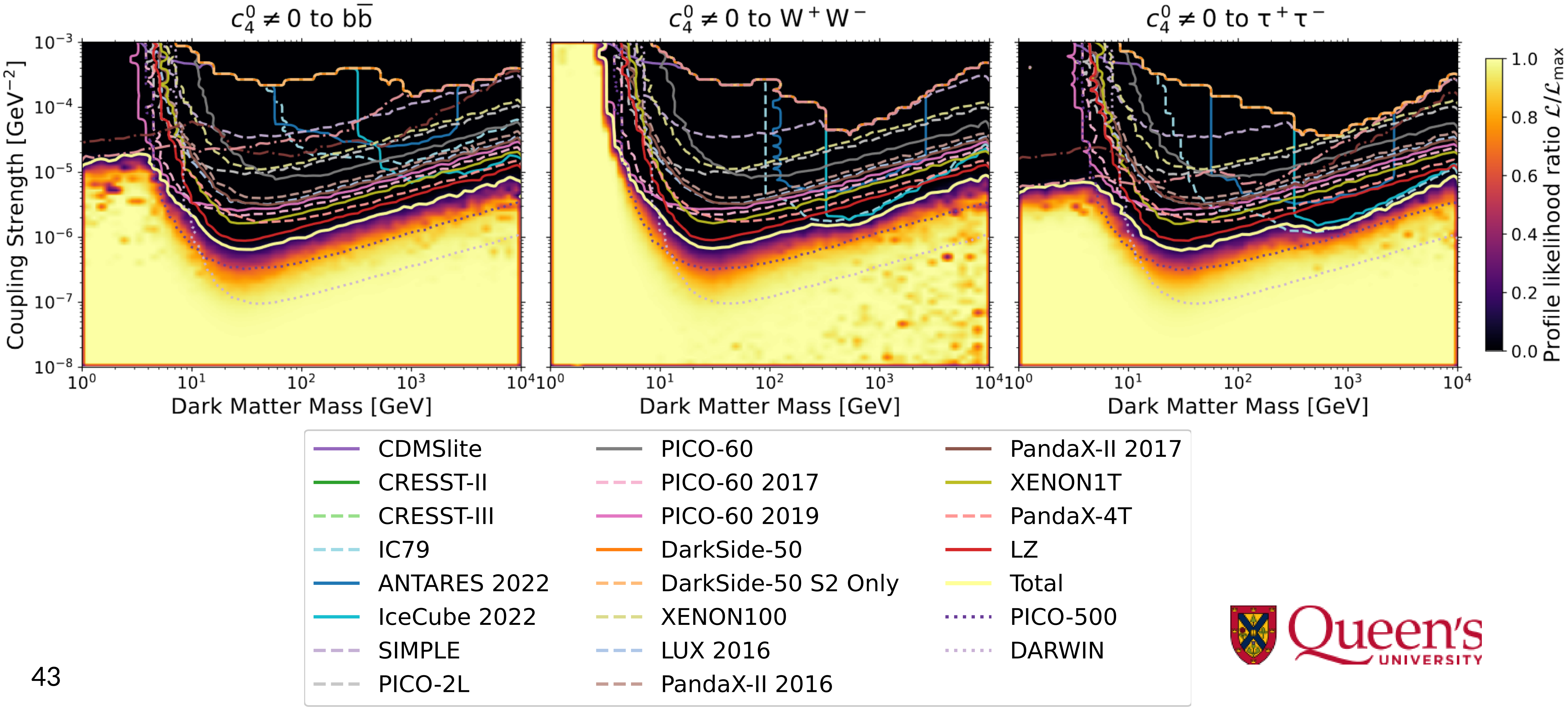
c_4 Channels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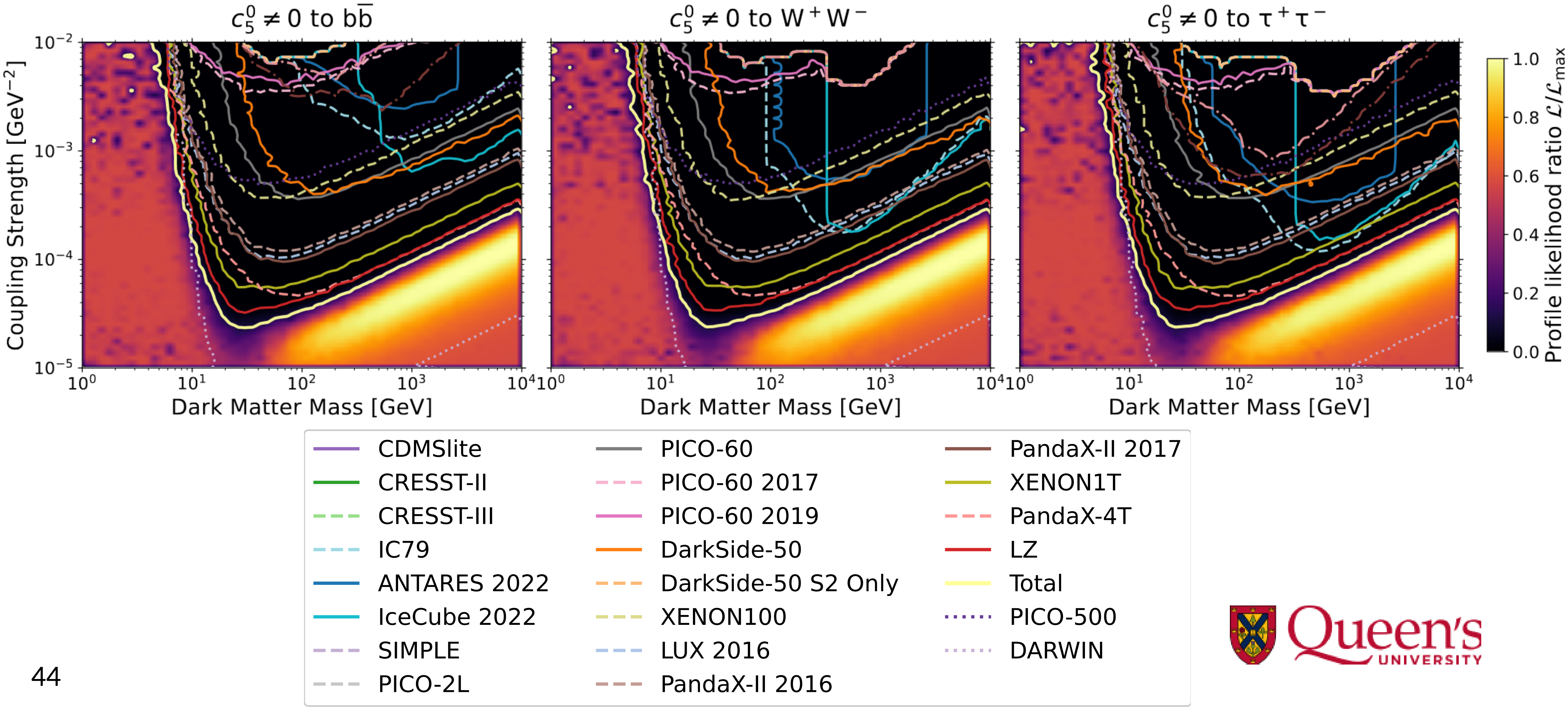
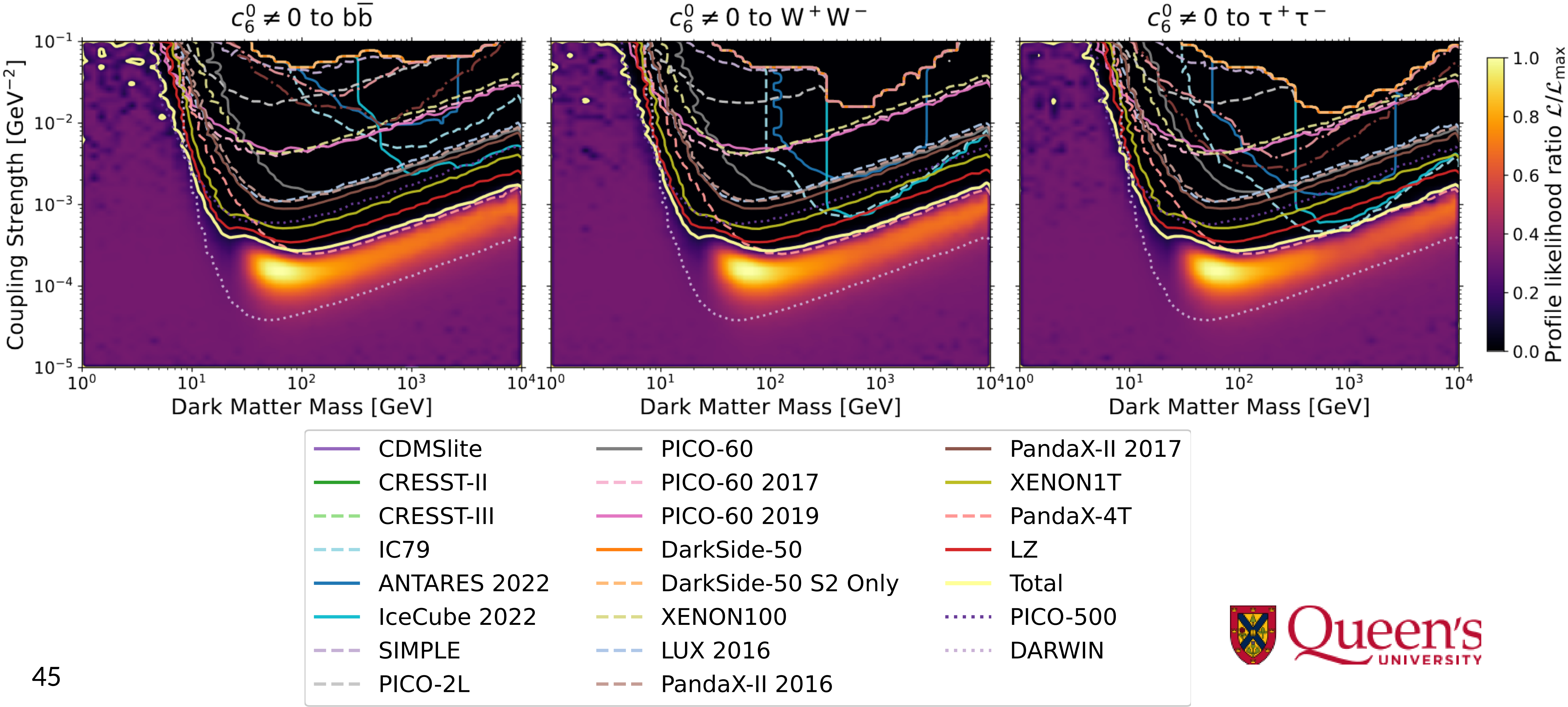
$c_4^0 \neq 0$ to W^+W^-
$c_4^0 \neq 0$ to $\tau^+\tau^-$
Coupling Strength [GeV^{-2}]
Dark Matter Mass [GeV]
Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{max}$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^0
10^1
10^2
10^3
10^4
1.0
0.8
0.6
0.4
0.2
0.0
CDMSlite
CRESST-II
CRESST-III
IC79
ANTARES 2022
IceCube 2022
SIMPLE
PICO-2L
PICO-60
PICO-60 2017
PICO-60 2019
DarkSide-50
DarkSide-50 S2 Only
XENON100
LUX 2016
PandaX-II 2016
PandaX-II 2017
XENON1T
PandaX-4T
LZ
Total
PICO-500
DARWIN

