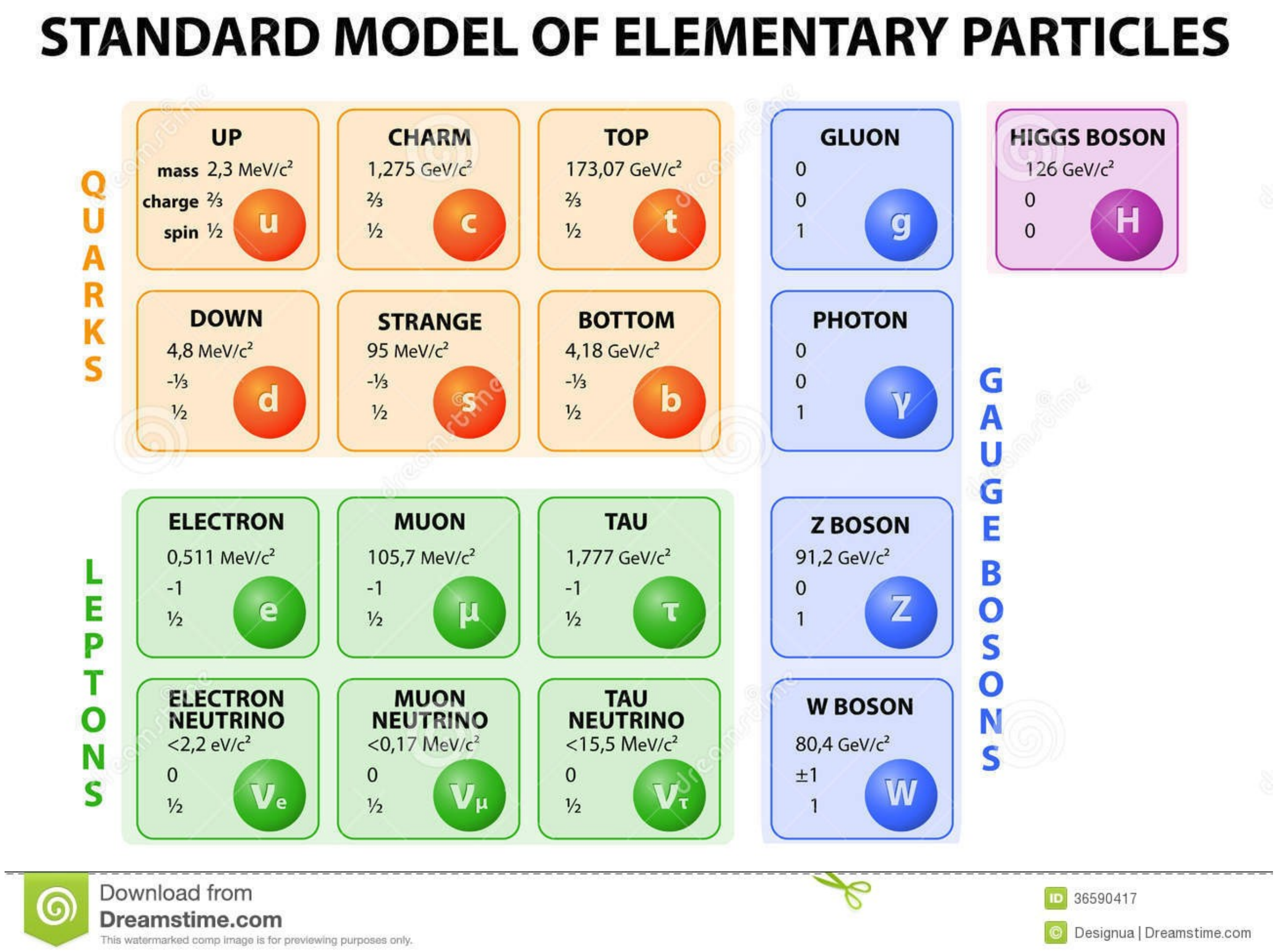
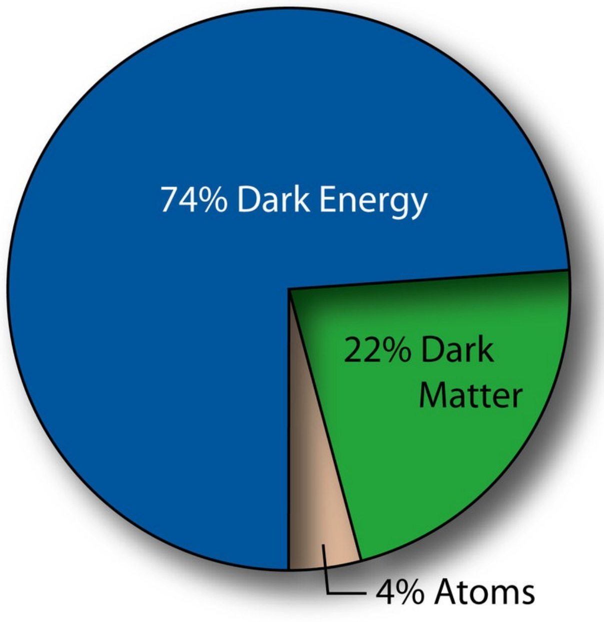
CTAO sensitivity for realistic dark matter models

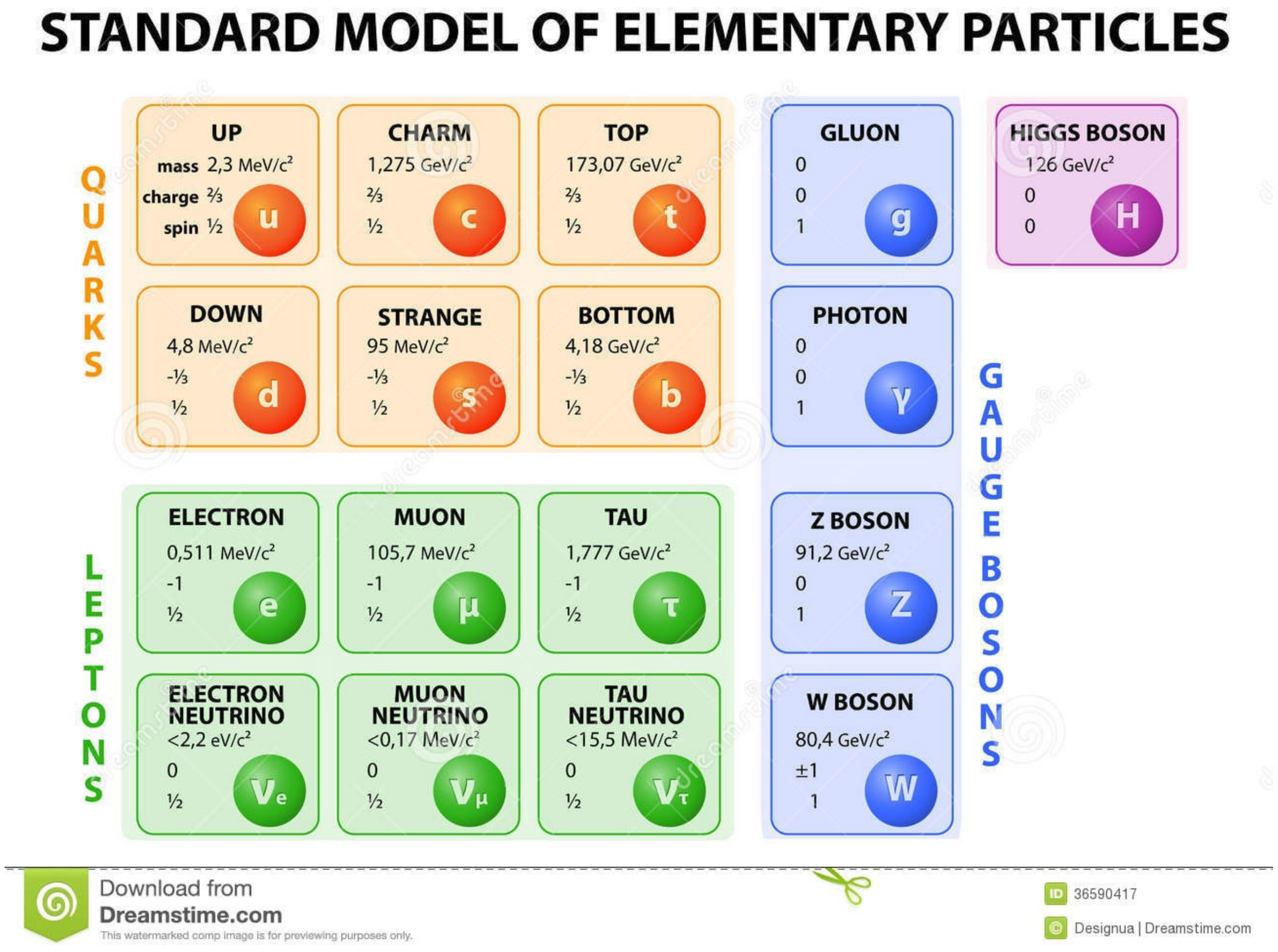
Martin White
(forthcoming work with Emmanuel Moulin, Igor Reis, Andre Scaffidi)

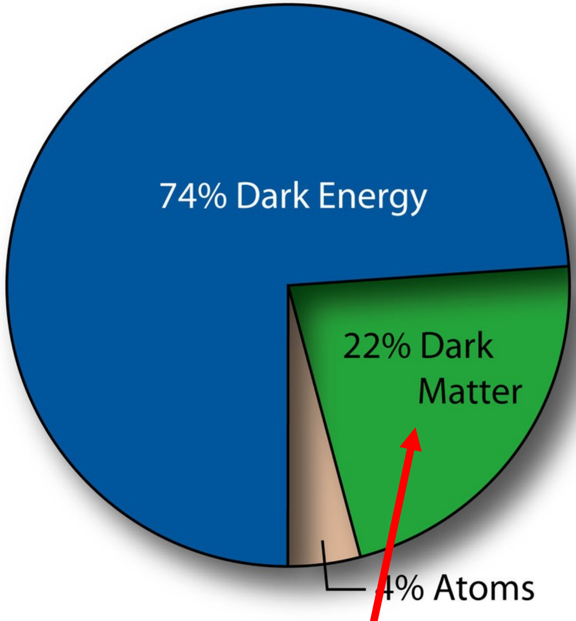
What we know and don't know





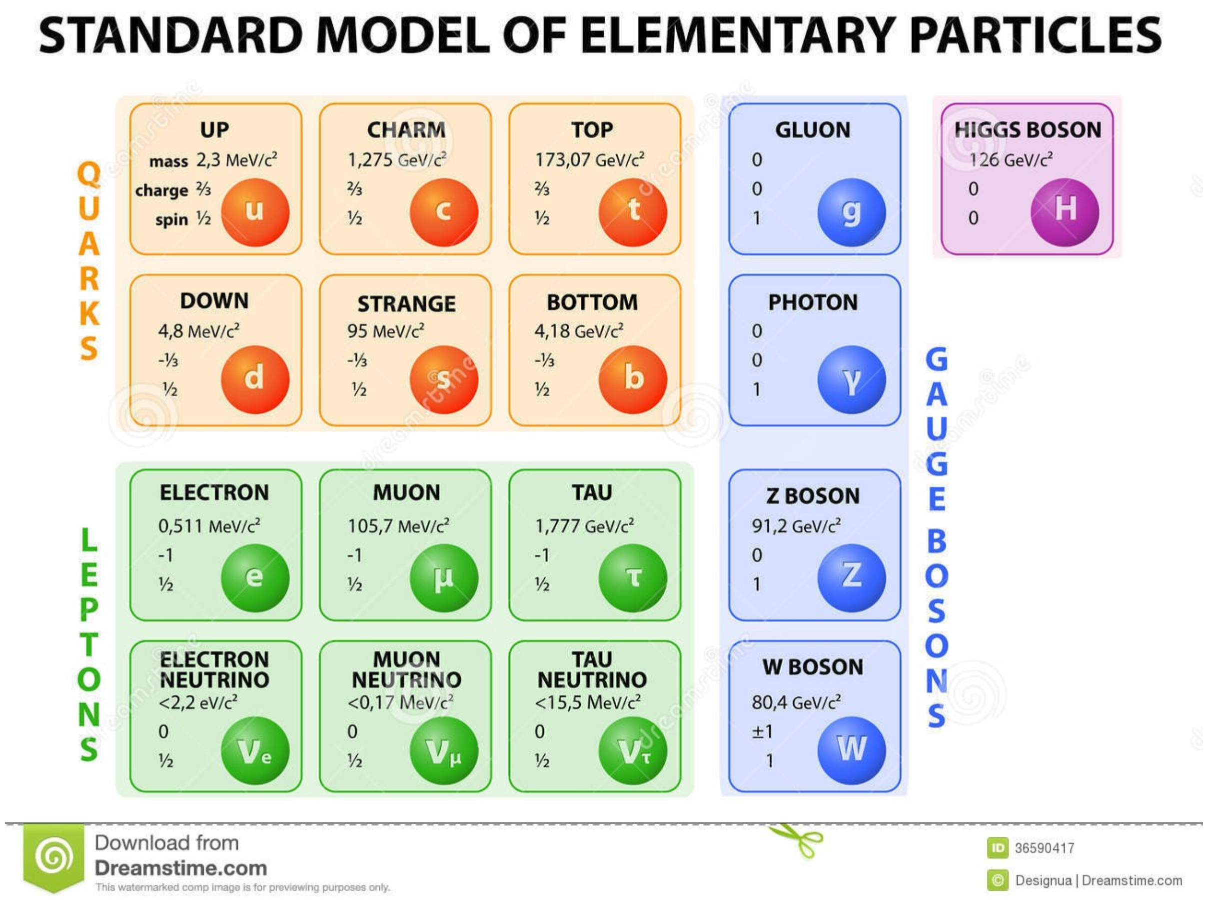
What we know and don’t know





Need beyond-Standard Model (BSM) physics...