c_5 Channels



$c_5^0 \neq 0$ to $b\bar{b}$
$c_5^0 \neq 0$ to W^+W^-
$c_5^0 \neq 0$ to $\tau^+\tau^-$
Coupling Strength [GeV^{-2}]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^0
10^1
10^2
10^3
10^4
Dark Matter Mass [GeV]
Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{max}$
1.0
0.8
0.6
0.4
0.2
0.0
CDMSlite
CRESST-II
CRESST-III
IC79
ANTARES 2022
IceCube 2022
SIMPLE
PICO-2L
PICO-60
PICO-60 2017
PICO-60 2019
DarkSide-50
DarkSide-50 S2 Only
XENON100
LUX 2016
PandaX-II 2016
PandaX-II 2017
XENON1T
PandaX-4T
LZ
Total
PICO-500
DARWIN

c_6 Channels



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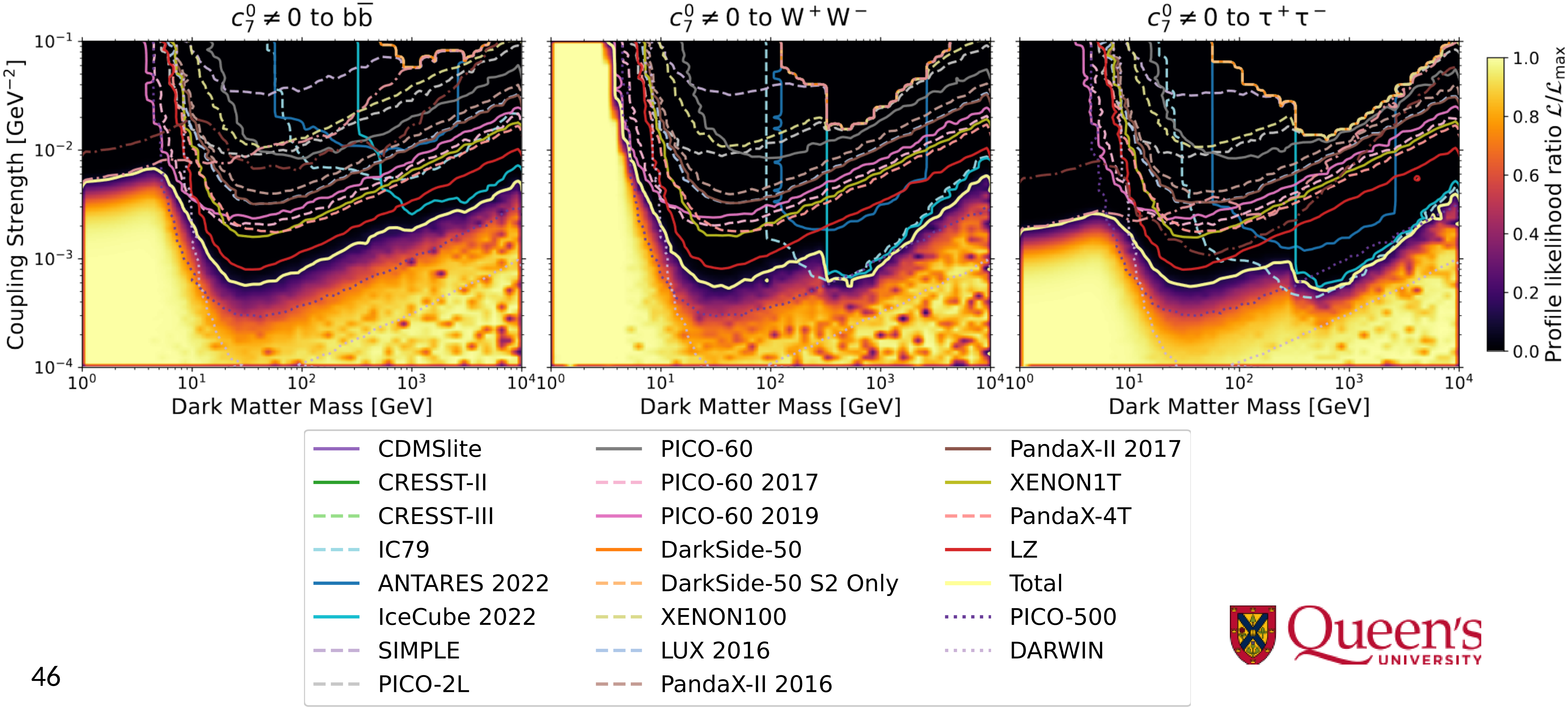
c_7 Channels