The Standard Model in full detail

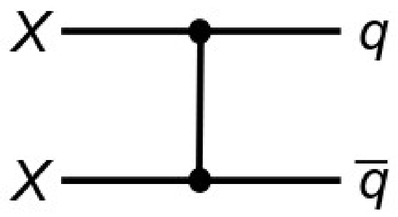


1 $$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
2 $$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} +$$
$$\frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] -$$
$$\frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4 H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] -$$
$$g M W^+_\mu W^-_\mu H - \frac{1}{2} g \frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) -$$
$$W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ -$$
$$\phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) +$$
$$i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \frac{1 - 2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$$
$$i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] -$$
$$\frac{1}{4} g^2 \frac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- +$$
$$W^-_\mu \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- +$$
$$W^-_\mu \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j -$$
3 $$\bar{d}^\lambda_j (\gamma\partial + m_d^\lambda) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\frac{4}{3}s_w^2 -$$
$$1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d^\lambda_j)] + \frac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) +$$
$$(\bar{u}^\lambda_j \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \frac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 +$$
$$\gamma^5) u^\lambda_j)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] -$$
4 $$\frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) +$$
$$m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \gamma^5) d^\kappa_j] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 -$$
$$\gamma^5) u^\kappa_j] - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 -$$
5 $$\frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- -$$
$$\partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y -$$
$$\partial_\mu \bar{Y} X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ -$$
$$\partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] +$$
$$\frac{1 - 2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] +$$
$$i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]$$

The “WIMP miracle”

- Get correct thermal relic abundance for DM with weak annihilation cross-section and mass ~100 GeV

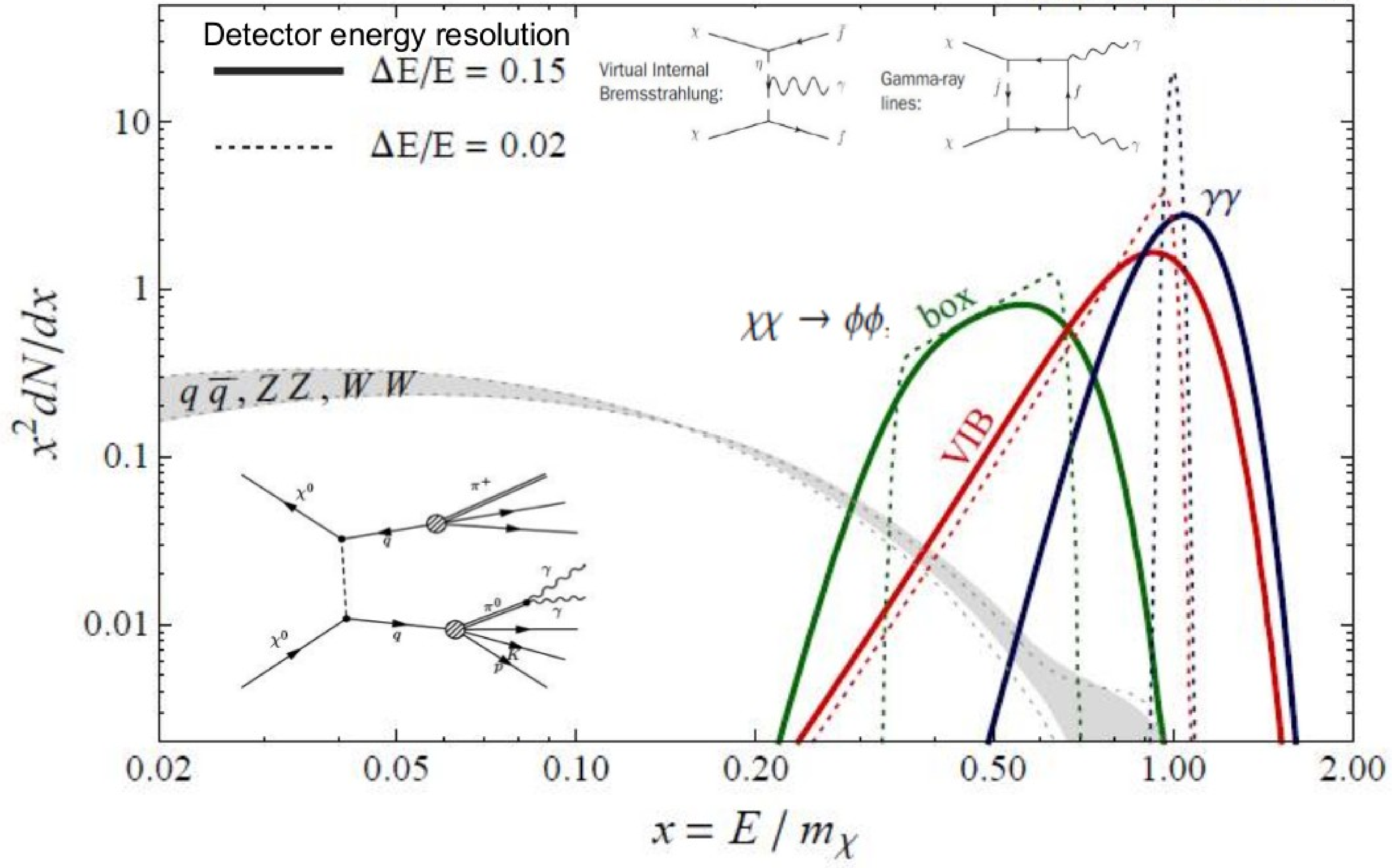
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



- Note: Need to measure $\langle \sigma v \rangle$ to rule out WIMP hypothesis

How does CTA see WIMPs?

Bringmann & Weniger (2012)



Making a WIMP theory

- Many theoretical options exist

- Bottom up approach: simply add particles to SM by hand, stabilise with a Z_2 symmetry

e.g. Scalar singlet DM

$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S.$$

See e.g.
1907.06485,
1808.10465,
1705.07931,
1512.06458

- Top down approach: take a BSM model and exploit particles with the right properties

e.g. supersymmetric models, universal extra dimensions, little Higgs, some composite Higgs theories, etc

See e.g.
2309.05709,
2303.09082,
1809.02097,
1705.07917,
1705.07935

A very general approach to DM

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm int} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi$$

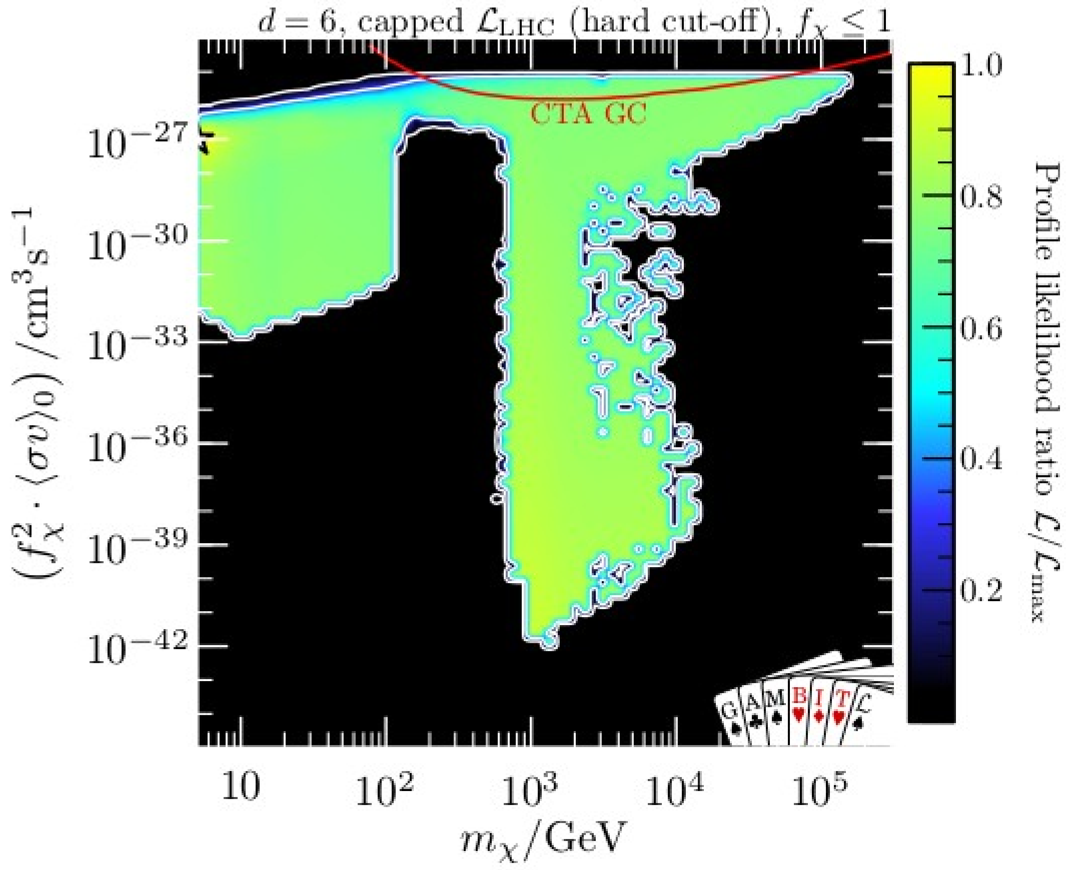
$$\mathcal{L}_{\rm int} = \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)}$$

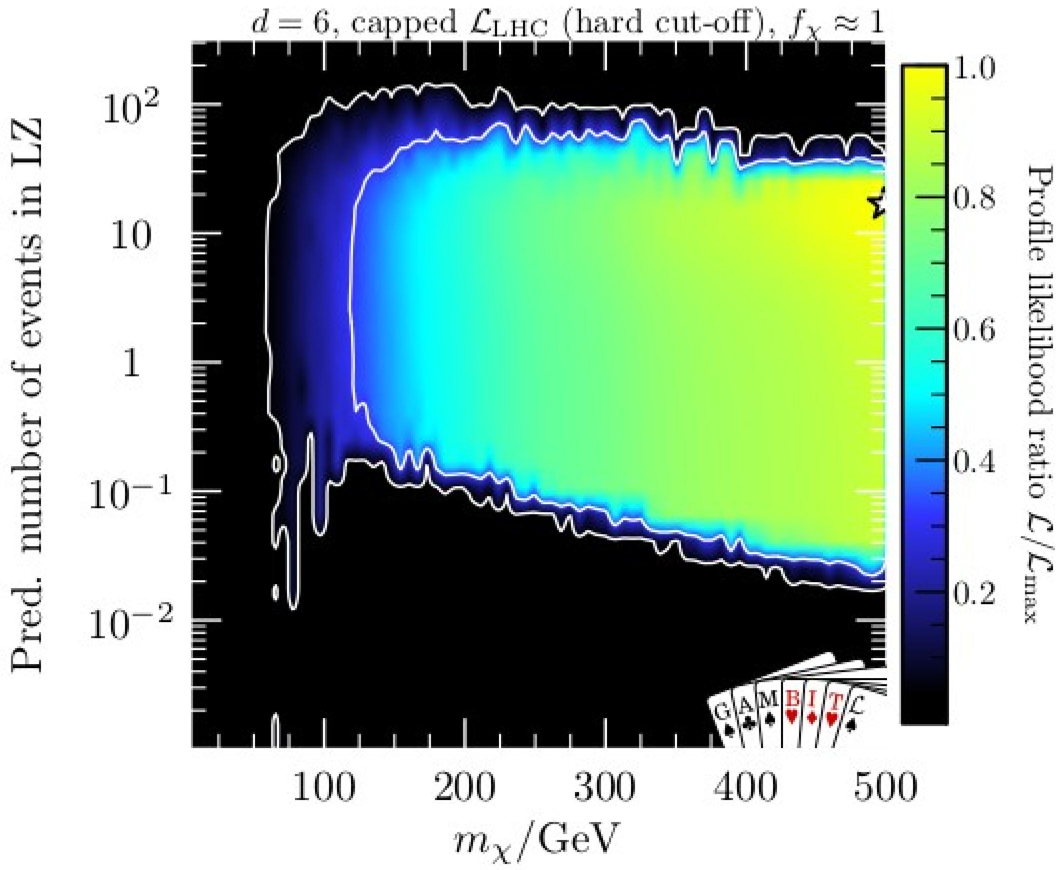
$$\mathcal{Q}_{1,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}_{2,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}_{3,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,,$$
$$\mathcal{Q}_{4,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)$$

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$
$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$
$$\mathcal{Q}_{5,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}q)\,,$$
$$\mathcal{Q}_{6,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}q)\,,$$
$$\mathcal{Q}_{7,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{8,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{9,q}^{(7)} = m_q(\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu}q)\,,$$
$$\mathcal{Q}_{10,q}^{(7)} = m_q(\overline{\chi}i\sigma^{\mu\nu}\gamma_5\chi)(\overline{q}\sigma_{\mu\nu}q)\,.$$

- Assume Dirac fermion gauge-singlet DM, write all allowed operators that connect DM with SM fields – Effective Field Theory (EFT)
- Note EFTs differ below and above EW scale, and are matched at that scale
- Ignore dim-6 operators with lepton interactions, also ignore operators with products of DM and Higgs currents above EW scale
- Drop additional dim-7 operators with derivatives (redundant information)

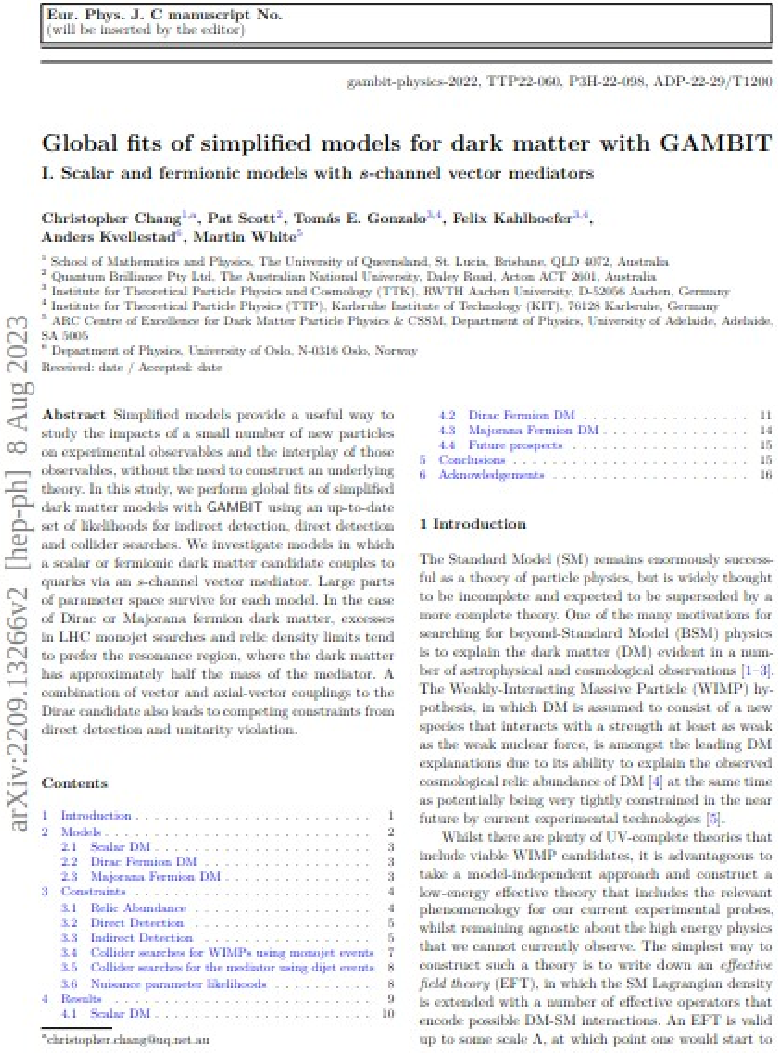
GAMBIT scan





https://arxiv.org/abs/2106.02056

Beyond DM EFT: simplified models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Global fits of simplified models for dark matter with GAMBIT