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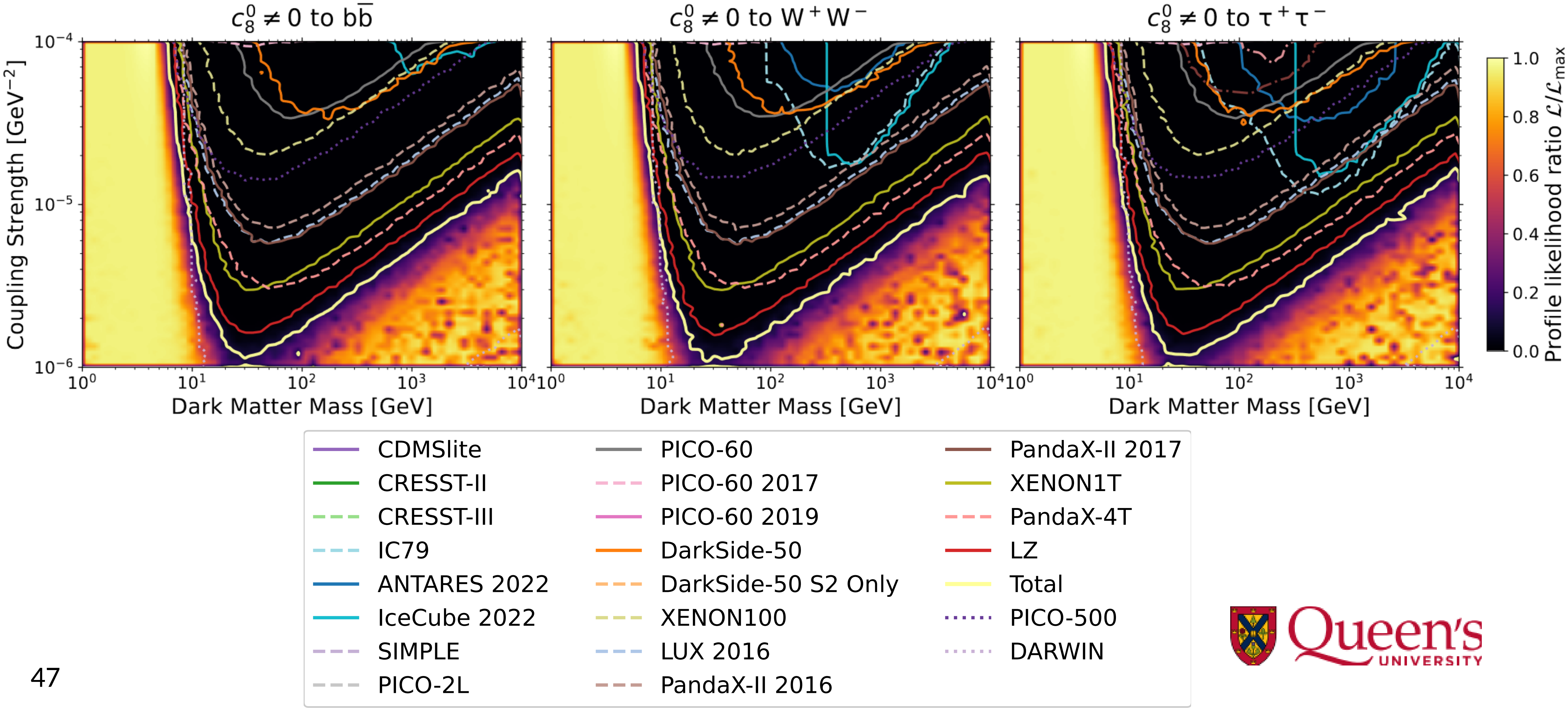
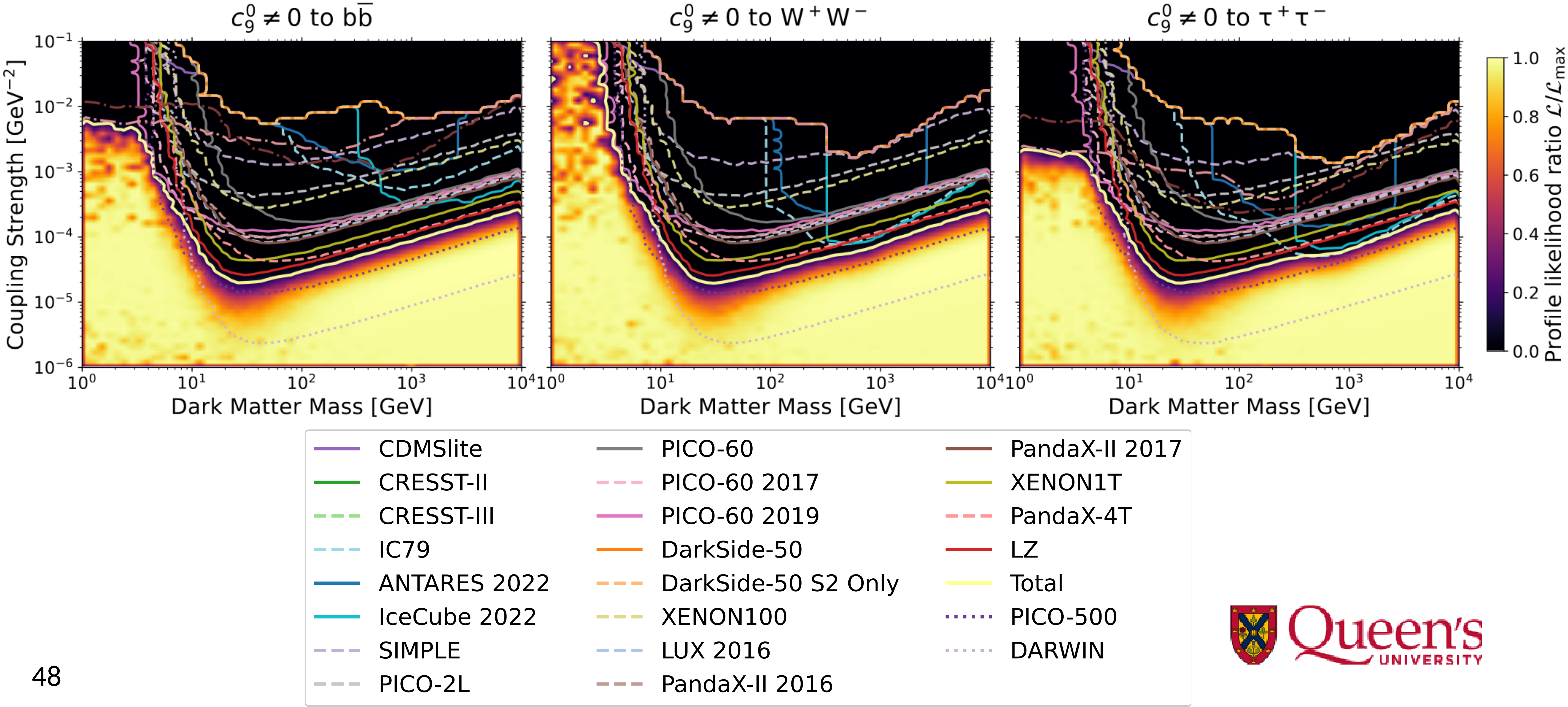
c_8 Channels