I. Scalar and fermionic models with s-channel vector mediators

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Abstract Simplified models provide a useful way to study the impacts of a small number of new particles on experimental observables and the interplay of those observables, without the need to construct an underlying theory. In this study, we perform global fits of simplified dark matter models with GAMBIT using an up-to-date set of likelihoods for indirect detection, direct detection and collider searches. We investigate models in which a scalar or fermionic dark matter candidate couples to quarks via an s-channel vector mediator. Large parts of parameter space survive for each model. In the case of Dirac or Majorana fermion dark matter, excesses in LHC monojet searches and relic density limits tend to prefer the resonance region, where the dark matter has approximately half the mass of the mediator. A combination of vector and axial-vector couplings to the Dirac candidate also leads to competing constraints from direct detection and unitarity violation.

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1 Introduction

The Standard Model (SM) remains enormously successful as a theory of particle physics, but is widely thought to be incomplete and expected to be superseded by a more complete theory. One of the many motivations for searching for beyond-Standard Model (BSM) physics is to explain the dark matter (DM) evident in a number of astrophysical and cosmological observations [1–3]. The Weakly-Interacting Massive Particle (WIMP) hypothesis, in which DM is assumed to consist of a new species that interacts with a strength at least as weak as the weak nuclear force, is amongst the leading DM explanations due to its ability to explain the observed cosmological relic abundance of DM [4] at the same time as potentially being very tightly constrained in the near future by current experimental technologies [5].

Whilst there are plenty of UV-complete theories that include viable WIMP candidates, it is advantageous to take a model-independent approach and construct a low-energy effective theory that includes the relevant phenomenology for our current experimental probes, whilst remaining agnostic about the high energy physics that we cannot currently observe. The simplest way to construct such a theory is to write down an *effective field theory* (EFT), in which the SM Lagrangian density is extended with a number of effective operators that encode possible DM-SM interactions. An EFT is valid up to some scale Λ, at which point one would start to

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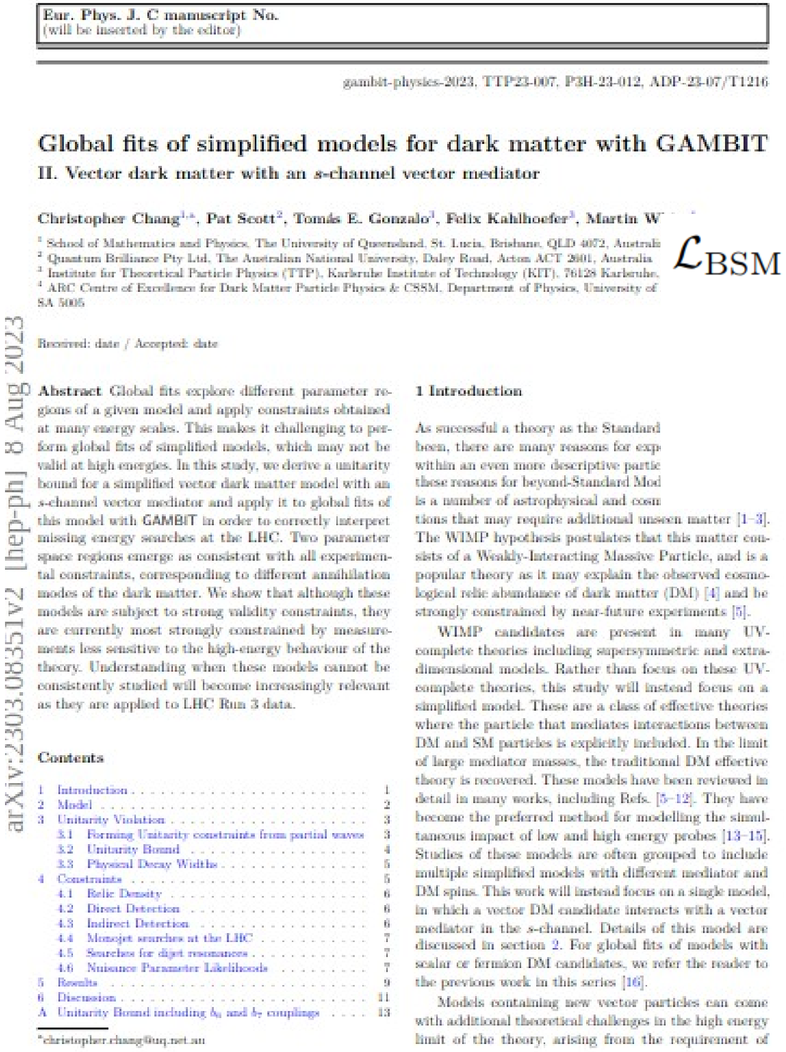
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gambit-physics-2023, TTP23-007, P3H-23-012, ADP-23-07/T1216

Global fits of simplified models for dark matter with GAMBIT

II. Vector dark matter with an s-channel vector mediator

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Abstract Global fits explore different parameter regions of a given model and apply constraints obtained at many energy scales. This makes it challenging to perform global fits of simplified models, which may not be valid at high energies. In this study, we derive a unitarity bound for a simplified vector dark matter model with an s-channel vector mediator and apply it to global fits of this model with GAMBIT in order to correctly interpret missing energy searches at the LHC. Two parameter space regions emerge as consistent with all experimental constraints, corresponding to different annihilation modes of the dark matter. We show that although these models are subject to strong validity constraints, they are currently most strongly constrained by measurements less sensitive to the high-energy behaviour of the theory. Understanding when these models cannot be consistently studied will become increasingly relevant as they are applied to LHC Run 3 data.

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1 Introduction

As successful a theory as the Standard been, there are many reasons for exp within an even more descriptive partic these reasons for beyond-Standard Mod is a number of astrophysical and cosm tions that may require additional unseen matter [1–3]. The WIMP hypothesis postulates that this matter consists of a Weakly-Interacting Massive Particle, and is a popular theory as it may explain the observed cosmological relic abundance of dark matter (DM) [4] and be strongly constrained by near-future experiments [5].

WIMP candidates are present in many UV-complete theories including supersymmetric and extra-dimensional models. Rather than focus on these UV-complete theories, this study will instead focus on a simplified model. These are a class of effective theories where the particle that mediates interactions between DM and SM particles is explicitly included. In the limit of large mediator masses, the traditional DM effective theory is recovered. These models have been reviewed in detail in many works, including Refs. [5–12]. They have become the preferred method for modelling the simultaneous impact of low and high energy probes [13–15]. Studies of these models are often grouped to include multiple simplified models with different mediator and DM spins. This work will instead focus on a single model, in which a vector DM candidate interacts with a vector mediator in the s-channel. Details of this model are discussed in section 2. For global fits of models with scalar or fermion DM candidates, we refer the reader to the previous work in this series [16].

Models containing new vector particles can come with additional theoretical challenges in the high energy limit of the theory, arising from the requirement of

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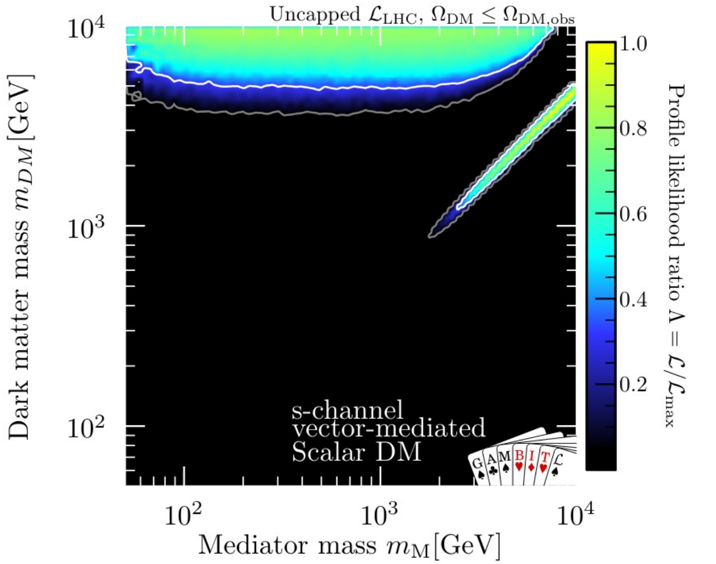
$$\mathcal{L}_{\rm BSM} = \partial_\mu\phi^\dagger\partial^\mu\phi - m_{\rm DM}^2\phi^\dagger\phi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_{\rm M}^2V_\mu V^\mu + g_{\rm q}V_\mu\bar{q}\gamma^\mu q + ig_{\rm DM}^{\rm V}V_\mu\left(\phi^\dagger(\partial^\mu\phi) - (\partial^\mu\phi^\dagger)\phi\right),$$



DM reach at CTA

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Sensitivity of the Cherenkov Telescope Array to the detection of a dark matter signal in comparison to direct detection and collider experiments

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Imaging atmospheric Cherenkov telescopes (IACTs) that are sensitive to potential γ-ray signals from dark matter (DM) annihilation above $\sim 50\,\mathrm{GeV}$ will soon be superseded by the Cherenkov Telescope Array (CTA). CTA will have a point source sensitivity an order of magnitude better than currently operating IACTs and will cover a broad energy range between 20 GeV and 300 TeV. Using effective field theory and simplified models to calculate γ-ray spectra resulting from DM annihilation, we compare the prospects to constrain such models with CTA observations of the Galactic center with current and near-future measurements at the Large Hadron Collider (LHC) and direct detection experiments. For DM annihilations via vector or pseudoscalar couplings, CTA observations will be able to probe DM models out of reach of the LHC, and, if DM is coupled to standard fermions by a pseudoscalar particle, beyond the limits of current direct detection experiments.

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I. INTRODUCTION

Astrophysical evidence suggests that 84 % of the matter in the Universe is composed of cold dark matter (DM) [1]. New particles beyond the Standard Model (SM) might constitute the entirety of DM, but the characteristics of such particles and their interactions with the SM remain unknown. One widely studied candidate is a *weakly interacting massive particle* (WIMP). According to the so-called WIMP miracle, if DM consists of such particles with masses of the order of TeV and weak scale interactions, they could provide the right DM relic abundance [2].

A large number of experiments are searching for DM using essentially three different approaches. Direct detection (DD) looks for recoils caused by nucleon-WIMP scattering. Different collaborations have used different target materials such as liquid xenon (XENON, LUX, or PandaX experiments [3–5]) or solid state detectors (Ge: CDMS, CoGeNT, NaI: DAMA [6–8]). See Ref. [9] for a recent review. In collider searches, DM could be produced in the collisions of SM particles and manifest itself as missing energy in the final state. The ATLAS and CMS experiments at the Large Hadron Collider (LHC) continue to search for such signatures [10–15]. The third approach is indirect detection (ID) where one searches for SM particles as a result of DM decay or annihilation from astrophysical objects which should harbor a large amount of DM (we focus on DM annihilation in this work). Examples are the IceCube telescope, which looks for neutrinos [16, 17], AMS, which measures charged cosmic rays [18, 19], as well as the *Fermi* Large Area Telescope (LAT) and imaging air Cherenkov telescopes (IACTs) such as H.E.S.S., VERITAS, and MAGIC that are sensitive to high and very high energy γ rays, respectively [20–28].

To compare constraints from these different experiments and approaches, one has to invoke an underlying theory of the DM interaction. Effective field theories (EFTs) and simplified models provide such a framework in a generic way. In EFTs, the only additional degree of freedom is the DM particle. Any fields mediating be-

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- DM EFTs and simplified models were previously explored in a CTA context by Csaba and collaborators in 2017
- Lots of things have changed in the last 7 years
  - - changes to the CTA analysis
  - - changes to the astrophysical background models
  - - new knowledge of DM spatial and velocity distributions from Fire-II numerical simulations
  - - LHC and direct search limits have changed
- **It's a good time to revisit the CTA reach for DM effective field theories and simplified models…**

EFT (notation changed to match Csaba)

$$\mathcal{O}_S = \frac{m_q}{M_\star^3}(\bar{\chi}\chi)(\bar{q}q),$$

$$\mathcal{O}_P = \frac{m_q}{M_\star^3}(\bar{\chi}\gamma^5\chi)(\bar{q}\gamma^5 q),$$

$$\mathcal{O}_V = \frac{1}{M_\star^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q),$$

$$\mathcal{O}_A = \frac{1}{M_\star^2}(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q),$$

- These operators cover a range of interesting behaviour at CTA

EFT annihilation cross-sections

$$\langle \sigma v \rangle_{\mathcal{O}_S} = \sum_q \Theta(m_\chi - m_q) \frac{m_q^2}{M_\star^6} \frac{3m_\chi^2}{8\pi} \left(1 - \frac{m_q^2}{m_\chi^2}\right)^{3/2} v^2.,$$

$$\langle \sigma v \rangle_{\mathcal{O}_A} = \sum_q \Theta(m_\chi - m_q) \frac{1}{M_\star^4} \frac{m_\chi^2}{4\pi} \sqrt{1 - \frac{m_q^2}{m_\chi^2}} \times \left(6\frac{m_q^2}{m_\chi^2} + \frac{8 - 22m_q^2/m_\chi^2 + 17m_q^4/m_\chi^4}{4\left(1 - m_q^2/m_\chi^2\right)} v^2\right),$$

$$\langle \sigma v \rangle_{\mathcal{O}_P} = \sum_q \Theta(m_\chi - m_q) \frac{m_q^2}{M_\star^6} \frac{3m_\chi^2}{16\pi} \sqrt{1 - \frac{m_q^2}{m_\chi^2}} \times \left(8 + \frac{2 - m_q^2/m_\chi^2}{1 - m_q^2/m_\chi^2} v^2\right), \tag{2.6}$$

$$\langle \sigma v \rangle_{\mathcal{O}_V} = \sum_q \Theta(m_\chi - m_q) \frac{1}{M_\star^4} \frac{m_\chi^2}{2\pi} \sqrt{1 - \frac{m_q^2}{m_\chi^2}} \times \left(6 + 3\frac{m_q^2}{m_\chi^2} + \frac{8 - 4m_q^2/m_\chi^2 + 5m_q^4/m_\chi^4}{8\left(1 - m_q^2/m_\chi^2\right)} v^2\right),$$