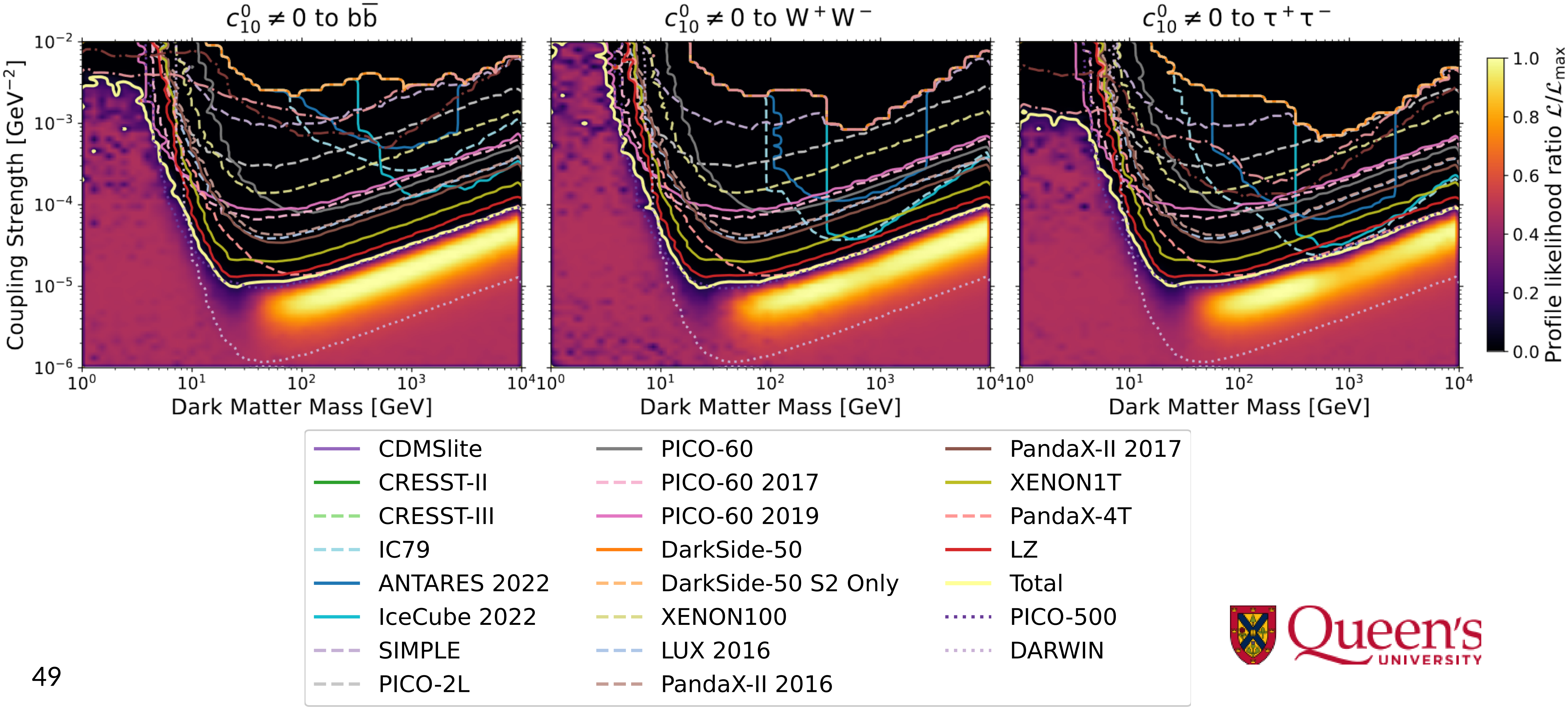
$c_8^0 \neq 0$ to $b\bar{b}$
$c_8^0 \neq 0$ to W^+W^-
$c_8^0 \neq 0$ to $\tau^+\tau^-$
Coupling Strength [GeV^{-2}]
10^{-4}
10^{-5}
10^{-6}
10^0
10^1
10^2
10^3
10^4
Dark Matter Mass [GeV]
Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{max}$
0.0
0.2
0.4
0.6
0.8
1.0
CDMSlite
CRESST-II
CRESST-III
IC79
ANTARES 2022
IceCube 2022
SIMPLE
PICO-2L
PICO-60
PICO-60 2017
PICO-60 2019
DarkSide-50
DarkSide-50 S2 Only
XENON100
LUX 2016
PandaX-II 2016
PandaX-II 2017
XENON1T
PandaX-4T
LZ
Total
PICO-500
DARWIN