$$, \tag{2.7}$$

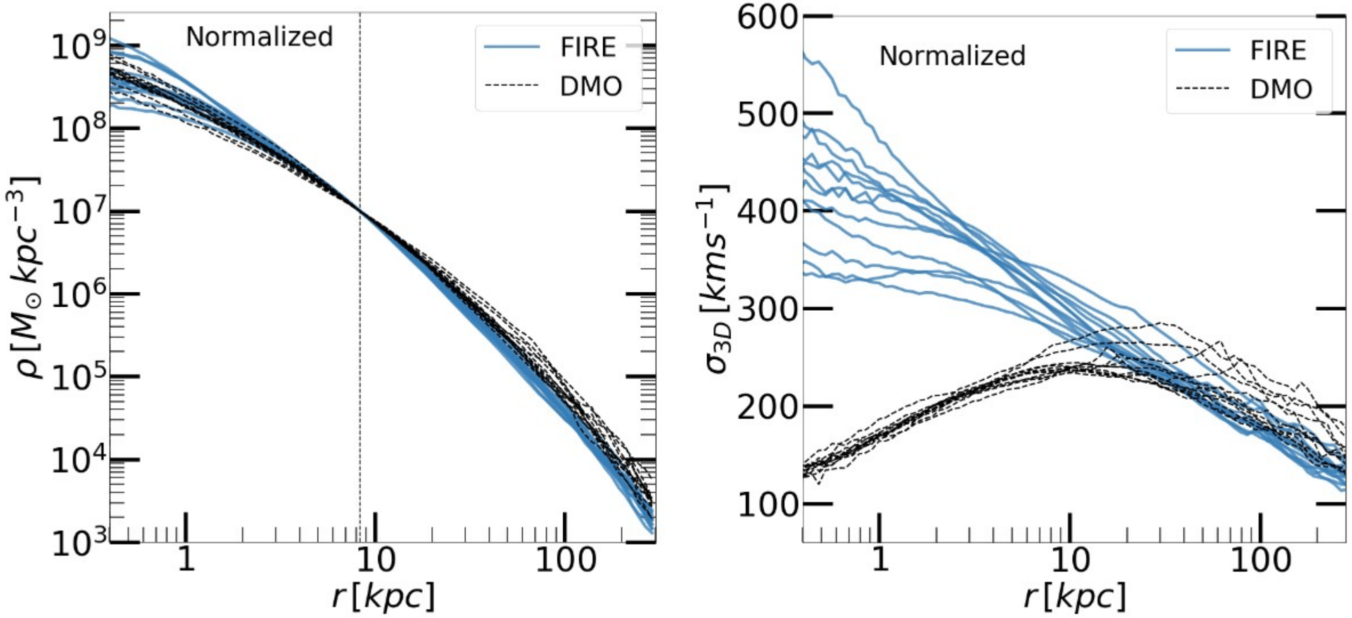
Photon flux

$$\frac{d^2\Phi}{dEd\Omega}(E,\Omega) = \frac{\langle \sigma v \rangle}{4\pi\epsilon\, m_\chi^2} \sum_f \mathrm{BR}_f \frac{dN_f}{dE}(E)\, \frac{dJ_n}{d\Omega}$$

$$\frac{dJ_n}{d\Omega} = \int_{\mathrm{los}} ds\, \rho_\chi^2(r[s,\theta]) \times \int d^3 v_\chi\, g_r(v_\chi) \int d^3 v_{\bar\chi}\, g_r(v_{\bar\chi}) \frac{|\vec{v_\chi} - \vec{v_{\bar\chi}}|^n}{c^n},$$

$$\langle \sigma v \rangle = A + Bv^2, \quad \longrightarrow \quad \frac{d^2\Phi}{dEd\Omega}(E,\Omega) = \frac{1}{16\pi\, m_\chi^2} \sum_q \mathrm{BR}_q \frac{dN_q}{dE}\left(A_q \frac{dJ_0}{d\Omega} + B_q v^2 \frac{dJ_2}{d\Omega}\right),$$

J factors



https://arxiv.org/abs/2111.03076

- Leading source of uncertainty on gamma ray yields
- Recent hydrodynamical simulations incorporating the effects of baryonic feedback have led to new predictions of the DM density profile and 3D velocity dispersion
- Can perform a correct treatment of the J factors for s-wave and p-wave annihilation processes

CTA analysis

- Focus on 5° region around the Galactic Centre (GC)
- 500 hour observation time
- Divide into regions of interest (concentric annuli of 0.1° width around GC)
- Residual background taken from IRFs of CTA southern hemisphere site
- Masks applied for a variety of known sources, plus ±0.3° covering galactic plane

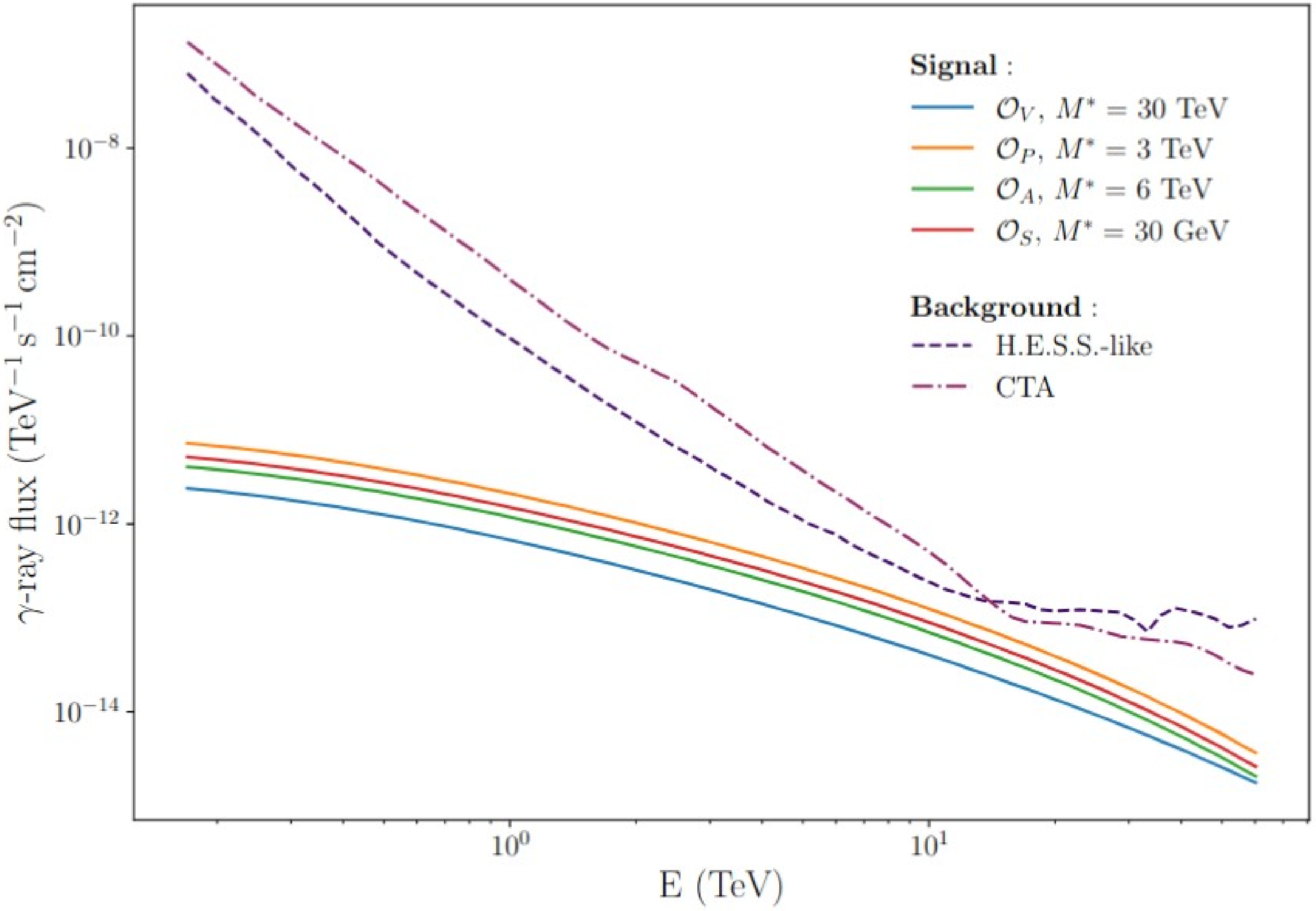
$$N_{ij}^{S} = T_{\mathrm{obs},i} \int_{E_j-\Delta E_j/2}^{E_j+\Delta E_j/2} dE \int_{-\infty}^{\infty} dE' \, \frac{d\Phi_{ij}^{S}}{dE'}(\Delta\Omega_i, E') \, A_{\mathrm{eff}}^{\gamma}(E') \, G(E-E'),$$

Total observation time

Effective area

Energy resolution

EFT flux and backgrounds (1 TeV WIMP)



Statistical treatment for limits

$$\mathcal{L}_{ij}(N^S_{ij}, N^B_{ij}, N^{\rm CR}_{ij}, \bar{N}^S_{ij}, \bar{N}^B_{ij}, \beta_{ij} \,|\, N^{\rm ON}_{ij}, N^{\rm OFF}_{ij}) = \ \mathrm{Pois}[\beta_{ij}(N^S_{,ij} + N^B_{ij} + N^{\rm CR}_{ij}), N^{\rm ON}_{ij}]$$

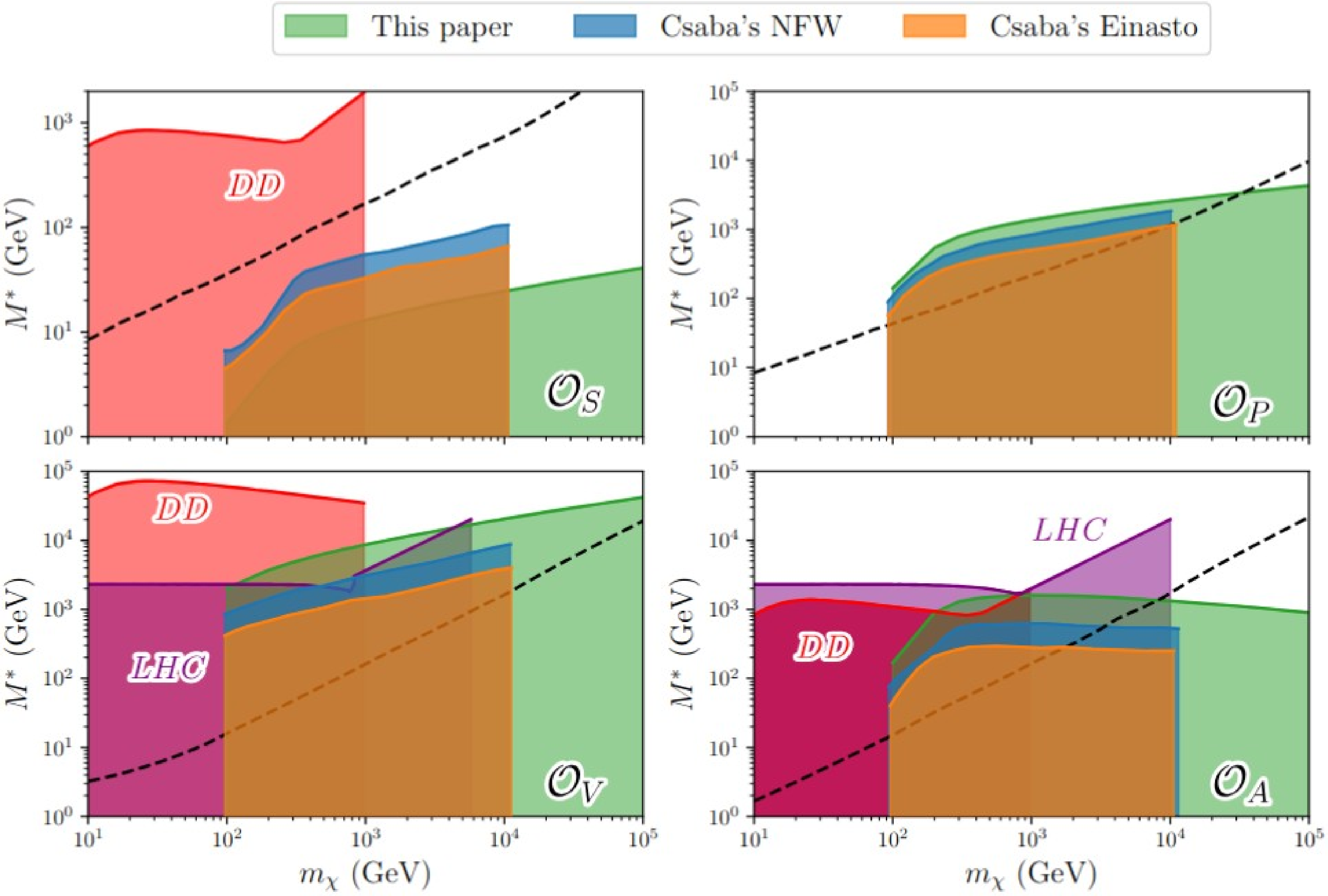
$$\times\ \mathrm{Pois}[\beta_{ij}(\bar{N}^S_{ij} + \bar{N}^B_{ij} + \alpha_i N^{\rm CR}_{ij}), N^{\rm OFF}_{ij}] (4.2)$$

where $\mathrm{Pois}[\lambda, n] = e^{-\lambda}\lambda^n/n!$. N^{ON}_{ij} and N^{OFF}_{ij} are the number of events observed in the On and OFF regions, binned in i spatial and j energetic bins. N^S_{ij} and $\bar{N}^S_{ij}$ represent the expected signal in the ON and OFF regions, respectively. Similarly, N^B_{ij} and $\bar{N}^B_{ij}$ stands for the background in the ON and OFF regions. Since the residual background used in this analysis comes from Monte Carlo $\mathcal{L}_{ij}$, such as $\mathcal{L} = \prod_{\rm ij} \mathcal{L}_{\rm ij}$. that the signal in the OFF regions is zero, and therefore $\bar{N}^S_{ij} = 0$.

$$\mathcal{L} = \prod_{\rm ij} \mathcal{L}_{\rm ij}.$$

$$\mathrm{TS}(m_\chi) = -2 \ln \frac{\mathcal{L}(M^*, m_\chi)}{\mathcal{L}(\widehat{M^*}, m_\chi)},$$

Preliminary results



Summary

- We're in the process of updating the CTA reach for realistic dark matter theories (effective field theory and simplified models)
- Have shown EFT results today – these are complementary to LHC and direct detection constraints, and can probe different regions
- The new J factors from the FIRE II simulations have a significant impact on the results
- Note: there is a nice follow up study here using GammaBayes – need to chat to/share code with Liam, Csaba and Eric!