c_9 Channels

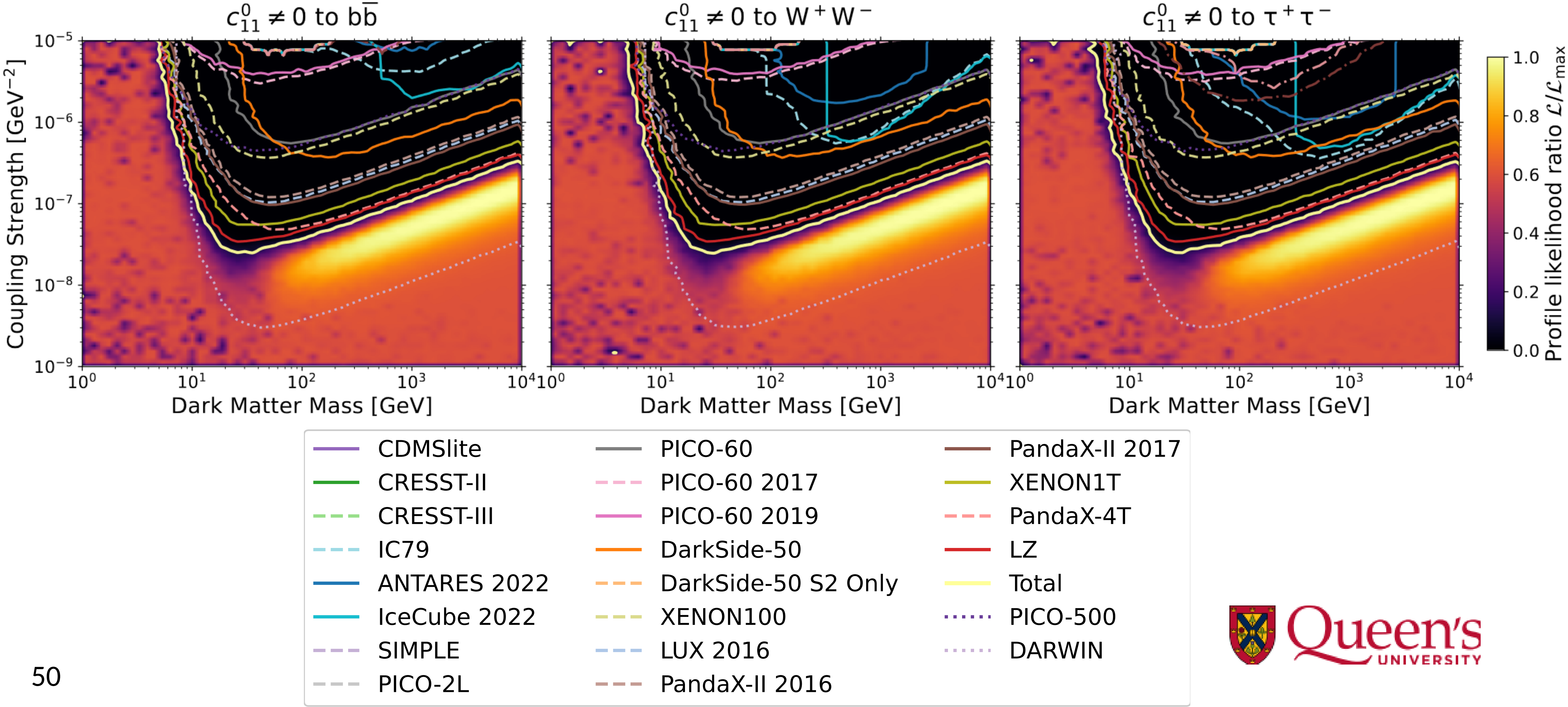


$c_9^0 \neq 0$ to $b\bar{b}$
$c_9^0 \neq 0$ to W^+W^-
$c_9^0 \neq 0$ to $\tau^+\tau^-$
Coupling Strength [GeV^{-2}]
Dark Matter Mass [GeV]
Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{max}$
CDMSlite
CRESST-II
CRESST-III
IC79
ANTARES 2022
IceCube 2022
SIMPLE
PICO-2L
PICO-60
PICO-60 2017
PICO-60 2019
DarkSide-50
DarkSide-50 S2 Only
XENON100
LUX 2016
PandaX-II 2016
PandaX-II 2017
XENON1T
PandaX-4T
LZ
Total
PICO-500
DARWIN

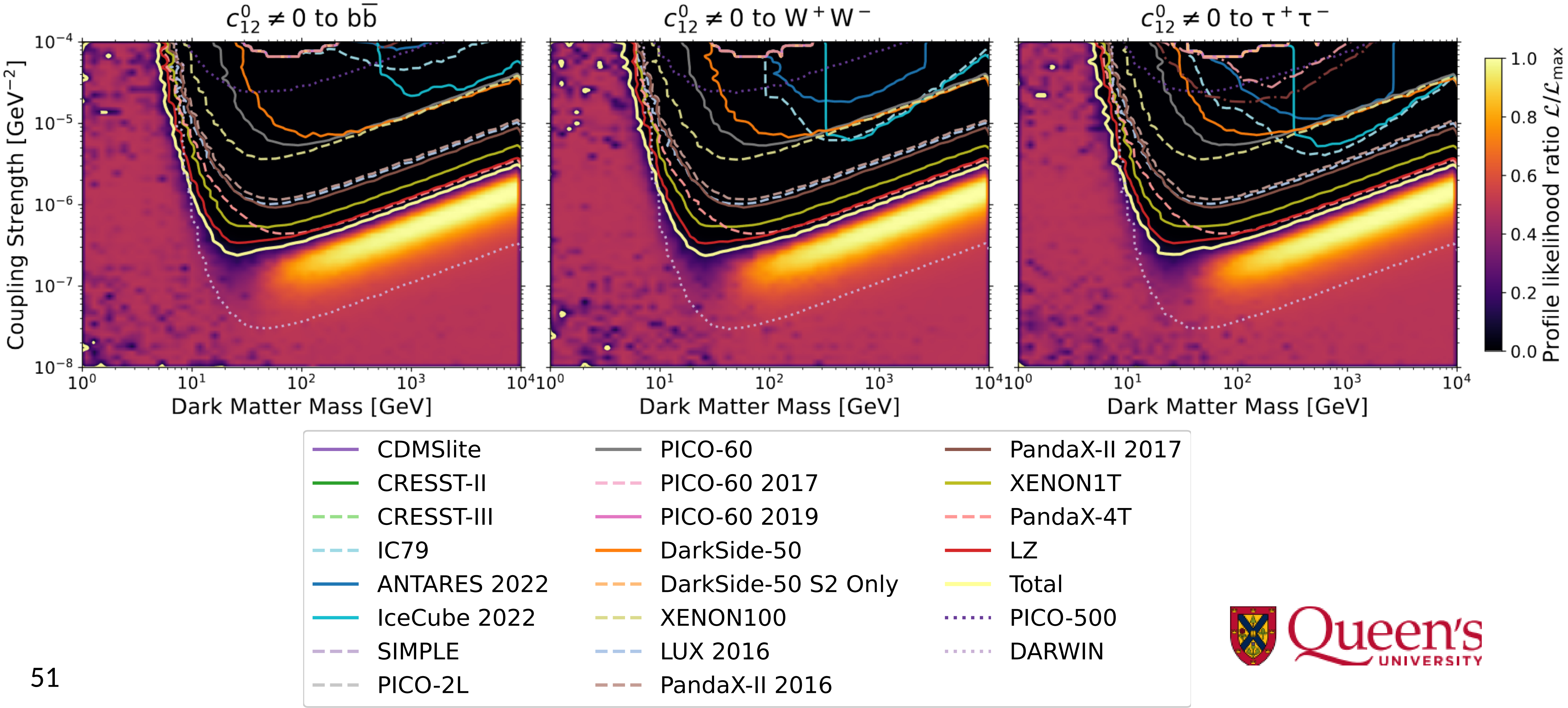
c_{10} Channels



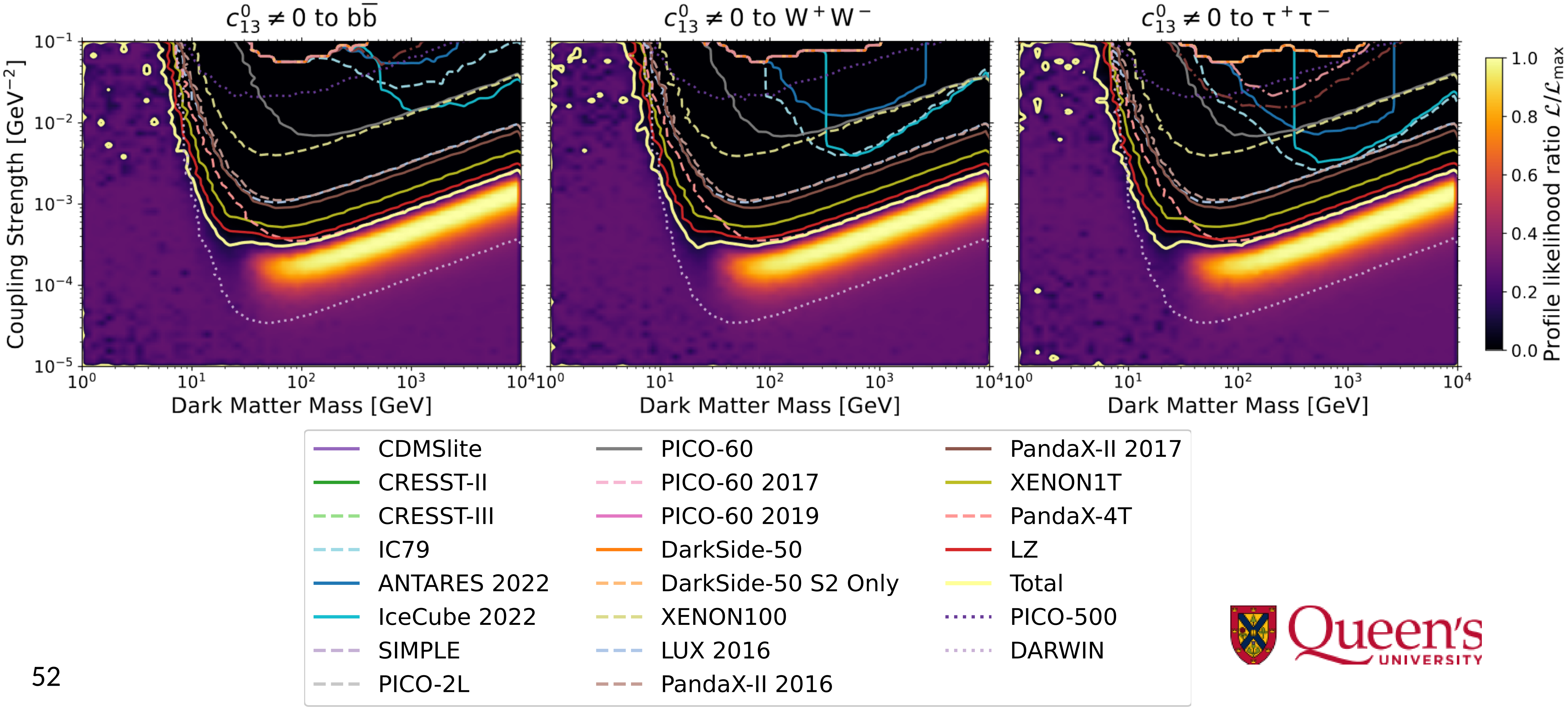
c_{11} Channels



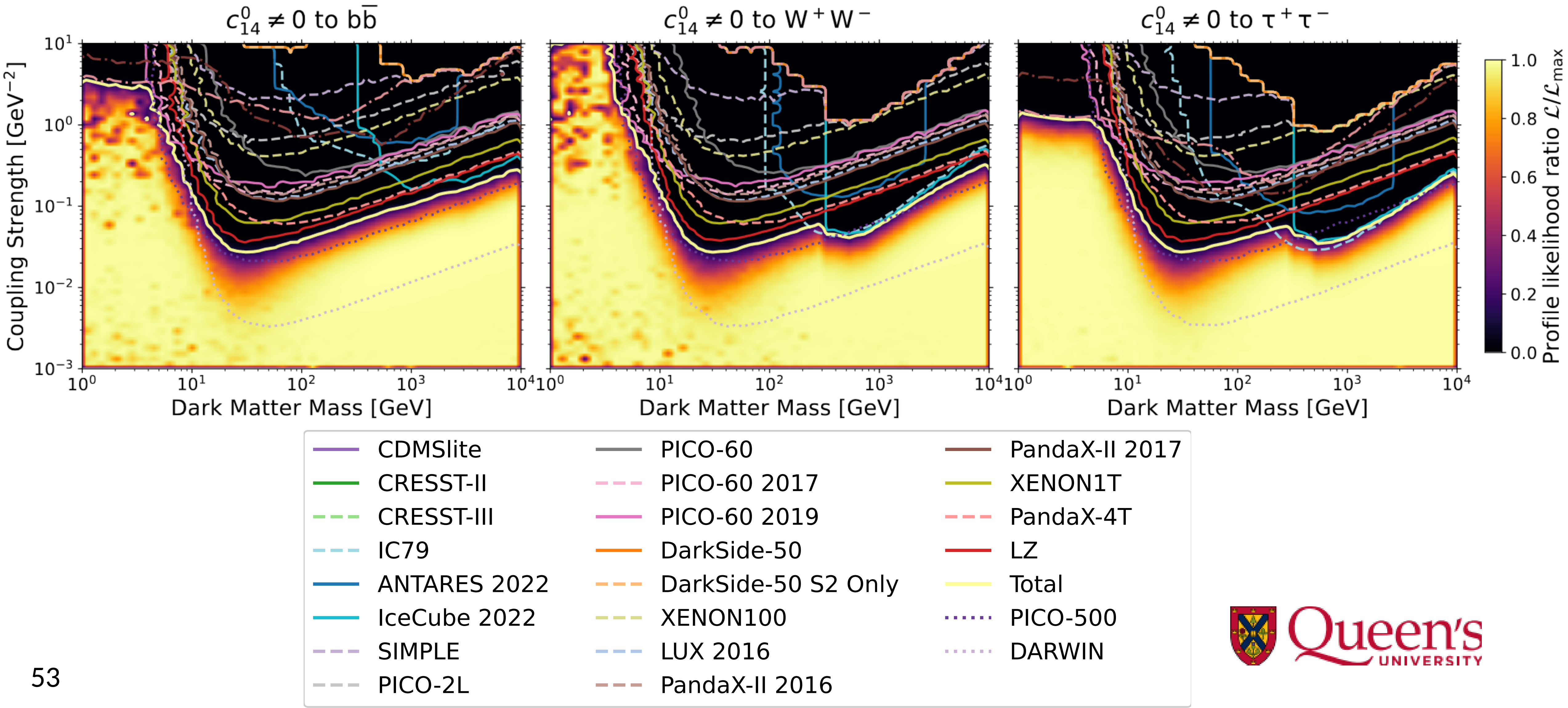
c_{12} Channels



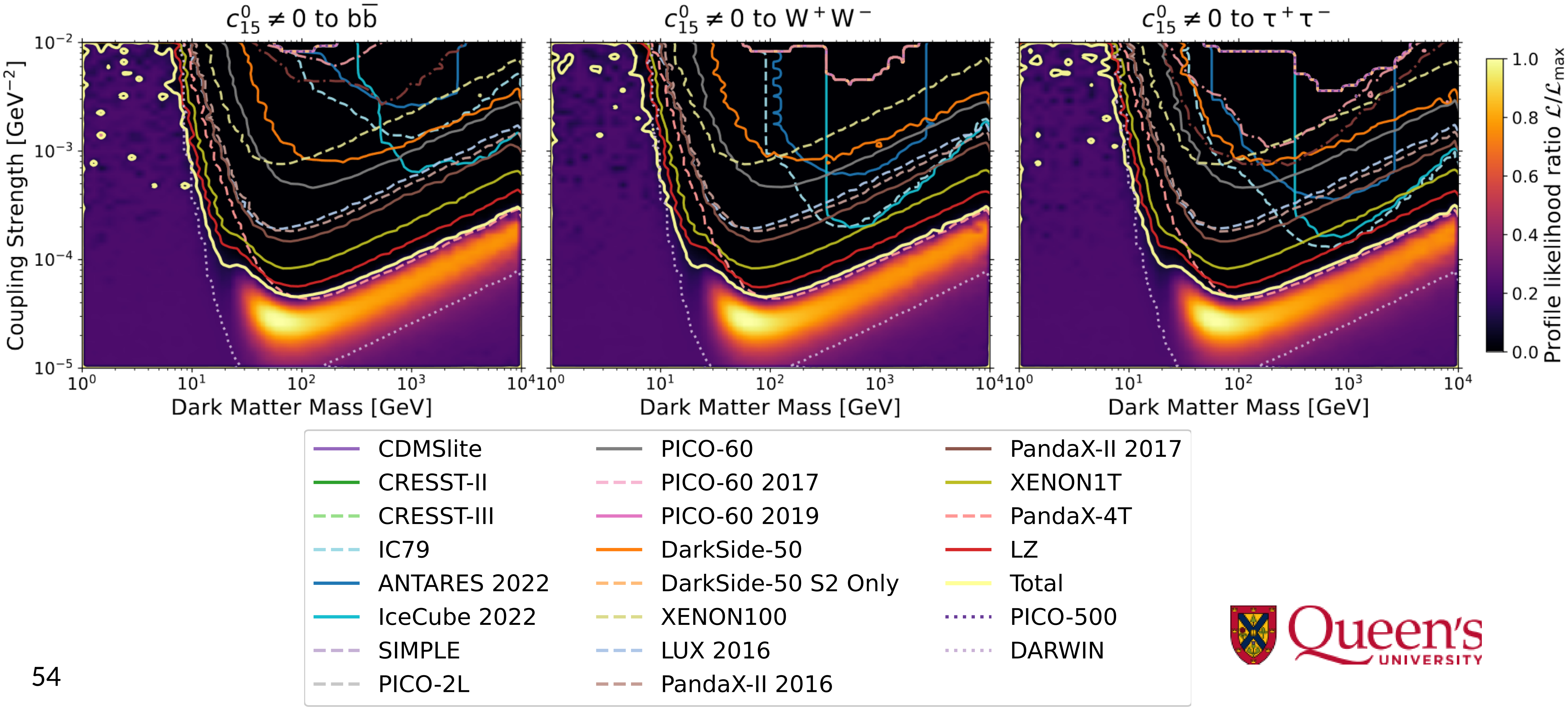
c_{13} Channels



c_{14} Channels



c_{15} Channels



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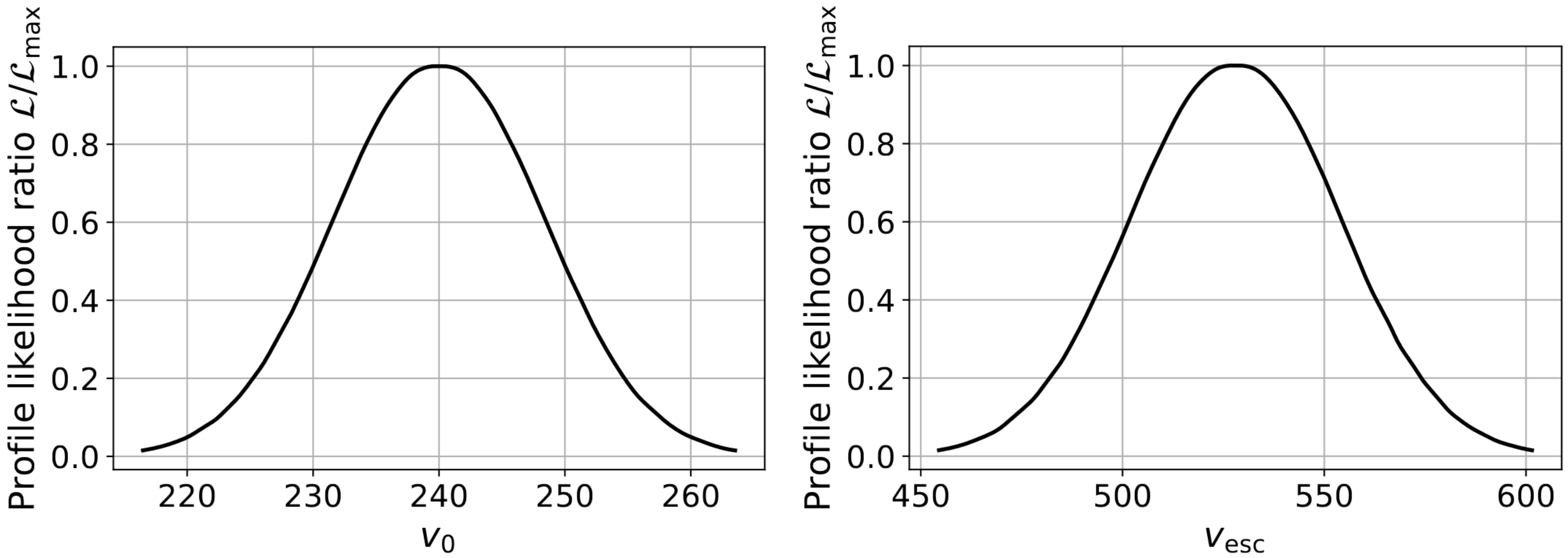
Nuisance Parameters

- The nuisance parameters showed no preference



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